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October 1983

Dear Colleague:

We are pleased to enclose Chapter 4, Biologic and Microbiologic Quality of Surface and Ground Water, and Chapter 8, Evaporation and Transpiration, of the "National Handbook of Recommended Methods for Water-Data Acquisition."

Once you add the two chapters we are sending you today to the parts of the Handbook we have sent you before, your Handbook should contain the following:

2 Binders
13 Dividers (Chapters 1-12 and Appendix)
Introduction, dated Rev. 7/80
Chapter 1, dated 8/80
Chapter 2, dated 1/80 (except Page 128, dated Rev. 8/81)
Chapter 3, dated 6/78
Chapter 4, dated 5/83
Chapter 5, dated 1/77 (except various pages, dated Rev. 1/78 and Rev. 4/79)
Chapter 6, dated 1/82
Chapter 7, dated 6/78 (except Page 18, dated Rev. 8/81)
Chapter 8, dated 6/82
Chapter 9, dated 12/79 (except Page 13, dated Rev. 8/81)
Chapter 10, dated 1/80

Chapters 11 and 12 and the Appendix will be released in the future.

To bring your Handbook up-to-date, you can request needed copies of printed chapters or revisions by writing to the above address or by calling 703/860-6935 (FTS 928-6935).

To ensure that you automatically receive future chapters and updates, please notify us of any change or correction of address.

Sincerely yours,

Porter E. Ward

Porter E. Ward, Chief
Office of Water Data Coordination

Enclosures:
Chapter 4
Chapter 8

To: All Users of the "National Handbook of Recommended Methods for Water-Data Acquisition"

The U.S. Geological Survey (USGS) recently published a comprehensive description of state-of-the-art standardized streamgaging procedures. The report is intended to be a training guide and reference, primarily for engineers and technicians in USGS, but it is also appropriate for other streamgaging practitioners, both in the United States and elsewhere. People who use Chapter 1, Surface Water, of the National Handbook should find the new report, called "Measurement and Computation of Streamflow," by S. E. Rantz and others, a valuable source of information.

The report, published as USGS Water-Supply Paper 2175, is for sale by the U.S. Government Printing Office. If you would like to purchase a copy, write to:

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national handbook of recommended methods for water-data acquisition

prepared cooperatively by agencies of the United States Government

This handbook was prepared by representatives of Federal agencies working through The Interagency Advisory Committee on Water Data and The Interdepartmental Committee on Meteorological Services with the assistance and cooperation of non-Federal organizations through The Advisory Committee on Water Data for Public Use.

The handbook meets part of the general requirements for coordination of water data activities and meteorological services as specified in Office of Management and Budget Circulars Nos. A-67 and A-62.

national handbook of recommended methods for water-data acquisition

A UNITED STATES CONTRIBUTION TO THE
INTERNATIONAL HYDROLOGICAL PROGRAM

Prepared under the sponsorship of the
Office of Water Data Coordination
Geological Survey
U.S. Department of the Interior
Reston, Virginia

1977

NATIONAL HANDBOOK OF RECOMMENDED METHODS FOR WATER-DATA ACQUISITION

INTRODUCTION

The increased demand for water and the concern for the quality of the water resources of the United States logically has led to an increased demand for water-resources data. The search for appropriate data revealed numerous deficiencies in the data base, one of which was the difficulty of ascertaining the quality of existing data. Another deficiency was the lack of comparability and compatability of water data collected by different organizations. Many of these deficiencies were caused by the differences in methods used for collecting and handling data. The magnitude of these differences can be appreciated when it is realized that water data in the United States are collected by approximately 30 Federal agencies, hundreds of State, county, and city agencies, and an unknown number of other organizations.

In 1963 and 1964, the Office of Management and Budget issued circulars that called for coordinating certain Federal hydrologic activities. Circular A-62 (1963), prescribed policies and procedures for coordination of Federal meteorological services and Circular A-67 (1964) prescribed guidelines for coordinating Federal activities related to acquiring certain water data from streams, lakes, reservoirs, estuaries, and ground waters. To ensure that the hydrologic data encompassed by both circulars and collected by all agencies were of acceptable quality, an agreement was made among the collecting and using agencies to develop a set of recommended methods for measuring, sampling, and analyzing water, and processing hydrologic data. The purpose of the *National Handbook of Recommended Methods for Water-Data Acquisition* is to assure greater comparability, compatibility, and usability of water data by documenting the methodologies collectors and users of the hydrologic data agree to be most suitable, thereby providing a coordination mechanism for data acquisition.

SCOPE

The *National Handbook* presents the water-data acquisition methods recommended by a large sector of major U.S. water-data collectors and users. The continuously updated handbook includes field, laboratory, and office methods for acquiring and handling data related to the quantity and quality of water underground, and in streams, lakes, reservoirs, estuaries, and the atmosphere. Methods of acquiring data related to fluvial sediment, soil water, drainage-basin characteristics, evaporation and transpiration, and snow and ice are presented also. Descriptions of methods are given in detail only where references, manuals, or acceptable standards are not available. However, sufficient information is provided in each chapter for the user to evaluate and select the best method for obtaining desired data. Some of the chapters also include nomenclatures, definitions,

measurement units, precision and accuracy evaluations, quality-control procedures, and discussions of necessary equipment. To help locate more detailed information, references are given in each chapter.

The handbook consists of an introduction, 12 technical chapters, and an appendix. The appendix contains recommendations related to metric units, conversion factors, precision of metric measurements, and metric conversion of equipment for all measurements associated with hydrologic data. Following are brief descriptions of the contents of each technical chapter.

Chapter 1. Surface Water.—Methods for measuring river stage and flow, lake and reservoir level, and estuary stage and circulation are recommended. Direct and indirect techniques for measuring hydrologic variables such as flow velocity, depth, and direction are included. Proper care and use of equipment are discussed, and standard field installations and remote-sensing devices are described. Quality control techniques and computation of streamflow, lake, reservoir, and estuary records are discussed.

Chapter 2. Ground Water.—Methods are recommended for measuring hydrogeologic and hydrologic properties of ground-water flow systems. These measurements are used in resource appraisal and management. Included are detailed descriptions of equipment and test procedures for field and laboratory measurements of rock, fluid, and other flow-system properties.

Chapter 3. Sediment.—Methods related to collection and analysis of sediment data are described. Operation of various suspended-sediment and bed-material samplers is discussed, and the proper samplers for different conditions are recommended. Laboratory methods are recommended for analyzing suspended-sediment and bed-material samples. Methods for reservoir sedimentation surveys are included.

Chapter 4. Biologic and Microbiologic Quality of Surface and Ground Water.—Techniques for collecting, analyzing, and reporting data on biological and microbiological organisms and their constituents are recommened. Sampling equipment and sample preservation are described. Quantitative and qualitative measurements are included. Instruments and analytical methods required for certain sampling techniques are identified, and limitations on their capabilities are given.

Chapter 5. Chemical and Physical Quality of Water and Sediment.—Field and laboratory procedures for measuring inorganic, organic, and radioactive constituents in water and sediment are presented. The methods are applicable to atmospheric precipitation, to surface and ground water, to fresh and saline water, and to brines and sea water. Sampling and preservation techniques are described and quality control guidelines are recommended.

Chapter 6. Soil Water.—Techniques for measuring and reporting water movement and storage in the unsaturated zone are presented. Recommended field equipment for measuring and observing soil water movement and quantity is described.

Chapter 7. Drainage-Basin Characteristics.—Procedures for identifying, measuring, and classifying drainage-basin characteristics relating to surface-water movement and sedimentation are recommended. Guidelines for describing basin charactereistics, including descriptions of recommended measurements and observation techniques, are given. Influences of basin characteristics on basin hydrology are discussed also.

Chapter 8. Evaporation and Transpiration.—Methods for observing and measuring the physical processes related to evaporation and transpiration are recommended. Detailed descriptions of equipment commonly used for index measurements are given.

Chapter 9. Snow and Ice.—Techniques and procedures for measuring water in snow, firn, ice packs, ice caps, and glaciers are recommended. Equipment recommended for measuring and observing snow and ice in the field, in the laboratory, and by remote sensing is described. Methods for monitoring ice movement and snow melt are described also.

Chapter 10. Hydrometeorological Observations.—Methods are presented for measuring and analyzing atmospheric and interactive solar processes that have direct bearing on the hydrological analyses covered by several other chapters of the *National Handbook.* Techniques for measuring and analyzing precipitation (including falling snow and rime), air temperature, humidity, atmospheric pressure, and wind are recommended. Equipment commonly used for measuring and observing these, including remote-sensing techniques, is described.

Chapter 11. Water Use.—Methods for collecting, processing, storing, and disseminating water-use data are recommended; direct and indirect techniques for measuring water usage are included. Primary and secondary water-use categories are defined; and preferred methods for aggregation and application of data are presented.

Chapter 12. Water-Data Handling and Exchange.—Methods are recommended for the handling and exchanging of water data. Techniques and formats are presented for the transfer of data in machine-readable form between data systems and users. Identification methods and identifer lists for water-data parameters and geographic locators are recommended also.

BACKGROUND

A Federal Interagency Work Group was impaneled in 1970 by the Geological Survey's Office of Water Data Coordination to develop recommended methods for water-data acquisition. Six task groups were established by the Work Group, each of which was assigned a specific area of concern. More than 70 scientists, representing 17 Federal agencies, participated in the task groups. The efforts of these scientists resulted in the production of a preliminary report, *Recommended Methods for Water-Data Acquisition,* in December 1972. This report discussed data-acquisition methodology for surface water; ground water; biological, bacteriological, and chemical water quality; fluival sediment; and automatic water-quality monitors. The report did not have legal status, but it did represent the first consensus among involved individuals and agencies on the most appropriate methods for water-data acquisition.

Prior to publication, the recommended methods in the preliminary report were reviewed by Federal agencies and the non-Federal community. All concerned Federal agencies were involved through representation on either the Work Group, the task groups, or the Department of the Interior's Interagency Advisory Committee on Water Data, which reviewed all actions of the Work Group and task groups. Members of Interior's Advisory Committee on Water Data for Public Use (Non-Federal Committee) also reviewed the report. The Non-Federal Committee includes representatives of water-oriented professional and technical societies; national, State, and regional organizations; the academic community; and private enterprise. The need for standard methodologies was demonstrated not only by the willingness with which Federal agencies participated in

this early activity, but also by the widespread demand——both nationally and worldwide——for the preliminary report.

Following publication of the preliminary report, the Interagency Advisory Committee on Water Data appointed a subcommittee to evaluate the recommended methods activity and to advise on future activities. As a result of the subcommittee's recommendations, the Interagency Committee decided that a continuing activity was necessary. The committee endorsed plans for expanding the program to cover all phases of the hydrologic cycle and for distributing the findings in a continuously updated loose-leaf handbook. In addition, the Interagency Committee recommended a more formal structure to include, within the Office of Water Data Coordination, a Methods

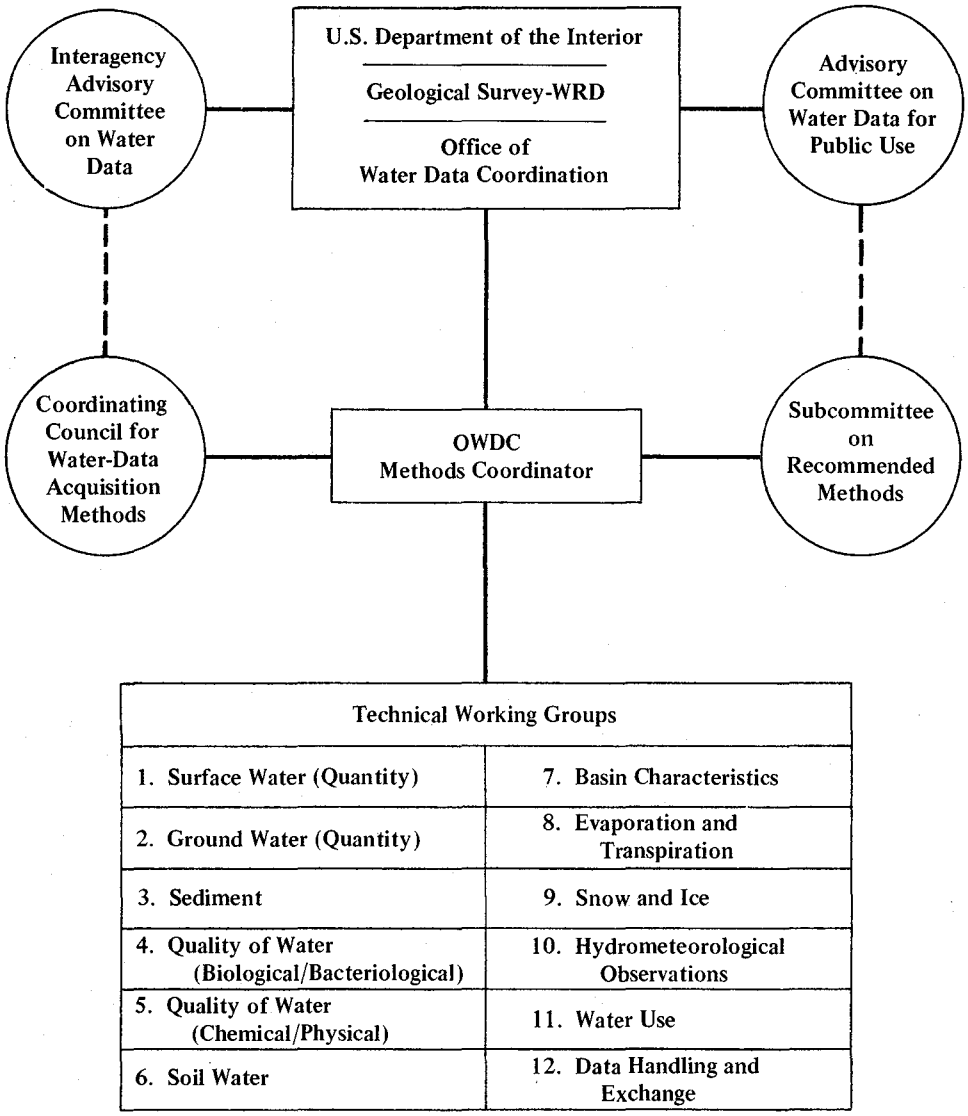

Figure 1.—Organizational relationships in developing the *National Handbook of Recommended Methods for Water-Data Acquisition.*

Coordinator responsible for overseeing the activity. To implement the recommendations and to advise the Methods Coordinator on policy and operating guidelines, representatives from 17 Federal agencies were organized into the Coordinating Council for Water-Data Acquisition Methods. In addition, heads of all concerned Federal agencies were invited to nominate personnel to any of 10 technical working groups which would produce the new handbook. Over 170 engineers and scientists representing 25 Federal agencies were nominated to the 10 working groups. In 1979, two additional technical working groups covering (1) water-use data and (2) data handling and exchange were formed. The working-group members are listed at the beginning of the chapter for which they are responsible.

More involvement of the non-Federal community was solicited for preparing the new handbook. A subcommittee on Recommended Methods was formed from members of the Advisory Committee on Water Data for Public Use, with representation from such organizations as the American Society of Civil Engineers, Association of Western State Engineers, and several State and interstate agencies. In addition, the American Society for Testing and Materials, American National Standards Institute, American Water Works Association, American Public Health Association, and other technical and standards-setting societies were consulted. Organizational relationships are shown in figure 1, and individuals involved are listed in tables 1–3.

Recommendations presented in the *National Handbook* result from a consensus of all participating members. This consensus represents open communication and willing participation by all involved agencies. It is believed that the best methods for producing high quality, comparable, compatible, and usable data have been selected through this approach.

Because designating specific methods for each water-data activity does not mean solving the problem forever, it is necessary to continue the standardization effort. Therefore, after the handbook is completed, the 12 working groups will continue to make corrections and update the chapters. The updates will include modifications to existing methods based on the latest developments in technology, and recommended methods for additional parameters. The handbook's loose-leaf format will facilitate inserting updates and removing old material.

ACKNOWLEDGMENTS

The Office of Water Data Coordination appreciates the work of the many individuals and organizations who wrote and reviewed the chapters of the *National Handbook*. Included are members of the 12 technical working groups, the Interagency Advisory Committee on Water Data, the Advisory Committee on Water Data for Public Use, the Coordinating Council, the Subcommittee on Recommended Methods, and the many reviewers from technical societies, non-Federal agencies, universities, and private industry. Appreciation also is expressed to the staff of the Office of Water Data Coordination for reviewing, editing, and typing the chapters and the staff of the Reports Section of the Geological Survey's Water Resources Division for editing, illustrating, and photo-offsetting the handbook. Special acknowledgment is given to Joan M. Rubin of the Reports Section for design of the handbook cover and chapter dividers. Without the dedicated assistance of all these individuals, the *National Handbook of Recommended Methods for Water-Data Acquisition* would not have been possible.

National Handbook users who have any questions, comments, or suggestions, or who need additional information about the methods recommended, may contact:

Chief, Office of Water Data Coordination
U.S. Geological Survey
MS–417, National Center
Reston, VA 22092

Table 1.—*Interagency Advisory Committee on Water Data*

Membership as of May 1980

CHAIRMAN: Philp Cohen
Chief Hydrologist
Geological Survey

ALTERNATE CHAIRMAN AND
EXECUTIVE SECRETARY: P. E. Ward
Acting Chief, Office of Water Data Coordination
Geological Survey

Department/Agency	*Representative*	*Alternate*
AGRICULTURE		
Economics, Statistics, and Cooperatives Service	Melvin L. Cotner	J. Horsefeld
Forest Service	Robert H. Tracy	
Science & Education Administration		
Agricultural Research	J. B. Burford	David A. Farrell
Cooperative Research	Paul E. Schleusener	Boyd W. Post
Soil Conservation Service	Robert E. Rallison	
COMMERCE		
Bureau of the Census	John P. Govoni	David T. Ely
Bureau of Industrial Economics	Patrick H. MacAuley	
National Bureau of Standards	William H. Kirchhoff	Lottie T. McClendon
National Oceanic & Atmospheric Admin.	Robert A. Clark	Allen F. Flanders
DEFENSE		
Army		
Corps of Engineers	Vernon K. Hagen	Eugene A. Stallings
Navy		
Naval Facilities Engineering Command	James Spatarella	
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Bonneville Power Administration	Robert Lamb	George E. Bell
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Division of Regional Assessments	Randolph R. Newton	
Federal Energy Regulatory Commission	Neal C. Jennings	Eugene A. Jarecki
HOUSING AND URBAN DEVELOPMENT	Truman Goins	
INTERIOR		
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Bureau of Land Management	Ronald L. Kuhlman	
Bureau of Mines	Wilton Johnson	

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Table 1.—*Interagency Advisory Committee on Water Data*—Continued

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Geological Survey	R. H. Langford	Thomas J. Buchanan
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National Park Service	Victor A. Berte	
Office of Surface Mining	David R. Maneval	Donald W. Willen
Office of Water Research & Technology	Raymond A. Jensen	Luther C. Davis, Jr.
Water and Power Resources	James D. Ellingboe	Roy H. Boyd
TRANSPORTATION	Vacant	Phillip L. Melville
INDEPENDENT AGENCIES		
Council on Environmental Quality	John. D. Buffington	
Environmental Protection Agency	Edmund M. Notzon	
International Boundary & Water Comm.	James J. Ligner	
International Joint Commission	Stewart H. Fonda, Jr.	
Nuclear Regulatory Commission	Thomas J. Nicholson	
Tennessee Valley Authority	Maurice G. Msarsa	Claude H. Smith
Water Resources Council	Dick Thompson	Kerie Hitt

Table 2.—*Advisory Committee on Water Data for Public Use*

Membership as of July 1980

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H. W. Menard, Director
U.S. Geological Survey
Reston, Virginia

ALTERNATE CHAIRMAN
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U.S. Geological Survey
Reston, Virginia

EXECUTIVE SECRETARY
P. E. Ward, Acting Chief
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U.S. Geological Survey
Reston, Virginia

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Lexington, Kentucky

NATIONAL ASSOCIATION OF CONSERVATION DISTRICTS
Mr. Robert E. Raschke, Western Representative
National Association of Conservation Districts
Lakewood, Colorado

*Member of Subcommittee on Recommended Methods.

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Vacant

NATIONAL WATER RESOURCES ASSOCIATION
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Executive Vice President
National Water Resources Association
Washington, D.C.

NATIONAL WATER WELL ASSOCIATION
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UNIVERSITIES COUNCIL ON WATER RESOURCES
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Water Resources Research Institute
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*Dr. William C. Walton, Geohydrologist
Camp Dresser & McKee
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*Member of Subcommittee on Recommended Methods.

Table 3.—*Coordinating Council for Water-Data Acquisition Methods*

Membership as of July 1980

CHAIRMAN: F. Paul Kapinos
Acting Methods Coordinator
Office of Water Data Coordination
Geological Survey

Department/Agency	*Representative*
AGRICULTURE	
Forest Service	Robert H. Tracy
Soil Conservation Service	Norman Miller
COMMERCE	
National Bureau of Standards	William H. Kirchhoff
National Oceanic & Atmospheric Admin.	Allen F. Flanders
*National Oceanic & Atmospheric Admin.	Joseph Schiesl
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Naval Facilities Engineering Command	James Spatarella
ENERGY	
Bonneville Power Administration	Robert Lamb
INTERIOR	
Geological Survey	Leslie B. Laird
National Park Service	Victor A. Berté
Office of Surface Mining	Donald W. Willen
Water and Power Resources Service	James D. Ellingboe
INDEPENDENT AGENCIES	
Council on Environmental Quality	John D. Buffington
Environmental Protection Agency	Edmund M. Notzon
International Boundary & Water Commission	James J. Ligner
Nuclear Regulatory Commission	Thomas J. Nicholson
Tennessee Valley Authority	R. T. Joyce

*Representing the Interdepartmental Committee for Meteorological Services (OMB Circular A-62).

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Table 3.—*Coordinating Council for Water-Data Acquisition Methods*

Membership as of June 1977

Department of Agriculture	
David A. Falletti	Forest Service
Norman Miller	Soil Conservation Service
Department of Commerce	
Robert E. Ferguson	National Bureau of Standards
Allen F. Flanders	National Oceanic and Atmospheric Admin.
*Raymond L. Richardson	National Oceanic and Atmospheric Admin.
Department of Defense	
Eugene A. Stallings	Department of the Army
Paul J. Yaroschak	Naval Facilities Engineering Command
Department of the Interior	
Victor A. Berté	National Park Service
John P. Dillard	Bonneville Power Admin.
James D. Ellingboe	Bureau of Reclamation
**Arnold I. Johnson	Geological Survey
Edward A. Moulder	Geological Survey
Donald W. Willen	Bureau of Land Management
Independent Agencies	
R.T. Joyce	Tennessee Valley Authority
James J. Ligner	International Boundary and Water Commission
Donald L. Milliken	Nuclear Regulatory Commission
Edmund M. Notzon	Environmental Protection Agency
James J. Reisa	Council on Environmental Quality
Arthur A. Schoen	Energy Research and Development Admin.

*Representing the Interdepartmental Committee for Meteorological Services (OMB Circular A-62).
**Chairman of the Coordinating Council and Methods Coordinator, Office of Water Data Coordination.

Chapter 1

Surface Water

CHAPTER 1—SURFACE WATER

Prepared by
Work Group 1 on Surface Water
August 1980

WORK GROUP ON SURFACE WATER

Department of Agriculture

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Department of Commerce

Gershon Kulin	National Bureau of Standards
Harold S. Lippmann	National Oceanic and Atmospheric Admin.

Department of Defense

Eugene T. Fleming	Army Corps of Engineers

Department of the Interior

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Russell A. Dodge	Bureau of Reclamation
Ernest D. Cobb	Geological Survey
* Alvin F. Pendleton	Geological Survey
Gerard A. Verstraete	Heritage Conservation and Recreation Service
Richard W. Ketcham	National Park Service

Independent Agencies

Carl M. Walter	Environmental Protection Agency

* Chairman

COMMENTS ON CHAPTER 1

National Handbook of Recommended Methods for Water-Data Acquisition

I found this "National Handbook" chapter to be useful. Comments:

_____

_____

_____

I found the following method to be unsatisfactory: _____

Method _____

Reference _____

The method is unsatisfactory for the following reason(s): _____

_____

_____

_____

Submitted by (Name): _____

(Organization): _____

(Address): _____

(Telephone): _____

Date: _____

_____

Thank you for submitting your views on Chapter 1 of the "National Handbook." Your comments will be considered in revising the "National Handbook" to benefit all users. Please mail this form to:

Office of Water Data Coordination
U.S. Geological Survey
MS-417, National Center
Reston, VA 22092

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CHAPTER 1– SURFACE WATER

1.A. INTRODUCTION

Collection and analysis of surface-water data and information is a complex task. A variety of instruments, measurement methods and analytical techniques usually are required to produce a surface water record for a single site. A degree of standardization of certain aspects of this surface-water data acquisition has been achieved in instrumentation, methods of observation, methods of measurement, analytical procedures, and publication practices. Most of the federal agencies that acquire and/or use water data and information have worked together with non-federal agencies to develop procedures, methods and instrumentation. Although each agency, organization, and person confronted with the acquisition and use of water data and information has different problems and needs, everyone can benefit from a set of recommended methods developed over time through experience. The Working Group on Recommended Methods for Surface Water Data hopes this chapter can help those interested in surface-water data acquisition by recommending methods and procedures.

There is growing awareness and recognition of the fact that standardization and a means to insure data comparability are needed in surface-water data collection and analysis. Many national and international organizations are expanding their activities to deal with these needs. National organizations such as the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), the American Society of Mechanical Engineers (ASME) and the American Society of Civil Engineers (ASCE), to name a few, are actively contributing handbooks, standards, or guidelines dealing with water data. International groups such as the International Organization for Standardization (ISO) and the World Meteorological Organization (WMO) are developing and/or sponsoring international standards, practices and guides to promote the standardization of hydrological and hydrometeorological methods and procedures. Many of the federal and non-federal experts working to develop the Recommended Methods for Water Data Acquisition are also participants in both the national and international organizational efforts.

1.A.1. PURPOSE AND SCOPE

Every aspect of the hydrologic cycle, particulary the surface water environment, is extremely dynamic in nature. To acquire good factual data and information from overland flow, streams, lakes, reservoirs, or estuaries can be very expensive and requires planning, organization and cooperation, coupled with some ingenuity and imagination. Water data and information acquired by any nationwide water-data storage and retrieval system must be compatible, comparable, of acceptable quality to the user concerned (including courts of law), and must be coded adequately to identify acquisition source and analysis type.

To ensure acceptable quality of data, an understanding and agreement must be reached among the operating, the contributing, and the user agencies and organizations on standards and recommended methods to be used in measuring, sampling, analyzing, processing and publishing the data. If mutually accepted standards are not used, data meticulously collected using up-to-date procedures and equipment may well be combined with estimates or data of questionable quality in an unreliable hodge-podge.

Recommended methods for water data acquisition also should serve another purpose. This purpose is to assist anyone new to the field of data acquisition by helping them select methods, practices and instrumentation which are time-tested, reliable, in general use, and recommended by peers.

This work group recognizes the need to identify the areas of surface-water data acquisition where recommended methods must be formulated. However, the formidable task that would be involved just to collate existing standards, guides, practices and methods is also recognized. Considering the task involved we have tried to maximize the use of readily available and recommended methods that are already documented by referencing them. Where methods have not been adequately documented elsewhere, we briefly describe the method we recommend.

The methods recommended in this chapter are designed for collecting data on surface waters occurring upon or immediately adjacent to land areas including methods for overland flow, open channel flow, closed conduit flow, and waters in lakes, ponds, reservoirs, and estuaries. The scope does not include acquisition of data for the major oceans (oceanography) per se unless a recommended method for a lake or reservoir is applicable. The scope is also limited to the methods for the measurement, sensing, recording, transmission, analysis and presentation of data concerning quantity of surface water (i.e., stage, flow rate, storage volume, etc.). The recommended methods for measurement of physical, chemical, biological, and bacteriological quality of these same surface waters are discussed in chapters 4 and 5.

1.A.2. USE AND AUDIENCE

The methods described in this chapter are designed for the technical aspects of data acquisition. The intended audience is the hydrologist, engineer, or scientist who deals with the measurement, sensing, recording, transmitting, analyzing, publishing or interpreting of surface-water data.

The use of recommended methods and/or standards for water data acquistion help ensure that the data incorporated into the National Water Data Network will meet certain requirements for content, uniformity, and timeliness for a wide variety of purposes. Standards should provide explicit guidelines for processing and analyzing data prior to entry into the data handling system.

1.A.3. DATA ACQUISITION NETWORK

Office of Management and Budget Circular A-67 prescribes guidelines for coordination of Federal activities in acquiring water data from streams, lakes, reservoirs, estuaries and ground waters. It sets forth the requirement that a National Water Data Network be designed and operated to meet the water quantity measurement requirements of all Federal agencies and to provide water quality measurements common to the needs of two or more agencies.

There is in effect a "network-in-being" in the United States wherein all types of surface water data are being acquired. Most water data today are collected (1) in response to an existing need, (2) in compliance with a political or legal obligation to collect and document, or (3) in anticipation of a future need. Most water-data acquisition programs have just evolved with time. They were not developed according to any great scheme or grand design. In fact, many water-data acquisition activities are not subject to design because of unforeseen changes in data needs. One of the best examples of a network in-being that evolved in response to recognized needs is the national network of surface-water flow stations.

Data acquisition in designed or existing networks will benefit appreciably through the standardization of methods.

1.A.4. UNCERTAINTY IN DATA ACQUISITION METHODS

1.A.4.a. GENERAL MEASUREMENT UNCERTAINTY

All measurements and samples made in chemistry, hydraulics, geology, meteorology and the related sciences are inaccurate to some degree. Accordingly, all measurements and samples of physical quantities in any hydrologic data network contain some uncertainties, inaccuracies, and errors. The fact that the exact or true value of the physical quantities being measured cannot be determined poses problems when it is necessary to quantify the errors of observation and accuracy of results.

Many of the Federal interagency committees have expressed real concern over the fact that current procedures for acquiring, analyzing, storing, and retrieving water data have few, if any, provisions to guarantee, evaluate, or express any measure of accuracy for the data involved. When data quality in unknown, it is necessary to evaluate the data accuracy (1) subjectively, through implication because of the acquisition and analysis procedures, or by inference considering office conditions of collection and analysis, and (2) quantitatively through statistical or mathematical estimations. The system usually cannot guard against inclusion or misrepresentation of data collected by non-recommended procedures or by questionable methods.

On the other hand, data possibly collected under trying circumstances or by marginal or non-recommended procedures, must be available to the data users because they are the only data available. Some method is needed to flag or code the data to categorically quantify, qualify, or disqualify them according to accuracy. Various approaches to flagging or coding must be considered in developing the storage and retrieval system for the National Water Data Network. The work of hydrologists, engineers, or scientists should not be limited or influenced by unavailability of the true value of a hydrologic parameter. A set of samples or measurements can be used to determine the most accurate value under the existing conditions and the accuracy of this value can be estimated. This can only be done through the use of statistical concepts and methods.

1.A.4.b. RANDOM ERROR OF UNCERTAINTY

The random uncertainty associated with repeated measurements or observations is related to the reasons for the disagreement or error between the individual values and the true value. This random uncertainty is considered to be due to chance or experimental or accidental error and is usually attributable to error in judgement (variation in reading); to fluctuating conditions (i.e., pulsations, turbulence, wind, etc.); or to inadequate definition of method or procedure.

Random errors are considered to be determinate errors which may be evaluated by some logical procedure, either theoretical or experimental. Some of this random uncertainty may be removed by application of suitable corrections. A measurement or observation having small random error is said to have high precision, i.e. a high level of repeatability.

1.A.4.c. SYSTEMATIC ERROR OF UNCERTAINTY

Uncertainties associated with repeated measurements or observations (see above) which are constant or in error by the same amount are called systematic. These uncertainties relate to (1) errors in calibration of instruments, (2) personal idiosyncracies due to habit (consistently read high, timed slowly or oversound on depth readings), (3) actual instrument or equipment measurement or observation conditions (i.e., pressure, temperature, etc.) which have a constant difference from calibrated conditions and for which correction is applied, or (4) an imperfect method or technique.

Systematic errors may sometimes be determinate if evaluated by calibration of the instrument or equipment against an available standard. In other cases it may be inherently impossible to evaluate the systematic errors (they are indeterminate). Their presence may be inferred only indirectly by comparison with other measurements of the same quantity using radically different methods.

A measurement or observation having small systematic error is said to have high accuracy, if it represents the observed or measured characteristic.

1.A.4.d. TOTAL UNCERTAINTY

The total uncertainty or error inherent in hydrologic data and information is generally very complex and difficult to assess. Direct reading scalar values such as stream stage, channel width, or stream depth present little chance for error thus the uncertainty is small. Stream discharge, on the other hand, is more complex because the discharge determination is made using a combination of scalar and vector quantities, each having inherent errors that are additive (algebraically) in evaluating the total uncertainty.

Much of the uncertainty associated with acquisition of water data and information can be eliminated through the use of standard recommended methods. Because almost all errors (both random and systematic) are due to either the observer, the instrument or equipment, the measurement method, or technique or process, the total uncertainty can be decreased appreciably through standardization, familiarity, confidence, and use of recommended methods for water-data acquisition.

By decreasing the random error, systematic error, and therefore, the total error, the accuracy and precision of the data are increased and the reliability of the data and information is increased.

1.A.5. UNITS OF MEASUREMENT

The units of measurement used in this chapter are SI units. The following list summarizes the metric (SI) units recommended for use:

Table 1-1.—SI units

Data Type	SI Unit	Symbol
Stage (gage height)	meters (generally to nearest 2 mm)	m (or mm)
Velocity, stream	meters per second	m/s
Discharge or flow rate		
Large volumes/time	cubic meters per second	m^3/s
Small volumes/time	liters per second	L/s
Storage, water		
Small volumes	cubic meters	m^3
Large volumes (e.g. most reservoirs)	cubic dekameter; cubic hectometers	dam^3, hm^3
Extreme volumes (e.g. world water balance)	cubic kilometers	km^3
Precipitation	millimeters	mm
Evaporation	millimeters	mm
Transpiration	millimeters	mm
Lengths (distance)		
Stream depth	meters	m (or mm)
Stream width	meters	m
Stream length	kilometers	km
Elevation (sea level) datum	meters (generally to nearest 1 mm)	m (or mm)
Altitude	meters	m

Table 1-1.—SI units—Contiued

Data Type	SI Unit	Symbol
Area		
Stream cross-section	square meters	m^2
Land area (small)	hectares	ha
Land area (large)	square kilometers	km^2
Temperature	degrees Celsius	°C
Pressure		
Head	meters (or mm) of fluid	m (or mm)
Barometric (Atmospheric)	kilopascals	kPa
Viscosity		
Dynamic (absolute)	pascal-seconds or newton-seconds per square meter	Pa•s or $N \cdot s/m^2$
Kinematic	square meters per second	m^2/s
Density, mass density (mass/unit volume)	Kilogram per cubic meter	kg/m^3
Acceleration	meters per second squared	m/s^2
Gravity	meters per second squared	established 9.81 m/s^2
Time	second, minute, hour, day, year (annum) also permissible	s, min, h, d, a
Runoff or Yield		
by volume	cubic meters (or mutliples dam^3, hm^3, km^3)	m^3 (or dam^3, hm^3, km^3)
by time rate	cubic meters per second (or multiples by various time units)	m^3/s (or hm^3/d, km^3/a)
per unit area	cubic meters per second per square kilometer	$m^3/s/km^2$
as depth over basin	meters (or millimeters)	m (or mm)

1.B. FIELD MEASUREMENTS

1.B.1 OVERLAND FLOW

1.B.1.a. DEFINITION AND SCOPE

Overland flow is water flowing on the land surface without the ordinary constraint of definable, continous channel boundaries. Most commonly, the term refers to the flow occurring when storm rainfall rates exceed surface infiltration rates. This type flow may be termed rainfall-excess overland flow. Eventually—usually within 100 meters (300 feet)—this flow enters a channel network. This surface flow is one of two general sources of channel flow. The other is direct groundwater contribution to streams in the form of seeps or springs. Streamflow may result, depending on the local climate, weather systems, and soil, from either or both sources.

Another type of overland flow occurs when a stream leaves its normal channel and the water flows on normally dry surfaces. Overbank flow on a flood plain is a form of overland flow. Another relatively important form of overland flow occurrs in many areas of the southwestern United States where ephemeral streams discharge onto large flattened alluvial pediment cones. Overland flow in these cases may be called channel-source overland flow.

Probably the most important characteristic of all types of overland flow is that it is ephemeral. Overland flow is seldom uniform and usually very shallow. These characteristics imply that overland flow is not subject to direct measurement for data collection except for specific research studies. Channel-source overland flow in particular results from random hydrologic extremes not suited to data collection techniques. Nevertheless, the depths and extent of such sheet-like spreading of floods from ephemeral arroyos is of interest in flood damage studies. Overland flow is generally determined in an indirect or derived manner. For this reason, measurement of related watershed and meteorological variables is important.

Overland flow from rainfall excess may occur only rarely or not at all in some climatic and geographic areas. Where soil is porous and intense thunderstorms do not occur, overland flow may be unknown. In other areas, such as the semiarid southwest, overland flow is often the sole source of streamflow, and all streams are ephemeral in nature. Most areas fall somewhere between these extremes.

Rainfall-excess overland flow is important in the production of many types of nonpoint pollution. It is an important erosion agent and sediment transport mechanism. Likewise, channel-source overland flow can act as an important sedimentation device in spreading sediment-laden water from ephemeral floods. Surface water flow from rainfall carries significant quantities of chemicals into stream channels (Stewart and others, 1975). The erosive and carrying capacity of overland flow is related not only to its unit discharge, but also to its velocity and depth and the rilling which the surface has undergone. Thus the slope, hydraulic roughness, and length of flow path are important characteristics to be determined.

1.B.1.b. HYDRAULIC MEASUREMENT OF OVERLAND FLOW

As a result of the ephemeral nature of overland flow, very little field measurement has been attempted. Thus, techniques have not been sufficiently developed to allow recommending any single field measurement method. Numerous studies have been published, however, of measurements of overland flow in laboratory conditions, where the surface is truly flat, and flow occurs as true sheet flow. Some of these studies may be adaptable to field measurements.

Overland flow velocity may be measured in the laboratory or the field by following the progress of a tracer introduced at a known point at a known time (see sec. 1.B.2.c.6.). Studies of this type have been accomplished in the field by Correia, 1972, and by Emmett, 1970. The observer may rely on visual recognition of the movement of highly colored dyes, or use portable detection equipment.

Flow depths have been sampled in field conditions by Emmett, 1970, by use of an ordinary point gage, sampling across a bordered strip 7 feet wide (see sec. 1.B.2.a.2.e.). The sampled mean depth was taken as hydraulically representative, and this information along with the tracer-sampled velocity was used to calculate a value for overland flow unit discharge (volume per unit time per unit width).

A more reliable method of sampling unit discharge of overland flow is to interrupt the flow and collect the discharge from a measured surface width into a volumetric tank, flume, or other device for measuring small-scale flows (see sec. 1.B.2.d.1. and 1.B.2.e.2.a.). If the velocity is also measured by tracer methods, the mean depth for any irregular surface may then be calculated.

Flow on smooth impervious surfaces, such as is encountered in urban hydrology, has been studied and measured in field scale experiments. One of the most notable studies was conducted by the Los Angeles district, U.S. Corps of Engineer (1955). Overland flow depths were measured both by point gages and small stilling wells. The data was studied for hydraulic relations by Yu and McNown (1964).

1.B.1.c. MEASUREMENT OF RAINFALL

Whether or not the surface of interest is pervious, and regardless of its hydraulic roughness, the rate of overland flow is highly dependent on the rate of rainfall. Rainfall measurement is discussed in detail in chapter 10.

1.B.1.c.1. RAINFALL INTENSITY

Because standard rainfall recording devices integrate the rainfall rate, determination of the pattern of rainfall rates is somewhat difficult. Unfortunately, overland flow is most important in climates with the most rapid variation in rainfall rates. Standard weighing or tipping bucket rain gages cannot trace the rate of rainfall input to overland flow with the precision often needed for calculation of overland flow rates from equations for the hydraulics of spacially varied surface flow.

1.B.1.c.2. RAINFALL DEPTH

Where accumulated volume of overland flow is of interest, the depth of rainfall measured by standard rain gages should be adequate. This information, as for rainfall intensity, must be accompanied by data on infiltration to allow estimates of overland flow.

1.B.1.d. MEASUREMENT OF INFILTRATION

Infiltration measurement is discussed in chapter 6. For hydrologic application to overland flow calculation, it is important to note that infiltration relations obtained in studies of ponded surface conditions will ordinarily not be the same as infiltration patterns resulting from natural rainfall. Depending on the rainfall rate pattern, a certain volume of water must be infiltrated before the surface becomes saturated and runoff and overland flow occur (Smith and Chery, 1973, Mein and Larson, 1973). Current models for infiltration patterns can, however, account for this initial infiltration before ponding, as well as variations in initial soil moisture (See chapter 6). To the extent that it is available, information about the soil on a watershed slope can be used to refine estimates of the infiltration rate, and therefore the pattern of input to overland flow.

1.B.1.e. MEASUREMENT OF WATERSHED CHARACTERISTICS AFFECTING OVERLAND FLOW
(see also chapter 7)

Overland flow depth varies both along the slope and with time. Flow can be hydraulically steady or unsteady and even for flat impervious conditions, watershed slope and roughness must be measured or estimated to calculate depth of overland flow.

Hydraulic roughness is presently thought to vary in a two stage manner with Reynolds number (Woolhiser and others, 1970), with lower flows exhibiting laminar flow characteristics, and higher flows exhibiting turbulent flow characteristics. The general relation of velocity, u, to depth, h, and slope, S, can be expressed

$$u=\sqrt{\frac{8g}{f}Sh}=\alpha h^{1/2} \tag{1-1}$$

where g is gravitational acceleration, and f is Darcy-Weisbach friction factor. Here the surface characteristics of slope and roughness are represented by α.

Slope can be measured directly, or taken from topographic maps, depending on the scale of the map and length of overland flow. The length can rarely be found adequately from topographic maps, but often aerial photographs can aid in identifying small channel intercepts.

Roughness can be calculated if slope, velocity and unit discharge are measured as outlined above. Published graphs of roughness relations (Woolhiser and others 1970; Rovey, 1974) can aid in

interpreting roughness for a wide range of watershed surface conditions, from smooth asphalt to dense turf. See fig. 1-1.

The coefficient α represents the product of slope effect and roughness effect, and

$$f = k/N_R \qquad \text{(dimensionless)} \quad (1\text{-}2)$$

$$N_R = \frac{uh}{\nu}$$

in the laminar range, where N_R is Reynolds number, ν is kinematic viscosity and k is a coefficient. In the turbulent flow range, for a Chezy relationship

$$f = 8g/C^2 \qquad \text{(dimensionless)} \quad (1\text{-}3)$$

where C is the Chezy (empirical) roughness coefficient (Woolhiser and others, 1970).

The flow paths of overland flow may not be parallel; in fact local topography often causes convergent flow. This accelerates rill and micro-channel formation. Woolhiser (1969) has dealt with the theory and experimental aspects of this topic.

Other watershed characteristics that affect overland flow are discussed in chapter 7.

1.B.2. OPEN CHANNEL FLOW

Open channel flow is a term applied when water flows with a free surface within definable, continous channel boundaries. Hence, the term is generally used to refer to water bodies such as streams, rivers or canals having a longitudinal boundary surface consisting of a bed, banks or sides, and a free or open water surface. However, the term can also refer to water movement in large closed conduits which are flowing only partially full.

In this section, equipment and recommended methods for the measurement of stage (gage height), datum, channel dimensions, water velocity and discharge (flow rate) associated with open-channel flow are described. The methods cited are not all-inclusive but are those recommended for use in meeting the various installation, measurement, and use requirements dictated by the particular open-channel flow data needs.

One or more of these recommended methods may be used in acquiring data of a particular type at any specific site. Accordingly, the advantages and inherent problems associated with the methods are discussed. Factors such as ease of making the measurements, associated equipment and instruments needed, relative accuracy requirements, and associated costs will influence the decision as to which of the recommended methods should be used.

Particular attention must be paid to the hydrologic variables in selecting and using recommended methods. Conditions of extremely variable flow, rapidly changing stage, surge, variable backwater, ice, freezing and thawing, scouring and filling, sediment and particulate matter, flow regulation, access to site, and seasonal changes are some of the factors which must also be considered.

Sometimes the best methods may be rendered impractical or impossible by adverse conditions, including flood, weather or equipment failure. Faced with these conditions it is imperative that alternative recommended methods be used so that the measurement may be made.

The field measurement of open-channel flow is a subject approaching infinite scope. This section is meant to narrow down the options by recommendation of specific methods.

1.B.2.a. MEASUREMENT OF STAGE

The stage of an open channel is the height of the water surface above an established datum plane. Gage height, on the other hand, is the water surface elevation referred to a specific gage

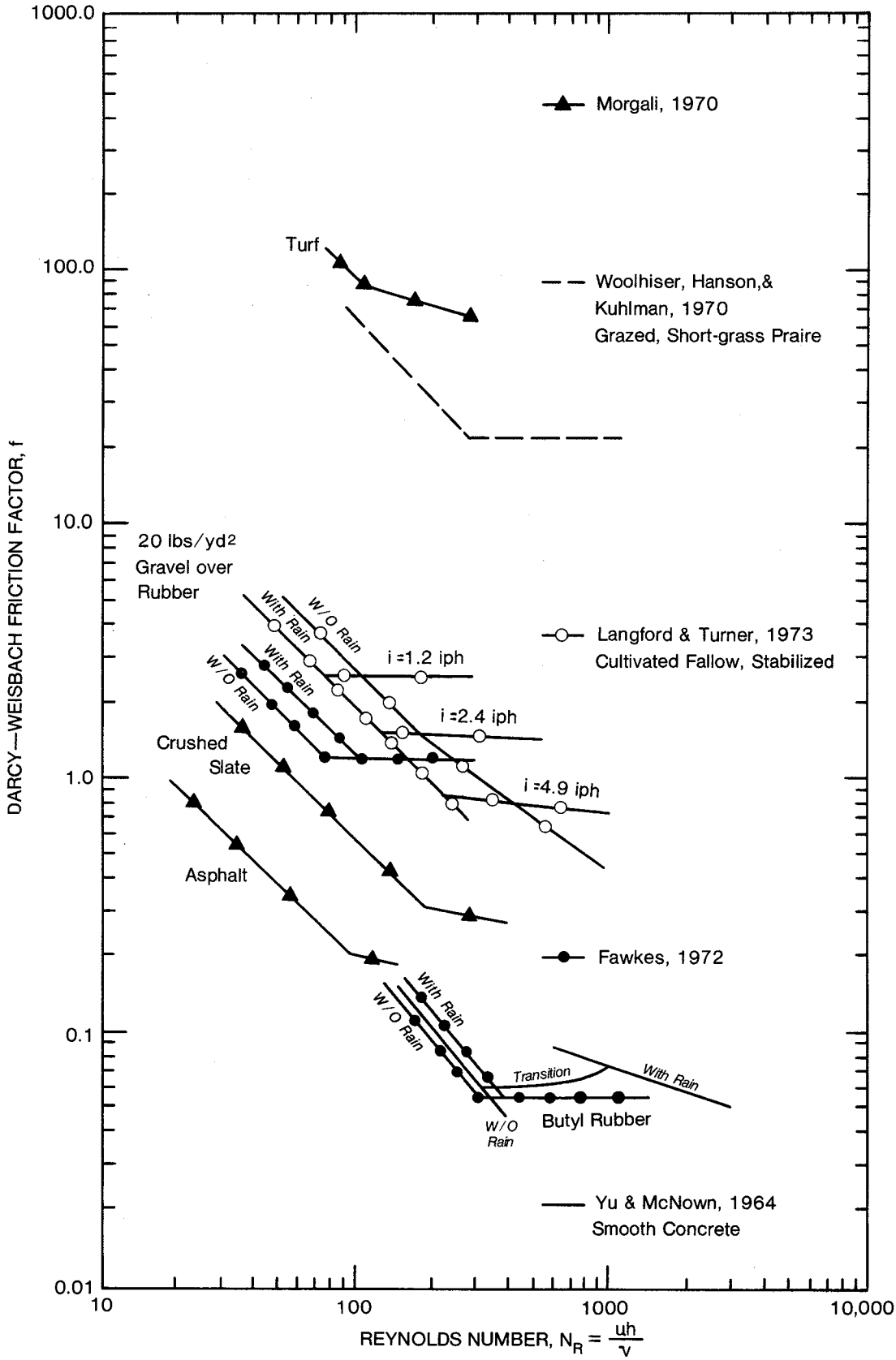


Figure 1-1.—Darcy-Weisbach Factor vs Reynolds Number.

datum and is considered a more appropriate term than stage when used in connection with a reading on a gage.

Measurement of stage is extremely important for many reasons. Stage data are particularly valuable in assessing flood damage or flood insurance claims, in designing structures or water development projects affected by water surface elevation, and in managing or zoning flood plains. Water surface profiles along an open channel are valuable tools in delimiting property lines and assessing property values.

Gage heights, while primarily related to water-surface elevations at a specific point (in reference to a gage datum), are used as the independent variable in a stage-discharge relation to derive discharge. Where water moves through reservoirs and lakes, gage heights provide indexes of head, contents, storage capacity, and other properties, in addition to elevations.

1.B.2.a.1. GAGE DATUM

The datum of the gage may be a recognized datum, such as mean sea level, a local datum related to project or research activities, or an arbitrary datum selected for expediency or convenience. Normal practice is to select an arbitrary datum below the elevation of possible zero flow. This selection of datum makes it possible to work with positive gage heights at extremely low stages. The datum of the gaging station is the elevation of the zero point of the base or reference gage.

A permanent datum must be maintained so that only one datum for gage-height record is used for the life of a data-collected station (Buchanan and Somers, 1968). To maintain a permanent datum at each gaging station requires at least two or three reference marks that are independent of the gage structure. Reference marks are independent auxiliary datum references used to verify or reestablish the gage datum. All gages should be periodically checked by running levels using the reference marks to maintain a fixed datum.

Where an arbitrary datum is used, it is recommended that it be referred by levels to a benchmark of known elevation above sea level. This procedure allows recovery of the arbitrary datum and possible re-establishment of a station where the gage or the reference marks are destroyed.

1.B.2.a.2. NON-RECORDING GAGES

Non-recording gages are very seldom used as primary gages unless periodic readings fulfill the purpose of the gage. Non-recording gages, however, are used extensively as reference and/or auxiliary gages at recording gaging stations.

Non-recording gages have the advantages of simplicity, ease of installation or removal, and low initial costs. These gages require systematic and frequent readings to develop an estimated continous (sketched) gage-height record. They also generally lack the accuracy inherent in the continously recorded gage-height record. They have the disadvantage of requiring an observer when used as the primary gage.

Non-recording gages are of two general types: (1) those that are read directly, such as a staff gage, and (2) those that are read by measurement to the water surface from a fixed point, such as wire-weight, float-tape, electric-tape, point and hook gages. Staff, wire-weight and chain gages are popular as both outside auxiliary and reference gages. Vertical staff, float-tape, electric-tape, hook and point gages are commonly used as inside auxiliary or reference gages.

The following description summarizes the non-recording methods recommended for the measurement of stage. The type of use (i.e., as a reference gage, auxiliary gage, or primary gage) determines the effect of the gage on the overall quality and accuracy of the stage record at a site.

1.B.2.a.2.a. Staff Gages

Staff gages are normally rigid boards or rods, precisely graduated and accurately located for scalar measurement sections. The gages may be installed either vertically or inclining.

Vertical staff gages usually are porcelain enameled iron sections, securely bolted or fixed to a secure backing or staff. Inclined staff gages generally consist of a heavy timber securely fastened to a permanent foundation and with especially graduated markings to conform to the slope of the streambank. Inclined gages built flush with the streambank or sloping canal walls are less likely to be damaged by floating debris, ice, floods, and drift than are projecting vertical staffs.

1.B.2.a.2.b. Wire-Weight, Weight-Tape, or Chain Gages

A wire-weight gage consists of a drum wound with a single layer of cable, a weight (usually bronze) attached to the end of the cable, a graduated disc and counter, and a check bar of known elevation. The gage is housed within a small lockable box (usually cast aluminum) and generally mounted to a rigid structure (i.e., bridge or trestle) directly above the water surface. (See Buchanan and Somers, 1968, p. 22). The graduated disc is permanently connected to the counter and to the shaft of the drum. The drum reel is equipped with pawl and rachet for holding the suspended weight at any desired elevation.

The check bar for the wire-weight gage is set by levels as a reference elevation to gage datum. The gage is set so that when the bottom of the suspended weight is at the water surface, the gage height is indicated by the combined readings of the counter and the graduated disc.

A weight-tape gage consists of a graduated steel tape, to which is fastened a small cylindrical or conical weight. The gage is used in conjunction with a fixed reference point by suspending the weight-tape from the reference point (measuring) to the water surface. The gage height is indicated by direct reading of the suspended tape where it intercepts the fixed reference gage. The reference point at most recording stations is usually the front of the recorder shelf, directly above the water surface in the gage well.

The chain gage is constructed by horizontally mounting one or more enamel gage sections (usually along a cantilevered arm extending out over the stream) and a heavy sash chain, with attached weight which runs over a pulley at the end of the gage mounting (or cantilevered arm). The weight is attached on the streamward end of the chain and an index marker is attached near the other end. The gage height (See Bureau of Reclamation, 1967, p. 140) is indicated by lowering the weight until it touches the water surface and reading the position of the index marker on the chain extended along the horizontal gage.

The chain gage is especially useful along steep banks where staff gage sections are inconvenient, impractical to install, difficult to maintain, or where there is no structure over the open channel from which to mount any other outside gage. Levels should be run frequently on chain gage installations, especially those with long cantilevered extensions, to confirm reliability of gage-height readings to established gage datum. Structure settlement, frost heaving, temperature, wind, and many other factors all appreciably affect gage stability.

1.B.2.a.2.c. Pressure-type gages

The pressure exerted by water is lineally related to the depth of water overlying the measuring point. This principle can be used to measure stage. Water pressure can be transmitted through a tube to a manometer inside a gage shelter. Stage can also be measured by bubbling gas freely into the stream through a tube and orifice located at a fixed elevation in the stream. The gage pressure in the tube is equal to the piezometric head on the bubble orifice. This system can be regarded as a remote indicating staff gage and usually consists of a mercury manometer with a stainless-steel reservior,

vertical glass indicator tubing, and a graduated gage scale. This gas-purge system is the principle used to operate the bubble-gage sensors.

Proper placement of the orifice is essential for an accurate record. The orifice should be placed where the height of water over it represents the stage in the open channel. If the orifice is partly buried in mud and sand, the recorded stage will be greater than that actually in the channel. The orifice should not be located in highly turbulent flow or in swift currents.

1.B.2.a.2.d. Crest-Stage Gages

The crest-stage gage was developed to measure the maximum instantaneous stage or flood crest under conditions of transitory or transient flow. The Geological Survey has tested many different types of crest-stage gages (see Buchanan and Somers, 1968, p. 27) and has found the most satisfactory version is a vertical piece of 2-inch galvanized pipe which contains an aluminum or wood staff held in a fixed position relative to a datum reference. Proper placement of intake holes in the bottom of the pipe to minimize the nonhydrostatic drawdown or superelevation inside has been determined a part of the design and testing of the gage.

The crest-stage gage functions by redepositing granulated cork stored in the botton of the capped pipe. As the transitory flood wave passes, the water rises in the pipe and the cork floats on the water surface. As the water recedes, the cork adheres to the staff inside the pipe thereby retaining the crest stage of the flood. The gage height of the flood peak is obtained by measuring the elevation of the floodmark relative to an established reference point elevation on the pipe.

Crest-stage gages are sometimes used as auxiliary gages at recording stations but are more often used as the primary gage at a partial record staion where flood frequency is the main concern.

1.B.2.a.2.e. Hook or Point Gages

Measurement of water-surface stage or gage height is sometimes accomplished using water-level needle gages. In these measurements the tip of the gage just touches the free surface of the water as though attempting to pierce its skin. The two types of needle gages are:

1. The hook gage which is hook-shaped; the tip is submerged and approaches the free surface from below.
2. The point gage, the tip approaches the free surface from above.

Hook gages are most commonly confined to inside use where the water surface is calm. They have the advantage of attaining high measurement accuracy but are generally limited to the measurement of relatively small ranges in stage. Corbett and others (1945, p. 194) discuss the common use of the hook gage in connection with stage measurement in open-channel flow.

A point gage equipped with an electric signalling device (battery, voltmeter and metallic point gage in circuit) is a good inside reference gage. If oil is floating on the water surface, the gage will read the gage height of the interface because oil is a dielectric.

1.B.2.a.2.f. Float Gages

The float gage has been used for many years primarily with an analog water stage recorder and it is an excellent inside reference gage. The float-tape gage is the most popular float gage and consists of a float attached to a counterweight by means of a graduated stainless steel tape, passed over a suitable pulley assembly. The pulley assembly usually includes a wheel (generally 6 inches in diameter) mounted in a standard, an adjustable index, and a reference point. Either the reference point or the adjustable index may be selected for indicating the gage height on the graduated tape.

Stability, sensitivity and accuracy require that a relatively large float and counterweight be used. A 10-inch copper float and a 2-pound lead counterweight are normally adequate.

1.B.2.a.2.g. Other Non-Recording Gages

Other types of non-recording gages used for measurement of stage include the electric tape gage, the water-level finder (see Buchanan and Somers, 1963, p. 23), and various combinations of the methods described above.

The electric tape gage consists of a graduated steel tape to which is fastened a cylindrical weight, a reel in a frame for the tape, a battery and a voltmeter. The electrical connections are:

1. One battery terminal to a ground connection.
2. One battery terminal to one voltmeter terminal.
3. One voltmeter terminal through the frame, reel and tape, to the weight.
4. The weight completes an electric circuit on contact with the water surface, and this registers on the voltmeter.

The electric tape gage is used in conjunction with an index or reference point, similar to the weight-tape and float-tape gages. The most common use is as an inside reference gage.

The water-level finder incorporates slight modifications in the electric-tape gage and the weight-tape gage so more accurate measurements can be made of surging or wave-active water surfaces. This is accomplished by using as the suspended weight a sensor made from a 10-inch length of 1-inch diameter pipe with a recessed (about 5 inch) section of brass rod. A graduated tape is attached to the brass rod. The rod, insulated from the pipe, is inserted through the upper end of the pipe, connected to a tape reel, a milliammeter, a battery, and an index to complete an electrical circuit when the brass rod makes contact with the water surface.

Because about 5 inches of pipe will be submerged before the brass rod comes into contact with the water, the pipe in effect acts as a miniature stilling well for the insulated brass rod. A small milliameter deflection will be recorded when the pipe initially makes contact with the water surface; however, a large deflection is apparent when the brass rod makes contact. Gage-height readings and tape connections are made relative to the bottom of the brass rod for datum control.

1.B.2.a.3. RECORDING GAGES

A water-stage recorder is an instrument for producing a graphic, punched or printed record of the rise and fall of the water surface in an open channel with respect to time. Hence, the recorder must be very accurate and reliable with regard to time and gage height. The time can be adequately recorded through the use of a spring, weight or electric clock mechanism. The gage height or stage recording is usually actuated and/or translated either by a float mechanism or a pressure-sensing device. In most water-stage recorders the timing device drives the recorder and the rise and fall of the water surface actuates the gage-height recording stylus, pen, punch, or printing mechanism.

Strip-chart (graphic) and digital recorders are designed to give a continuous record of stage. The ideal strip chart record will show an uninterrupted recording of the water level fluctations with time. Digital recorders punch or print out gage heights at preselected time intervals which, although interrupted in time may for most practical purposes be considered to be a continuous record of stage.

Continuous records of discharge at a gage site are computed from the gage-height (stage) record and a developed stage-discharge relationship. A continuous and accurate record of stage at a site adds immeasurably to the overall quality of the computed discharge record. Recommended methods must include provisions for (1) care in operating, setting, and maintaining the equipment to insure datum control; (2) avoidance of recorder malfunction; (3) maintenance of intake operation; (4) avoidance of stoppage due to clock, battery, gas supply, tape or chart termination; (5) elimination of record loss due to personnel carelessness or complacency; and (6) insurance of adequate documentation or notes relative to changing site, channel, and rating conditions and the effectiveness of the recorded gage-height record.

1.B.2.a.3.a. Analog Recorders

An analog (graphic) recorder produces a graphic plot proportional to the variable being sensed. An analog water-stage recorder produces a continuous record of stage (gage height) in a wide range of gage-height scales ranging from about 1:1 to 1:24 (1 inch = 2 feet).

Time scales are available in ranges from about 0.3 to 9.6 inches (8 to 244 mm) per day on strip-chart graphic recorders. (See Buchanan and Somers, 1968, p. 5.).

Most analog (graphic) recorders can record an unlimited range in stage by using a stylus-reversing device in strip-chart recorders or unlimited rotation of the drum with drum-type recorders. However, it is recommended that the proportional gage-height scale be compressed if a large range in stage is anticipated.

Where long periods of unattended use are required, the time scale and/or the type of graphic recorder should be selected accordingly. Most strip-chart recorders are designed to operate continuously for several months without servicing. Most drum-type recorders require weekly servicing.

The advantages of the analog recorder include a visual (graphic) record that is continuous in time and proportional in vertical scale. This record provides an instantaneous picture of the recent fluctuations in the water-surface elevations in the open channel. Analog records are extremely valuable where regulation, water-right adjudication, day-to-day operations, sporadic water-level fluctuations, backwater from ice, and other near real-time record needs demand graphical presentation amenable to quick and easy computation.

The analog recorder also has the advantage of simplicity and low cost without the complication and expense associated with the translation and computer computation of digital records. For small or isolated operations the use of the analog recorder is highly recommended.

1.B.2.a.3.b. Digital Recorders

A digital recorder documents information in digitally coded form but as a direct reading of the variable being sensed. Most on-site digital recorders in use at the present time are slow speed, battery operated, paper-tape punch mechanisms which utilize the binary decimal system for recording information (see Isherwood, 1963). This binary decimal code utilizes 4 binary bits for each of 4 decimal digits. Thus, a combination of up to three punches in a group represent digits from one to nine with a blank space for zero, and the four groups of punches (16 channels) represents all numbers from .01 to 99.99. The 4 decimal digits could be converted to represent metric readings by changing the circumference of the float wheel mounted on the input shaft.

Mechanically punched tape is the most practical for field use under widely varying conditions of temperature and moisture (see Buchanan and Somers, 1968, p. 5). Electronic translators convert the 16-channel punch-tape records to readings on a magnetic tape suitable for digital computer processing and computation of gage height and discharge records.

Because the digital recorder documents the gage height only at preselected time intervals of 5, 15, 30, or 60 minutes, the gage height of the absolute peak, especially on flashy streams, may be missed. The maximum peak occurring between inspections of the recorder can be obtained by attaching a paper clip or small magnet on the float tape just below the instrument shelf in such a manner that it will slide along the tape as the stage rises but stay in a fixed position as the stage falls. An auxiliary crest-stage gage or readings of high-water marks (especially those inside the well) will give a good peak gage-height value for the maximum stage.

Digital recorders provide the facility for rapid computing and processing of streamflow or stage records. On streams having artificial controls or stable stage-discharge ratings the processing of digital records can be done rapidly with a minimum of manual handling, corrections and interpretation.

1.B.2d.a.3.c. Telemetering Systems

Telemetering systems are used when current information on stream stage is needed at frequent intervals, and it is impractical to visit the gaging station each time the current stage is needed (Buchanan and Somers, 1968). Current stage data reports are usually necessary for reservoir operation, flood forecasting, and prediction of flows. The types of telemetering systems are:

1. Those which continuously indicate or record stage at a distance from the gage site. Examples of this type are the position-motor or impulse telemetering systems.
2. Those which report instantaneous gage readings on call or at pre-determined intervals. Examples of this type are Telemark and resistance telemetering systems. (See Buchanan and Somers, 1968, p. 17–19, for details on position-motor, impulse, Telemark, and resistance systems).

1.B.2.a.3.d. Dual or Multiple Parameter Records

Research projects, operations, and project management situations often require other related data and information to support recorded stage and/or discharge data. Attachments are available for certain types of continuous (graphic) strip-chart recorders for record water temperature or rainfall on the same chart with stage. Recommended methods for data acquisition for temperature (physical quality of water) and rainfall (hydrometeorological) are covered in other chapters of this handbook and will not be covered here. The tipping bucket rain-gage attachment for a water-stage recorder is discussed by Brice (1963).

1.B.2.a.3.e. Special Purpose Recording Gages

Special purpose recording gages sometimes are needed to collect specific data with stage. The data may be used for low flow studies, flood volume studies using partial record on ephemeral streams, or rainfall-runoff studies. Constraints on installation, range-in-stage, cost, security, or availability of personnel may dictate the design, modifications, and use of the recording gage. In any case, the modifications will include some combination or adaptation of the analog or digital recorders or on-site or telemetering systems. Water-surface stage may be recorded alone, or as a part of a dual or multiple parameter system. Special purpose recorders which are used extensively are cited by Buchanan and Somers (1968, p. 24-27) and include such specific adaptations as the model-T (low flow, limited range-in-stage) recorder and the SR (stage-rainfall) recorder.

1.B.2.a.4. STAGE-RELATED AND/OR DATUM-RELATED MEASUREMENTS

Personnel involved in the acquisition or measurement of stage or stage related data must always be aware of the problems involved in record interpretation, missing records, shifting control or backwater, intake drawdown or pile-up, plugged intakes, recorded range-in-stage, malfunctioning of timing mechanisms, ice or silt in the stilling well, and other problems, which impose some degree of uncertainty on the determination of stage and the associated stage-discharge relationship. Accordingly, it should be a standard and recommended practice to install auxiliary inside and outside gages in connection with the reference and recording gages, and to read and compare these readings as part of regular and routine inspections. Periodic levels (see 1.B.2.a.1., Gage Datum) should be run to all gages to assure datum control and gage-height comparison, especially where ice heaving, gage settling, construction, or subsidence could be a factor.

Complete notes or observations which explain changes or discrepancies in gage heights, stage-discharge relationships, datum, shifting-control corrections, backwater, recorder reversal, and recorded versus observed readings are recommended and encouraged. Special efforts to obtain stage-related and datum-related high-water marks (HWM's) and point of zero flow (PZF) should be

an integral part of each field person's routine. Stages related to over-bank flow at the gage site are also extremely important.

Where flow measurements are made by wading or from a cableway or bridge at the gage site, it is recommended that the cross-sections, areas, and velocity, as well as discharge, be tied to the gage height and gage datum at the time of the measurement. This allows additional relationships such as stage-velocity and stage-area to be developed at the site, thus simplifying the development of the overall stage-discharge relationship.

The cross-sections, reference points, and reach associated with indirect determinations of peak flow should be tied to the gaging station regarding stage, datum, and horizontal control. This will allow coordination and uniformity in making subsequent measurements and/or studies in the same area.

1.B.2.a.4.a. High-Water Marks and Point of Zero Flow

Extreme or anomalous events of stage and discharge create special problems and require additional data. These additional data are associated with flood frequency, low-flow frequency, probability of occurrence, flood risks, and associated insurance rates and land-use zoning. A special effort should be made to obtain the instantaneous maximum and minimum values for stage and discharge for various periods of time or above or below a threshold value. Where a graphic recorder is in operation, both the maximum and minimum instantaneous stage will be recorded. Where a graphic recorder is not in operation or where there is a malfunction, other means of determining the extremes of stage and discharge must be used.

It is recommended that HWM's be determined after each major flood event, both inside and outside of the gage house for recording and non-recording gages. Comparison of inside, outside, and recorded gage-height readings of the peak stage will serve as a check on intake operation and the relative differences, if any, between the gages. Where only periodic stages are obtained with digital recorders (i.e., 5-, 15-, 30-, or 60-minute intervals), the instantaneous maximum may be missed; hence, the determination of HWM's becomes extremely important. Information regarding the flood crest, its time of occurrence, and the duration of the flood can often be obtained from the observer or from local residents. (See Corbett and others, 1945, p. 230-232).

The PZF corresponds to the lowest point on the low-water control. Knowing this point helps to determine the position of the stage-discharge rating curve for low stages, especially for that part of the curve below the lowest discharge measurement. The elevation of the stage of zero flow is easily determined for artificial controls, but for sectional controls, natural riffles, and channel controls, the determinations are approximate.

It is recommended that field personnel take any opportunity during periods of low flow, especially on wadeable streams, to determine the position of the PZF. Several individual determinations by various field personnel may establish the PZF within narrow limits, although any single determination may not be very exact. The PZF stage can be determined by subtracting the depth of water over the lowest point on the control from the gage-height reading at the site at the time. If the control is some distance downstream from the gage, a slight adjustment for slope may be necessary.

1.B.2.a.4.b. Direct Level

Sometimes stage related and/or datum related measurements of water-surface elevations must be made by direct level methods. The specific procedure to be followed for relating stage to reference marks, gages, and reference points, will vary at each site depending on the types of gages and their relative position with respect to each other. Direct levels to the existing water surface, low point on control, intake pipes, high-water marks, bubbler orifice, stream thalweg (profile), stream cross-section points, bank overflow elevations, staff sections, gages, reference points, and reference

marks tie the various entities together and make subsequent record computation appreciably easier. (See Corbett and others, 1945, p. 212-220).

Direct leveling is required for high-water marks in profiles used for indirect determination of peak flow (see 1.B.2.d.3.) and for slope stations because flow computations depend on an exacting measurement of fall or slope in the reach. On many occasions the only high-water marks available for determination of the crest stage of a particular flood are not close to an auxiliary and/or reference gage. Direct leveling may be necessary to tie the HWM's to the station gage datum and to determine the peak or maximum instantaneous gage height for the flood.

1.B.2.a.4.c. Soundings

Soundings of water depth in cross section and in profile are particularly valuable in (1) the study of aggradation and degradation of open channels and their effects on the stage-discharge relation, (2) the verification of hydraulic roughness (see 1.B.2.d.3.a.), and (3) the shifting-control method of discharge determination. The relative changes occurring over time within the channel reach are made more apparent when stage-related and/or datum related soundings are taken at the station.

Soundings taken in conjunction with current-meter measurements, indirect measurements, or ponded area depths, and related to gage datum and gage height tie the cross sections and profiles into the overall physical setting at the gaging station. Where auxiliary gages, reference points, or reference marks are located at the discharge measurement cross section, the water-surface readings (soundings) become direct readings of gage height and/or elevation. Levels do not need to be run in conjunction with the individual measurement. Levels to HWM's and cross-sectional soundings are recommended for indirect determination of discharge.

1.B.2.a.5. GAGING STATION INSTALLATIONS AND EQUIPMENT

The type of installation and equipment needed to obtain a good gage-height (and discharge) record at a site is generally dictated by the physical setting, the intended use of the documented record, accessibility of the station, and related operational and maintenance costs. At most sites the stage record is not the primary product or reason for operation. The main purpose of the station is to establish a unique relationship between the stage, stage-slope or fall, and discharge. This relationship then allows the determination of flow from gage-height records in accordance with the expressed needs at that site. To establish this relation, it is necessary to make an adequate number of discharge measurements in conjunction with simultaneous readings of effective gage heights. Where slope or fall is a factor in development of a slope-stage-discharge or discharge-fall relation it is necessary to obtain concurrent stage readings at both the base and auxiliary gages at the time of the discharge measurement. (See Corbett and others, 1945, p. 130–167).

A preliminary survey of the proposed station site should be made to ensure that the physical and hydraulic features at the site will allow use of the proposed methods of stage and discharge determination.

The proposed site should be such that it is possible to measure the entire range in stage and all types of flow which are required by the study (ISO 1100, 1973b). The entire range of measurement should be referred to one base gage.

The site should be selected where the relationship between stage and discharge is substantially consistent and stable. However, this condition may not be possible in alluvial or sand-channel streams. The site should be sensitive, i.e., a significant change in discharge will be accompanied by a significant change in stage at the base gage (for sectional-control or single-gage station) or a significant change in fall (between the two gages) at slope or fall stations where two gages, base and auxiliary, are needed.

The site should be located to avoid, if possible, (a) variable backwater effect, (b) shifting-control problems caused by vegetative growth, beaver activity, ice, or tributary inflow downstream, (c) vortices, dead water, or other flow abnormalities, (d) access problems or limited access, (e) sharp bends in channel near the gage, and (f) overbank flow conditions.

Location of sites for collection of stage records should be near the sites for measurement of discharge. Accordingly, the possibility of inflow and/or outflow and the need for flow adjustments for changing channel storage between sites are eliminated.

In the case of slope or fall stations the length of reach between gages should be sufficient to make readings or observational errors at either gage negligible in comparison to the overall fall between the two gages.

1.B.2.a.5.a. Instrument Shelter

The primary purpose of the instrument shelter is to provide protection and security for the gages, instruments, and related equipment at the station. However, the design should be such as to facilitate ease of maintenance, inspection and repair, be such as to provide safety for the field personnel, and also be aesthetically acceptable in the environmental surroundings.

Where additional facilities can be installed or are available at little additional cost, the instrument shelter can become much more functional, more convenient, and add immeasurably to the quality of the acquired records. Some of these facilities in the instrument shelter might include pumps and flushing systems, heating units (to prevent well freezing in cold weather), electricity (for lights or heating), and covered storage to accommodate measuring equipment, sample bottles and other items required for routine station operation. Secured covered storage becomes especially valuable at remote gage sites where measuring weights and reels might otherwise have to be carried in at each visit.

The instrument shelter should be kept clean, well ventilated, free of rodents and insects, and well maintained.

1.B.2.a.5.b. Stilling Wells

If a station is equipped with a water-stage recorder and a stilling well, it is essential that the water level in the well correspond to the stage in the river or open channel. Most stations equipped with stilling wells are also equipped with flushing systems to keep the intake pipes clean of sediment and/or particulate matter and to maintain a corresponding stage in the stilling well and in the river outside. These flushing systems, in effect, force water under pressure (static head) out of the well through the intake pipe(s), thus cleaning the pipes of deposited matter and assuring circulation of water with changing stage.

Where the stilling well accommodates the float for a float-operated recorder, it is recommended that the stilling well meet the following conditions.

a. have sufficient height to accommodate the entire range in stage at the station and be vertical.
b. have intake pipes at various stages (elevations) to accommodate widely varying stages and silt contents.
c. have intake pipe(s) or intake holes of sufficient diameter to assure that the water level in the well will not lag the rise or fall of the water level in the stream.
d. have intake pipe(s) or holes of such diameter to damp out short period wave effect or oscillation (surging).
e. have capacity to allow for installation of oil tubes, heating units or frost barriers (floors below frost line) for insurance against lost record in cold climates.
f. have volume or facility to accommodate periodic cleaning. This may require a diameter adequate for a field man to work in the well.

1.B.2.a.5.c. Intakes

Intakes, in the most common usage, generally refer to intake pipes tubes which hydraulically and physically connect water in the river with water in an isolated (off-channel) stilling well, maintaining corresponding stages at both places. We might also consider the pipes or tubes which transmit the pressure head of water in the stream to the manometer location (i.e., in the bubbler or gas-purge system which does not require a stilling well) as intakes because they perform the same general function of maintaining a corresponding stage at both places. Both types are considered in this section.

Intake pipes used in conjunction with stilling wells should meet conditions described under (b) to (d) in 1.B.2.a.5.b., Stilling Wells, and should also be installed with the following conditions met.

a. The lowest pipe should be at least 0.5 foot (0.15 m) lower than the lowest expected stage in the stream and at least 0.5 foot (0.15 m) above the bottom of the stilling well.
b. In cold climates the intake(s) should be located, if possible, below the frostline.
c. Some provision for flushing or cleaning (plumbers snake or rod) is recommended where intakes are long and subject to plugging.
d. Some provision is recommended to reduce the possible effect of pileup or drawdown of the water level in the stilling well due to high water velocity past the intake. Static tubes (short length of perforated pipe attached at the stream end of the intake pipe, by an elbow or a tee, and extended horizontally downstream) are very effective (see Buchanan and Somers, 1968, p. 9–15).

Intake pipes or lines used to transmit the pressure head of water from the stream to the manometer in a gas-purge system should meet the following recommended conditions:

a. The fixed orifice at the stream end of the intake should be placed at least 0.5 foot (0.15 m) below the lowest expected stage in the stream.
b. The orifice should be kept free of mud and debris which will have the effect of making the recorded stage greater than that in the river.
c. The intake (tube) connecting the orifice with the manometer should be encased in metal pipe or conduit (if plastic) and buried to protect it from the elements, animals, and vandalism.
d. The orifice preferably should not be installed in swift currents. Where this is unavoidable, it should be installed at right angles to the direction of flow.
e. The orifice should not be installed where the flow is highly turbulent.
f. The intake line should be installed at a steep gradient up from the orifice and/or in conjuction with double tubing through a manifold to eliminate pockets of water or condensation in the line.

1.B.2.a.5.d. Auxiliary gages

Auxiliary gages installed in connection with the base or primary gage should be in close proximity such that relative readings at corresponding stages can be made. These established relationships and/or comparative readings allow detection of problems which might otherwise go unnoticed (i.e., differences between inside and outside staff gages at varying stages might indicate a plugged or sluggish intake).

The auxiliary gages should be located in such a manner as to accurately read the actual stage in the river. Hence, pile up or drawdown conditions in conjunction with gage emplacement must be considered.

Where the auxiliary gage is installed as the second gage (along with a base gage) at a slope-stage-discharge or fall-discharge station (see 1.B.2.a.5.) an accurate determination of distance and fall

between the gages is needed. Where non-recording readings are observed or recorders installed at the auxiliary gages, the same methods and conditions apply as for the operation of a base or primary gage.

It is recommended that everything considered in planning and installing the base, primary, or reference gage also be considered for installing the auxiliary gages.

1.B.2.b. MEASUREMENT OF WIDTH, DEPTH, AND CROSS-SECTIONAL AREA

For field measurement of open-channel flow, the method most used for the determination of flow rate is the velocity-area method (Sec. 1.B.2.d.2.). The principle of this method is effective and accurate measuring of the cross-sectional area and the flow velocity of the open channel. Accordingly, a flow or discharge measurement is computed as the summation of the products of partial areas of the flow cross section and their respective average velocities. In the formula

$$Q = \Sigma(av), \tag{1-4}$$

where

Q is the total discharge,
a is an individual partial cross-sectional area,
v is the corresponding mean velocity of the flow in and normal to the partial area.

To guarantee reliability and uniformity in the velocity-area method of discharge determination, the channel dimensions (channel width, channel depth and cross section) should be measured using standard methods.

Most direct measurements of width and depth are quite routine. However, because the measurement of width involves horizontal angles and the measurement of sounded depth involves both horizontal and vertical angles, these measurements are much more complicated. Determination of effective depth when measuring the flow of water under ice cover is a special problem.

Recommended methods, along with correction tables for vertical angles, air-line length and wet-line length have been developed with years of research and operational experience to handle the difficult problems encountered in measuring width, depth, and cross-sectional area. These difficult problems are most apparent in deep, swift, open-channel flow. Research and development of streamlined sounding weights and instructions for their use have greatly facilitated the ease and accuracy of depth determinations.

1.B.2.b.1. DIRECT MEASUREMENT OF WIDTH

The distance to any point in an open channel cross section is measured from an initial point on the bank. Cableways, highway bridges, or foot bridges used regularly for making discharge measurements are commonly marked at convenient distance intervals by paint markings. Steel tapes, metallic tapes or premarked taglines are used for width determinations during discharge measurements made by wading, from boats, or from unmarked bridges. (See Buchanan and Somers, 1969, p. 17).

Tag lines, galvanized steel aircraft cable of various diameters, are marked with solder beads at various measured intervals and accommodate maximum widths of 1000–3000 feet (305–914 m). Standard tag-line lengths of 300, 400, and 500 feet (91, 122, and 152 m) are also available. Extra heavy-duty tag-line reels for use in measuring wide streams by boat accommodate a maximum of 3000 feet (914 m) of 1/8-inch (3.2 mm) diameter cable.

It is practically impossible to string a tag line for discharge measurements from a boat when the width of open channel is greater than 2500 feet (762 m). Tag-line reels with brakes and a means of taking up the slack (i.e., possible block and tackle arrangement) may be required on these long spans. Problems with navigational traffic may occur when a tag line is used. If there is traffic on the

channel a person must be stationed on the bank to raise and lower the tag line to allow the traffic to pass. Streamers should be placed on the tag line so that it may be seen by boat pilots.

Direct measurement of width using tapes, premarked cableways and bridges, and tag lines, even on long spans, can be very accurate with proper precautions. Orientation normal to the flow pattern of the river and elimination of most of the sag (through support or tension) are recommended for improved accuracy.

1.B.2.b.2. TRANSIT-STADIA MEASUREMENT OF WIDTH

If there is a continual flow of traffic on the channel to be measured, if there is no suitable bridge, or if the width of the channel is too great to stretch a tag line or cableway, then measurement from a boat may be necessary. However, personnel safety becomes a limiting factor in the use of boats on channels having high flow velocity and heavy wave action. The use of a boat under these conditions requires special means to position the boat and effectively measure the channel width.

When no tag line is used, the boat can be kept in the cross section by lining up with flags positioned on each end of the cross section. (See fig. 1-2). Flags on one bank would suffice but it is better to have them on both banks. The position of the boat in the cross section can be determined by a transit on the shore and a stadia rod held in the boat. (See fig. 1-2).

Another method of determining the position of the boat is by setting a transit on one bank some convenient known distance from and at right angles to the cross-section line. The position of the boat is computed be measuring the angle α to the boat. (See fig. 1-3).

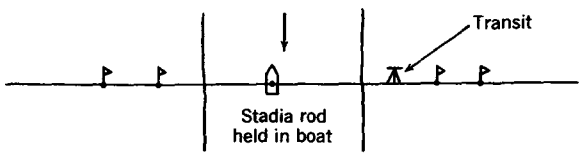
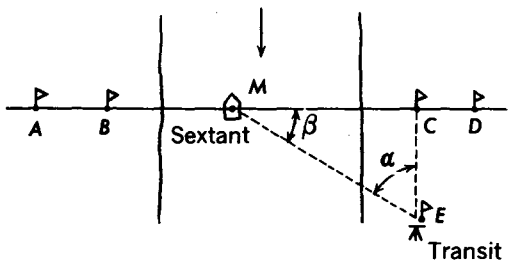


Figure 1-2.—Determining position in the cross section, stadia method (from Buchanan and Somers, 1969).



$$MC = CE \tan \alpha \text{ (transit)}$$

$$MC = \frac{CE}{\tan \beta} \text{ (sextant)}$$

Figure 1-3.—Determining position in the cross section, angular method.

A third method of determining the position of the boat uses a sextant read from the boat. This can be done by placing a flag on the cross-section line and another at a known distance perpendicular to the line. The boat position can be computed by measuring the angle α with the sextant. (See fig. 1-3).

Unless anchoring is more convenient, the boat must be held stationary by the motor when readings are being taken.

Width determination in connection with the moving-boat method (See 1.B.2.d.2.d.) of discharge determination (Smoot and Novak, 1969) are computed as incremental widths across the stream using the equation $L_b \approx L_v \cos \alpha$. (See fig. 1-4).

This equation is based on the assumption that a right-triangle relationship exists among the velocity vectors involved in the flow measurement. If the flow is not normal to the cross section, this situation does not exist and the equation will give computed values that are too large or too small (fig. 1-4) depending on whether the vector quantity representing the oblique flow has a horizontal component that is opposed to or in the direction of that of the boat.

Ideally the correction error in the computed width for the moving-boat method would be applied to that particular increment in the width where the error occurred. This is not possible because in practice only the overall width of the cross section is directly measured for comparison with the computed width. Correction for true width is made by adjusting each incremental width proportionately.

The moving-boat method uses the relationship between the measured and computed widths of the cross section to determine a width-area adjustment factor. This factor is obtained as

$$K_B = \frac{B_m}{B_c} \tag{1-5}$$

where

K_B = width-area adjustment factor,
B_m = measured width of cross section, and
B_c = computed width of cross section.

The adjustment factor is then used to adjust both total area and total discharge of the measurement by one percentage as though the width error had been evenly distributed across each width increment of cross section. (See Smoot and Novak, 1969, page 19).

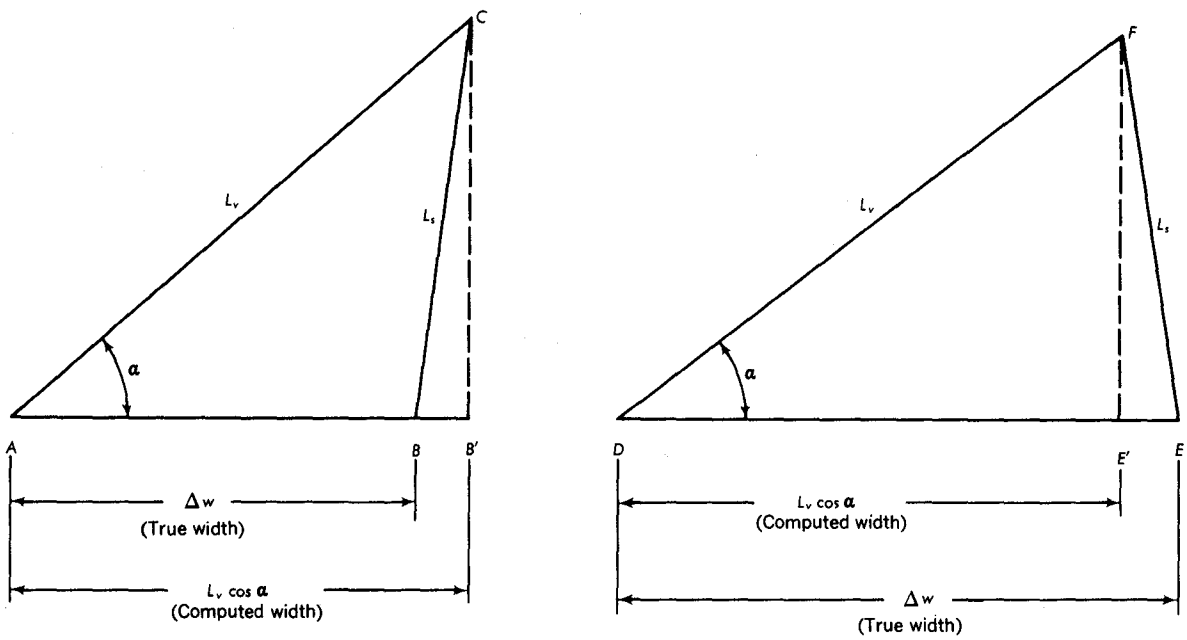


Figure 1-4.—Comparison of actual and computed values of incremental widths.

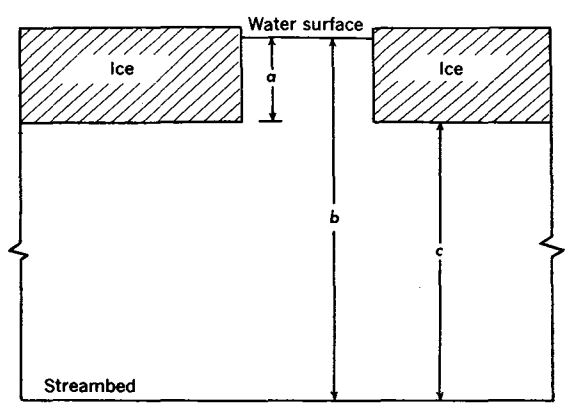
Direct measurement of depth (sounding) is usually done by mechanical means depending upon the type of measurement being made. Channel depth and position in the vertical are normally measured by rigid rod or by a sounding weight suspended from a cable. The cable is controlled by a reel or by a handline. A sonic sounder is also available, but is usually used in conjunction with a reel and sounding weight.

Depth measuring equipment includes wading rods, sounding reels, handlines, and the sonic sounder. The sonic sounder is particularly adaptable for measurements by the moving-boat method (Smoot and Novak, 1969, p. 8–10) to provide a continuous strip-chart record of the channel depth (i.e., a profile of the cross section).

The measurement of channel depth in a wading measurement or from a foot bridge is made using either the top-setting or round wading rod. The sliding support used to adapt and position the rotating element current meter fits on the rod and can be adjusted to place the current meter at any depth setting. (See Buchanan and Somers, 1969, p. 9–11). The round rod is also used in making ice measurements.

Extreme care must be exercised in measuring depths under ice cover where the total depth of water may not correspond to the effective depth of flow. (See fig. 1–5). The effective depth of water is the total depth minus the distance from the water surface to the bottom of the ice. The total depth of water is usually measured with an ice rod or with a sounding weight and reel, depending on the depth. The distance from the water surface to the bottom of the ice is usually measured with a graduated ice-measuring stick with an L-shaped projection on the lower end. The L-shaped projection slides along the underside of the ice making a direct reading of the distance *a* in fig. 1–5 possible.

Measurement of depth using a sounding weight suspended from a cable can be routine if certain basic facts are recognized and appropriate corrective procedures are followed. One of the main considerations is using a sounding weight heavy enough to minimize drift downstream. Buchanan and Somers (1969) have shown that where it is possible to sound the depths, but the weight and meter drift downstream, the depths measured by the usual methods are too large. (See fig. 1–6). The correction for this error has two parts—the air-line correction and the wet-line correction. The air-line correction is shown in fig. 1–6 as the distance *cd*. The wet-line correction in fig. 1–6 is shown as the difference between the wet-line depth *de* and the vertical depth *dg*.



a = Water surface to bottom of ice
b = Total depth of water
c = Effective depth ($c = b - a$)

0.2-depth setting = $a + 0.2c$
0.8-depth setting = $b - 0.2c$
0.6-depth setting = $b - 0.4c$

Figure 1–5.—Depth measurement and meter settings for measurements under ice cover (from Buchanan and Somers, 1969).

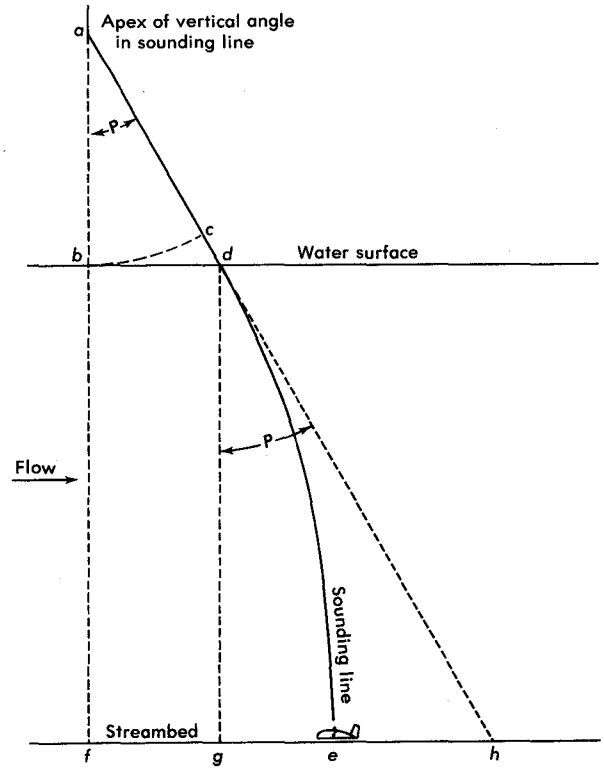


Figure 1-6.—Position of sounding weight and line in deep, swift water.

The air-line correction, as shown in fig. 1-6, depends on the vertical angle *P* and the distance *ab*. The air-line correction may be minimized by using tags at selected intervals on the sounding line and using the tags to refer to the water surface when sounding.

Depth-measuring equipment, such as rods, reels, protractors, and sounding weights, and recommended methods and corrections for wading, cableway, boat and bridge measurements are described in detail by Buchanan and Somers (1969). Buchanan and Somers (1969) also give computed tabular values for air-line, wet-line, and angular corrections for almost all possible combinations of length and angular measurements while measuring depth using a sounding weight suspended from a cable.

1.B.2.b.4. COMPUTATION OF AREA

Because total flow determination in an open channel is a summation or integration process, the overall accuracy of the measurement is generally increased by increasing the number of partial cross sections. Generally 25 or 30 partial cross sections, even for extremely large channels, are adequate depending on the variability and complexity of the cross-sectional shape and flow patterns. With a smooth cross-section and good velocity distribution, fewer sections may be used. Partial sections should be spaced so that no partial section contains more than 10 percent of the total flow. The ideal measurement would have less than 5 percent of the flow in any one partial section

Where recommended methods are used for measurement of width and depth (See 1.B.2.b.1., 1.B.2.b.2., and 1.B.2.b.3.), the computation of area becomes a matter of selecting a recommended and/or standardized procedure. A comprehensive study by the USGS in 1950 making a comparison of the mid-section versus the mean-section methods of computing cross-sectional area and/or discharge resulted in the USGS adopting the mid-section method as the standard or recommended procedure. Although the mid-section method was shown to give only slightly more accurate figures

for discharge and required no appreciable difference in field procedure, the main reason for adopting the mid-section method was time and money savings over the mean-section method. The mid-section method of computing cross-sectional area for discharge measurements is recommended.

The partial cross-section at location 4 (heavily outlined in fig. 1–7) represents the typical partial area(s) which can be summated to obtain the overall cross-sectional area computed by the mid-section method. (See 1.B.2.d.2. for discharge computation, this method). The area computation is:

$$a_4 = \left(\frac{b_5 - b_3}{2}\right) d_4 \qquad (1\text{–}6)$$

$$A = \Sigma(a)$$

1.B.2.b.4.a. Mid-Section Method

The mid-section method of measurement assumes that the velocity sample at each depth sampling point represents the mean velocity in the partial rectangular cross-sectional area. The partial area extends laterally from half the distance from the preceding meter location to half the distance to the next, and vertically from the water surface to the sounded depth. (See fig. 1–7). The channel cross section is defined by depths at locations 1,2,3,4, . . . n.

1.B.2.b.4.b. Mean-Section Method

The mean-section method of computing cross-sectional area for discharge measurements, as stated previously, is not the method recommended for computation of area, but is only mentioned here as a basis of comparison with the mid-section method.

The mean-section method assumes that the velocity and depth sample at each location represents only the velocity and depth at the end of each partial section; hence, the area of a particular partial section is computed by averaging the depths at adjacent locations and multiplying by the horizontal distance between them. It is apparent that the computational procedure for discharge will be much more time consuming because velocities similar to depths, have to be averaged for each partial section.

Using fig. 1–7 for comparison, it can been seen that area computation is

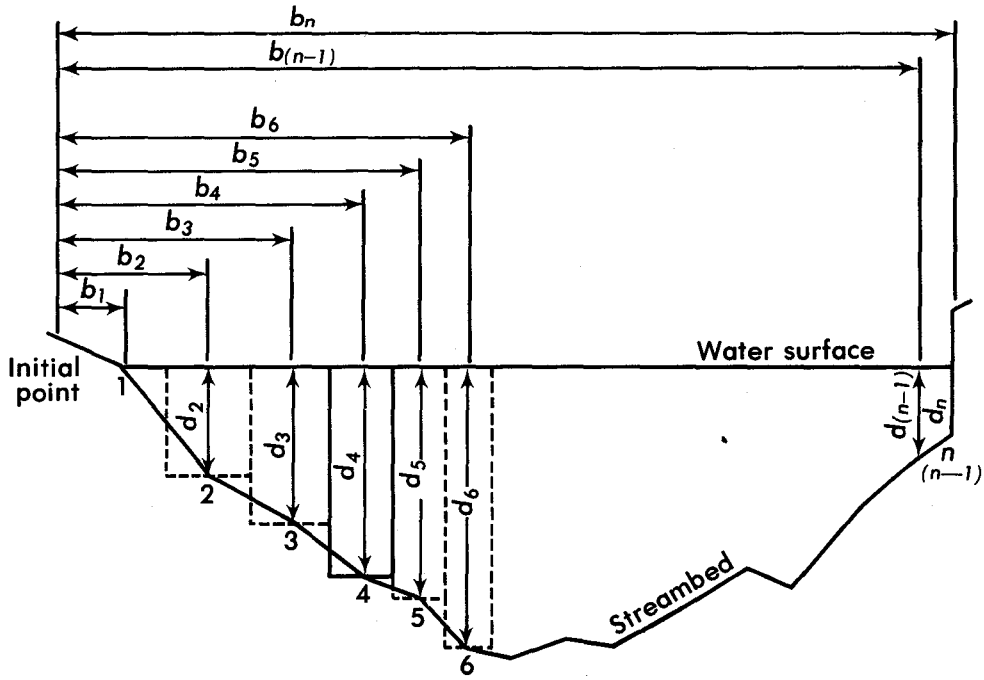
$$a_{3\text{–}4} = \left(\frac{d_3 + d_4}{2}\right)(b_4 - b_3) \qquad (1\text{–}7)$$

$$A = \Sigma(a)$$

1.B.2.c. MEASUREMENT OF VELOCITY

In determining the mean velocity in a cross-section used in making a discharge measurement by velocity-area methods, the mean velocity normal to the measuring section can be measured in each vertical, along selected horizontal paths as in acoustic methods, or as an overall mean for the cross section as in tracer methods. Because velocity-area methods are the most widely used direct methods for discharge determination on velocity measurement, an extensive discussion is presented.

The recommended methods all have advantages and limitations in application and use. None of the methods is best under all circumstances, therefore, the user must make a choice on the basis of specific application. Where measurement of velocity in open-channel flow is complicated by the existence of turbulent flow, steep gradients, extremely low velocities or flow, irregular channel conditions, unsteady flow, or possibly by uniform and/or steady flow, the logical choice of a "best" method becomes more limited. Despite its limitations, the rotating-element current meter is presently the most widely used and popular velocity-measuring device and is likely to remain so for a long time.



EXPLANATION

1,2,3.....n	Observation points
b_1, b_2, b_3.....b_n	Distance, in feet, from the initial point to the observation point
d_1, d_2, d_3.....d_n	Depth of water, in feet, at the observation point
Dashed lines	Boundary of partial sections; one heavily outlined discussed in text

Figure 1-7.—Definition sketch of midsection method of computing cross-section area for discharge measurements (from Buchanan and Somers, 1969).

Velocity-measuring methods discussed range from very simple, but nevertheless important mechanical devices such as rotating-element current meters and deflection vanes, to highly sophisticated electrical systems such as electromagnetic and acoustic (ultrasonic) flow meters. Floats, drag-bodies, tracers, optical methods, and velocity-head methods are also discussed.

The discussions of methods generally focuses on principles of operation; on the advantages and disadvantages of their use, either in general or special applications; and on the limitations which curtail certain potential uses and applications.

1.B.2.c.1. ROTATING-ELEMENT CURRENT METERS

Most current meters used to measure open-channel flow are the rotating-element type in which the operation is based on the proportionality between the velocity of the water and the resulting angular velocity of the meter rotor. By placing a current meter at a point in a stream and counting the number of revolutions of the rotor during a measured interval of time, the velocity of water at that point is determined. Buchanan and Somers (1969) give an excellent treatise on the electrical circuits, contact chambers, contact signals, meter operation, meter design, and general limits of use.

ISO 3455 (1976) discusses the standard procedure for calibration of rotating-element current meters and the limits of meter application. Smoot and Novak (1968) discuss the recommended methods for use, calibration, rating, maintenance and repair of rotating-element (vertical-axis type) current meters to assure a high level of quality control.

1.B.2.c.1.a. Methods of Operation

Rotating-element current meters can be classified into either vertical-shaft or horizontal-shaft types. The most common of the vertical-shaft type are those with the S-shaped or Savonius rotor or with the bucket wheel made up of conical or hemispherical cups. Most common of the horizontal-shaft type are those with the helical rotor or the blade propeller. Each has its good and bad features.

No rotating-element current meter is ideal for any extended period of unattended operation, but for attended operation they give excellent results when properly selected, maintained and used; and they are inexpensive, simple in design, and rugged.

1.B.2.c.1.a.1. Vertical-Axis Type (Cup) The bearing systems in the vertical-axis meters are simpler in design, more rugged, and consequently easier to maintain and service than horizontal-axis type meters. Also, because of the bearing system, the vertical-axis meters have a lower starting threshold of 0.1 foot per second (0.03 meters per second) and will operate at lower velocities than horizontal-axis meters. The bearings are well protected from silty water, the bearing adjustment is usually less sensitive, and the calibration at lower velocities where friction plays an important role is more stable. A single rotor serves for the entire range of flow velocities. The rotor is repairable in the field without adversely affecting the rating.

The most common vertical axis meters in use included the Price meter, type AA, for regular velocity measurements; the Price, type AA, low-velocity meter (no pentagear); the Price pygmy meter, for shallow depths and low velocity; and a newly developed (by USGS) four-vane ice meter. See Buchanan and Somers (1969) for recommended uses and/or limitations for these meters.

1.B.d.2.c.1.a.2. Horizontal-Axis Type (Propeller) Horizontal-axis rotors disturb the flow less than vertical-axis rotors because of axial symmetry with the flow direction. Horizontal axis meters are also less sensitive to vertical velocity components than is the vertical-axis meter which in most instances overregisters. Also, the vertical-axis meter cannot correct for oblique flow whereas some of the helical rotors are designed to act as nearly perfect cosine meters.

The horizontal-axis meter design, because of its shape, is less susceptable to fouling. This meter also has less bearing friction than the vertical-axis meter because bending moments on the rotor are eliminated.

The most common horizontal-axis meters in use include the Ott (German), the Neyrpic (French), the Haskell (United States) and the Hoff (United States). Because the propeller-type meter is generally less durable than the vertical-axis meter, it is not used extensively in the United States. Smoot and Novak (1969) recommend the use of the component propeller-type current meter in moving-boat measurements because it is less susceptible to disturbance and therefore, minimizes errors created by the bobbing of the boat. See Buchanan and Somers (1969, p. 4–7) regarding other recommended uses of horizontal-axis meters.

1.B.2.c.1.b. Method of Velocity Determination

Rotating-element current meters measure velocity at a point. The method of making discharge measurements (see 1.B.2.b.4.a. and 1.B.2.d.2.) at a cross section requires determination of the mean velocity in each of the selected verticals. The mean velocity in a vertical is obtained from velocity observations at many points in the vertical. The mean can be approximated by making a few velocity observations and using a known vertical-velocity curve based on observed velocities plotted against depth. (See fig. 1–8).

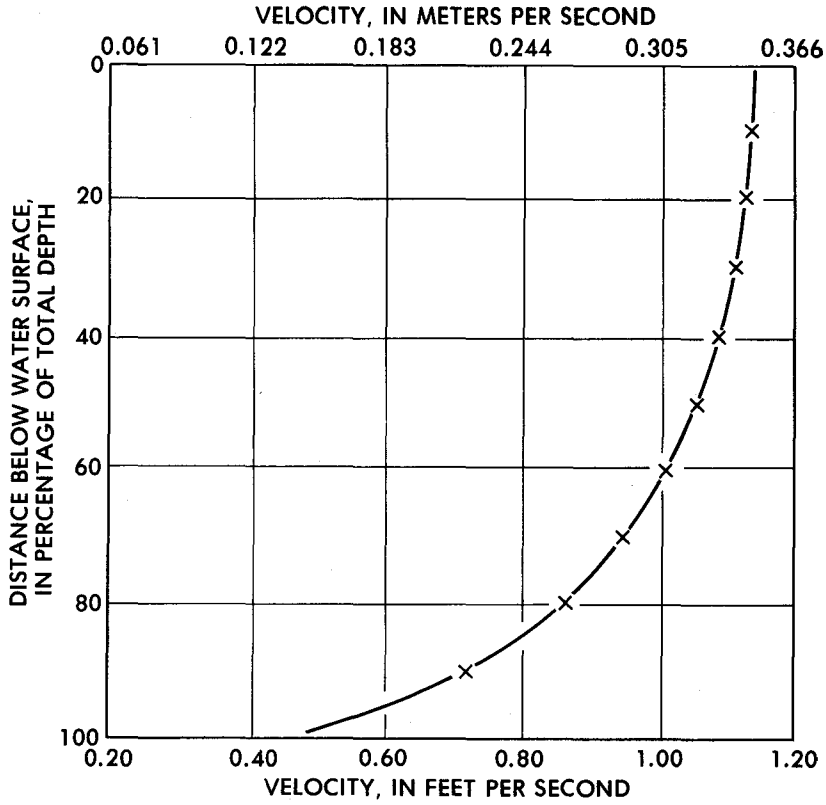


Figure 1-8.—Typical open-channel vertical-velocity curve. (Modified from Buchanan and Somers, 1969.)

There are various recognized methods of measuring the mean velocity in the vertical. Each method has its merits depending on the time available to make the measurement, the width of the cross section and the depth of the water, the bed conditions, the changing stage, whether flow is steady or unsteady, whether cable suspension is being used, and the needed accuracy of results.

1.B.2.c.1.b.1. Six-Tenths Depth Method The six-tenths depth method (0.6 of the total depth below water surface) uses the observed velocity at this depth as the mean velocity in the vertical. This method gives extremely reliable results whenever the water depth is between 0.3 and 2.5 ft. (.09 and 0.76 m), whenever the meter placement above a sounding weight makes it possible to obtain a 0.8 depth observation for the two-point method, whenever large amounts of slush ice or debris prevent observation of the 0.2 depth velocity for the two-point method, or whenever the stage or flow is changing rapidly and a measurement must be made quickly.

1.B.2.c.1.b.2. Two-Tenths Depth Method The two-tenths depth method (0.2 of the total depth below water surface) observes the velocity at the stated depth below the surface and applies a coefficient to this velocity to obtain a value for the mean in vertical. This method is used mainly during periods of extremely high flow when the velocities are great, making it impossible to obtain velocities at the 0.8 or 0.6 depths. A general knowledge of the cross-section, the relative depths with stage, and the vertical-velocity curve at the location are needed if it is impossible to obtain depth soundings. A sizeable error in the assumed 0.2 depth is not critical to accuracy because the vertical-velocity curve at this point is usually nearly vertical. The two-point and 0.6 depths methods are preferred to this method because of their greater accuracy.

1.B.2.c.1.b.3. Two-Point Method The two-point method (0.2 and 0.8 depth below the water surface) averages the velocities observed at these relative depths at each location and this average is used as the same mean velocity in the vertical. Experience has shown that this method gives more consistent and accurate results than any of the other methods except the vertical-velocity curve method. The two-point method is generally not used at depths less than 2.5 feet (0.76 m) because the current meter settings would be too close to the water surface and stream bed for dependable results.

1.B.2.c.1.b.4. Three-Point Method The three-point method consists of measuring the velocity at 0.2, 0.6, and 0.8 of the depth, thereby combining the two-point and six-tenths depth methods. The mean velocity is obtained by averaging the 0.2 and 0.8 depth observations and then averaging the result with the 0.6 depth measurement. This method is used when the velocities in the vertical are abnormally distributed. The depths must exceed 2.5 feet (0.76 m) before this method is used.

1.B.2.c.1.b.5. Vertical-Velocity Method The vertical-velocity curve method of mean velocity determination (see fig. 1–8) normally observes velocity readings at 0.1 depth increments between 0.1 and 0.9 of the depth. This method is valuable in determining coefficients for application to results of other methods but is generally not adapted to routine discharge measurements because of the large amount of time required to collect field data at each vertical and to compute a mean velocity. The mean velocity in the vertical is normally determined by integrating the plotted vertical-velocity curve.

1.B.2.c.1.b.6. Subsurface Method The subsurface method of velocity determination observes the velocity at some small distance below the water surface and converts this velocity determination to a mean velocity in the vertical through the use of a coefficient. The observation of velocity should be far enough below the water surface to avoid the effect of surface disturbances. This method is used when it is impossible to obtain depth soundings.

1.B.2.c.1.b.7. *Surface Method*—The surface method has limited use, but is used on occasion with float determinations. The vertical-velocity curve at the location and a reliable estimate of an applicable coefficient are used to convert surface velocity to a mean velocity in the vertical. A coefficient of about 0.85 is commonly used. This surface or float method should be used when it is impossible to use a current meter because of excessive velocities and depths or where velocities and depths are too low for a current meter measurement. (See sec. 1.B.2.c.4.a. and 1.B.2.c.4.b.)

1.B.2.c.2. ACOUSTIC METHODS

Several acoustic (ultrasonic) velocity meter systems have been developed using variations of the same basic theory (Smoot, 1974). These systems measure water velocity by determining the travel times of sound pulses moving in both directions along a diagonal path between transducers mounted near each bank of the stream. The water velocity indicated by the system is the average velocity component parallel to the acoustic path between two transducers. In the systems that have reached prototype or field-level configuration, three general approaches have been employed. These are the sing-around circuit, the total travel-time circuit, and the differential time circuit.

The total travel-time circuit is the simplest in concept. Measurement of water velocity is possible because the velocity of a sound pulse in moving water is the algebraic sum of the acoustic propagation rate, C, and the component of water velocity parallel to the acoustic path. Therefore, the traveltime of an acoustic pulse, originating from a transducer at point A (See fig. 1–9) and traveling in opposition to the component of water velocity along path AB, can be expressed as:

$$T_{AB} = \frac{L}{C - V_P} \tag{1-8}$$

where C = velocity of sound in still water,
L = length of acoustic path from A to B,
T_{AB} = traveltime from A to B,
T_{BA} = traveltime from B to A,
V_P = average water velocity parallel to the acoustic path,
V_L = average water velocity at the elevation of the acoustic path, and
θ = the angle of departure between the streamline of flow and the acoustic path. An angle of about 45° is desirable.

Since for a pulse traveling with the flow,

$$T_{BA} = \frac{L}{C + V_P}, \tag{1-9}$$

it can be shown that

$$V_P = \frac{L}{2}\left(\frac{1}{T_{AB}} - \frac{1}{T_{BA}}\right) \tag{1-10}$$

$$V_P = V_L \cos\theta \tag{1-11}$$

$$V_L = \frac{L}{2\cos\theta}\left(\frac{1}{T_{AB}} - \frac{1}{T_{BA}}\right) \tag{1-12}$$

In this total traveltime circuit, corrections for changes in the acoustic velocity of sound are automatically eliminated by the treatment of the data.

In a system built on the total traveltime circuit, traveltimes are measured sequentially for pulses originating at A and traveling against the current, and then for pulses originating at B and traveling with the current. Accuracy of a system of this type depends on the precision with which the individual traveltimes can be measured. Errors in indicated velocities are a linear function of timing errors in either direction.

The sing-around circuit concept, sometimes referred to as the pulse-repetition frequency system, has been tried by several developers. In such a system, cumulative measurements of traveltimes are made by using the received pulse at the far end of an acoustic path to immediately trigger a second transmittal pulse at the originating transducer. Arrival of the second pulse triggers

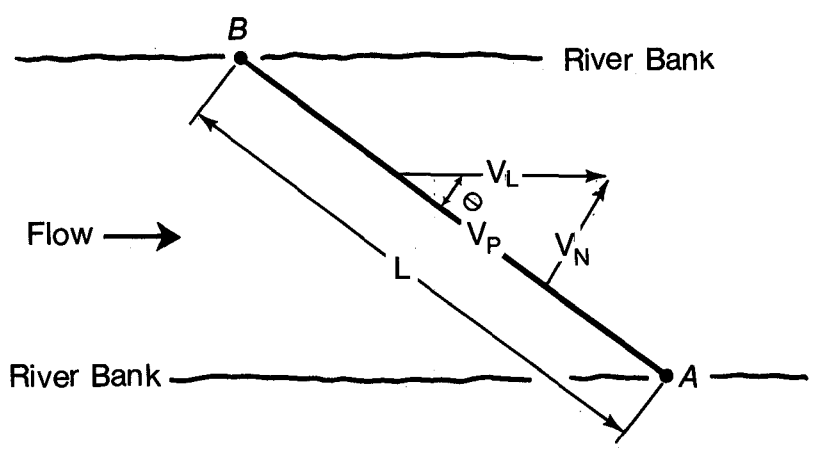


Figure 1-9.—Operation of acoustic velocity meter.

Transit time of the acoustic wave is resolved either by measurement of the total time for completion of a fixed number of cycles or by reduction of the cycling rate to a continuous pulse-repetition frequency. Where a single pair of transducers is employed, such systems usually measure transit times for a given period in one direction along the acoustic path and then in the other direction. Sometimes, two pairs of transducers are used, tuned to different frequencies and operating simultaneously.

The quotients $1/T_{BA}$ and $1/T_{AB}$ in equation 1-12 are the pulse-repetition frequencies for acoustic transmission in each direction that would be measured in a sing-around circuit system. Difficulties have usually been problems of acoustic signal recognition and maintenance of stable operations. Successful application of the sing-around circuit has been limited to measurement of flow in conduits and smaller channels.

The differential time circuit differs from the two circuits previously discussed in that the difference in the time of arrival of acoustic pulses, triggered simultaneously at each end of the path, is measured directly. When two transducers transmit signals simultaneously toward each other, the flow of water in the path will increase the speed of one signal and decrease the other. The signal transmitted in the downstream direction arrives first and is used to start a time clock; the signal transmitted in the opposite direction arrives later in time and is used to stop the clock. The time increment recorded is thus the differential between the total traveltimes involved and is linearly proportional to the water velocity. In this system, the measure of average total traveltime in each direction must also be recorded to compensate for changes in the speed of sound in water.

One of the most important items in any of the acoustic velocity meter systems is accurate measurement of time. Four differing signal-recognition methods have been employed by various designers. They are (1) the leading-edge detection method, (2) a method that utilizes a differential of the voltage-time pulse train, (3) a method that recognizes the first "zero" crossover after the first peak above a given threshold level, and (4) a method comparing phase relations of the received and transmitted signals.

Acoustic (ultrasonic) velocity meter systems do operate satisfactorily, giving good accuracy of measurement but they are complex, expensive, and costly to operate. It must be emphasized that the acoustic path(s) are normally fixed at a certain elevation in the channel cross section. A relation between the mean velocity along the path(s) and the mean vertical-velocity curves for the channel must be developed because the acoustic velocity meter measures only line velocity and not variation of depth.

1.B.2.c.3. DEFLECTION-TYPE OR DRAG-BODY METHODS

Many types of velocity-measuring devices have been tried employing drag bodies of various shapes and configuration. (See Smoot, 1974.) All such devices are governed by the basic drag equation:

$$F=\frac{C_D \rho A V^2}{2} \tag{1-13}$$

where: F = drag,
ρ = density of fluid,
A = projected area,
V = velocity of fluid, and
C_D = coefficient of drag.

It is apparent that the drag is proportional to the square of the velocity. Consequently, all drag-body current meters are insensitive to extremely low velocities. The drag is also proportional to the coefficient of drag, a function of the Reynolds number. The drag coefficient changes if the surface of the drag body becomes fouled with aquatic growth or debris.

The two basic drawbacks to the use of these methods for velocity measurement in open channels should be carefully considered in evaluating the deflection-type or drag-body meter.

The vertical-axis deflection vane is one of the most common drag-body meters.
Advantages of it are:

1. The counterbalancing weight can be easily changed to change ranges.
2. It can be made to integrate velocities throughout the greater portion of a vertical.
3. Mechanical output can be recorded.
4. Visual readout of deflection is simple.

Disadvantages are:

1. Its tendency to collect debris.
2. High degree of bearing friction, resulting from its heavy weight, adds to the insensitivity problem at low velocities.
3. Removal for service or repair is relatively difficult.

The *horizontal-axis or pendulum-type deflection vane* has many uses and overcomes many of the disadvantages of the vertical-axis deflection vane.

Advantages are:

1. Direction and velocity output.
2. Drag element is very easily changed for range changes.
3. Line can be shortened or lengthened so that the drag element can be set to detect velocity at various depths.

Disadvantages are:

1. No method of recording output; must be manually operated.
2. Complex and somewhat uncertain corrections for drag on the line are required.

The *drag sphere* is typical of the many drag-body devices.
Advantages are:

1. Usually detection elements are on both the X and Y axes and both direction and deflection can be resolved.
2. Electrical signal output can be easily recorded.
3. Can be completely submerged.

Disadvantages are:

1. No visual readout.
2. Eddy shedding causes a great deal of vibration of element. (Note.—This is true of all such devices, but to a lesser extent on other shapes.)
3. Single velocity range.

The *inclinometer* has proven satisfactory for some special applications for measurement of low velocities.

Advantages are:

1. Very sensitive to low velocities.
2. Can be completely submerged.
3. Both velocity and direction can be resolved.

Disadvantages are:

1. Only one velocity range.
2. Data must be manually processed.

Despite the many drawbacks of drag-body meters, they are relatively inexpensive and for certain applications function as well as any currently available device.

1.B.2.c.4. FLOATS

As stated by Buchanan and Somers (1969), floats have a very limited use in stream gaging, but there are occasions when they prove useful. A float can be used where the velocity is too low to obtain reliable measurements with a current meter. They are also used for velocity determination where flood measurements are needed and the measuring structure(s) has been destroyed and/or flow conditions or debris make it impossible to use a meter.

Floats are the most primitive method for estimating the velocity of flowing water. The determination of mean velocity, V, is based on the measurements of distance, s, traveled by the float(s) in a corresponding time, t.

$$V=\frac{s}{t} \tag{1-14}$$

Velocities determined by floats normally must be adjusted by a coefficient to obtain a mean velocity of flow in the vertical. This coefficient varies from about 0.80 to 1.00 depending on the relative depth of immersion of the float and the vertical-velocity profile.

1.B.2.c.4.a. Surface Floats

The velocity and discharge of a canal or stream may sometimes be determined approximately by the use of surface floats (See Bureau of Reclamation, 1967). This can be done by dividing the width of the canal or stream into segments and determining the average depth of each segment. Float velocities can be obtained for each segment, adjusted to approximate the mean velocity in each segment, and multiplied by the cross-sectional area for each segment to calculate discharge. The sum of the segment discharges is the total discharge for the reach of open channel.

A coefficient of about 0.85 is commonly used to convert surface velocity to mean velocity. This value is an average of many observations, although for a particular channel, the coefficients may be as low as 0.80 or as high as 0.95.

It should be emphasized that measurements of velocity and/or discharge by surface floats are only approximations and should be used accordingly. Under good conditions of fairly uniform flow and cross-section, no waves or surface winds, and with a certain amount of care, an error of less than 10 percent is possible. With poor flow conditions in a poor reach of channel, the measurements could be as much as 25 percent in error.

1.B.2.c.4.b. Vertical Floats

Vertical floats or rod floats are wooden or thin-walled metal rods weighted at the lower end so they will float upright (vertical) in the stream. The loading of the rod is fixed so that its velocity approximates the mean flow velocity in the vertical plane parallel to the channel axis.

The immersed portion of a vertical rod float is general about 0.90 to 0.95 of the depth of flow. However, the rod float must never touch the streambed.

Coefficients for rod floats vary from 0.85 to 1.00 depending on the shape of the cross-section and the velocity distribution. (See Buchanan and Somers, 1969).

1.B.2.c.5. PRESSURE METHODS

Impact-pressure velocity measurements are used to determine local (point) flow velocities. The principle of operation is based on the proportionality of the point velocity to the square root of the

dynamic pressure head which may be measured directly or as the difference between the total and static pressure heads.

The necessary part of these impact pressure velocity measuring devices is an impact tube (i.e., Pitot tube, Barcy tube, Prandtl tube, differential impact-pressure tube, and Brabbe tube). The tube is a cylinder or a sphere with properly aligned piezometric holes, connected to an open glass-tube gage or to the tubes on a differential manometer.

The Pitot tube is probably the most often used of the impact-pressure measuring devices. In the Pitot tube the kinetic energy of the liquid impinging on the tube orifice is converted into pressure energy which causes an increase in the head in the vertical limb of the tube. Hence, using Bernoulli's equation and assuming total conversion of velocity energy into pressure energy, the point velocity of the flowing water can be expressed as

$$v = \sqrt{2gh} \tag{1-15}$$

Allowing for disturbances and losses in the Pitot tube, the true point velocity will be

$$v = \psi \sqrt{2gh} \tag{1-16}$$

where ψ is a velocity coefficient which depends on the tube shape and the liquid. The ψ will ordinarily run about 0.92 for water.

1.B.2.c.6. TRACER METHODS

Tracer methods for the determination of velocity have many common requirements and characteristics. In general, the methods vary with the type of tracer used and the methods for detecting the passage of the tracer at downstream locations. Time-of-travel measurements are a special type of velocity measurement having several distinct features. The following discussion refers to all of the tracer velocity methods except the time-of-travel method.

For tracer methods, a uniform, constant cross-section channel must be used. Irregularities will allow the formation of pools and eddies which trap the tracer and introduce error in the velocity measurement.

The tracer is injected into the stream as a slug. This can be at one point or at a number of points across the channel to provide for faster mixing of the tracer in the flow. However, the time required for injection should be very brief.

Allowance must be made for a mixing zone in which the tracer becomes thoroughly mixed across the flow. Section 1.B.2.d.4. discusses recommended mixing distance.

Downstream from the mixing zone, a measured length of channel must be established to measure velocity. The length of measurement reach must be great enough so that small errors in timing of the tracer cloud through the reach will not create significant errors in velocity.

Concentration-time curves or visual observations of the tracer as it passes the upstream and downstream points of the measured reach are made. The average velocity is then determined as the length of measured reach. The most precise measurement is made by using the centroid of the concentration-time curve to determine the travel time, t. However, the measurement of time between peak concentrations at the upstream and downstream points is nearly as accurate.

Concentrations should be determined at comparative locations in each of the two cross sections. Otherwise, errors will be introduced because the peak concentration of the tracer in the center of the stream will pass a point before the peak along the stream sides. The sampling point should be well out into good flowing water.

1.B.2.c.6.a. Salt Dilution

A salt, usually sodium chloride, is used as the tracer in this method. The salt increases the conductivity of the water and it is this characteristic that makes this method practical. Electrodes are placed at both the upstream and downstream ends of the measured reach. The electrodes are connected to a central recording galvanometer which records the water's electrical conductivity at each pair of electrodes with respect to time (U.S. Bureau of Reclamation, 1967, p. 161–162). The time between peak concentrations or centroids of the time-conductivity curves is used for the determination of velocity.

1.B.2.c.6.b. Dye Dilution

Dye dilution or color-velocity methods are dependent on visual observation of the color of the dye in the water or, for some dyes, on their fluorescent characteristics. Some dyes such as fluorescein, which produces a green color in slightly alkaline water, can be visually observed as the dye passes the upstream and downstream sections. The exact time of passage of the peak concentration can be difficult to determine visually. Therefore, the reach length should be long enough to minimize the error caused by this uncertainty in the time measurement.

When fluorescent dyes such as Rhodamine WT (Wilson, 1968) are used, then concentrations can be determined by use of a fluorometer with good accuracy (less than 5 percent) and at very low concentrations (1 g/L). The benefit of using fluorometric determinations of dye passage is the accuracy with which the travel time can be determined.

1.B.2.c.6.c. Radioisotope

A radioactive material is used as the tracer in this method. Downstream concentrations are determined by use of geiger or scintillation counters.

The use of this method requires special handling of the radioactive material to prevent harmful radiation exposure to the user and others. A Federal license is required to handle the materal and approval must be obtained from Federal, State, and in some cases local Government agencies before the isotopes can be used (U.S. Bureau of Reclamation, 1967, p. 167–168).

1.B.2.c.6.d. Time of Travel

Time of travel refers to the movement of water and soluble materials which are moved with the water from point to point in a stream for steady or gradually varied flow conditions. The most common tracers used for time-of-travel measurements are fluorescent dyes. Dyes, because of cost, ease of handling, and effectiveness in obtaining good data, are recommended for most time-of-travel studies.

Dyes injected into a stream behave in the same manner as the water particles. Therefore, a measurement of the movement of the tracer is in effect a measurement of the movement and dispersion characteristics of the stream.

The mixing action, or dispersion, of the tracer in the receiving stream takes place in all three dimensions. Mixing in the vertical normally takes place rather quickly. Mixing horizontally across the stream takes longer. Estimates of the distance for various degrees of lateral mixing are discussed by Yotsukura and Cobb (1972). Mixing in the longitudinal direction continues indefinitely and is the dispersion component of primary interest in most time-of-travel studies.

The movement of a dye cloud past any point downstream from a instantaneous dye injection can be represented by a curve of concentration versus time. The concentration-time curve is defined by the anaylsis of water samples taken at selected time intervals during the dye cloud passage and is the basis for determining traveltime and dispersion characteristics of streams. As the dye moves

downstream, dispersion causes the time for the dye to pass a point to increase and the peak concentration to continue to decrease.

The mean traveltime for the flow in a reach is defined as the elapsed time between passage of the centroids of the concentration-time curves measured at the upstream and downstream measuring points of the reach. Also of interest are the traveltimes of the leading edge, the peak concentration, and the trailing edge of the tracer. The passage time of the entire dye cloud may also be of interest.

It should be noted here that the travel time of the water is not the same as might be expected for a flood wave in an open channel. Buchanan (1968) determined that the traveltime of a wave on the Raritan River in New Jersey was 1.1 to 2.2 times as fast as the velocity of the water. The highest ratios were found on reaches with dams.

Rhodamine WT is commonly used and is recommended as a tracer for time-of-travel studies. The dye should be injected at one or more points in a stream or as a line injection across the stream. The amount of Rhodamine WT dye, 20 percent solution required for a time-of-travel study can be estimated from the equation given by Kilpatrick (1970) which is

$$\forall_d = 2.0 \times 10^{-3} \left(\frac{Q_m L}{V}\right)^{0.93} C_P \qquad (1\text{–}17)$$

where $\forall_d$ = volume of dye, in liters of solution,
Q_m = maximum discharge in the reach, in cubic meters/second,
L = length of reach, in kilometers,
V = estimated mean velocity in the reach, in meters/second, and
C_P = peak concentration, in micrograms per liter desired at the downstream end of the reach and generally should not exceed 5 micrograms/liter.

If a long reach of stream is to be measured, it is often best to divide it into a number of subreaches. Several points may be sampled in each subreach. The dye should generally be injected far enough upstream from the start of each subreach so that the dye is fairly well mixed across the stream. See sec. 1.B.2.d.4. for estimation of mixing distances. Care should be taken to prevent the dye clouds from mixing from adjacent reaches due to longitudinal dispersion of the dye and thus confuse the time-concentration curves. Reference should be made to Collings (1968) for a discussion on the selection of injection and sampling sites. If mixing is known to be complete, samples may be taken at one point only, but if there is any question concerning the completeness of cross-channel mixing, samples should be taken at three or more points across the section. Generally, 20 to 30 samples will be needed at each sampling point to define the time-concentration curve. Sampling should continue until the concentration on the tail of the dye cloud has reached 10 percent of the peak or 0.2 micrograms per liter.

Samples of the dye injected into the stream should be collected for calibration purposes. Samples of the stream should also be obtained at each sampling location prior to the arrival of the dye so that effective background concentrations can be determined.

Wilson (1968) and Smart and Laidlaw (1977) discuss the properties of various dyes that are or might be used as tracers. Wilson (1968) also discusses equipment needed for time-of-travel measurements and provides recommended equipment procedures.

Measurements should be made at two or more discharges for better definition of the time-of-travel characteristics of a stream. Time-of-travel, t, generally varies with discharge, Q, as:

$$t = kQ^{-a} \qquad (1\text{–}17)$$

where k and a are constants defined for a particular steam. Discharge determinations should be made at each sampling site for each time-of-travel measurement so that the data can be generalized.

1.B.2.c.7. ELECTROMAGNETIC METHODS

According to Smoot (1974) a great deal of attention is being directed toward the development and refinement of electromagnetic (EM) current meters. Such meters are based on Faraday's Law of electromagnetic induction (fig. 1-10.). As a liquid, in this case water, cuts the lines of magnetic flux, an electromotive force (Emf) is induced in the water and is picked up by the two electrodes. The amount of induced Emf is proportional to the strength of the magnetic field and the velocity of the water.

In order to avoid thermoelectric effects, electro-chemical effects, and D.C. detection problems, an alternating-polarity magnetic field is generated, usually at or near 60 Hz. However, the alternating magnetic field can cause a quadrature volture problem resulting in an offset in zero point, thereby indicating a flow under actual no-flow conditions.

Although the electromagnetic current meter shows much promise, there are still several problem areas. The most serious problems are hydrodynamic. The EM probe is usually shaped as a strut or cylindrical rod. Its presence in the flowing water creates disturbances in the flow field which in turn produce erroneous readings of velocity and direction. Because the strength of the magnetic field is inversely proportional to the square of the distance from the magnet, the greatest potential is produced closest to the surface of the transducer; therefore minimizing such disturbances is essential.

Shedding of vortices, particularly at higher velocities, as well as the natural turbulence of the water, can cause vibrations of the probe which result in overregistration of velocity. Streamlining of the probe is not necessarily a cure-all either, since then it must be alined perfectly with the flow; otherwise, the disturbance becomes even more severe.

Problems also persist with selection of materials and electronic design. Among these problems are:

1. Fouling of electrodes,
2. Susceptibility to the presence of the electrical and magnetic fields in the area.

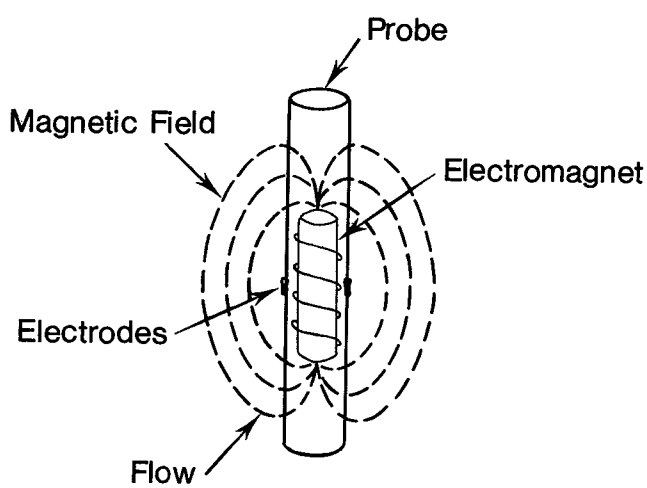


Figure 1-10.—Operating principles of electromagnetic current meter.

Not all of these problems are common to all meters, but they are the most frequent.

Solutions to problems are being rigorously sought by manufacturers because the EM meter has several major advantages and only minor disadavantages. Advantages are:

1. Solid state—no moving parts.
2. Fairly rapid response time—on the order of 1 second or less.
3. Mutually orthogonal pairs of electrodes—both velocity and direction can be determined.

The primary disadvantage is the relatively high power consumption, caused by the electromagnet, which makes battery operation impractical for extended periods.

This method of velocity measurement could be used to advantage in channels of a fixed geometric cross section where a velocity profile is repeatable and/or where an index velocity at a point could be consistently related to the mean velocity for the entire cross section. There are meters now available which the developers claim to be maintenance free, with no moving parts, and ideal for measuring point velocities from a fixed mounting.

Researchers in the United Kingdom are developing an electromagnetic river gaging station with large coils buried below the bed of a small river to generate a vertical magnetic field across the full width of the channel. Accordingly, the Emf generated transverse to the flow is directly proportional to the magnetic field intensity, the average velocity of the river water, and the river width. This technique looks promising where weed growth, debris, low velocities and/or reverse flow are problems. Furthermore, there are no channel constrictions to navigation or fish migration, no backwater effect, and no visual instrumentation other than a recorder shelter.

1.B.2.c.8. OPTICAL METHODS

The optical current meter as described by Smoot (1974) is a stroboscopic device designed to measure surface velocities of water in open channels without immersing equipment in the stream. The meter is a light-weight, battery-powered unit, consisting of a low-powered telescope, a set of rotating mirrors, a variable-speed drive motor, and a tachometer. Velocity measurements are made from an observation point above the stream by looking down at the water surface through the meter while gradually increasing the angular speed of the rotating mirrors. As synchronization is reached, the apparent motion of the water surface, seen through the eyepiece as a succession of images, slows down and is finally stopped. The angular speed of the mirror wheel at this null point and the vertical distance from the optical axis of the meter to the water surface are the only factors needed to compute the velocity.

$$V_X = (2W)\, D \sec^2 \theta \qquad (1\text{–}18)$$

where V_X = surface velocity,
D = the vertical distance from the mirror to the water surface,
W = the mirror speed in radians per second, and
θ = angular speed of rotating mirrors, at null point.

The meter has been used successfully to measure velocities ranging from 5 to 50 feet (1.52 to 15.2 meters) per second.

The velocities determined are only surface velocities and will have to be adjusted and used accordingly (See 1.b.2.c.4.a.). The method has the distinct advantage of not requiring immersion of equipment into the flowing water. Use of the optical meter is especially applicable to streams having extremely high velocities where the use of conventional velocity measuring equipment is not recommended.

1.B.2.d. MEASUREMENT OF DISCHARGE

The methods recommended for use in making discharge measurements in open channels are described in this section. As with the recommended methods for measurement of width, depth, cross-sectional area and velocity, no one method is ideal for all conditions. The user must select the methods and equipment which best meet the problems and needs involved in any particular flow situation.

Discharge, or streamflow, is defined as the volume rate of flow of water including any sediment or other solids that may be dissolved or mixed with it.

$$\text{Volume of flow (total flow)} = \int Q dt = A \int V dt \qquad (1\text{–}19a)$$

and if there are no variations in the rate of the flow during the measuring period,

$$\text{Volume of flow (total flow)} = Qt \qquad (1\text{–}19b)$$

where,

Q = rate of flow
V = mean velocity
A = cross-sectional area
t = time

and, $Q = AV$.

1.B.2.d.1. VOLUMETRIC METHODS

Corbett and others (1945) states that the volumetric method of measuring discharge is considered the most accurate of all methods with the possible exception of weighing. It consists either of observing the time required to fill a container of known capacity, or of determining the rate at which a calibrated tank or reservoir will fill. The volumetric method may be used advantageously in measurements of small flows in the calibration of weirs and artificial controls. A modification of this method has been used in measuring the discharge over broad-crested weirs and dams where the depths are small and the flow is otherwise unmeasurable. The modification consists of diverting and effectively measuring the flow through selected short sections at several places along the crest of the weir or dam. The total flow then is measured by interpolation between sections and summation of flow along the entire crest length.

The Bureau of Reclamation (1967, p. 176) uses the volumetric method for determination (measurement) of larger flows by adjustment for gain or loss in storage. This method is used when the capacity, gain or loss in storage, and the inflow or outflow for a reservoir are known, to compute the unknown outflow or inflow. Slight adjustments for bank storage, evaporation and wind effect on gage readings may be necessary in large-area reservoirs; however, the overall determination of flow is quite accurate.

1.B.2.d.2. VELOCITY-AREA METHODS

In 1.B.2.b.4. and 1.B.2.b.4.a. the mid-section method for computing cross-sectional area was recommended and described. Figure 1–7 also showed a sketch of the mid-section method of computing the cross-sectional area for discharge measurements. It was pointed out in 1.B.2.b. that in the velocity-area method of discharge determination the discharge is computed by summation of the products of the partial areas (partial sections) of the flow cross-section and the average velocities for each of those sections as:

$$Q = \Sigma(av)$$

As stated in 1.B.2.b.4.a., the mid-section method assumes that the velocity sample at each depth sampling point (location) represents the mean velocity in the partial rectangular cross-sectional area.

Referring to fig. 1-7 it can be shown that the partial discharge is now computed for any partial section (Buchanan and Somers, 1969) as:

$$q_x = v_x\left(\frac{(b_x - b_{(x-1)})}{2} + \frac{(b_{(x+1)} - b_x)}{2}\right)d_x \tag{1-20a}$$

$$= v_x\left(\frac{b_{(x+1)} - b_{(x-1)}}{2}\right)d_x,$$

where q_x = discharge through partial section x,
v_x = mean velocity at location x,
b_x = distance from initial point to location x,
$b_{(x-1)}$ = distance from initial point to preceding location,
$b_{(x+1)}$ = distance from initial point to next location,
d_x = depth of water at location x.

Thus, for example, the discharge through partial section 4 (heavily outlined in fig. 1-7) is

$$q_4 = v_4\left(\frac{b_5 - b_3}{2}\right)d_4. \tag{1-20b}$$

The procedure is similar when x is at an end section. The "preceding location" at the beginning of the cross section is considered coincident with location 1; the "next location" at the end of the cross section is considered coincident with location n. Thus,

$$q_1 = v_1\left(\frac{b_2 - b_1}{2}\right)d_1, \text{ and} \tag{1-20c}$$

$$q_n = v_n\left(\frac{b_n - b_{(n-1)}}{2}\right)d_n. \tag{1-20d}$$

For the example shown in fig. 1-7, q_1 is zero because the depth at observation point 1 is zero. However, when the cross-section boundary is a verticle line at the edge of the water as at location n, the depth is not zero and velocity at the end section may or may not be zero. The formula for q_1 or q_n is used whenever there is water only on one side of an observation point such as at piers, abutments, and islands. It usually is necessary to estimate the velocity at an end section as some percentage of the adjacent section because it normally is impossible to measure the velocity accurately with current meter close to a boundary.

The velocity-area method of discharge determination, using the rotating-element current meter for velocity measurement, is currently the principal method for measuring flow in open channels. The measurement, made by wading, cableway, bridge, boat, ice, etc. is the method used in transiting or crossing the open channel. Recommended methods for use with velocity-area measurements are considered below.

1.B.2.d.2.a. Wading

Current-meter measurements by wading are preferred if a stream is shallow and relatively slow moving. Wading measurements are preferred also because they generally afford a much better selection of available cross sections and allow for elimination of problems presented by bed roughness, relative roughness, piers and abutments (bridges), horizontal flow angles, and poor flow distribution.

The limit for wading is set by safety considerations. The amount of water which can be waded safely varies slightly with each individual; however, a "rule-of-thumb" used by field personnel generally sets this limit at a discharge of about 12-13 cfs/ft (1.12–1.21 m^3/s per m) of width.

Measurement of total width, spacing of the depth soundings, and the width of the partial sections are usually measured using a tagline (See 1.B.2.b.1.). Depth soundings are made with a rigid rod (See 1.B.2.b.3.) at intervals dictated by the roughness, uniformity of flow, and accuracy limitations (See 1.B.2.b.4. recommended partial sections).

If the Price-type (rotating-element) current meter is used for velocity observations, it is recommended that the Type AA meter (or Type A) be used where depths exceed 1.5 feet (0.46 m), the Price pygmy be used where depths are between 0.3 and 1.5 feet (0.9 and 0.46 m) and velocities are below 2.5 feet per second (0.76 meters per second), 0.2 and 0.8 depth method (See 1.B.2.c.1.b.2.) be used where depths exceed 2.5 feet (0.76 m), and the 0.6 depth method (See 1.B.2.c.1.b.1.) be used when depths are from 0.3 to 2.5 feet (0.09 to 0.76 m).

When the direction of flow is not at right angles to the cross-section, the velocity vector normal to the cross-section is needed for determination of discharge. The velocity measured by the current-meter multiplied by the cosine of the horizontal angle will give the velocity component normal to the measuring cross-section. The U.S. Geological Survey prints a template on the measurement form by which the coefficients for the cosine of the horizontal angle are indicated as a series of marked points on the measurement note form and the cosine value is read directly by orienting the note form or clip-board with the cross-section and the direction of flow.

It is recommended that personnel involved in making wading measurements stand in a position that least affects the velocity of the water passing the current meter. The best position is usually found to be about 1 to 3 inches (25 to 76 mm) downstream from the tagline and 18 inches (0.46m) or more from the wading rod, holding the wading rod at the tag line, and standing in a position facing the bank. Care must be taken to keep the meter pointed directly into the flow and to keep the rod in a vertical position.

1.B.2.d.2.b. Cableway

Current-meter measurements made from cableways usually have the advantage of unobstructed flow and small, if any, horizonal angles. Two minor problems involved in cableway measurements are (1) possible oscillation of the car and cable and (2) the sag of the cable.

The cableway should be normal to the flow of the channel at higher stages, high enough (1) to permit operation of the cablecar above the elevation of maximum flood, (2) to clear water-borne traffic, and (3) to provide a high degree of safety to personnel in case of entanglement of suspended equipment with floating debris.

Measurement of total width and sounding locations is normally determined from markings painted at selected intervals along the cableway. Depth soundings are made using large sounding weights suspended from the cablecar. (See Buchanan and Somers, 1969). Tags or colored streamers placed on the sounding line at a known distance above the center of the meter facilitate the measurement of depth, eliminate possible air-line corrections (See 1.B.2.b.3.), facilitate setting the meter at the proper depth, and prevent meter damage caused by ice and debris or the meter freezing in cold air. See 1.B.2.b.3. for recommended wet-line corrections to sounded depths.

The Price-Type-AA current meter is recommended for most discharge measurements from a cableway. Columbus or C-type sounding weights are recommended (See Buchanan and Somers, 1969, p. 11) because of their streamline shape and minimum resistance to flow. See table 1–2 for velocity-measurement methods for various suspensions and depths.

Correction for horizontal angles is made as recommended for wading measurements (see 1.B.2.d.2.a.). See 1.B.2.b.3. for recommended corrections for vertical angles in deep, swift streams.

1.B.2.d.2.c. Bridge

Current-meter measurements from bridges have the same advantages and/or limitations as cableways. Bridges with piers obstructing the normal flow pattern in the stream cause additional problems to the hydrographer due to the interruption of the streamlines of flow, or "pile-up" of water around piers. If piers are in the measuring cross section, it is usually necessary (and recommended) that additional partial sections (more than 25-30) be used to obtain results that are comparable and as reliable as the normal measurement from a bridge without piers.

Total width and sounding locations are generally made from permanent markings painted at selected intervals along the deck or railing of the bridge or from a tag line stretched along the bridge at the cross section. Depth soundings are made using the same suspension and weight recommendations used for cableways (see 1.B.2.d.2.b.). Velocity-measurement methods using reels and suspension equipment should be the same as those recommended in table 1-2.

Handlines, a sounding reel supported by a bridge board, or a portable crane to suspend the meter and sounding weight from the bridge, allow wider selection of equipment than the lighter equipment used from a cableway. However, the use of these methods may be constrained by highway traffic patterns and safety considerations on the bridge. Footbridges are popular for measuring small streams, canals, and trailraces and generally allow the use of rod suspension.

1.B.2.d.2.d. Boat (including moving-boat method)

Discharge measurements from boats are made when there are no cableways, suitable bridges, or the stream is too deep and/or swift to wade. The safety of personnel involved is a prime consideration in the use of boats on channels having high velocities, undulating or turbulent flow.

Width and/or determination of sounding location are generally measured using a stretched tag line (see 1.B.2.b.1.) or by transit-stadia (see 1.B.2.b.2.) Position of the boat can be held by motor, by anchor, or by boom and crosspiece affixed to the boat and tag line to maintain the boat perpendicular to the tag line.

If the depth of the cross section is less than 10 feet (3.15 m) and the velocity is low, a rod can be used for sounding the depth and supporting the current meter. At greater depths the procedure for sounding depths and measuring velocities from a boat is the same as that for measuring from a bridge or cableway.

On large streams and estuaries, the conventional methods of measuring discharge are frequently impractical and involve costly and tedious procedures (see Buchanan and Somers, 1969). At some sites, unsteady flow conditions require that measurements be made as rapidly as possible. Measurements on tide-affected rivers not only must be made frequently but continually throughout a tidal cycle.

Table 1-2.—Velocity-measurement method for various suspensions and depths (from Buchanan and Somers, 1969).

Suspension	*Minimum depth (feet)*	
	0.6 method	*0.2 and 0.8 method*
15 C .5, 30 C .5	1.2 (0.37 m)	2.5 (0.76 m)
50 C .55	1.4 (0.43 m)	2.8 (0.85 m)
50 C .9	2.2 (0.67 m)	4.5 (1.37 m)
75 C 1.0, 100 C 1.0, 150 C 1.0	2.5 (0.76 m)	5.0 (1.52 m)
200 C 1.5, 300 C 1.5	[1]3.8 (1.16 m)	7.5 (2.29 m)

[1] Use 0.2 method for depths 2.5-3.7 feet (0.76-1.13m) with appropriate coefficient (estimated 0.88).

The moving-boat technique is a method of measuring rapidly on large streams. It requires no fixed facilities, and lends itself to the use of alternate sites if conditions make this desirable. The moving-boat technique is described in detail by Smoot and Novak (1969). It is similar to the conventional current-meter measurement in that the velocity-area method to determine discharge is used; the total discharge is the summation of the products of the partial areas of the stream cross section and their respective average velocities. During the traverse of a boat across a stream, a sonic sounder records the geometry of the cross section, and a continuously operating current meter senses the combined stream and boat velocities. Three men are required to operate the boat and equipment. The data they collect are converted to discharge quickly, efficiently, and inexpensively. Experience has shown that measurements obtained by the moving-boat technique compare within 5 percent of measurements obtained by conventional means.

1.B.2.d.2.e. Under Ice Cover

Measurement of discharge under ice cover can be frustrating, uncomfortable, and dangerous, but very necessary for the continuity and computation of discharge records during long, severe winter periods.

Selection of possible cross sections for measurement under ice cover can best be done during periods of open water in order to evaluate the channel conditions. Total width and sounding locations can be measured by using a tag line stretched over the ice surface. Sometimes the cross section at the cableway site will be excellent for ice measurements and will also provide the required information on channel width and stationing based on previous open-channel measurements.

Cutting or drilling holes in the ice, location of the depth soundings (stationing), and measurement of the effective depth of flow under the ice (See fig. 1–5 and sec. 1.B.2.b.3.) are extremely critical to the overall quality of the measurement. The hydrographer must be sure that (1) the flow is well distributed in the cross section, (2) no slush ice is affecting the flow, (3) part of the cross section is not effectively blocked by slush or frazil ice, (4) an adequate number of sections are obtained (at least 20 sections are recommended), (5) the meter is free to rotate, (6) the meter is not affected by vertical pulsations in the cut holes, and (7) the meter is not affected by icing caused by intermittent exposures to cold air.

The velocity distribution under ice cover is similar to that in a pipe with a lower velocity near the underside of the ice. (See fig. 1–11).

The 0.2- and 0.8-depth method is recommended for effective depths of 2.5 feet (0.76 m) or more and the 0.6-depth method is recommended for effective depths less than 2.5 feet (0.76 m). A coefficient of about 0.92 is usually required to correct velocities obtained by the 0.6-depth method.

A vane ice meter (see Buchanan and Somers, 1969, p. 6) is recommended for use under ice cover because the vanes do not plug-up with slush ice as do the cups of the Price-type meter.

1.B.2.d.2.f. Through Control Structures and Closed Conduits

Measurement of discharge through control structures and closed conduits by velocity-area methods is addressed in those sections dealing specifically with control structures (see 1.B.2.e.) and closed conduits (ss 1.B.3.a.4.).

1.B.2.d.3. INDIRECT METHODS

Measurements of discharge must often be obtained after the discharge event has occurred. A number of techniques have been developed for measuring flows indirectly. These include slope-area methods, flow measurements at contracted openings, flow through culverts, and flow over dams and weirs.

Step-backwater methods may be used to determine the stage of a hypothetical flow or to establish a stage-discharge relation where direct flow measurements have not or cannot be made. Such relations should be checked when possible by direct methods.

Indirect methods of determining peak discharge are based on hydraulic equations which relate the discharge to the water-surface profile and to the geometry of the channel. Generally, field surveys are made after a high-flow event to determine the location and elevation of high-water marks and to define the channel characteristics (Benson and Dalrymple, 1968).

1.B.2.d.3.a. Slope-Area

Slope-area measurements are based on the Manning equation:

$$Q = \frac{1.486}{n} A R^{2/3} S^{1/2}, \qquad \text{(in English units)} \qquad (1\text{-}21)$$

where Q = discharge, in cubic feet per second,
A = cross sectional area of the flow, in square feet,
R = hydraulic radius and is equal to the area, A, divided by the wetted perimeter of the cross section, in feet,
S = friction slope of the flow, and
n = roughness coefficient.

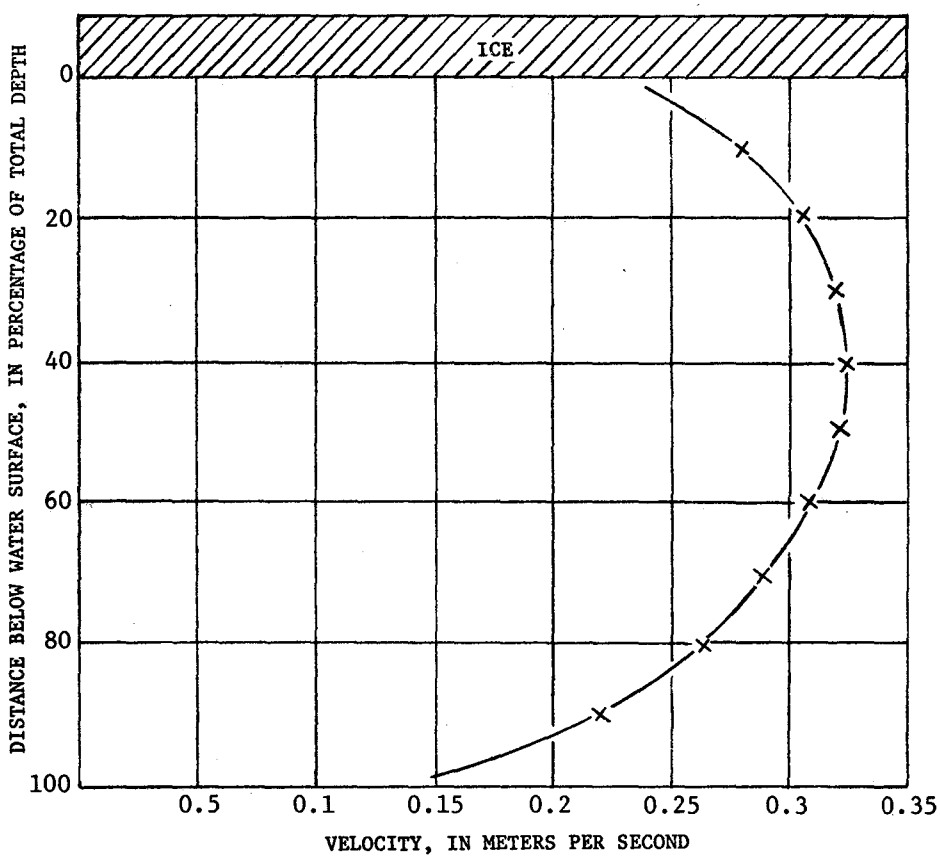


Figure 1-11.—Typical vertical-velocity curve under ice cover (from Buchanan and Somers, 1969).

This equation was developed for uniform conditions of flow in which the water-surface profile and energy gradient are parallel to the streambed and the area and hydraulic radius are constant.

For the non-uniform conditions found in natural channels, it is recommended that a minimum of three cross sections be surveyed in the measurement reach. The slope-area equations for two, three, and multiple cross sections are given below.

Number of cross sections

2 $$Q = K_2 \sqrt{\frac{\Delta h}{\frac{K_2}{K_1}L + \frac{K_2^2}{2gA_2^2}\left[-\alpha_1\left(\frac{A_2}{A_1}\right)^2(1-k) + \alpha_2(1-k)\right]}} \qquad (1\text{-}22)$$

3 $$Q = K_3 \sqrt{\frac{\Delta h}{\frac{K_3}{K_2}\left(\frac{K_3}{K_1}L_{1\text{-}2} + L_{2\text{-}3}\right) + \frac{K_3^2}{2gA_3^2}\left[-\alpha_1\left(\frac{A_3}{A_1}\right)^2(1-k_{1\text{-}2}) + \alpha_2\left(\frac{A_3}{A_2}\right)^2(k_{2\text{-}3}-k_{1\text{-}2}) + \alpha_3(1-k_{2\text{-}3})\right]}} \qquad (1\text{-}23)$$

Multiple

(n) $$Q = K_n\sqrt{\frac{\Delta h}{A+B}}\text{, where} \qquad (1\text{-}24)$$

$$A = K_n^2\frac{L_{1\text{-}2}}{K_1K_2} + K_n^2\frac{L_{2\text{-}3}}{K_2K_3} + \ldots \frac{K_n^2L_{(n-2)-(n-1)}}{K_{(n-2)}K_{(n-1)}} + \frac{K_n^2L_{(n-1)-n}}{K_{(n-1)}K_n}$$

$$B = \frac{K_n^2}{A_n^2 2g}\left[-\alpha_1\left(\frac{A_n}{A_1}\right)^2(1-k_{1\text{-}2}) + \alpha_2\left(\frac{A_n}{A_2}\right)^2(k_{2\text{-}3}-k_{1\text{-}2}) + \alpha_3\left(\frac{A_n}{A_3}\right)^2(k_{3\text{-}4}-k_{2\text{-}3}) + \ldots\right.$$

$$\left. + \alpha_{(n-1)}\left(\frac{A_n}{A_{(n-1)}}\right)^2(k_{(n-1)-n} - k_{(n-2)-(n-1)}) + \alpha_n(1-k_{(n-1)-n})\right].$$

The subscripts refer to the cross-section number starting with the upstream section as section 1. The other variables are defined below.

$K = \frac{1.486}{n} AR^{2/3}$. This is called conveyance and is computed for each section.

Δh = the difference in water-surface elevation between sections, in feet.

L = the distance between sections measured along a smooth line following the main flow of the channel, in feet.

g = acceleration due to gravity.

k = a coefficient used in the computation of energy loss[1] due to contraction or expansion of the channel. The recommended value of k is 0.5 for expanding reaches and 0.0 for uniform and contracting reaches. Expansion or contraction is based on the conveyance of the cross sections at the ends of the reach being considered.

$\alpha = \frac{(\Sigma K_i^3/a_i^2)}{K_T^3/A_T^2}$ and is called the velocity head coefficient.

$\alpha = 1$ for a channel that is not subdivided,

K_i = the conveyance for each subsection of a cross section,

a_i = the area of each subsection of a cross section,

K_T = the conveyance for the entire section, and

A_T = the area of the entire cross section.

Selection of a measurement reach is a most important part of a slope-area measurement. Usually, ideal sites cannot be found and a site must be selected that most nearly meets the ideal conditions.

The site must be located where reliable high-water marks are available. The channel should be fairly uniform and free from marked changes. Simple trapezoidal channels are preferred. However, complex channels may be used if they remain fairly uniform throughout the measurement reach. Abrupt changes in the channel upstream from the reach should be avoided. Such changes will distort the flow patterns and the results of the measurement. Ponded conditions are to be avoided. The stream channel should be contracting in the downstream direction. A reach containing free-falling water cannot be used.

The reach should be far enough from bends to allow the flow distribution across the channel to become normalized. If a straight reach away from the influence of bends cannot be found, it is best to include a long reach that includes one or more channel bends with terminal sections in straight portions of the channel.

The length of the reach should be adequate to develop a fall which is well beyond the range of error due to alternate interpretations of the high-water profile or to uncertainties regarding the computation of velocity head. According to Dalrymple and Benson (1967) one or more of the following criteria should be met, if possible, in selecting the length of a slope-area reach.

---

[1] The energy loss due to contraction or expansion of the channel in the reach is assumed to be equal to the difference in the velocity heads, $V^2/2g$, at the two sections, times the coefficient k. The Geological Survey (Dalrymple and Benson, 1967) assumes 50 percent of the energy lost ($k = .5$) in an expanding reach; whereas, the energy is conserved in a uniform or contracting reach ($k = 0$). On the other hand, the Corps of Engineers uses $k = .9$ for expanding reaches and $k = .3$ for uniform and contracting reaches.

This procedure and the magnitude of the coefficient, k, are very questionable for expanding reaches and, thus, major expansions are avoided, if possible, in selecting sites for slope-area measurements.

1. The length of the reach should be equal to or greater than 75 times the mean channel depth.
2. The fall in the reach should be equal to or greater than the velocity head.
3. The fall in the reach should be equal to or greater than 0.50 feet (0.15 m).

A number of high-water marks should be obtained on each side of the channel to define the high-water profile. Marks selected on the upstream side of obstructions, such as rocks and trees, are likely to be too high, while those located on the downstream side are likely to be too low. Marks should be identified in the field notes as to type and also how good they are, such as excellent, good, fair, or poor.

High-water marks may be drift lines, seed lines on trees and utility poles, wash lines on clean banks, or mud, silt, foam or stain marks. Generally, the top of a mound of drift is the proper location of a high-water mark. Drift may also be found on trees and brush, but care must be exercised to determine that the drift represents the highest flow level and that the drift did not catch on the tree or brush when it was bent over in the flow.

Wash lines are generally poor high-water marks, as the material may slough to elevations above the high-water level. Usually, the straighter the wash line, the better its reliability as an indicator of the peak elevation.

High-water elevations may sometimes be obtained by interviewing local residents. Care should be taken to interview more than one resident so that high-water elevations can be confirmed.

Transit-stadia surveys are recommended for surveying high-water marks. Both horizontal and vertical control must be maintained. Gage datum should be used where possible. Otherwise, an arbitrary datum may be used and reference marks of a permanent nature established to permit recovery of the datum at a later time. Prior to surveying high-water marks, the level or transit should be checked using a peg test and the instrument should be adjusted as needed (Benson and Dalrymple, 1968, p. 4–7).

Sections should be located after the high-water marks have been plotted and profiles drawn. If the profiles appear to represent a series of somewhat regular waves, the cross sections should be located at each end of the selected reach at comparable parts of the waves. Sections should be located in typical parts of the reach. The profiles should be well defined at each cross-section location.

Roughness coefficients, n, should be selected in the field by trained and experienced personnel. Coefficients are selected for each subsection and should be representative of the reach and conditions at the time of the peak flow. Reference should be made to Barnes (1967) for the selection of n values. Sections are divided into subsections according to changes in shape of the section. Photographs should be obtained of each section for documentation.

A Froude number should be completed for each cross section after the final discharge has been determined. The Froude number is defined as

$$F=\frac{V}{\sqrt{gd_m}}, \qquad \text{(no units, dimensionless)} \qquad (1\text{–}25)$$

where V is the mean velocity and d_m is the average depth in the cross section.

A Froude number less than 1 in a rectangular channel indicates tranquil flow while a value greater than 1 indicates rapid or supercritical flow. The slope-area method is valid for both tranquil and rapid flow. However, if the flow changes from rapid to tranquil within a reach there is a possibility that a hydraulic jump has occurred in the reach. A change from tranquil to rapid flow might indicate a sharp contraction or the presence of "free fall" in the reach. In either case, the profiles should be examined for sharp drops which might bear out these possibilities. If either of these conditions exists, the discharge determination is not reliable. However, if the transition between types of flow is gradual, the discharge computations should be accepted as valid.

The consistency of results from different subreaches is some indication of the reliability of the results. If the spread in discharges exceeds 25 percent, the results should be classified as poor.

1.B.2.d.3.b. Contracted Opening

Contracted-opening measurements of flow are based on continuity and energy equations and are possible because of the abrupt drop which occurs in water-surface elevations between an approach section and the contracted section. Usually this type of measurement is made at bridges but may also be applicable for some other types of contractions.

A number of agencies have developed methods for determining the backwater effect of bridge contractions. These are generally used for design and project evaluation purposes. The general use of energy and continuity equations is common to each of the procedures. Methods described in the Bureau of Public Roads Hydraulic Design Series Number 1 (Bradley, 1970) and the Soil Conservation Services National Engineering Handbook Section 4, Chapter 14 (1972) can be used to obtain discharges. However, the Geological Survey method described by Matthai (1968) was developed primarily for the determination of discharge.

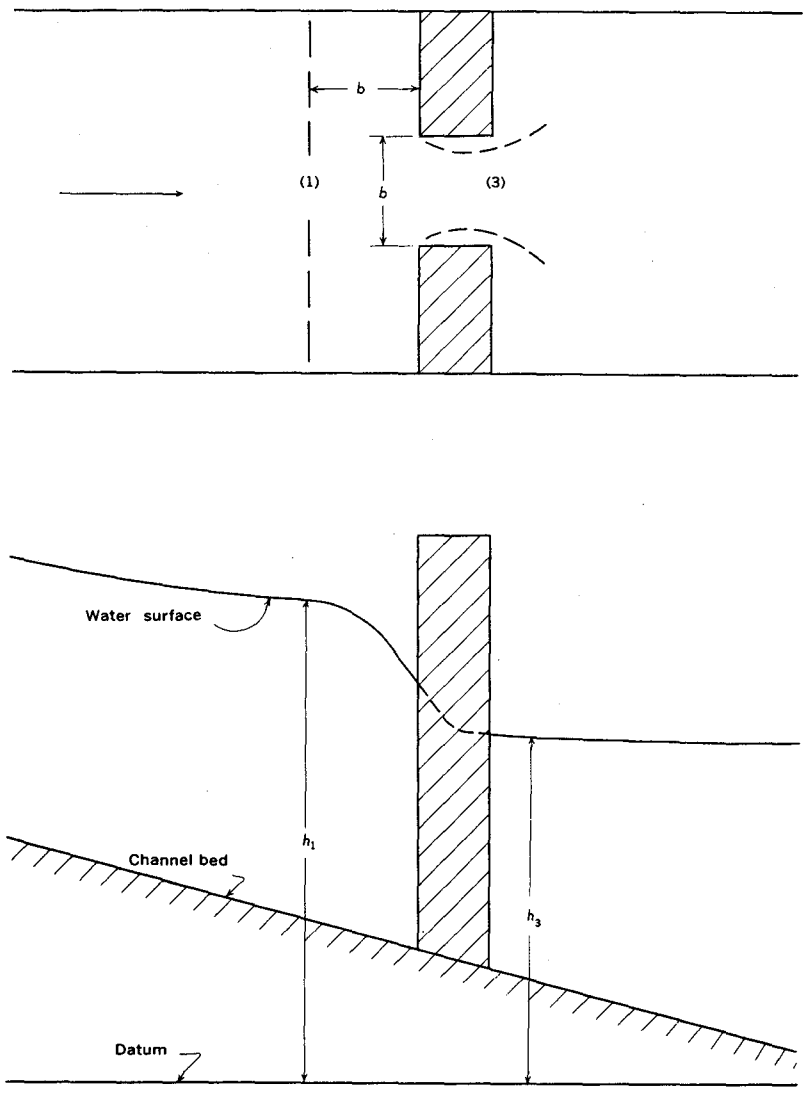


Figure 1-12.—Open-channel contraction.

The discharge equation used for contracted opening measurements relates the drop in the water-surface level between an upstream section, section 1, and a contracted section, section 3, to the corresponding change in velocity. (See fig. 1-12).

$$Q = CA_3\sqrt{2g\left(\Delta h + \alpha_1\frac{V_1^2}{2g} - h_f\right)} \quad \text{(in metric or English units)} \qquad (1\text{-}27)$$

where Q = discharge,
C = coefficient of discharge,
A_3 = gross area of section 3; this is the minimum section parallel to the constriction between the abutments and is not necessarily at the downstream side of the bridge.
Δh = difference in elevation of the water surface between sections 1* and 3.
$\alpha_1\frac{V_1^2}{2g}$ = weighted average velocity head at section 1*, where V_1 is the average velocity, Q/A_1, and α_1 is the velocity head coefficient and is defined in section 1.B.2.d.3.a., and
h_f = the head loss due to friction between sections 1 and 3.

This equation requires a trial and error solution. If you know C, a direct solution can be obtained if Q/A_1 is substituted for V_1 and $L_w(Q^2/K_1K_3) + L\,(Q/K_3)^2$ for h_f. The resulting equation is then

$$Q = 8.02CA_3\sqrt{\frac{\Delta h}{1-\alpha_1C^2\left(\frac{A_3}{A_1}\right)^2 + 2gC^2\left(\frac{A_3}{K_3}\right)^2\left(L+\frac{L_wK_3}{K_1}\right)}} \quad \text{(in English units)} \qquad (1\text{-}28)$$

where A_1 = cross sectional area at section 1,
K_1, K_3 = the conveyance at sections 1 and 3 respectively,
L = the length of the bridge opening, and
L_w = the length of the approach reach. (See Matthai, 1968).

The contracted section, section 3, defines the minimum area on a line parallel to the contraction, generally between bridge abutments. Section 3 is parallel to the contraction even when the bridge is skewed with the flow. The area A_3, is always the gross area of the section. No deductions are made for the area occupied by piles, piers, or submerged parts of the bridge which lie in the plane of the contracted section. However, the conveyance, K_3, is computed with the areas of piles, piers, or submerged bridge parts deducted from the gross area of section 3. Also the wetted perimeter will include the lengths of the sides of piles, piers, or bridge surfaces in contact with the water.

The characteristics of a site considered for use as a contracted opening measurement should meet the following criteria:

1. The channel under the bridge should be fairly stable.
2. The fall in water surface between sections 1 and 3 should be at least 0.5 feet (0.15 m).

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*The approach section, section 1, is a cross section of the natural unconstricted channel upstream from the beginning of the draw-down and is located one bridge opening width, b, upstream from the contraction. Section 1 includes the entire width of the stream channel perpendicular to the line of flow.

3. The fall should be at least four times the friction loss between sections 1 and 3.
4. The bridge geometry should be reasonably close to one of the standard or modified types described below.

If the above criteria cannot be met, consideration should be given to alternative measurement methods (Matthai, 1968).

The approach section is located one bridge width, b, upstream from the contraction. When this section lies in a zone of heavy vegetation, often a cross section along the edge of right-of-way will be representative of the approach section. The roughness coefficient, n, should be representative of the conditions between the assumed location of section 1, one bridge-opening width upstream, and the bridge opening. If a bridge is completely contracted from one side only, the approach section should be located two bridge opening widths upstreams.

The smallest cross section between the abutments on a line parallel to the constriction is needed for section 3. This usually occurs at the downstream side of the bridge.

High-water marks are obtained along each side of the stream upstream from the bridge. The water-surface elevation at section 1 is obtained from a profile drawn through these marks. Where a high degree of contraction exists, profiles from marks obtained along the upstream face of the embankment may be used. If this profile is level for an appreciable distance along the embankment, this elevation can be assumed the same as section 1. The water-surface elevation for section 3 is obtained from high-water marks on the downstream side of the embankment adjacent to the abutments.

Water-surface elevations are determined as the average for both banks except where there is a high degree of eccentricity of the contraction. In this situation, use only the profile on the contracted side.

Bridge geometry measurements should include wingwall angles and lengths, lengths of abutments, positions and slopes of the embankments and abutments, elevation of roadway, top width of embankment, details of piers or piles, and elevations of the bottom of girders or beams spanning the contraction. These measurements are used for computation of the coefficients of discharge.

Coefficients of discharge have been calculated for four standard contraction types. The contraction types are described below (Matthai, 1968).

Type 1.—A type 1 contraction has vertical embankments and vertical abutments with or without wingwalls. The entrance rounding or the wingwall angle, the angularity of the contraction with respect to the direction of flow, and the Froude number in section 3, F_3, affect the discharge coefficients. The computation of the Froude number is described in sec. 1.B.2.d.3.a.

Type 2.—A type 2 contraction has sloping embankments and vertical abutments. The depth of water at the abutments and the angularity of the contraction with respect to the direction of flow affect the discharge coefficient.

Type 3.—A type 3 contraction has sloping embankments and sloping spill through abutments. The entrance geometry and the angularity of the contraction with respect to the direction of flow affect the discharge coefficient.

Type 4.—A type 4 contraction has sloping embankments, vertical abutments, and wingwalls. The wing wall angle, the angularity of the contraction with respect to the direction of flow, and for some embankment slopes, the Froude number, F_3, affect the discharge coefficient.

Coefficients of discharge for all types of contractions are primarily a function of a channel contraction ratio and a ratio of the length of the bridge opening, L, to the bridge opening width b. Coefficients of discharge for the four standard contractions are given by Matthai (1968).

Matthai (1968) has also provided adjustment factors to be applied to coefficients of discharge for the effects of spur dikes, piers and piles, and for bridge submergence.

Floods often cause flow over a road near the bridge in addition to flow through the bridge. In this situation, approach section properties must be computed differently. Basically, the entire area

of section 1 should be used to compute the flow over the road. Then, just that part of section 1 supplying flow to the bridge is used to compute section properties at section 1 for contracted opening computations.

A multiple-opening contraction is defined as a series of independent single-opening contractions, all of which freely conduct water from a common approach channel. Independence of openings is generally indicated when two or more pairs of abutments and one or more interior embankments exist. In this situation, the flow upstream from the bridge is divided into segments in proportion to the area, A_3, corresponding to each opening. Considering each artificial flow boundary as being a stream boundary, a contracted-opening measurement is made for each opening and the discharges added to obtain a total discharge.

1.B.2.d.3.c. Culvert

Various agencies have developed methods for analyzing flow through culverts. For example, the Bureau of Public Roads (1965) and the Soil Conservation Service (1972) describe methods for computation of a stage-discharge rating upstream from culverts based on flow-through-culvert analysis. In general, the purpose of these methods is design or hydraulic evaluation of culverts. Generally, the methods used are based on the continuity and energy equations and have been tested often using similar data.

The method presented by Bodhaine (1968) determines the discharge of specific flow events where high-water profile data and conditions at the time of the flow are available. It is beyond the scope of this chapter to evaluate the difference in the methods.

For convenience of computation, culvert flow has been classified into six types on the basis of the location of the control section and the relative heights of the headwater and tailwater elevations. The six types of flow and some of their characteristics are illustrated in fig. 1–13.

The terms which are used in fig. 1–13 and which are not self explanatory are defined below.

A_c = Area of section of flow at critical depth.
A_o = Area of culvert barrel.
C = Coefficient of discharge.
d_c = Maximum depth in critical flow section.
g = Gravitational constant.
$h_c = d_c + z$.
$h_{f_{1\text{-}2}}$, $h_{f_{2\text{-}3}}$ = Head loss due to friction respectively between the approach section and the culvert inlet and between the culvert inlet and outlet.
n = Manning coefficient of roughness.
Q = Discharge.
R_o = Hydraulic radius of culvert barrel.
S_c = Critical slope.
S_o = Bed slope of culvert barrel.
V_1 = Mean velocity of flow at the approach section.
α_1 = Velolcity head coefficient and is defined in sec. 1.B.2.d.3.a.

High-water profiles are needed upstream and downstream from a culvert for further analysis. High-water marks should be obtained along the upstream embankment and upstream from the culvert for a distance of at least two culvert diameters. Tailwater marks are needed along the embankment or channel close to the outlet.

An approach section is needed at a location of one culvert diameter (width) upstream from the culvert. Roughness coefficients, n, and points of subdivision need to be selected in the field.

Roughness coefficients need to be selected for both the approach section and for the culvert. Values of n for most culvert materials are provided by Bodhaine (1968).

Complete details of culvert dimensions including projections, wingwall angles, size of fillets and chamfers, degree of entrance rounding, size and shape of opening, type of entrance, and length are needed. Also needed are the type of material of which the culvert is made as well as its condition. Invert and crown elevations are needed as well as elevations of the ends of culvert aprons. The positions of the culvert, wingwalls, aprons, and other features are needed. The skew of the culvert relative to the flow must also be determined. Photographs of the culvert and approach conditions are helpful in documentation.

Special conditions that existed at the time of peak flow must be noted. This might include debris lodged in the culvert or an effect from ice or snow. Some culverts have natural stream bottoms or have changes in slope within the culvert. These details and elevations within the culvert should be documented.

When computing the discharge, several checks must be made to determine the type of flow which occurred in the culvert. Some of these criteria are listed in fig. 1-13. The reader is referred to Bodhaine (1968) for additional criteria and techniques which can be used to help define the flow type.

Factors to which the coefficient of discharge, C, are related are listed below:

1. Ratio of headwater to pipe diameter,
2. Mitering of pipes set flush with a sloping embankment as opposed to a flush entrance in a vertical headwall,
3. Entrance rounding or beveling,
4. Pipe projection from a headwall,
5. Froude number at downstream tailwater section (section 3),
6. Wingwall angle, and
7. Degree of channel contraction.

Coefficients have also been determined for special entrances. Reference should be made to Bodhaine (1968) for the determination of the coefficient of discharge for a specific flow problem and the Federal Highway Administration (1972) design methods for improved inlets, an extension of the methods and information presented by the Bureau of Public Roads (1965).

Computations of flow are made using the equation associated with the appropriate flow type as shown in fig. 1-13. It should be noted that the determination of discharge for flow types 1, 2, and 3 involve trial and error computations. That is, a discharge must be assumed, computations made, and a comparison of the assumed and computed discharge made. If the comparison indicates too great a difference, a new discharge must be assumed and computations repeated.

For some nonstandard conditions, the flow equations in fig. 1-13 are not appropriate. Examples of nonstandard conditions are very large approach velocity, large head or friction loss, variation in cross-sectional dimensions through the culvert, and changes in slope in the culvert. For these conditions the flow must be routed upstream. The routing method solves the following equation.

$$\text{Headwater elevation} = [(\text{control section elevation}) + (\text{velocity head at the control section}) + (\text{friction loss between control section and entrance}) + (\text{entrance loss}) + (\text{friction loss between entrance and approach section})] - (\text{velocity head at approach section}). \tag{1-26}$$

The routing method involves trial and error computations. The routing procedure can be used for standard and nonstandard conditions but cannot be used for type 5 flows. Bodhaine (1968) provides guidelines for routing different types of flows. Instructions for flow routing through culverts

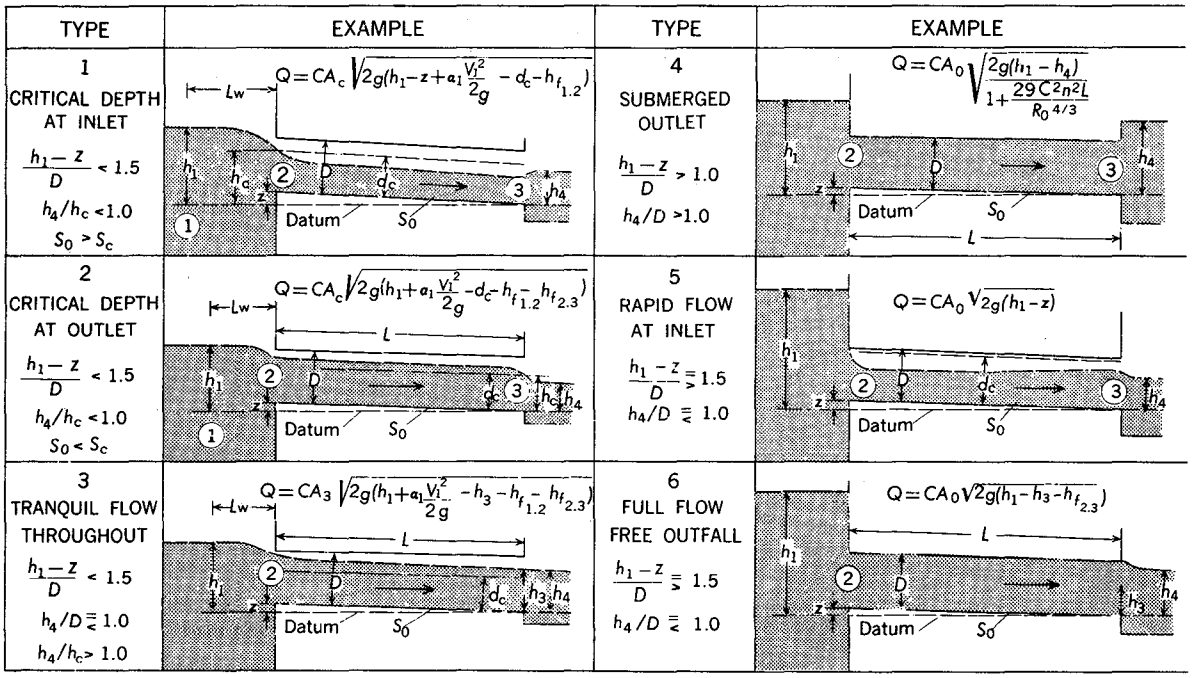


Figure 1-13.—Classification of culvert flow.
Note—the equation for Type 4 flow contains the value "29" which equals $\frac{2g}{(1.486)^2}$ in English units.

are also provided by the Soil Conservation Service (1972). At times, culverts may be made of different materials, laid at different slopes, installed at different invert elevations and be of different sizes in the same stream crossing. Bodhaine (1968) describes special considerations which must be given to multiple culvert installations.

Under most field conditions, the computation of peak discharge through culverts should provide reliable results. In low-head flow, very good results may be expected up to headwater-diameter ratios of 1.25 except where critical depth occurs upstream from the entrance. Good results may also be expected for high head flow when the type is definitely known and the headwater-diameter ratio is greater than 1.75. Good results may always be expected for type 6 flows.

Flow in the transition range between various flow types should not be considered better than fair. Pipe arch computations are generally more reliable for pipes flowing nearly full than for those with shallow flows.

Factors to be considered when evaluating the accuracy of the measurement are:

1. Accuracy to which headwater and tailwater elevations can be determined,
2. Stability of the approach channel,
3. Conformity of the entrance conditions to standard conditions,
4. The shape and condition of the culvert,
5. Scour or fill in the culvert, and
6. The possibility of the culvert being partly plugged by debris at the time of the peak flow.

1.B.2.d.3.d. Dams and Weirs

Many agencies have used flow over dams and weirs for measuring discharge. The emphasis in this section is on the use of dams and weirs for measuring peak flows. Many times dams and weirs

are in a location where peak flow data are needed and other means are not available for obtaining the data. Often these structures were not designed for the purpose of computing discharge. Sections 1.B.2.e.2.b. and 1.B.2.e.2.c. discuss the use of weirs and dams which are designed specifically for the measurement of discharge. The method discussed is primarily from the report by Hulsing (1967).

There are three fairly distinct general classes of weirs—sharp crested, broad crested, and round crested. However, many weirs do not neatly fit into these three classes, because of the shape, or physical condition of the channel, or the hydraulic conditions under which the weirs are operating. For example, a sharp-crested weir may act like a broad-crested weir because of fill in the approach channel, or a broad-crested weir may act like a sharp-crested weir because the head is sufficient to make the nappe spring clear.

High-water mark data are needed on both banks to define headwater and tailwater elevations. The headwater elevation on the dam is measured upstream from the crest a distance of 3 to 4 times the water depth at the crest. A cross section located here is needed for an approach section. Therefore, it is very important that the high-water profile be well defined in this area. Tailwater elevations obtained downstream from the energy recovery zone are needed to determine the degree of submergence, if any.

The shape and characteristics of the dam or weir are needed in considerable detail. Also needed are the cross-sectional shape of the crest and any changes in the shape, the slope of the upstream face, the rounding of the upstream edge, the width of the crest, the roughness of the crest, and the slope of the downstream face. The shape must be measured accurately in both the horizontal and vertical planes. Pier and abutment details including the radius of rounding of the upstream corner of the abutments also are needed for deriving the discharge coefficient.

The installation of gates or flashboards, their placement, and their condition at the time of peak flow must be determined. Any debris lodged on the dam or in the gates should be documented by notes and photographs. Any flow bypassing the structure through canals, power plants, or other structures should also be documented.

For computations of flow, a weir is considered to be sharp crested if the lower nappe springs clear of the downstream edge of the weir. The discharge equation for rectangular, sharp-crested weirs is:

$$Q = C\,b\,h^{3/2}$$

where C = discharge coefficient,
b = width of weir crest normal to the flow, excluding width of piers, and
h = static or piezometric head on the weir relative to the crest as measured at the approach section.

The discharge coefficient for a free-flowing, rectangular, sharp-crested weir is a function of h/P, b/B, and E

where P = the height of the weir above the stream channel, as measured in the b width at the approach section,
B = surface width of channel at the approach section, and
E = the slope of the weir face.

Corrections must be made to the discharge coefficients if abutment corners are rounded.

If the elevation of the tailwater is above the elevation of the weir crest, the effect of submergence must be considered. The ratio of discharge under submerged conditions to that for free flow is a function of h_t/H and H/P where

h_t = height of tailwater above the weir crest,
H = height of headwater above the weir crest and is equal to h plus the velocity head, $\frac{V_1^2}{2g}$, at the approach section.

Where V_1 is the average velocity at the approach section and g is a gravitational constant.

A broad-crested weir has a nearly horizontal crest of length, L, in the direction of flow and the flow over the crest becomes parallel to the crest. Under high head-to-length ratios, h/L, the nappe tends to spring clear of the weir crest and the weir functions as a sharp-crested weir. At the opposite extreme, for a very small h/L ratio, the weir crest tends to act as a reach of open channel in which frictional resistance predominates and for which weir formulae are no longer applicable.

The head-to-length ratio at which a weir functions as a broad-crested weir is dependent on the completeness of aeration of the space beneath the downstream nappe, the h/P ratio, the sharpness of the upstream weir edge, and the slope of the upstream weir face.

The basic flow equation for broad-crested weirs is

$$Q = C\,b\,H^{3/2} \tag{1-30}$$

It should be noted that because of the inclusion of the velocity head in the term H, the equation must be solved by estimating a discharge and then using the formula to compute the discharge. The computed and estimated discharges must be compared and if necessary the process must be repeated until acceptable agreement is obtained.

The discharge coefficient C for broad-crested weirs is a function of h/L, R/h, E_1, E_2, b/B, and r/b.

where R = the radius of rounding of the upstream vertical face of the weir crest,
r = the radius of rounding of the side abutment, and
E_1, E_2 = respectively, the slope of the upstream and downstream face of the wier.

The degree of submergence of a broad-crested weir is defined by the ratio of the downstream static head, h_t, to the upstream static head, h. Submergence has no effect on the discharge coefficient if the submergence ratio, h_t/h, is less than 0.85. The effect for ratios greater than 0.85 is significant but undefined.

Round-crested weirs are defined as weirs with crests that are smooth single-curved surfaces. The longitudinal profile of the crest generally is a complex curve which cannot be described in simple geometric terms. The crests of overflow spillways which have the form of the lower surface of the nappe which would result from a full-width thin-plate weir, are special examples of round-crested weirs and are commonly called ogee or design-head dams.

The intersection of the curvilinear crest and the vertical or inclined face of the weir is called the spring point. The height of the weir, P, above the stream channel is measured to the spring point.

The discharge equation for round-crested weirs is

$$Q = C\,b\,h^{3/2} \tag{1-31}$$

The discharge coefficient for round-crested weirs is a function of both weir geometry and head. Because of the endless variety of weir shapes, no general solution for the discharge coefficient is available. One of the following methods is generally used to establish discharge coefficients for a particular weir (Hulsing, 1967).

1. Results of model tests for the particular dam used in the measurement.
2. Comparison with other crest for which the discharge coefficient is known.
3. Nappe-fitting method.
4. Index-measuring method.

Model tests are likely to be available only on very large dams. Perhaps the most widely used method is that of comparing the weir crest with one for which the discharge coefficient is known. For good comparison, it is necessary that reasonably good correspondence of the crest profiles be obtained, especially from the spring point to the crown; also that the relative heights of the weirs be similar, especially if one weir is low; and that the width-contraction aspects of the calibrated weir be reasonably similar to those of the weir being used for flow measurement. A proportional and not an equal value of head must be used for determination of the discharge coefficient.

The nappe-fitting method gives good results if the crest of the weir follows the form of the lower nappe from a full-width thin-plate weir. The method involves determining a reference head on a sharp-crested weir which produces a lower nappe that coincides with the crest profile. Hulsing (1967) provides tables and curves to help determine the reference head and from that to determine the appropriate discharge coefficient.

The index-measurement method depends on a measurement of discharge to define the discharge coefficient, C_i, for a corresponding total head, H_i. The coefficient for other heads may then be determined from a relationship between C/C_i and H/H_i (Hulsing, 1967).

Hulsing (1967) has provided corrections for the discharge coefficient for submergence of round-crested weirs. If the degree of submergence, as defined by the ratio, h_t/H, is greater than about 0.6, other methods of measurement should be investigated as the reliability of measurement over a round-crested weir will be low.

Flow over highway embankments is a special type of weir problem. The basic equation for flow over roadways is

$$Q = C\,b\,H^{3/2} \tag{1-32}$$

Because of shallow depths over the road and often, a very flat longitudinal slope (normal to flow) of the roadway, the depth of water at the road crest is assumed to be 5/6 of the maximum value of the total head, H, for the section. The width, b, is then determined corresponding to the depth at the crest.

The discharge coefficient for free flow over highways is a function of h/L and the type of road material such as paving or gravel. L is the width of the roadway including the roadway shoulders. If the degree of submergence, h_t/H, is greater than 0.9 the results cannot be considered reliable. Brogden (1964) and Hulsing (1967) provide characteristics and curves for determining the discharge coefficients and adjustments for submergence.

Discharge coefficients have been determined for a number of weirs of unusual shape which cannot be classified as sharp-, broad-, or round-crested weirs. A good source of information for a variety of such weirs is Water Supply Paper 200 by R. E. Horton (1907). Hulsing (1967) has summarized much of this information in his report.

The report by Hulsing (1967) should be consulted for tables and curves for determining discharge coefficients of weirs and for various corrections to the coefficient.

1.B.2.d.3.e. Step-backwater

Step-backwater analysis is different from other indirect measurement methods in that the other methods proceed from available high-water marks to compute a discharge. Step-backwater analysis proceeds from a discharge to the computation of a stage. This technique has a variety of uses, most of which are related to determining a flow profile along a stream or for determining a stage-discharge relation. The flow profile analysis must often include methods for routing flow through bridges and over embankments.

Computations of water-surface profiles are based upon the principle of conservation of energy between two cross sections. Proper application of the energy equation is dependent upon the following assumptions:

1. Steady flow exists in the subreach defined by the two cross sections.
2. The flow regime in the subreach is entirely, (a) critical, (b) critical and subcritical, or (c) subcritical.
3. The longitudinal water-surface and channel slopes are small enough that the depth normal to the longitudinal channel profile and the vertical depth may be considered equal.
4. The water surface is level across each individual cross section.
5. Effects from sediment and air entrainment are negligible.
6. All losses are properly evaluated.

The energy equation used for flow-profile computations is:

$$H_1 + H_{v_1} = H_2 + H_{v_2} + H_f + H_e \tag{1-33}$$

where H_1, H_2 = upstream and downstream water-surface elevations for two adjacent stream cross sections,

H_{v_1}, H_{v_2} = upstream and downstream velocity heads,

H_f = loss of head due to friction in the reach

$= LQ^2/(K_1K_2)$

$= LS$

where L = distance between sections,

Q = average flow in the reach,

K_1, K_2 = upstream and downstream conveyances (See 1.B.2.d.3.a.),

S = friction slope of the flow (See 1.B.2.d.3.a.), and

H_e = head loss or energy loss due to expansion or contraction of the channel

$= k(H_{v_1} - H_{v_2})$

$= k\left(\frac{\alpha_1 V_1^2}{2g} - \frac{\alpha_2 V_2^2}{2g}\right)$ (See 1.B.2.d.3.a. for definition of α), and

where the recommended values for k are 0.5 for an expanding reach and 0.0 for a contracting reach (See discussion on values for k in 1.B.2.d.3.a., in Chow (1959), and in Boyer (1964).

Note—There are many and varied ways of computing the head loss due to channel friction, H_f. The equation shown above uses the average conveyance to compute the friction slope. Equally satisfactory solutions for the friction slope are the average friction slope equation or the harmonic mean friction slope. These solutions are available in standard hydraulic design texts.

The solution of this equation requires an iterative process in which the discharge is established and the downstream head known or assumed and the upstream head estimated. If the equation does not balance within acceptable limits, new estimates for the upstream head must be assumed and the procedure repeated until an acceptable balance is obtained. The energy equation can be rewritten in terms of the accuracy, A, of the energy balance as follows:

$$A = H_1 + H_{v_1} - H_2 - H_{v_2} - H_f - H_e \tag{1-34}$$

Computation of flow profiles is a tedious time consuming task if done manually. Therefore, sophisticated computer programs have been developed for computing profiles using step-backwater procedures. It is beyond the scope of this chapter to compare these computer programs. Three of the most widely used programs are (1) the U.S. Geological Survey computer program E431 (Shearman, 1976), (2) the Corps of Engineers (1968) HEC-2 program, and (3) the Soil Conservation Service (1975) WSP2 program.

Differences in profiles have been obtained in some cases using these programs due to varying assumptions used in their development. Special problems exist in the computation of flow profiles when the flow passes under bridges or over embankments. A modified version of the Bureau of Public Roads' (Bradley, 1970) method of routing flow through bridges is used in the E431 program and is described by Shearman (1976). While the routing of flow through bridges may at times be considered more of an art than a science, the modified Bureau of Public Roads' method is probably one of the better scientific approaches to the problem. However, this method is applicable only when the energy grade line is below the top of the roadway, low flow controls, subcritical flow occurs between bridge piers, and the downstream depth is greater than critical depth. When the flow makes contact with the bridge girders, orifice type flow occurs and special procedures as described by Shearman (1976) are required.

Often, flow will occur through a bridge and over the road at the same section. The road acts as a broad-crested weir in this case and routing of flow over a broad-crested weir is required as described by Shearman (1976). When both flow through a bridge and flow over a road occur at the same location, an upstream water-surface must be determined which will provide for the sum of flows through the bridge and over the embankment. The HEC-2 program has procedures for all flow conditions at bridges and embankments normally encountered in practice.

Adequate cross sections are needed to define changes in the stream channel. In the absence of bridges, a reach is subdivided into subreaches located normal to the direction of flow. Sufficient ground points must be obtained so that the cross-section geometry is well defined. These cross sections must be subdivided into subareas for adequate elevation of flow variation created by the geometric and/or roughness differences of individual subareas. A report prepared by Davidian (1979) should be consulted for subdivision criteria. Manning roughness coefficients must be selected for each subdivison. The distance between sections is measured along a line representing the locus of the centroids of flow in the reach.

When bridges are encountered, the following sections are required.

1. An exit cross section immediately downstream of the bridge.
2. A cross section of the bridge opening.
3. An approach cross section located one bridge opening distance upstream from the bridge.

In addition, two other cross sections may be needed. They are:

1. A cross section describing piers and abutments.
2. An embankment (roadway) cross section. This is usually obtained at the centerline of the road but may be at the top of a curb if the curb acts as a weir crest. Special subdivision requirements are needed for cross sections associated with bridges and/or embankments. The investigator is referred to Davidian (1979) for proper subdivision procedures.

Two of the programs mentioned previously, the Geological Survey's E431 and the Corps of Engineer's HEC-2, provide for the computation of floodways. This is a procedure for calculating the amount of flooodplain encroachment resulting from a given increase in the water-surface profile.

Because a special situation exists in step-backwater computations when supercritical flows are encountered, all profile computations should be checked to determine if supercritical flow has occurred. Under subcritical flow conditions, an error in profile elevation at one section will tend to be corrected as the flow is routed upstream. The reason for this can be seen in the shapes of backwater curves (Chow, 1959, p. 226). Under supercritical conditions, profiles routed upstream will tend to diverge, but, if routed downstream, they will tend to approach the true profile. Therefore, in general, supercritical flows should be routed in a downstream direction. The Corps of Engineers' HEC-2 profile computation routine, as well as a newly developed U.S. Geological Survey program, J635, allow for the downstream routing of supercritical flows.

Step-backwater methods are generally not applicable for routing flows through subreaches where the flow goes from subcritical to supercritical or vice versa, especially for conditions where abrupt changes occur in the profile such as at hydraulic jumps. Neither are the techniques directly applicable at locations where the flow experiences free fall. Under these conditions, special techniques may have to be used and considerable judgment is required to develop the flow profile.

1.B.2.d.4. DILUTION METHODS

Dilution methods are well suited to measuring turbulent flow in natural streams and in many manmade structures including pipes and canals. These methods may be utilized to measure any flow where turbulence and mixing length are sufficient to ensure mixing of the injected tracer throughout the whole flow. See Kilpatrick (1968) for application of dilution methods to a variety of measurement problems.

Measurement of stream discharge by dilution methods depends on the determination of the degree of dilution of an added tracer by the flowing water. A variety of dilution methods are often referred to such as salt-dilution, color- or dye-dilution, and radioisotope methods. Basic concepts are common to all of these methods. Differences exist primarily with the tracers used and the methods of detecting and measuring the concentration of the tracer after dilution has occurred.

Two methods may generally be used for determining the discharge of a flow by dilution methods. They are (1) the constant-rate-injection method which requires that the tracer solution be injected into the stream at a constant-flow rate for a given period of time, and (2) the total-recovery method which permits introduction of the tracer into the stream in several different ways but requires that the total volume of tracer be accounted for at the sampling site.

A constant-rate-injection system, as shown in fig. 1–14 will, if the tracer solution is injected for a sufficient time period, give at a point downstream, a concentration-time curve as shown in fig. 1–15. The relation of the concentration to the stream discharge is given as:

$$QC_b + qC_1 = (Q+q)\,C_2, \quad \text{(in English or metric units)} \qquad (1\text{–}35)$$

$$Q = \left(\frac{C_1 - C_2}{C_2 - C_b}\right) q,$$

where q is the rate of flow of the injected tracer solution,
Q is the discharge of the stream,
C_b is the background concentration of the stream,
C_1 is the tracer concentration of the solution injected into the stream, and
C_2 is the measured concentration of the plateau of the concentration-time curve (fig. 1–15).

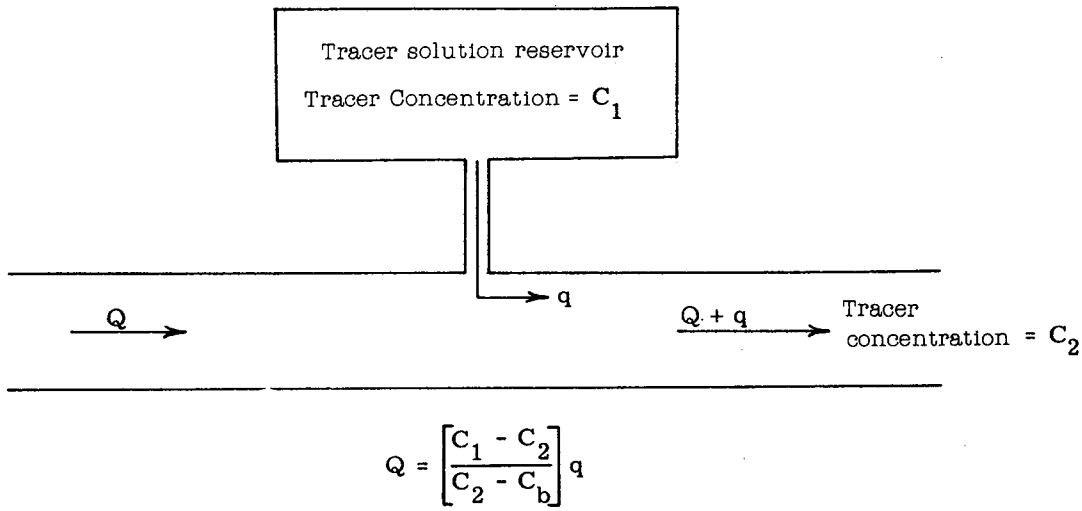


Figure 1-14—Constant-rate injection system.

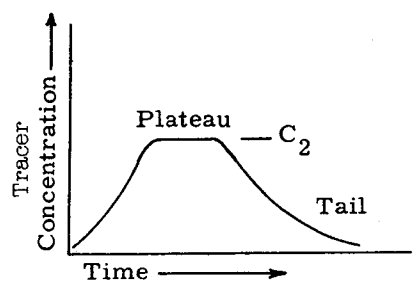


Figure 1-15.—Concentration-time curve for constant-rate injection.

If the tracer solution is suddenly dumped into a stream (as will frequently be done using the total-recovery method) a concentration-time curve, as shown in fig. 1-16 may be measured at a given point downstream. The relation of the concentrations to discharge for the total-recovery method is

$$Q = \frac{V_1 C_1}{\int_0^\infty (C - C_b)dt}, \quad \text{(in English or metric units)} \qquad (1\text{-}36)$$

where Q = discharge of the stream,
V_1 = volume of tracer solution introduced into the stream,
C_1 = tracer concentration of the solution injected into the stream,
C = measured tracer concentration at a given time at the sampling point,
C_b = background concentration of the stream, and
t = time.

The term $\int_0^\infty (C - C_b)dt$ is the total area under the concentration-time curve. In practice the term $\int_0^\infty (C - C_b)dt$ can be approximated by the term

$$\sum_{i=1}^{N} (C_i - C_b)(t_{i+1} - t_{i-1})/2, \qquad \text{(in English or metric units)} \qquad (1\text{-}37)$$

where i is the sequence number of a sample,
N is the total number of samples, and
t_i is time when a sample, C_i, is obtained.

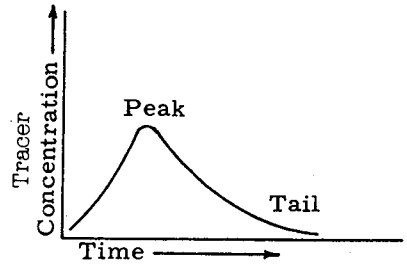


Figure 1-16.—Concentration-time curve for sudden dump.

Theory for dilution-flow measurements requires complete vertical and lateral mixing of the tracer in the stream at the sampling site. Vertical mixing is usually accomplished very rapidly as compared to lateral mixing; therefore, the distance required for lateral mixing is the primary mixing consideration.

Complete mixing as defined for the total-recovery method occurs when the area under the concentrations-time curve is equal at all points across the section. Concentrations near the stream banks may lag those in the center of the stream because of the slower velocities near the banks. This may result in the shapes of the concentration-time curves near the banks being different from those near the center of the stream. The definition of mixing considers only the area under the concentration-time curve, not the lag time or shape of the curve. When the constant-rate-injection method is used, complete mixing is obtained when C_2, shown in fig. 1—13, is equal at all points across the section. Complete mixing will seldom if ever be attained, but satisfactory results can usually be obtained with a degree of mixing of at least 0.95.

The degree of mixing is defined by Yotsukura and Cobb (1972). A simplification of the formula for the degree of mixing, P_m, is

$$P_m = 1 - \tfrac{1}{2}\left[\Sigma_0^1 \left| \frac{C}{\bar{C}} - 1 \right| \Delta\left(\frac{q}{Q}\right)\right] \qquad \text{(no units, dimensionless)} \qquad (1\text{-}38)$$

where

$\bar{C}$ = the average concentration across the section or the average area under the concentration-time curve across the section.

C = the concentration or area under the time-concentration curve at a point in the section.

q/Q = nondimensional cumulative discharge (discharge ratio).

The downstream distance required for the tracer to travel before a 0.95 degree of mixing is obtained can be estimated from the report by Yotsukura and Cobb (1972). For average conditions, the mixing length, X, can be estimated for a center-point injection as

$$X = \frac{0.024\, V B^2}{D^{3/2}\, S^{1/2}} \qquad \text{(in metric units)} \qquad (1\text{-}39)$$

where V = average stream velocity, in meters/second,

B = stream width, in meters,

D = average stream depth, in meters, and

S = stream-energy gradient.

From the above equation, it can be determined that if the tracer is injected into the stream from the side, the mixing distance will be four times as great as for a center injection. The distance obtained from this equation should be considered a minimum distance between tracer injection and sampling points. The reach length can be reduced by properly spaced mulitiple injections. Samples should be obtained from at least three points across the stream to verify the adequacy of mixing.

The accuracy of a dilution measurement is directly related to the tracer loss in the measurement reach. Tracer losses are primarily due to sorption and chemical reaction with materials in the water. An effect equivalent to tracer loss results from failure to detect extremely low concentrations of tracer released from storage in deadwater areas of a reach.

The constant-rate-injection method is generally more accurate than the total-recovery method as the total-recovery method requires definition of the entire concentration-time curve, including the sometimes hard-to-define tail of the curve. Only the plateau part of the curve needs to be defined with the constant-rate-injection method. With an adequate injection period, the measurement reach will tend to become saturated with tracer and losses due to sorption and deadwater areas will be minimized.

The effect of inflow or loss of water in the measurement reach will cause the point of measurement to change for a dilution-type measurement. A dilution-type measurement made where there is no increase or decrease of flow in the measurement reach will measure the flow occurring at any point in that reach.

If there is inflow between the injection point and the sampling site, the flow measured will be that at the sampling site. The inflow must be mixed with the rest of the stream at the sampling site, in order to obtain a reliable discharge.

The effect of the loss of flow between the injection point and the sampling site is dependent upon the extent of mixing. If the tracer is completely mixed before the flow loss, the discharge determined at the sampling site is that prior to the flow loss. If the tracer is not mixed before the flow loss a disproportionate division of the tracer will likely occur and the use of the concentrations obtained at the sampling site could result in an erroneous discharge determination.

Constant-rate-injection methods require a mechanism for injecting the tracer into a stream at a constant rate. A number of devices that can be used for this purpose are described by Cobb (1968). Such devices include Mariotte units, spring-diaphragm units, floating siphons, constant-level reservoirs, and constant-rate pumps.

Tracers used for dilution-type measurements should (1) have a high detectability range, (2) have little effect on flora or fauna, (3) have a low sorption tendency, (4) have a low decay rate, (5) be soluble and disperse readily in water, (6) be chemically stable, (7) be inexpensive, (8) be distinguishable from background, and (9) be easy to handle.

A number of dyes used for dilution measurements are described by Wilson (1968) and by Smart and Laidlaw (1977).

Fluorescent dyes are commonly used for tracer methods. Concentrations are determined by the use of a fluorometer. Techniques described by Wilson (1968) for use of fluorometers are recommended.

When salts are used as a tracer, standard chemical analysis should be used to determine concentrations. As with all types of tracers, the effective concentration of the tracer material in the natural water before injection as well as that of the injected solution must be determined.

When radioisotopes are used, Geiger or scintillation counters are used to determine the levels of the radioisotopes (U.S. Bureau of Reclamation, 1967). Because of the special measuring equipment used, the discharge formula for this tracer becomes

$$Q=\frac{FA}{N} \tag{1-40}$$

where F = a calibration factor for the probe and counting system,
A = total amount of radioactivity injected into the stream, and
N = total count recorded by the detector.

The best location for a single-point injection is normally at the center of the cross section. A center injection generally produces the minimum possible mixing length when the tracer is introduced at only one point. The injection points for a multiple-point injection should be spaced such so that each tracer injection diffuses equal lateral distances.

Obtain at least three background samples from the stream and three samples of the injection solution. These samples may be taken at the start of the injection or just before the injection is completed. If the total-recovery method is used, determine the volume of tracer solution that will be introduced into the stream.

If constant-rate injection is used, the required duration of the injection will depend on the characteristics of the stream and the distance to the sampling site. Inject the tracer solution for a sufficient time period to allow at least a 15-minute concentration plateau. Note that the duration time of the plateau is reduced as the tracer moves downstream due to longitudinal dispersion. Consequently, the plateau duration will always be less than the injection duration.

A minimum of five stream samples should be obtained to define the concentration plateau at each sampling point when the constant-rate-injection method is used. The effects of nonrepresentative surges of high or low concentrations can be minimized by allowing a little time to elapse between samples. Do not mistake a temporary leveling off of the concentration-time curve for the actual plateau.

Sufficient samples to define the entire concentration-time curve are needed when the total-recovery method is used. This will usually require 20 or more samples at each sampling point.

Samples should be taken just below the water surface and far enough from the bank to be out of low-velocity or dead-water areas. Select sampling sites at contracted sections or at sections where there are satisfactory velocities across the entire section.

The time that the concentration plateau or leading edge of the tracer arrives at the sampling site can be estimated using an estimated mean stream velocity. It is usually desirable to start sampling a little before the estimated time of arrival and to continue sampling after the estimated time of passage of the tracer to be certain of obtaining the required samples.

The reader is also referred to Kulin and Compton (1975, p. 64–69) for additional information on dilution-type flow measurements.

1.B.2.d.5. METHODS FOR PULSATING (UNSTABLE) OR SLUG FLOW

Pulsating flow in an open channel is defined by Chow (1959, p. 580) as a manifestation of unstable-flow conditions in which a series of translatory waves of perceptible magnitude develops and moves rapidly downstream. These translatory waves are commonly called roll waves or slug flow. If the overriding translatory wave carries an appreciable part of the total flow, conventional stream-gaging methods cannot be used to determine the discharge. Conventional water-stage recorders of either the float or pressure-sensing type do not react quickly enough to record the rapidly fluctuating stage; depths and velocities change too rapidly to permit discharge measurements by current meter; no stage-discharge relation exists for pulsating flow; and the commonly used formulas for computing stable open-channel discharge are not applicable (Thompson, 1968).

Discharge measurements for slug flows in uniform shaped channels can be made by considering separately the overriding wave and the shallow-depth flow. The overriding wave shape can be considered as a triangle for purposes of computation. A recommended procedure for determining the dimensions of the wave is to establish a grid with set vertical and horizontal spacing on one wall of the channel. Wave shape can then be determined by photography or by direct observation. The leading edge of the wave is assumed to be vertical. The field data that are needed are the stage of the wave crest and the stage of the flow between waves. When direct observations are made, the horizontal length of the wave is most easily determined by measuring the time of arrival at a fixed

point of the wave crest and the end of the wave. Other measurements needed are the time of arrival at a fixed point of each wave measured and the time required for the wave to travel a fixed distance.

The velocity of the wave can be determined from the travel length divided by the travel time of the wave. Using this velocity the base length of the wave can be determined by multiplying the velocity by the interval of time required for the wave to pass a given point. The volume per unit of time then gives the discharge of the wave component. Since these translatory waves are not always equally spaced, a number of waves should be measured to determine an average flow.

The shallow-depth component of flow can be determined from the cross-sectional area of flow and the velocity V, which is determined from the Manning equation:

$$V = \frac{1.486}{n} S^{1/2} R^{2/3} \qquad \text{(in English units)} \qquad (1\text{–}41)$$

where n = roughness coefficient for the channel,
S = friction slope which for the assumption of steady shallow flow is equal to the slope of the water surface, and
R = hydraulic radius.

The combination of the two components of flow yields the total flow in the channel. The reader is referred to Thompson (1968) for further details of data collection and of the overall concepts.

1.B.2.e. MEASUREMENT OF DISCHARGE AT CONTROLS

A control used in flow measurement is a channel feature, either natural or artificial, which controls the stage of a stream for a given range of discharges.

In many channels, the control feature will change with the flow; at low flows it may be a low-water structure while at higher stages, it may be a downstream feature.

Artificial controls are structures built in a stream or artificial channel to stabilize the stage-discharge relation and thereby simplify the procedure of obtaining accurate records of discharge. At times, and especially for artificial channels, the control may be designed to have a predetermined stage-discharge relationship. The determination of whether or not to install an artificial control is dependent on the flow-data requirements, the suitability of natural control features, and the cost of installation.

Artificial controls should be designed to have the following characteristics where at all possible (Carter and Davidian, 1968).

1. The shape of the structure should permit the passage of water without creating undesirable disturbances in the channel upstream or downstream from the control.
2. The structure should be of sufficient height to eliminate the effects of variable downstream conditions.
3. The profile of the crest of the control should be designed so that a small change in discharge at low stages will cause a measurable change in stage, and the relation of changes in stage to changes in discharge should produce a rating curve of a shape that may be extrapolated to peak stages without serious error.
4. The control should have structural stability and should be permanent.
5. The control should be self-cleaning and should not be subject to obstruction by debris and ice or to deposits of sand, gravel, or silt in its immediate vicinity, either upstream or downstream.

The stage-discharge relation for all controls should be established or checked by current-meter or other types of measurement. Very seldom is a control fabricated and installed just as it was tested in the laboratory. These structural differences can have significant effects on the rating (stage-

discharge relationship) for the control. Also sediment and aquatic growth conditions can affect the rating in a variable way with time. Therefore, the rating should be periodically checked by current meter or other type of measurement.

The stage-discharge relationship should be developed for a location upstream of the drawdown, unless the control is otherwise designed, but close enough to the control that no significant fall in water level occurs between the stage-measurement point and the control. Stage should be measured where the effect of deposited sand or other material has a minimal effect on the rating.

1.B.2.e.1. NATURAL CONTROLS

Natural channel features are often used as controls in the measurement of streamflow. Such controls may consist of channel reaches which may have varying degrees of stability, or consist of channel bends, rock or gravel riffles, or bedrock outcrops.

At times, the control may approximate a broadcrested weir. For this type of control, the discharge, Q, will vary with stage, G, to the 1.5 power where stage is the effective head over the control. If the effective weir length varies with stage, the discharge may vary with stage up to a power of 3 or

$$Q \sim f(G^{3/2}) \text{ to } f(G^3). \tag{1-42}$$

Where the effective control is a combination of features in a fairly long reach of channel, discharge will vary with stage to the 1 to 1.67 power. Channel roughness may also have an effect on the exponent of stage. Usually, for most natural controls, the value of the exponent varies between 1.3 and 1.8 and very seldom reaches a value as high as 2.0.

The stage-discharge relation for most natural controls will vary as a result of shifting bed material (especially after high flows), changing land and aquatic growths, deposition or scour of material, and ice conditions. Often the changes are the result of nature but at times they are the result of human activity. For shifting controls it is necessary to measure the flows frequently enough to adequately monitor the shifting.

A special type of shifting control occurs where the channel is composed of sand. This type of channel can take on a variety of forms depending on the bottom material, velocities, depth of flow, and even the water temperature. The reader is referred to the report by Simons and Richardson (1962) for details on the causes of variations in ratings and the rating characteristics in sand-channel streams.

1.B.2.e.2. CALIBRATED CONTROL STRUCTURES

In any situation where repeated current metering is impractical or uneconomical, where natural stream control is expected to change often or where high accuracy is required, a precalibrated control structure is often the best method of discharge measurement. Artificial controls provide a fixed section of the stream where the capacity is a minimum. They also create a small backwater above the control and force the flow to pass through a critical section.

Within the category of precalibrated measuring controls are two types of structures—weirs and flumes. A weir requires the flow to pond behind an overfall with loss of practically all momentum and with flow measurement dependent on being able to measure the total potential energy behind the overfall. Significant approach velocity is dealt with by corrections. A flume does not depend on loss of kinetic energy but on the constancy of the backwater curve produced by the critical control section. Measurement is typically obtained upstream from the critical section in the accelerating subcritical region. Where higher velocities are found and sediment loads are high, measurement may be taken below the critical section in the super critical transition region of a throat section with steeper slope than the stream channel.

1.B.2.e.2.a. Flumes

A variety of flumes have been developed and used for measuring discharge. These flumes possess required characteristics of controls listed in sec. 1.B.2.e. No flume, however, will meet all the criteria for a good measuring structure in all natural situations. A particular flume should be selected carefully, and consideration should be given to such factors as amount of sediment necessary to be passed, rate of change of stage, expected discharge frequency relation, shape of the stream cross section compared to the flume, and construction cost.

1.B.2.e.2.a.1. Critical Depth Flumes Critical depth flumes typically measure depth in the drawdown approach above a section where critical flow is forced, either by wall contraction or floor superelevation. Flow is usually returned to subcritical velocity before exiting the flume structure. The Parshall flume is one of the most common flumes in use. Its principal advantage is its relatively low head loss. For moderate sediment loads, it will pass most sediment. These characteristics make it particularly well suited for flow measurement in irrigation canals and in some natural channels. The shape of the Parshall flume is shown in fig. 1–16. The Parshall flume's dimensions can be obtained from reports by the U.S. Bureau of Reclamation (1967, p. 46–47) and by Kulin and Compton (1975, p. 4–5). In free flow, the discharge depends solely upon the width of the throat, W, and the depth of water, H_A (U.S. Bureau of Reclamation, 1967, p. 48). The rating curve is affected by submergence, S, defined as

$$S = 100\frac{H_B}{H_A} \qquad \text{(no units; dimensionless)} \qquad (1\text{–}45)$$

when S exceeds 50 percent for small flumes or 80 percent for large flumes (see fig. 1–17 for location of H_A and H_B measurements). At a submergence of 95 percent, the flume is no longer considered to be an effective flow-measuring device. The discharge equation for free flow through a Parshall flume is of the general form

$$Q = C H_A^n \qquad \text{(in English or metric units)} \qquad (1\text{–}44)$$

where values of C and n are given by Kulin and Compton (1975, p. 4–6). Discharge tables and submergence corrections for a variety of Parshall flumes are provided by the U.S. Bureau of Reclamation (1967) and by Kulin and Compton (1975).

It is possible to pass a given discharge through any one of several different sized flumes. Usually the smallest flume which will handle the expected flows should be used. However, consideration should also be given to the channel in which the flume is to be installed. Generally, a flume should be about one-third to one-half as wide as the channel (U.S. Bureau of Reclamation, 1967).

Proper operation of a Parshall flume requires proper location of the flume. The flume is designed for use as an in-line structure in a channel where reasonably smooth flow is uniformly distributed across the width and depth of the cross section. A small amount of flow redistribution can take place in the flume but departure from the design conditions adds uncertainty to the rating. Proper vertical placement of a Parshall flume in a channel is given by the U.S. Bureau of Reclamation (1967).

Stage readings must be determined at the H_A and H_B gages (See fig. 1–17). The exact location of these gage points and other flume dimensions are given in the report by Kulin and Compton (1975). Staff gages can be used on the inside face of the flume walls for stage readings but some uncertainty will be introduced because of waves and fluctuations at the upstream gage and turbulent conditions at the downstream gage. For this reason, stilling wells with provision for flushing out sediment should be a part of the flume installation. If the flume will never be submerged, the gage at H_B can be eliminated.

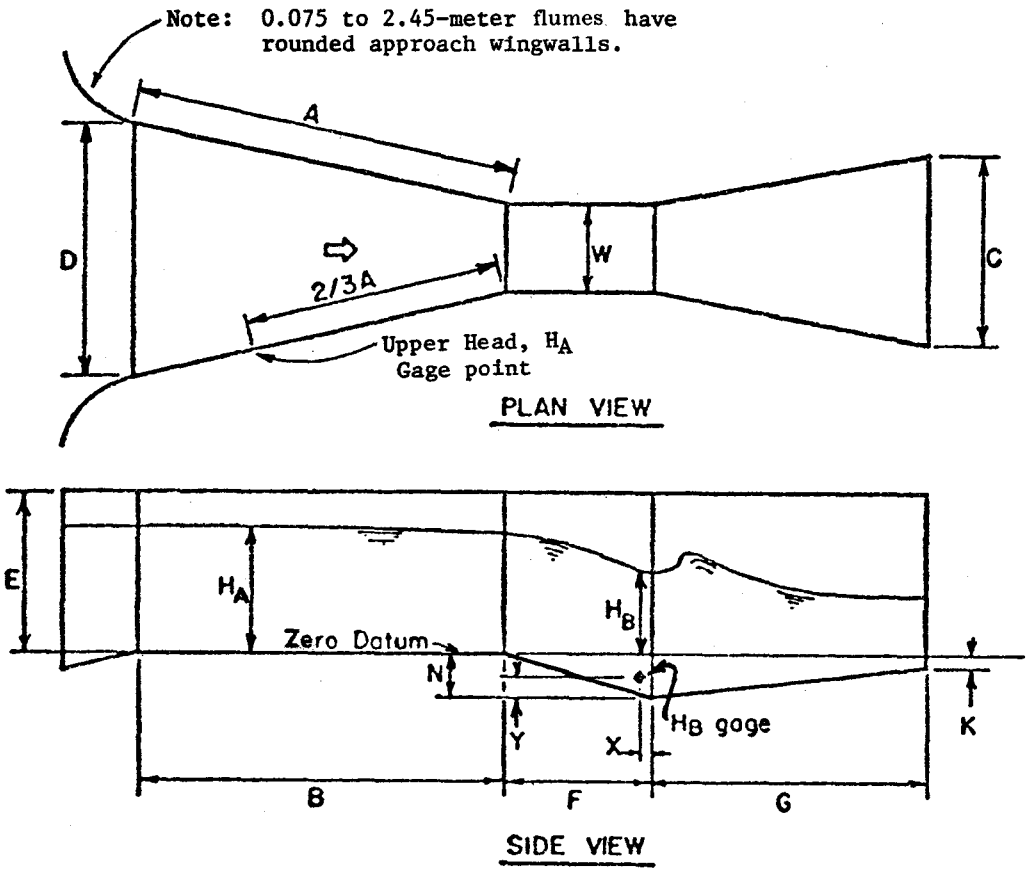


Figure 1-17.—General shape of Parshall flumes.

A modified portable Parshall measuring flume is used by the U.S. Geological Survey (Buchanan and Somers, 1969) for measuring discharge when the depths are shallow and the velocities are low. When the flume is properly placed and operating under free-flow conditions, an accuracy within 2 to 3 percent can be expected. The Bureau of Reclamation (1967) describes the characteristics of a number of modified Parshall flumes. Ratings for standard Parshall flumes also are applicable for free-flow conditions. If submergence occurs, ratings will have to be developed from current meter or other type measurements.

Venturi flumes depend upon contraction of the flow through critical depths either by tapering the sidewalls of the flume or by changing the elevation of the flume floor or both. If the channel is trapezoidal in shape, the flat-bottomed venturi flume can also be made trapezoidal to better fit the channel (U.S. Bureau of Reclamation, 1967). The general relation between head, H, and discharge, Q, for venturi flumes is

$$Q = KH^n \qquad \text{(in English or metric units)} \qquad (1\text{–}45)$$

where K and n depend mainly on the flume geometry with n between 2.0 and 3.0. The stage-discharge relationship for a venturi flume is best determined after installation by using current meters or other measurements of flow. For best results, the flat-bottomed venturi flume should be set flush with the upstream bottom of the channel. The head measuring station should be located just upstream from the start of convergence of the flume. A stilling well should be used to avoid

waves and fluctuations in the water surface. The U.S. Bureau of Reclamation (1976) has provided fabrication and rating details on one such flume. Replogle (1971, 1975) has described several sizes and shapes of venturi flumes and provided discharge ratings for each. He correctly points out how well suited these structures are for canals and other artificially shaped conveyance channels. A definition sketch for a typical venturi-type critical depth flume is shown in fig. 1-18.

H-flumes are a type of critical depth flume in wide use where discharges measured do not exceed approximately 100 cubic feet per second (2.83 cubic meters per second). These flumes employ a free overfall like a weir, but do not assume negligible velocity head at the measuring section. They are built to close tolerance, usually of metal, and the dimensions specify a predetermined rating. Fig. 1-19 shows typical dimensional relations and shape of the H-flume. Narrower geometries (HS) and wider geometries (HL) are also specified and ratings given. Details for construction and rating are given in Holtan and others (1962). A side-sloping floor is used in moderate silt loads to concentrate low flows for improved silt carrying capacities and to direct low flows on receding-stages past the stilling well opening. Ratings are negligibly affected.

The *cutthroat flume* is a flat-bottomed flume whose main advantage is extreme simplicity of form and construction. It has a horizontally contracting entrance and flared exit section but no parallel-wall throat section, hence its name. The discharge equation for this flume is

$$Q = KW^{b_1}h_a^{b_2} \qquad \text{(in English or metric units)} \qquad (1\text{-}46)$$

where Q = discharge
K = free flow coefficient
W = throat width
h_a = upstream depth
b_1, b_2 = coefficients which are given in English units by Kulin and Compton (1975, p. 15).

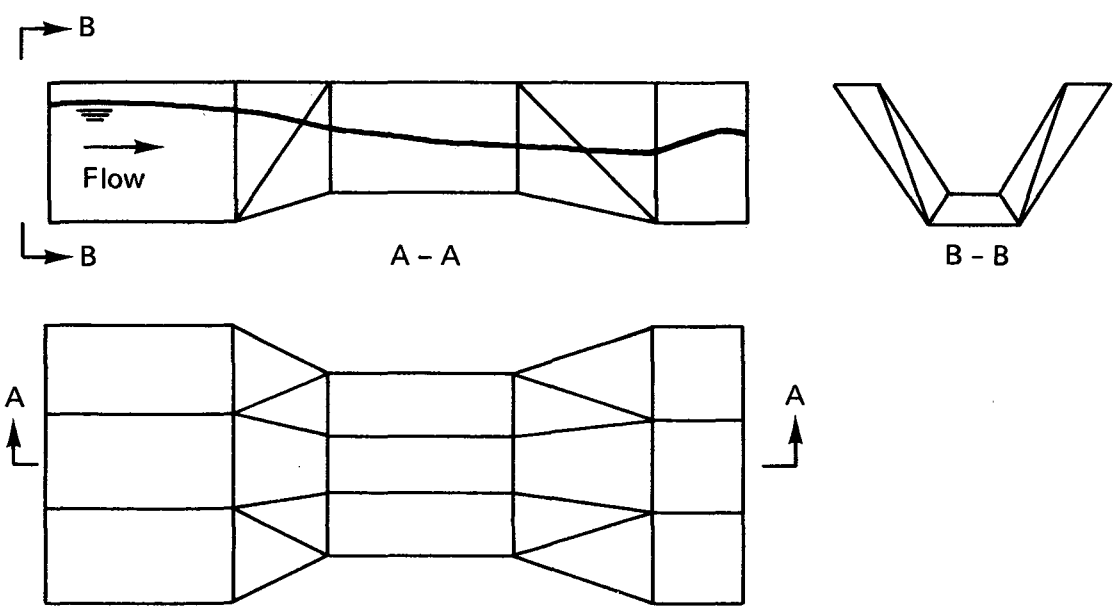
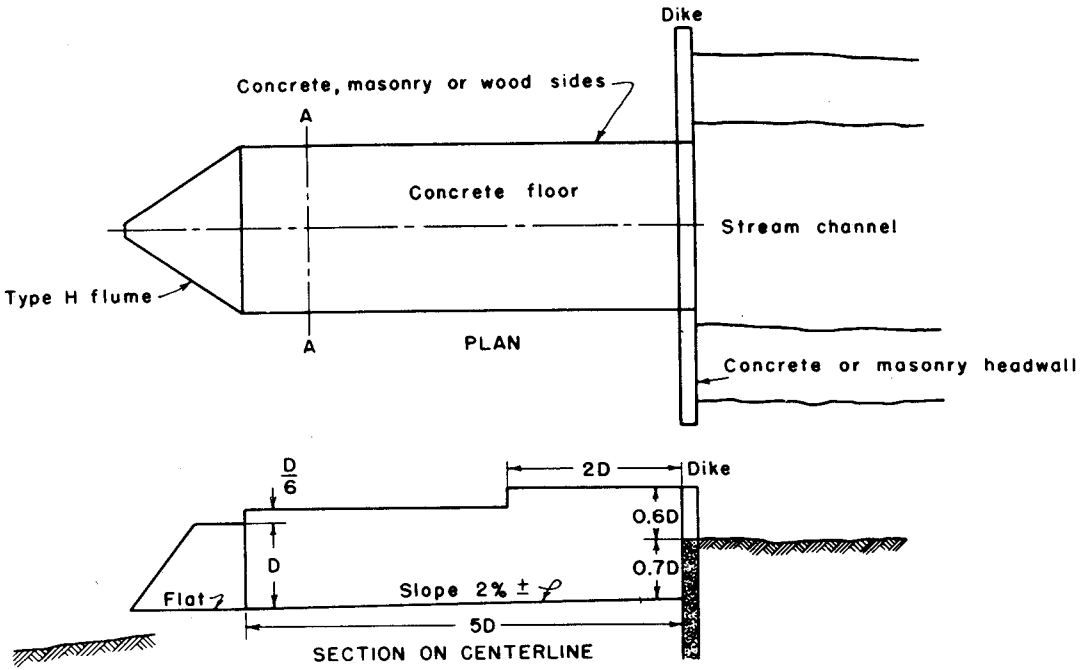
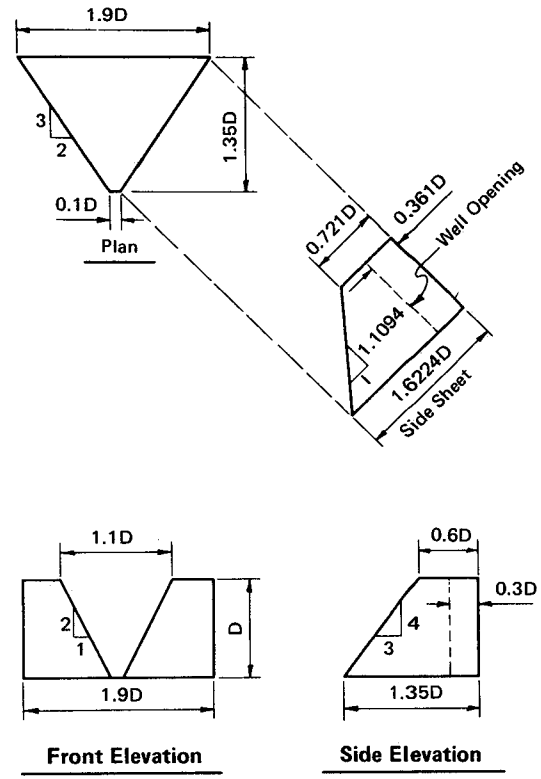


Figure 1-18.—Typical venturi-type critical-depth flume.



STRAIGHT HEADWALL INSTALLATION
(for use when flume is to be installed in a well defined natural channel)



Proportions of the Type H Flume

Approximate Capacities	
Depth-D Feet	Capacity FT.^{3}/s
0.5	0.3+
0.75	1-
1.0	2
1.5	5+
2.0	11
2.5	19
3.0	30+

Note: For flumes less than 1 foot deep, the length of flume is made greater than 1.35D so that the float may be attached.

Figure 1-19—H-flume dimensions and capabilities.

The upstream depth is measured at 2/9 of the total flume distance upstream from the throat. A downstream depth is also needed if submergence occurs. Kulin and Compton (1975) provide general dimensions and coefficients and exponents for a variety of cutthroat flumes. They have also provided a discharge equation and discharge coefficients for submerged flows. If the flume is installed with a sloping bottom, the stage-discharge relation can change significantly.

Palmer-Bowlus flumes are formed by placing inserts into the channel to raise the bottom and constrict the sidewalls (Kulin and Compton, 1975). The flume is easily constructed and installed. Critical flow occurs in the throat section. Depths are measured just upstream from the flume.

1.B.2.e.2.a.2. *Supercritical Depth Flumes* These types of flume accelerate the flow past a critical section by providing a throat with a supercritical bottom slope, and measuring depth in the throat where flow is accelerated. Some consideration should be given in installation to energy dissipation at the flume exit, and depth should be measured a distance at least as far ahead of the exit as the maximum flow depth. In a well designed and installed supercritical flume sedimentation should not affect ratings.

The *San Dimas flume* is designed to handle debris-laden flows. The floor of the flume is set on a 3° slope and the flow is funneled into the flume, producing supercritical flows. The flume has a rectangular cross section and except for the rounded entrance contraction is of equal width throughout its length. The flow equation is

$$Q = aW^{b_1}H^{b_2 - b_3 W^{b_4}} \quad \text{(in English or metric units)} \qquad (1\text{–}47)$$

where values of a, b_1, b_2, b_3, and b_4 are given in English units by Kulin and Compton (1975, p. 21) and

W = width of flume, and
H = head as measured 3.0 feet (0.91m) downstream from the entrance to the rectangular part of the flume.

The San Dimas flume is not sensitive or accurate at low flows. Further description of this flume and its rating characteristics is given by Kulin and Compton (1975).

The *trapezoidal flume* has both greater capacity and can provide more stage sensitivity to changes at low flows than San Dimas flumes. The flume shown in fig. 1-20 has sloping sidewalls and bottom to produce supercritical flow. The measurement of stage is made in the supercritical flow section of the flume. Kulin and Compton (1975) provide dimensions and rating curves for 1.0 and 3.0 foot (0.3 and 0.9 m) flumes. Chamberlain (1957) and Robinson (1961) discuss development and ratings of these flumes for use by the Forest Service. Because of the flat bottom of this flume, (1) low flows in natural streams are not well contained laterally, (2) sensitivity is lost, and (3) some error is introduced in the records.

The *Walnut Gulch Flume* improves on the same basic idea by providing a vee-shaped floor section in place of the flat floor. Gwinn (1970) describes model rating of these flumes, pictured in fig. 1-21. The original design allowed for shifting of the control section location, an unnecessary complication which was corrected in a later design flume called the *Santa Rita Flume*. This flume is described and calibration of several size flumes is reported by Smith and others (1978). The Santa Rita Flume is illustrated in fig. 1-22.

1.B.2.e.2.b. Weirs

A weir may be defined as an overflow structure built across an open channel, usually to measure the rate of flow of water (U.S. Bureau of Reclamation, 1967, p. 7). For free flow, the discharge is a function of the water in the pool upstream from the crest relative to the crest elevation, and the size and shape of the weir.

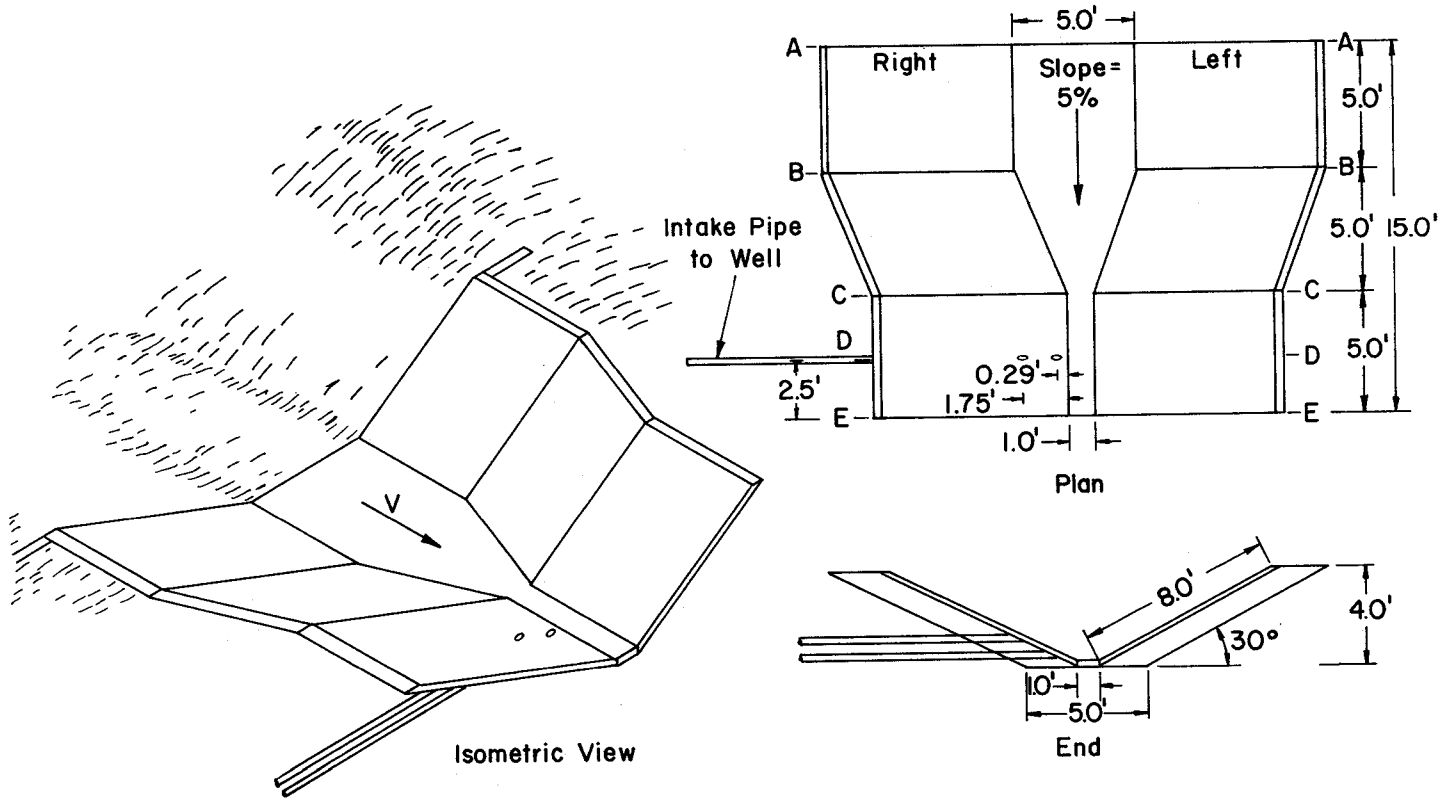


Figure 1-20.—Trapezoidal supercritical flume (from Robinson, 1961).

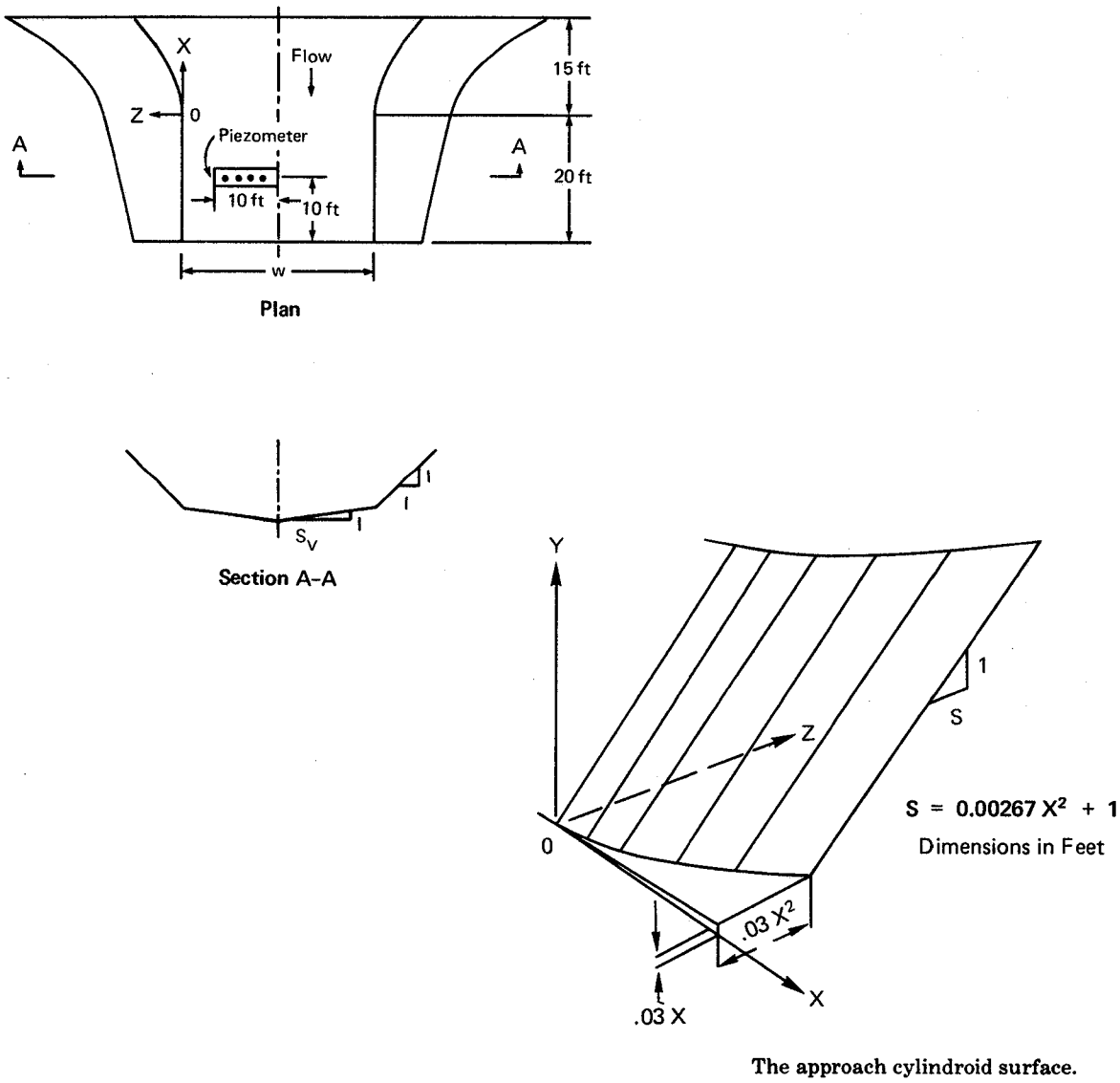
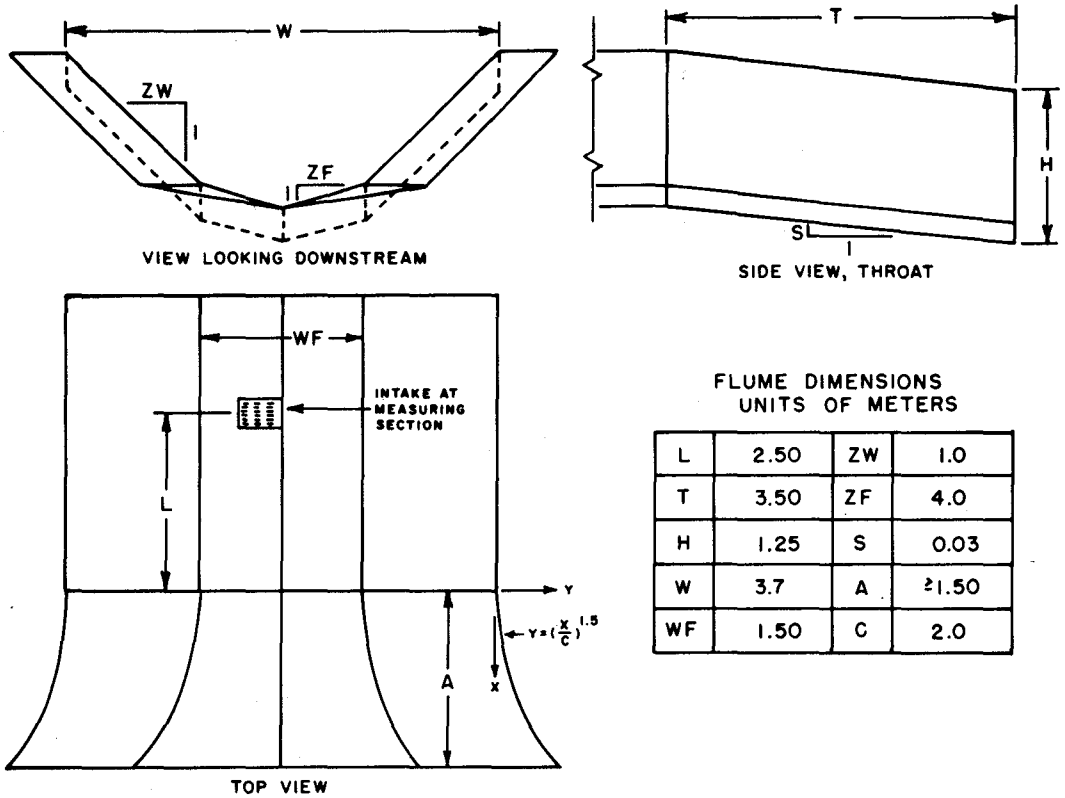


Figure 1–21.—Walnut Gulch supercritical flume (from Gwinn , 1970).

Free flow occurs when the water level in the downstream channel is sufficiently below the crest to allow free access of air to the underside of the nappe and aeration of the nappe is not suppressed by the walls. If the nappe is not ventilated, the discharge may be increased because of the low pressure beneath the nappe. When the downstream water level rises above the crest elevation, the flow is considered to be submerged. The effect of submergence on the rating will depend on the degree of submergence. For measuring weirs, free flow is generally desired. When complete contractions occur on the sides and bottom of the channel, the weir is called a contracted weir. For this condition, the ends of the weir should not be closer to the sides of the channel than twice the head on the weir (U.S. Bureau of Reclamation, 1967, p. 9). If the weir extends across the entire channel, it is called a suppressed weir. Suppressed weirs will usually have to be vented for full underside aeration of the nappe in order to properly use the free-flow equations.

SANTA RITA FLUME
DESIGN CAPACITY 5.0CMS



FLUME DIMENSIONS
UNITS OF METERS

L	2.50	ZW	1.0
T	3.50	ZF	4.0
H	1.25	S	0.03
W	3.7	A	≥1.50
WF	1.50	C	2.0

FLUME RATING

MULTIPLIER	HEAD AT MEASURING SECTION IN M FOR Q IN CMS Q, DISCHARGE RANGE : 0 – 5.0					
	0.01	0.1	1.0	10	100	1000
1.0	0.045	0.125	0.359			
1.2	0.048	0.135	0.396			
1.4	0.052	0.145	0.430			
1.6	0.055	0.153	0.462			
1.8	0.058	0.161	0.493			
2.0	0.061	0.169	0.522			
3.0	0.073	0.200	0.651			
4.0	0.083	0.227	0.762			
5.0	0.092	0.253	0.860			
6.0	0.099	0.276				
7.0	0.106	0.298				
8.0	0.113	0.319				
9.0	0.119	0.340				

Figure 1-22.—Santa Rita supercritical flume (from Smith and others, 1978).

The standard contracted rectangular weir (thin plate) has it crest and sides far enough removed from the bottom and sides of the channel that full flow contraction occurs. The U.S. Bureau of Reclamation (1967, p. 12-14) provides recommended fabrication and installation procedures. The head is measured at a point upstream from the crest a distance of at least four times the head on the weir. (See fig. 1–23).

An equation of flow which is considered to be accurate and is applicable for both rectangular contracted and suppressed thin plate weirs is the Kindsvater-Carter equation

$$Q = C_e L_e H_e^{1.5} \tag{1-48}$$

where C_e = a coefficient that is a function of the degree of width contraction, $L/_B$, and the ratio of head to crest height (i.e., H/p),
L_e = weir width plus a coefficient k_b, which is a function of the degree of width contraction, and
$H_e = H$, the head on the weir, plus 0.001 m (0.003 ft.).

Kulin and Compton (1975, p. 24, 27) provide relations for determining C_e and k_b. Advantages of this equation are that the velocity of approach is incorporated in the determination of the coefficients and all degrees of contraction are provided for. Kulin and Compton (1975, p. 31–32) provide some criteria for when to use the different rectangular weir equations (also see ISO 1438, 1975).

The standard *Cipolletti weir* is trapezoidal in shape. Its crest and sides are thin plates and set so that full contraction occurs.

The sides of the weir are sloped outward at a slope of 1 unit horizontal to 4 units vertical. The discharge equation is

$$Q = 1.859\, L\, (H + 1.5h)^{1.5} \qquad \text{(in metric units)} \tag{1-49}$$

This equation considers the velocity head, h, in the approach section and must be solved by a trial and error method (U.S. Bureau of Reclamation, 1967).

V-notch weirs are recommended for the measurement of low flow. These weirs are designed to act as contracted weirs. The minimum distance from the crest to the upstream channel bottom should be at least twice the head on the weir. Ordinary low approach velocities do not have much influence on V-notch weirs (U.S. Bureau of Reclamation, 1967, p. 15–16, 24–25). The equation of flow for a 90 degree fully contracted, sharp crested V-notch weir is:

$$Q = 1.343\, H^{2.48} \qquad \text{(in metric units)} \tag{1-50}$$

A flow equation which is good for a V-notch weir of any angle is

$$Q = (8/15)\,(2g)^{1/2} C_e \tan(\theta/2) H_e^{3/2} \qquad \text{(in English units)} \tag{1-51}$$

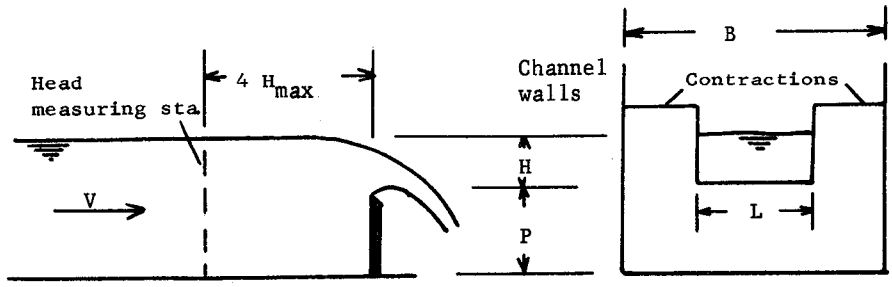
where C_e = coefficient,
θ = notch angle, and
H_e = measured head, H, plus a factor k_h

C_e and K_h are given by Kulin and Compton (1975, p. 29) and are a function of the notch angle θ.

The Soil Conservation Service, USDA, has developed and rated a series of V-notch weirs with thick crests, which in performance are more similar to sharp-crested than broad-crested weirs. Figure 1-24 shows general features of this weir, which is rated for crest slopes of 2, 3, 5, and 10 to 1. Details and ratings are given in Holtan and others (1962, p. 34–39). Velocity corrections for constricted approach sections are also given. These weirs are in wide use in research watersheds throughout the United States.

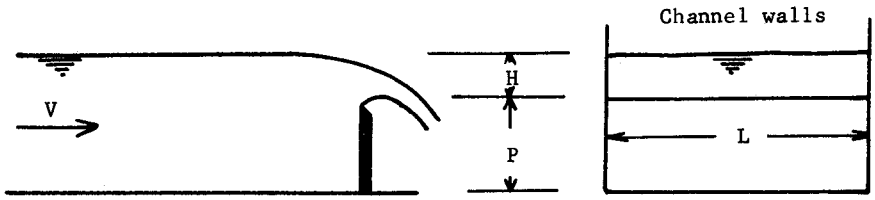
Measuring weirs should be selected with the following considerations (U.S. Bureau of Reclamation, 1967):

1. The minimum head should be at least 0.06 meter to prevent the nappe from clinging to the crest and for greater accuracy of head determination.

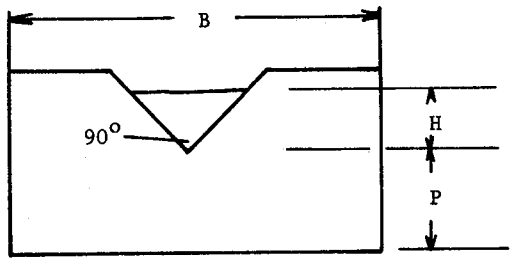


Note: Contractions > 2H; P> 2H, for full contraction

Fully contracted rectangular weir.



Suppressed rectangular weir.



V-notch 90 degree weir.

Figure 1-23.—Common shapes of thin-plate weirs (from Kulin and Compton, 1975, p. 25).

2. The length of rectangular and Cipolletti weirs should be at least three times the head.
3. The most accurate weir for measuring low flows is the V-notch weir.
4. The crest should, if possible, by placed high enough to permit free flow.
5. Weirs should never be used in sediment laden flows unless a regular cleaning schedule can be maintained.

If a broad-crested weir is used for flow measurement, it is recommended that the rating be determined by some type of discharge measurement. The discharge for this type weir is a function of the head to the 1.5 power.

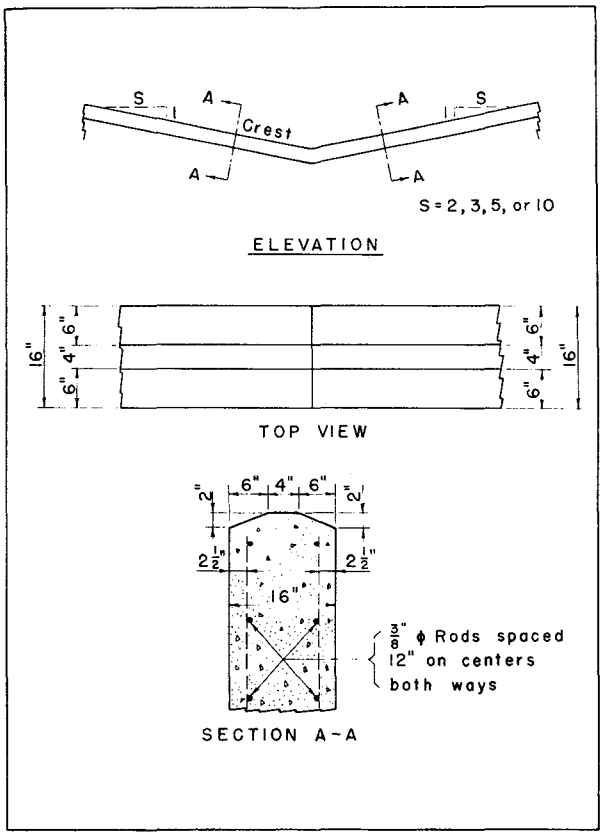


Figure 1-24.—Shape of a standard cross section of a triangular weir with a 16-inch crest width.

When a wide range of discharges must be measured, it may be desirable to use a combination of rectangular and V-notch weir. The ratings for such weirs should be determined in the field by current-meter or some other type of discharge measurement.

Where submergence occurs, the free-flow rating may need to be adjusted depending on the degree of submergence. It is recommended that this be accomplished by means of current-meter or other field measurement of flow. Irregular velocity distributions in the approach section may add significant error when using the standard free-flow equations. Suppressed weirs will usually have to be vented for full underside aeration of the nappe in order to properly use the free-flow equations.

The U.S. Bureau of Reclamation (1967, p. 7-41) provides recommendations for installation and maintenance of weirs and of the channels in the vicinity of weirs. Failure to follow proper installation and maintenance procedures can introduce errors into flow measurements using weirs.

1.B.2.e.2.c. Dams

Shapes and profiles of dams and their crests vary a great deal and consequently, the coefficients of discharge also vary. The general equation of flow over dams is:

$$Q = CLH^{3/2} \tag{1-52}$$

where Q = discharge,
C = coefficient of discharge,
L = length of the dam crest, and,
H = head on the crest.

The reader is referred to section 1.B.2.d.3.d., for the determination of coefficients of discharge for various type dams. Again, ratings should be checked or determined by the use of current-meter or other type measurement.

1.B.2.e.2.d. Orifices

An orifice used as a measuring device is a well-defined sharp-edged opening in a wall or bulkhead through which flow may occur. If the upstream water surface drops below the top of the opening, the flow ceases to follow the laws of orifice flow and tends to follow those of flow over a weir. Flow through orifices may either discharge freely into the air or into water as submerged flow. The submerged orifice conserves head and is therefore used where there is insufficient fall for a weir, and where for some reason, a flume cannot be justified. Both free and submerged orifices may be contracted or suppressed. A suppressed orifice is one whose perimeter partly or fully coincides with the sides of the approach channel.

The discharge through a vertical, sharp-edged, contracted, submerged orifice is given by Corbett and others (1943, p. 87–88) as:

$$Q = CA(2gH)^{1/2} \qquad \text{(in English units)} \qquad (1\text{–}53a)$$

where Q = discharge,
C = coefficient of discharge, and can usually vary from 0.59 to 0.63 but is usually considered to be 0.61, in English units,
A = area of orifice,
g = acceleration due to gravity, and
H = head on the orifice, equal to the difference of the head on the upstream and downstream sides of the orifice.

A negligible velocity of approach, complete orifice contractions, and an effective head large enough to minimize errors in its measurement are essential for obtaining accurate results. Streams having a heavy silt load may deposit silt in the approach and change the approach velocity, thus producing error.

When the velocity of approach becomes appreciable, the discharge equation becomes:

$$Q = 0.61\, A\, [2g\,(H + h)]^{1/2} \qquad \text{(in English units)} \qquad (1\text{–}53b)$$

where h is the velocity head in the approach to the orifice (U.S. Bureau or Reclamation, 1967, p. 92).

Where part of a submerged rectangular orifice is suppressed, the discharge equation becomes:

$$Q = 0.61\,(1 + 0.15\,r)\,A\,(2gH)^{1/2} \qquad \text{(in English units)} \qquad (1\text{–}54)$$

where r is the ratio of the suppressed portion of the orifice perimeter to the total perimeter.

The Bureau of Reclamation (1967) describes both a standard orifice and a special constant-head orifice used for regulation and measurement of flow, and the installation and operation procedures.

Culvert-type structures can sometimes be considered orifices and are often used as control structures. The reader is referred to sec. 1.B.2.d.3.c. for the use of culverts for flow measurement.

1.B.2.e.2.e. Meter Gates or Sluices

The flow of water is measured through gates and sluices in many irrigation systems. Generally each gate or sluice must be individually calibrated. This involves making current-meter or other type

discharge measurements at a variety of gage openings or depths of flow in sluices and developing discharge-head relations.

The head which should be used for calibrating gates is the difference between the head upstream and downstream from the gate. Head difference should be great enough to keep errors of measurement within allowable limits.

The Bureau of Reclamation (1967, p. 172–176) describes a metergate which is commonly used for controlling and measuring irrigation flows. The downstream head, h, is measured at a distance of one-third of the outlet pipe diameter downstream from the gate. The downstream end of the discharge pipe must be submerged, usually to a depth of at least 1 to 2 feet (0.3 to 0.6 m) above the crown of the pipe. Also, the water surface should be at least one pipe diameter above the top of the pipe at the entrance.

Laboratory tests have been conducted on square-bottom, flat-leaf metergates to describe the coefficient of discharge, C_d for the discharge equation:

$$Q = C_d A[2g(H-h)]^{1/2} \quad \text{(in English or metric units)} \qquad (1\text{–}55)$$

where A = nominal area of the pipe, and
$H-h$ = upstream and downstream head differential.

The coefficient of discharge was found to vary with the percent of gate opening as shown by the Bureau of Reclamation (1967, p. 176). The Bureau also describes the standard conditions of the calibrated metergate.

1.B.2.e.2.f. Others

Structures are often placed in natural stream channels to help stabilize the stage-discharge relation for the channel. Often these structures do not conform to any design for which laboratory tests have been run. These structures may conform to the local stream geometry and may be as simple as placing small crude weirs or dams between a series of boulders in a stream. Nevertheless, they usually help to stabilize the rating conditions.

All such controls should have, to the extent possible, the characteristics described in section 1.B.2.c. Ratings should be determined and checked by current meter or other type discharge measurement. Artificial control structures placed in streams will often become submerged and ineffective at high flows. Thus, the rating for such sites may become complex as the effective control changes from the low-flow structure to the high channel control.

1.B.2.e.2.g. Choice of Calibrated Control Structure

Although no simple criteria can be given for choice of a best structure in any given situation, general features of the structure listed above may be very briefly compared by means of the chart in fig. 1–25. The listed factors affecting choice of structure are by no means exhaustive but should serve as reminders for consideration in any given situation. Often, of course, agency policy or expediences such as using available structures, will override other factors. Attention should always be paid to (a) expected distribution of flows of primary interest to be measured, (b) amount of transported sediment which must be handled, and (c) cost of construction.

Figure 1-25.—Factors affecting choice or utility of control structures.

Control structure	Mean discharge	Stream variance or range	Sediment or trash load	Approach velocity	Site location	Stream X-section	Climate	Materials used	Relative expense	Relative accuracy
H-flumes	Small only (<250 cfs)	Some effect from upstream pondage.	Can pass moderate bedload.	Not critical with adequate ponding.	Can be fairly remote.	Narrow channel or use dikes. Requires approximately 1 ft. fall.	.....	Usually metal can be prefabricated. Concrete requires elaborate form work.	Moderate for small flumes.	High, well calibrated.
Weirs	Small to medium (<500 cfs)	Pondage must be considered in small watersheds or in rapidly changing flow.	Low or no bed load, unless repetitive cleaning is done.	Not too critical if large pondage used.	Can be remote under proper conditions.	Moderate bank slope to minimize storage, or use dikes.	Should pass most ice but will freeze.	Concrete or metal, masonry.	Moderate to low.	Moderate, easily calibrated.
Venturi flumes	Small to medium	Best for low variance flows.	Low to moderate will clog in many cases with bedload, but minimum disturbance of streamlines.	Must be $F_r<0.6$.	.....	Requires trapezoidal shape thru flume. Little fall needed.	.....	Concrete or steel for small installations, masonry.	Moderate.	Moderate, variable.
Parshal flumes	...do...	Best for low variance flows. No pondage.	Sediment must be able to pass thru approach section.	Subcritical, mild.	.....	Relatively narrow. Some fall needed.	.....	Concrete, steel.	Moderate to high.	Standard shapes are well calibrated.
Supercritical flow flumes	Low to high	High-good in ephemeral streams. No pondage.	Best for high sediment flows.	Good for F_r up to 1.0 or even more.	To avoid sediment problems in stilling well, may need electric power for other depth recording equipment.	Variable.	.....	Concrete or metal (small versions).	Varies with stream size. Can be expensive in large streams.	Good, can be calibrated by theory.

1.B.2.f. MEASUREMENT OF TURBULENCE AND DISPERSION

The measurement of turbulence in open-channel flow is extremely difficult and complex to make with any degree of accuracy or reliability. In fact, there is a pressing need for an instrument or technique that can measure the characteristics of turbulence in flowing water in all situations. The required turbulence measuring system must have:

1. A frequency response good enough to follow the velocity fluctuations instantaneously.
2. A sensor smaller than the areal extent of the smallest velocity fluctuation in the flow, and
3. A readily obtainable and stable relation between system output and actual velocity.

No existing instrument or technique is completely satisfactory for making turbulence measurements under conditions encountered in natural, open-channel flow.

Dispersion in open-channel flow is caused by combined action of many forces such as variable longitudinal convection, transverse diffusion and turbulent mixing. There appears to be no good standard or accepted method of estimating the degree, rate and distance of mixing or dispersion under various loading conditions.

The reader's attention is directed to the 1.B.2.f.1. and 1.B.2.f.2. discussions of the adequacy of the methods.

1.B.2.f.1. HOT-FILM ANEMOMETERS

Hot-film anemometers are used to measure the turbulence of water. This instrument's usefulness is somewhat limited in sediment and debris-laden streams because of a drift of the velocity-voltage relation when impurities collect on the sensor. Richardson and others (1967) have developed a method for correcting for this drift. However, the hot-film anemometer is also limited in its usefulness by its fragility and cost (Bennett and McQuivey, 1970).

The hot-film anemometer is not recommended at this time for open-channel measurements except for research purposes or for special laboratory studies.

1.B.2.f.2. DYE STUDIES

Dye studies are often used for the determination of mixing or dispersion characteristics of streams. Usually vertical dispersion occurs quickly enough that it is not considered in dye studies.

Field and general study methods for using dyes for dispersion measurements are discussed in section 1.B.2.c.6.d., for time-of-travel studies. The field and data-collection techniques and requirements are identical.

Because of the complexity of the methods for determining dispersion coefficients and other dispersion computations, it is recommended that the reader refer directly to the following publications. The concepts of transverse dispersion are presented in the report by Yotsukura and Cobb (1972). Concepts and applications of transverse and longitudinal dispersion are presented in the report by Yotsukura and others (1970).

1.B.3. CLOSED CONDUIT FLOW

1.B.3.a. MEASUREMENT OF DISCHARGE

User needs in closed conduit flowrate measurement vary so widely in regard to accuracy requirements, permissible head loss, access, cost, flow conditions, etc., that recommended methods have to take these situations into account. Therefore, many different methods of discharge measurement are included in this section and the characteristics which might make them appropriate for particular situations are cited. Probable accuracy figures are given when they have been cited by an authoritative body. However, the figure should be interpreted by readers only as estimates which are given for their information and for comparison purposes, and not necessarily as figures which

are routinely attained in the field. The caution with which potential accuracy statements must be treated is illustrated by comparative flow measurement tests at Finlarig power station (Hutton and Murdoch, 1962). Tests were carefully made on a large pipeline using several methods, including current meter traverse, salt velocity, dilution, Gibson method and a flume at the discharge end. The spread in measured flowrates was ±2 percent. Accuracies of up to ±1 percent are claimed for several of these methods.

A concise account of the state-of-the-art of a few of the most popular flow metering devices has been given by Spencer (1974).

1.B.3.a.1. VOLUMETRIC AND GRAVIMETRIC METHODS

Volumetric and gravimetric methods depend upon timing the collection of a measurable volume or weight of water, and thus these methods are directly referenced to basic quantities. However, they are generally used under laboratory conditions to calibrate other devices and procedures. Sometimes the volumetric method employs a piston or positive displacement facility. Olsen (1974) describes these methods and cites some of the precautions needed to maximize accuracy. Quantity or positive displacement meters, which basically perform repetitive volumetric measurements, are discussed in sec. 1.B.3.a.10.

1.B.3.a.2. DIFFERENTIAL HEAD FLOWMETERS

Differential head flowmeters relate the flowrate to the head difference produced when the flow is forced through a geometry, usually a constriction, which produces a pressure difference. In constriction devices the basic equation for discharge Q is

$$Q = \frac{CA_0(2gh)^{1/2}}{(1-\beta^4)^{1/2}} \tag{1-56}$$

where A_0 is the area of the constriction or throat, h, is the head difference in height of water between upstream and downstream taps (which must be located exactly according to recommendations), β is the throat-to-pipe diameter ratio, and C is a coefficient which depends upon geometry, Reynolds number, and pipe relative roughness. Clearly the accuracy of the flow measurement depends not only upon the accuracy of the flow coefficient associated with the device itself, but also upon the accuracy of the head difference measurement. That is, in all cases the entire measurement system must be considered. This section deals mainly with the properties of the device itself, i.e., the primary element. The referenced standards and guidelines for these elements include recommendations on the size, quality, and location of the pressure taps which are integral parts of the primary devices. Helpful informtion on the tubing or piping leading to the pressure-difference measuring devices, i.e., the secondary elements, is given by the American Society of Mechanical Engineers (1971) and by the International Standards Organization (1973a).

1.B.3.a.2.a. Venturi Meters

There are several modifications of the basic or classical venturi meter shape, but all have in common the distinctive single feature of the venturi, i.e., the gradual diffuser between the constriction or throat section and the downstream pipe diameter. This diffuser gives the venturi meter its low head loss, which is its main advantage, along with a concomitant self-cleansing capability. A disadvantage is its relative expensiveness in the larger sizes, as well as the substantial length needed to accommodate the diffuser. The discharge coefficient for this meter is a function of geometry, Reynolds number, roughness, and installation conditions. According to the American Society of Mechanical Engineers (1971), the uncertainty in published coefficients ranges up to about 1½ per-

cent. Recommended practices for venturi meter installation and use are also given by the International Standards Organization (1968), American Society for Testing and Materials (1969), and the British Standards Institution (1964). The last two documents include some information on tubing layouts for the pressure difference measurement. The British Standards Institution (1964) and International Standards Organization (1969) also give information on effects on classical venturi meters of departures from recommended contraction, Reynolds number and roughness.

1.B.3.a.2.b. Orifice Meters

Orifice meters are among the most widely used flowrate measuring devices and there exists a substantial body of literature on them. They are relatively inexpensive and easy to install, and their flow coefficients are well established to within perhaps two percent. Nevertheless, considerable care must still be exercised in their use, particularly in regard to plate conditions and upstream conditions. They are subject to gradual coefficient change due to erosion of the sharp upstream edge of the orifice. The main disadvantages are the large head loss and unsuitability for flows with solids components. Several pressure tap arrangements, e.g., corner taps or vena contracta taps, are used with orifice plates, and coefficients for all of these combinations, as well as recommended practices, are cited by the International Standards Organization (1967), American Society of Mechanical Engineers (1971) and the British Standards Institution (1964). The British Standards Institution (1965) discusses some effects of departures from recommended conditions, such as orifice edge roundness, incorrect location of pressure taps, eccentricity of orifice in the pipe, and select upstream and downstream pipe layout effects.

A related device is an orifice plate at the end of a pipe with fluid trajectory issuing into air. This setup is frequently used to measure irrigation water, and requires the measurement of only a single pressure upstream of the orifice. This method has not been refined to the accuracy level of the conventional orifice flowmeters outlined above, but it still may satisfy important field needs. Simplified methods of arranging this setup, along with orifice coefficients (based only on orifice-to-pipe diameter ratio) are given by the U.S. Department of Agriculture (1962).

1.B.3.a.2.c. Nozzles

Flow nozzles rank between orifices and venturis in cost. They have a large head loss, but their discharge coefficient is higher than that of the orifice (for the same throat size) and is less subject to change due to erosion wear. The suggested references are the same as for the orifice meter (see 1.B.3.a.2.b.).

1.B.3.a.2.d. Elbow Meters

The pressure differences associated with the centrifugal forces generated in flow around a pipe bend can be measured and used to determine a flowrate. This method is covered by the American Society of Mechanical Engineers (1971), and Replogle, Myers and Brust (1966a) discusses the limits of applicability of commercial elbows without in-place calibration.

1.B.3.a.3. TURBINE-TYPE (PROPELLER) FLOWMETERS

This flowmeter consists of a flow tube in which a bladed turbine rotor is mounted supported by one or more bearings, together with a means of generating an electrical signal proportional to the angular velocity of the rotor. These meters have the advantage of covering a large flow range, up to ten to one, and according to manufacturers have high accuracy and long-term repeatability. The disadvantages are that precision turbine meters can be used only in very clean liquids, and they are

susceptible to error from uneven upstream conditions, particularly swirl. Turbine meter are discussed by American Society of Mechanical Engineers (1971), Instrument Society of America (1972) and Strohmeier (1974).

A related device is the propeller meter, which is similar to the turbine meter except that the enclosing flow tube is not an integral part of the device. Therefore it can be installed, for example, near the end of a full-flowing pipe discharging into atmosphere and is sometimes used in this way to measure irrigation water. These meters are somewhat less accurate than turbine meters, but they can tolerate some impurities in the water. The bearings are the most common trouble spot as far as maintenance is concerned. These meters are discussed by the U.S. Bureau of Reclamation (1967).

1.B.3.a.4. VELOCITY-AREA METHODS

Velocity-area integrations of circular (or other shaped) closed conduits can be accomplished either with pitot tubes or with current meters. In this method, the performance of the velocity sensor itself must be accurately known (see sec. 1.B.2.c.1.a.1.), corrections to this performance must be applied where necessary (e.g., blockage effects and turbulence effects), and the velocity measurement locations must be properly selected and the velocity-area integration correctly performed. All of these factors are discussed in the standards cited. Only propeller-type current meters (as distinguished from vertical-axis meters) are used in this work. They are used either singly and moved from point to point, or in muliples in fixed mounted arrays. The quantitive effect of turbulence on current meters, which are virtually always calibrated in still water, is under investigation and has not been included in published standards. The references cited claim that accuracy can be as high as one to two percent with careful work. The British Standard Institution (1973) has issued guidelines for the velocity traversing of circular pipes with pitot tubes. Because pitot tube performance has been investigated in detail, this method has a potential for high accuracy. The International Electrotechnical Commission (1963) has published procedures for traversing circular and some non-circular conduits with current meters. Dodge (1965) has given a detailed description of current meter surveys in retangular turbine intakes with limited access. An International Standards Organization (1974a) draft standard is available for current meter traverses of circular and rectangular conduits.

1.B.3.a.5. CHEMICAL METHODS

Chemical-addition methods are of two types. The first, a transit-time method, uses the chemical as a tracer to determine the average velocity in the length of conduit under consideration. The velocity so determined is then multiplied by an average area to obtain a flowrate. The salt-velocity method is the best known of these transit time methods but others, such as color-velocity and radioisotope-velocity methods are also used. The second type of chemical-addition method uses the dilution of a known amount or rate of added tracer material to determine the flowrate. The additives for this method are usually fluorescent dyes, sodium dichromate or radioisotopes.

Both types of methods require full mixing of the additives across the conduit before transit time or concentration measurements are made. Recommended lengths for adequate mixing are given in several references, such as International Standards Organization (1974b). The transit-time method requires accurate measurements of the conduit geometry, while the dilution methods require accurate measurements of the concentrations of the total amount added. The advantages and disadvantages of the transit time and the dilution methods are discussed in International Standards Organization (1974b) along with the advantages of the various common chemical or tracer materials.

Chemical addition methods appear to have in common requirements for special equipment, scrupulous care, and often, considerable time for their execution and therefore they tend to be expensive. However, there frequently are flow situations in which no other methods are fully suitable. Also, these methods have the potential for high accuracy when carefully done, so they are often used for field calibration of other flow measurement devices.

1.B.3.a.5.a. Salt Velocity Method

In the salt velocity method, brine is injected suddenly at an upstream station in such a manner that is becomes well distributed across the section as rapidly as possible. The time of passage of the salt pulse between two downstream stations is measured by means of electrodes which detect the increased conductivity associated with the passage of the brine. The flowrate can then be determined provided the volume of the conduit between the electrode stations is known. This method has a potential for better than one percent accuracy if properly used. The major error sources are improper determination of the elapsed time between the centers of gravity of the recorded conductivity pulses and inaccurate determination of conduit volume. Straight sections of conduit are desirable, and fittings which cause separation zones should be avoided. The most detailed guidelines for this method are given by the International Electrotechnical Commission (1963) and the American Society of Mechanical Engineers (1971).

Related methods are the color-velocity and radioisotope-velocity methods. When a pipe discharges into air, the color velocity method can be rather crudely applied by visually estimating the arrival time of the color slug, as described by the U.S. Bureau of Reclamation (1967). However, better accuracy can be achieved by using fluorescent dyes and recording the passage of the dye slug with a fluorometer. No standard procedures have been documented for these methods, and most of the detailed descriptions were prepared for open channel application. Nevertheless readers can find useful information on dye handling and measurement in Replogle and others (1966) and Wilson (1968).

The radioisotope-velocity method, along with all radioactive tracer methods, has the advantage of potentially accurate and convenient monitoring from outside of the pipe. On the other hand, special training, exceptionally careful handling, and licensing are involved in such tests, along with a certain level of public apprehension. One description of procedures can be found in Schuster and Hansen (1969).

1.B.3.a.5.b. Dilution Methods

Dilution methods employ either constant rate (continuous) injection or slug injection. In both cases accuracy depends on, among other factors, adequate lateral mixing at the sampling station and accurate concentration measurement. Dilution methods can be further subdivided by the type of material added and/or by the property which is analyzed to determine the dilution, e.g., color, salinity, radioactivity, conductivity.

1.B.3.a.5.b.1. Constant-Rate Method—The principle of the constant rate method is expressed in the continuity equation

$$Q = q(C_1 - C_2)/(C_2 - C_0) \tag{1-57}$$

where Q is the flowrate to be determined, q is the injected constant flowrate of additive concentration C_1, C_2 is the concentration of the (completely mixed) additive at the sampling station, and C_0 is the background (ambient) concentration of the additive pre-existing in the water. In this method the concentration C_2 can be sampled during a concentration plateau, but offsetting this convenience is the fact that q and C_1 also have to be measured accurately. The foregoing continuity equation assumes that no additive is lost between the injection and sampling stations by physical or chemical action. Any loss will be reflected as apparent additional dilution and hence apparent greater flowrate. Dye loss or stability is discussed by Wilson (1968) and by Replogle and others (1966). The International Standards Organization (1974b) covers the advantages and disadvantages of a variety of additives as well as distances required for adequate transverse mixing.

Guidelines for the use of the constant rate method with sodium dichromate and fluorescent dyes are given in an International Standards Organization (1974c) draft standard. The use of radioisotopes in the constant rate method is described by the British Standards Institution (1967) for open channels, but many of the descriptions are useful in closed conduit work as well. Descriptions of radioisotopes used in closed conduits are given by Schuster and Hansen (1969, 1971).

1.B.3.a.5.b.2. Slug Injection—The principle of the slug injection method is expressed in the equation

$$Q \int_0^\infty (C_2 - C_0)d\tau = C_1(\text{Vol.}) \tag{1-58}$$

where the product C_1 (Vol.) is the amount of the injected slug of chemical, τ is time of passage of the tracer cloud past the sampling station, and Q, C_2 and C_0 are as previously defined. It is clear from this equation that the main disadvantage of this method is that the tracer wave has to be sampled over its entire time of passage. The earlier requirement for complete lateral mixing still pertains. The injection apparatus need not be as sophisticated as is required for the constant rate method because here only the total injected amount of tracer has to be known. Again there can be no loss of additive between injection and sampling stations.

1.B.3.a.5.b.3. Additives—Fluorescent dyes have been studied in detail by Wilson (1968). Rhodamine WT appears to show little loss to channel boundaries and to sediment and is therefore recommended for dilution tests. It has even been used successfully in raw sewage by Kilpatrick (1968). Existing fluorometers properly used are capable of one percent accuracy. Sodium dichromate is the dye most commonly used when dilution is determined by colorimetric (as distinguished from fluorometric) analysis. However, the accuracy can be affected by suspended matter in the flow or by chromium ions in wastewater (International Standards Organization, 1966). Salt can also be used as a dilution tracer with the concentration determination made by conductivity measurements. However, some flows will require large quantities of salt, and the method cannot be used where the background salinity is high.

1.B.3.a.6. ELECTROMAGNETIC FLOWMETERS

The magnetic flowmeter operates on the same principle as an electric generator. An electromotive force is induced in a conductor moving in a magnetic field. In this case the conductor is the flowing water, and insulated electrodes in the pipe (in a diametric plane normal to the magnetic

field) connected to a voltmeter measure the induced emf. The obvious advantages of this meter are that it is non-intrusive and contributes no added head loss to the flow. The effect of variation in water conductivity is minimal provided a certain threshold value exists. Velocity-distribution effects, particularly of pipe flow distributions which are not axisymmetric, are still uncertain and caution should be exercised in that regard. Build-up of deposit or scale can cause error depending upon the conductivity of the deposit. No standards or recommended practices for magentic flowmeters have been published, but useful description and other information can be found in American Society of Mechanical Engineers (1971). According to that source, a representative figure for the accuracy of magnetic flowmeters in actual use would be about one percent of span over a flow range of from five percent to full capacity. According to Spencer (1974), wet calibrations are still necessary and regular site checks are desirable.

1.B.3.a.7. ACOUSTIC FLOWMETERS

Acoustic flowmeters usually employ the difference in transit time of upstream and downstream directed ultrasonic pulses, this difference being caused by the velocity of the water along the paths. Different electronic methods can be used to implement this principle, i.e., direct measurement of the travel time difference or measurement of phase or frequency shifts. Other acoustic flowmeters use the acoustic Doppler principle to determine point velocities (which have to be converted to flowrates), while still others measure the deflection of an acoustic beam transmitted transversely to the flow.

Like the magnetic flowmeters, acoustic meters are generally nonintrusive and add no head loss to the flow. In the travel-time flowmeters, which are currently the most common type, accuracy depends upon the capability of the electronic circuitry and on the accuracy with which the measured chordal velocities can be integrated over the flow section.

There are no published standards regarding the use of this instrument. McShane (1974) provides a good summary of the principles of these meters as well as information on possible effects of velocity distribution. These meters are not suitable for water flows containing many gas bubbles, appreciable sediment, or large amounts of particulate matter.

1.B.3.a.8. DEFLECTION METERS

Deflection meters for closed conduits employ the deflection of a hinged plate from its equilibrium position as a measure of the fluid flow. A related device is the target meter, in which the force exerted by the water flow on a target (which could be, for example, a small disc mounted normal to the flow) is measured. In this case the actual deflection of the target element is very small. An advantage of these devices is their ability to pass sediment-laden flow. A calibration is needed for these types of instruments because, in general, discharge coefficients can be closely estimated from first principles. No published standards exist for their use, but they are described by the American Society of Mechanical Engineers (1971).

1.B.3.a.9. GIBSON METHOD

The Gibson or pressure-time method was developed for measuring flow in turbine penstocks. It can be used only in pipe lengths which are connected to a free-surface reservoir upstream and which have a flow control valve downstream. Another disadvantage is that it requires stoppage of the flow. The method is based on the second law of motion and involves recording the pressure-time behavior in the conduit as the flow is stopped over a measured period. That information together with knowledge of the conduit geometry and friction factor permits calculation of the flowrate. A complete description of the analytical basis for this method is given by the American Society of

Mechanical Engineers (1971), and a detailed description of procedures for conducting the test are given by the International Electrotechnical Commission (1963). The latter reference claims a potential accuracy for this method as good as one percent.

1.B.3.a.10. OTHER METHODS OF DISCHARGE MEASUREMENT

Although the foregoing paragraphs have described the meters most commonly used in water resource measurements, a number of flowmeters based on other principles are also commercially available. These include vortex-shedding, nuclear magnetic resonance, and swirl meters, all of which are described briefly by Replogle (1970).

1.B.3.a.10.a. Quantity Meters

The methods and meters described starting with sec. 1.B.3.a.2. have all aimed at a measurment of flowrate or discharge. Another large class of meters is the positive displacement type. They repetitively measure a fixed volume of water, and the number of repetitions yields the total volume of water passing the meter. Although in principle the volume associated with each cycle of the meter could be determined from the meter geometry, in practice these meters are usually calibrated to determine their discharge performance. The most common of these meters is the nutating-disk type, which is frequently used for household water metering. Descriptions of quantity meters are available in American Society of Mechanical Engineers (1971) and Replogle (1970).

1.B.3.a.11. APPROXIMATE METHODS

The methods listed in this section are significantly less accurate than the methods and devices described in the foregoing sections. They are nevertheless included in this overview because there are measurement situations where these methods are convenient, inexpensive, and still adequate.

1.B.3.a.11.a. California Pipe Method

The California pipe method can be used where water is discharged into air at low velocity from the end of a pipe. It involves measuring the overfall depth in a short horizontal pipe flowing partly full, which is connected to the end of the discharge pipe. The flowrate is related by an empirical equation to the measured overfall depth and pipe diameter as described by the U.S. Bureau of Reclamation (1967).

1.B.3.a.11.b. Trajectory Methods

Trajectory methods are based on measurement of a jet issuing into air from a horizontal pipe flowing full. One trajectory method is the Purdue method, in which published discharge data are based on laboratory experiments on jets issuing from pipes two to six inches in diameter. The second trajectory method simply uses the theoretical trajectory equations for freely falling bodies to deduce the average velocity of the jet as it issues from the pipe of known area. Both methods are described by the U.S. Bureau of Reclamation (1967).

1.C. OPEN CHANNEL FLOW DATA

The characteristics of flow in open channels are quite variable with time and seldom, if ever, satisfy the theoretical formulas for steady and uniform flow. Accordingly, it takes a large amount of data and information including discharge measurements; control conditions; channel slope and alignment; flow resistance caused by stream-bed and bank materials and vegetation; fall in channel

reach; overbank conditions; possible backwater effects; stage-discharge relations; and other flow, location, weather and environmental characteristics peculiar to each streamgaging site, in order to analyze and compute a continuous record of stage and flow.

The methods ordinarily used in recording open channel flow are based on determination of the relations of stage to discharge at sites where streamflow or discharge records are needed. Stream, canal, or channel stages may be observed or recorded (See sec. 1.B.2.a.) with simplicity and exactness, and the corresponding discharges (see sec. 1.B.2.d. and 1.B.2.e.) to those stages may be easily determined from a stage-discharge relation if that relation has been developed.

1.C.1. DEVELOPMENT OF STAGE-DISCHARGE RELATIONS

Stage-discharge relations (discharge ratings) at gaging stations are usually developed experimentally from measurments of stage and discharge.

The discharge rating for a stream or channel may consist of a simple relation between stage and discharge, or for a complex situation, it may be composed of several relation curves defining discharge as a function of stage, slope, rate of change of stage, or other variables.

The stage-discharge relations developed at one point in time are usually not permanent nor do they often represent long-time conditions. Changes in the stream channel such as scour and fill or changes in channel roughness, aquatic growth, debris, or backwater from ice, all result in changes in the stage-discharge relation. Hence, frequent discharge measurements are necessary to define the shape and/or changes in the discharge rating.

Discharge measurements are usually made by the current-meter method; however, it is sometimes necessary to resort to indirect measurements of flood flow (See sec. 1.B.2.d.3.) to define the upper portion of the stage-discharge relation.

Corbett and others (1945) give an excellent discussion of streamgaging procedure. They discuss the fact that the relation of stage to discharge is usually controlled by the station control, which is a section or reach of the channel below the gaging site that eliminates the effects of all the other downstream conditions on the velocity of flow at the gage. This control includes all of the physical features of the channel which hydraulically determine the stage of the stream at a given point for the various rates of flow. The station control may be natural or man-made and may be permanent or shifting. It may be a ledge of rock or an outcrop crossing the stream channel, a boulder-covered riffle, a broad-crested weir or overflow dam, a stable streambed, or any physical feature that can maintain an unchanging stage-discharge relation upstream.

A section control is a complete or partial control situated at a particular cross-section or over a very short length of stream channel; whereas a channel control affects the stage-discharge relation at a gaging site by the slope, shape, size, alinement, and frictional resistance in the stream channel over a long reach downstream.

1.C.1.a. PERMANENT CONTROL

Corbett and others (1945) discussed the subject as follows:

> A permanent control, complete in its effect, retains all its original effective physical characteristics, including its position with respect to the datum of the gage, its distance downstream from the gage, and the condition of the streambed between the gage and that part of the channel which controls the stage-discharge relation. A control satisfying these requirements will assure a permanent stage-discharge relation at all times when the conditions of slope remain the same. The fact that a generally recognized permanent control, such as a dam or ledge, may appear to have eliminated all effects from downstream conditions, or that a change in its original physical features is not readily apparent, is no complete assurance that the stage-discharge relation has remained unchanged. For instance, the velocity of approach

> may have changed because of scouring or deposition of sediment in the channel immediately upstream from the control, leakage within or under the control may have varied in amount, or the elements controlling the height of the water in the reach downstream from the control may have changed and created a more rapid rate of submergence of the permanent low-water control. These changes in conditions are not readily observed, but their occurrence may materially change the stage-discharge relations. It should be emphasized that, regardless of how stable and permanent a control may appear, it is always possible that change may be such as to be overlooked during an ordinary inspection of the controlling elements.

Much additional information on the subject of permanent controls and controls in general (including low water controls, high water controls, channel controls, etc.) is given in detail by Corbett and others (1945).

1.C.1.b. SHIFTING CONTROL

Corbett and others (1945) have a lengthy discussion of shifting controls which includes the following:

> The term shifting control as ordinarily used in connection with measurement of river discharge refers to that condition where the stage-discharge relations do not remain permanent but vary from time to time, either gradually or abruptly, because of changes in the physical features that form the control for the station.
>
> A stage-discharge rating curve will retain its original shape only so long as the elements that form the control retain their original physical characteristics or as long as the changes in characteristics are compensating with respect to their effects on the stage of water at the gage. The effect of a shift in the control must generally result, therefore, in a change in the stage for a given discharge, or conversely, in a change in the discharge shown by the standard rating for a given stage. Futhermore, if conditions such as vegetal or aquatic growths, accumulations of ice, or the confluence of tributary streams which tend to disturb the permanency of the stage-discharge relations are considered as the causes of changes in stage, any changes in stage-discharge relations due to shifting controls may be treated as though they were the direct result of scour or fill, or other normal changes in the physical characteristics of the bed or banks of the stream. The frequency of such changes and the magnitude of their effects are generally dependent upon the climate, physiographic, geologic, vegetal, and soil conditions within the valley through which the stream flows; and the situations are often so complex that it is impossible to foresee the changes that may occur in the stage-discharge relation at a gaging station.

1.C.1.b.1. CHANNEL MODIFICATION, NATURAL AND MAN-MADE

Channel modification above, below, or at the control may be such as to appreciably affect the normal stage-discharge relation at a gaging site. These modifications may be of such a nature or in such a location that any affect on the control may not be readily apparent. Sloughing of the banks upstream would be an example of a change resulting in subsequent effects on the magnitude and direction of the velocity-of-approach, change in thalweg and shape of the approach channel, or resultant fill between the gage and the control. Normal dredging, dam emplacements, rip-rap emplacement, channel realinement, brush cutting or mowing in high-water channel, channel constrictions, including bridge abutments, spur dikes, and levees, beaver activity, or normal scour and fill at the control are channel modifications where the effect on the stage-discharge relation of the variability of the shifting control are more evident. The magnitude of the shift or change in the stage-discharge relation can only be ascertained through adequate and frequent discharge

measurements during the period affected. Sometimes, where analog recorders are installed at a gage site, the change in stage (or shifting control change) caused by a channel modification which occurred instantaneously or over a relatively short time period is apparent on the recorded chart.

1.C.1.b.2. ALLUVIAL CHANNEL

The very nature of alluvial channels or sand channels is such that there is a continually changing (shifting) control with time, because of scour and fill, because of channel braiding or meandering patterns, and because of changes in the configuration of the channel bed due to ripples, dune, standing waves, antidunes and plane bed formation. See Simons and Richardson (1962) for additional information on the effect of bed roughness on depth-discharge relations in alluvial channels. Alluvial channels are more complex than rigid channels because the form or shape of the bed is a function of the flow and the bed material. That is, not only do the roughness elements resist the flow, but they in turn are formed by the flow.

The resistance to flow in an alluvial channel under any condition of flow is closely related to the form of bed roughness. In turn, the form of bed roughness varies with such factors as the magnitude of the shear stress exerted by the water on the bed, the characteristics of the bed material, the fine sediment load, seepage forces caused by flow through the bed and bank material, and temperature. The large changes in resistance to flow which occur as a result of changing the form of bed roughness, influence the form of the stage-discharge or depth-discharge relation in alluvial streams.

The upper portion of the stage-discharge relation is relatively stable if it represents the upper regime (plane-bed transition, standing-wave or antidune regime) of bed forms. The lower portion of the rating, however, is usually in the dune regime and the stage-discharge relation varies almost randomly with time. Frequent discharge measurements, in some cases daily, are necessary to define the stage-discharge relation or in some cases to determine the variation of discharge in the absence of any stable relation between stage and discharge.

A mean curve for the lower regime (plane-bed prior to movement, ripple or dune regime) is frequently used in situations with shifting controls. In some cases the shift defined by a single discharge measurement represents only the temporary position of a dune moving over a partial section control. A series of discharge measurements made at short time intervals over the period of a day may define a pattern of shifts due to dune movement. With constant discharge, the gage-height trace may also reflect dune movement as the stage-discharge relation changes.

Continuous definition of the stage-discharge relation in an alluvial channel at low flow is a very difficult problem. The installation of a control structure should be considered if it is feasible.

The stage-discharge relations are closely tied to the rate of change of discharge with time. Where ripples and dunes develop on the bed, the stage-discharge curve for the rising stage is usually quite different from that for a falling stage. These stage-discharge curves are valid only for the conditions upon which they are based and no general solution is possible. Shifting control corrections may need to be applied to the stage-discharge curve according to time, stage, or combined time and stage for computation of streamflow.

1.C.1.b.3. VARIABLE BACKWATER

Backwater is that condition of streamflow in which the velocity of steady flow gradually diminishes downstream and is manifested by a characteristic slope of the water surface in the direction of flow, which is always less than the surface slope that would occur if backwater was not present. There is some backwater at nearly every gaging station on a natural stream. This is particularly true for gaging stations situated above constrictions such as narrow reaches of channel; artificial structures such as dams, weirs and locks; reaches of channel affected by ice, growing vegetation, beaver activity, and moving sediment deposits; reaches of channel affected by the volume and stage of

tributary inflow downstream; and tide-affected reaches of channel. Backwater effects need not be considered unless they are so changeable that they produce material variations (variable backwater) in the slope at the same stage.

Variable slopes that affect flow in open channels are caused by variable backwater, by changing discharge, or by variable backwater in conjunction with changing discharge. The pair of differential equations given below provides a general solution to both gradually varied and unsteady flow

$$S=\frac{Q^2}{K^2}=-\frac{\partial H}{\partial x}-\frac{1}{g}\frac{\partial V}{\partial t} \tag{1-59}$$

$$\frac{\partial Q}{\partial x}=-B\frac{\partial h}{\partial t} \tag{1-60}$$

in which Q is the discharge, K is the conveyance of the cross section (See 1.B.2.d.3.a.), H is the total energy head, x the distance along the channel, g the acceleration of gravity, V the mean velocity, t the time, B the top width of the channel, and h is the water-surface elevation. A solution to these equations in uniform channels may be obtained by approximate step methods after the conveyance term has been evaluated by discharge measurements.

In practical problems of determining flow in open channels that require appplication of equation, the increment of slope due to the acceleration head $\frac{1}{g}\frac{\partial V}{\partial t}$ is, in general, so small with respect to the other two terms that its effect may be neglected.

Variable slopes at gaging stations are usually caused by variable backwater, due for example to a stream confluence, to manipulation of gates on a downstream dam, or to flow into and from storage pools created by valley constrictions. With a sufficient number of discharge measurements, it is possible to establish acceptable rating curves for these conditions by using the fall in water surface between two gages as an additional parameter. These methods do not account for the acceleration head and are thus applicable only to those sites where this head is relatively small.

It is difficult to anticipate the parameters that affect the discharge rating when a gaging station is initially installed. However, a series of stage-discharge measurements at medium and high stages will indicate the type of rating and whether a second gage is necessary to continuously measure water surface slope.

If the backwater from fixed obstructions is always the same at a given stage, the discharge is a function only of stage. If the backwater varies with some parameter other than stage, the discharge is a function of both stage and slope. Because slopes between two fixed points are measured by the falls between these points, it is more convenient to express discharge as a function of stage and fall. Stage-fall discharge ratings are usually determined empirically from observations of (1) discharge, (2) stage at the base gage, and (3) the fall of the water surface between the base gage and the auxiliary stage gage downstream. The general procedure used in developing the rating is:

1. A base relation between stage and discharge for uniform flow or a fixed backwater condition is developed from the observations. The discharge from this relation is termed, Q_r.
2. The corresponding relation between stages and the falls for conditions of uniform flow or fixed backwater is developed. These falls are termed rating falls, F_r. Fig. 1-26 shows schematically three forms the stage-fall relation may have.
3. The ratios of discharges Q_m, measured conditions of variable backwater, to Q_r, are correlated with the ratios of the measured falls F_m to the rating fall F_r.

Thus,

$$\frac{Q_m}{Q_r}=f\left(\frac{F_m}{F_r}\right) \tag{1-61}$$

The form of the relationship depends primarily on the channel features which control the stage-discharge relation without variable backwater.

It is convenient to classify stage-fall discharge ratings according to the types of relation that may be developed between stage and rating fall as follows:

1. *Rating fall constant.* This type of relation, shown as curve (a) in fig. 1-26 may be developed for channels which tend to be uniform in nature and for which the water-surface profile between gages does not have appreciable curvature. The stage-discharge relation without backwater may be controlled by a reach of channel below the gage, or it may be controlled by the combination of a dam downstream from the reach and channel characteristics.
2. *Rating fall a linear function of stage.* This type of relation, curve (b) in fig. 1-26 may be developed where a submerged sections control exits in the reach between gages and the control and the control does not become drowned by channel control even at high discharges.
3. *Rating fall a complex function of stage.* This type of relation curve (c) in fig. 1-26 may be developed where there is appreciable curvature in the water-surface profile between gages, where the reach is nonuniform or where conditions include a combination of those described in 1 and 2 above.

Basic principles and detailed procedures used in defining stage-fall discharge ratings are thoroughly discussed by Corbett and others (1945).

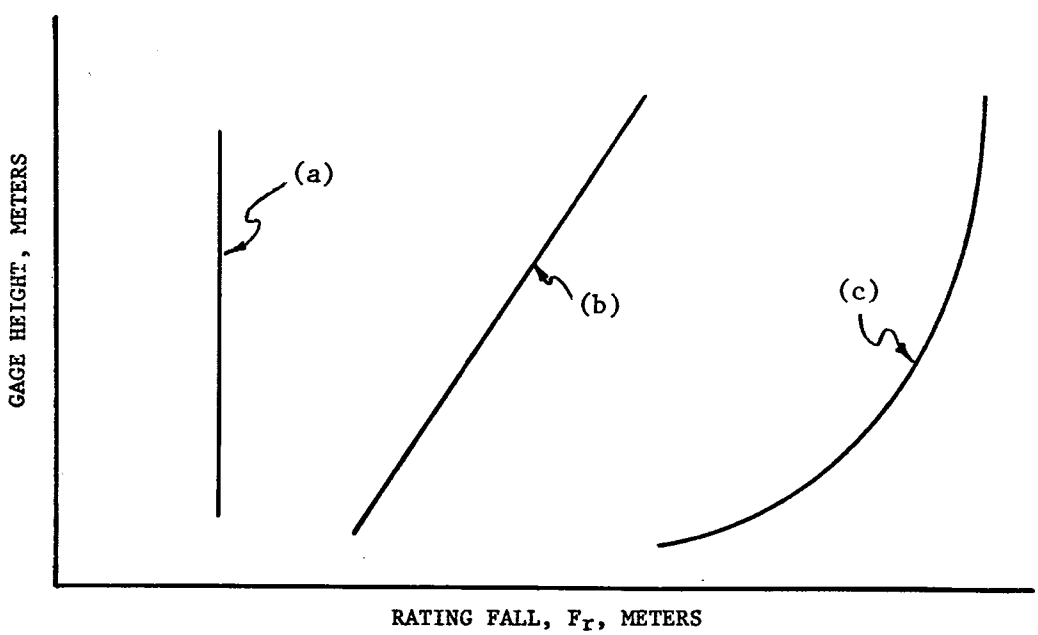


Figure 1-26.—Typical stage-fall relations.
Curve *a*—rating fall constant;
curve *b*—rating linear function with stage;
curve *c*—rating fall a complex function of stage.

Actual measurements of discharge have convincingly shown that the discharge for any river stage (level) is greater with a rising stage than it is with a falling stage. This fact, accordingly, is used in the development of river discharge ratings through the application of correction factors which relate discharges for steady and unsteady flow conditions. With uniformly progressive flow, it is possible, with a sufficient number of discharge measurements, to evaluate the effect of unsteady flow from the rate of change of stage at one gage.

The relation between the discharges for steady and unsteady conditions at the same stage can be derived from the general equation for unsteady flow. A simplified equation may be derived by neglecting all terms due to change of velocity head or acceleration such that

$$\frac{Q_m}{Q_c} = \sqrt{1 + \frac{1}{v_w S_c}\frac{dh}{dt}} \quad \text{(in English or metric units)} \qquad (1\text{-}62)$$

where

Q_m = discharge for unsteady flow
Q_c = discharge for steady flow at the same stage
v_w = wave velocity
S_c = energy slope for steady flow at the same stage

and

$\frac{dh}{dt}$ = rate of change of stage with respect to time.

The energy slope, S_c, may be evaluated by use of the Manning equation if some measurements are made under constant stage conditions,

$$S_c = \left(\frac{Q_c}{K}\right)^2 \qquad (1\text{-}63)$$

where

K = the conveyance of the channel

$$K = \frac{1.486}{n} R^{2/3} A \qquad \text{(in English units)}$$

$$K = \frac{1.0}{n} R^{2/3} A. \qquad \text{(in metric units)}$$

If S_c is computed in this manner for several stages, the relation between S_c and stage can be defined.

The wave velocity, v_w, can be evaluated using Seddon's law such that,

$$v_w = \left(\frac{1}{B}\right)\left(\frac{dQ}{dh}\right) \qquad (1\text{-}64)$$

where

B = width of channel at the water surface

and

$\frac{dQ}{dH}$ = slope of stage-discharge curve at constant-flow conditions.

Examination of formulas and experience indicate that the most probable value for the ratio of wave velocity to mean velocity, v_w/v, in open channels is about 1.3.

Individual measurements can be adjusted to constant stage conditions by using the above equation for Q_m/Q_c and values of S_c and v_w as defined above.

If a sufficient number of measurements have been made under conditions of both rising and falling stage at a gaging station, solution for Q_m/Q_c may be made by graphical methods devised by M. C. Boyer (See Corbett and others, 1945), without the necessity of computing the velocity of the flood wave or the energy slope.

By plotting the discharge measurements against stage in the usual manner, it is possible to construct a curve of the approximate stage-constant discharge relation from which the constant discharge, Q_c, may be determined for each discharge measurement. The measured discharge, Q_m, and the rate of change of stage (expressed in meters per hour for convenience) are known and by substitution of these figures in the simplified equation the term $1/v_wS_c$ is computed. The term $1/v_wS_c$ for each measurement is plotted against stage and a curve drawn to average the points. From this curve of relation each discharge measurement is adjusted by determining the value of $1/v_wS_c$ from the curve and solving for the constant discharge. An actual example of the application of this method (in English units) to a series of discharge measurements made on the Ohio River at Wheeling, W. Va., is shown in fig. 1–27.

1.C.1.b.5. VARIABLE CHANNEL STORAGE

At some gaging stations discharge measurements appear to be affected by changing slope resulting in changing discharge, when in reality they are affected by channel storage. If a discharge measurement is made at a considerable distance from the gage during a period of rising or falling stage, the discharge passing the gage at the time measurement is made will not be the same as the discharge at the measuring section because of the effects of channel storage between the measuring section and the gage. A correction for the channel storage may be applied to the measured discharge by adding to or subtracting from the measured discharge a quantity equal to the product obtained by multiplying the area of the water surface between the measuring section and the gage by the rate of change in stage at the gage. If the measurement is made below the gage, the correction will be positive for rising stages and negative for falling stages; if made above the gage, it will be negative for rising stages and positive for falling stages. The mean stage at the gage for the time of measurement is the gage height to be used with the adjusted discharge obtained by this method. Each discharge measurement should be adjusted to the equivalent discharge at the gage or at the section control by the means of the equation

$$Q_g = Q_m \pm WLC\frac{dh}{dt} \tag{1-65}$$

where

Q_g = discharge at the gage or section control
Q_m = measured discharge
W = average width of the stream
L = length of stream between section where Q_g and Q_m are determined
C = a constant relating the rate of change of stage $\frac{dh}{dt}$ to its equivalent effect in the reach. This constant is generally close to unity.

If sufficient discharge measurements are available to define a curve of relation between stage and discharge for constant-discharge conditions, Q_g may be obtained from this curve and the channel parameter WLC computed for each measurement under conditions of changing discharge. If channel storage is the dominant factor in the stage-discharge relation, the result will be a smooth curve.

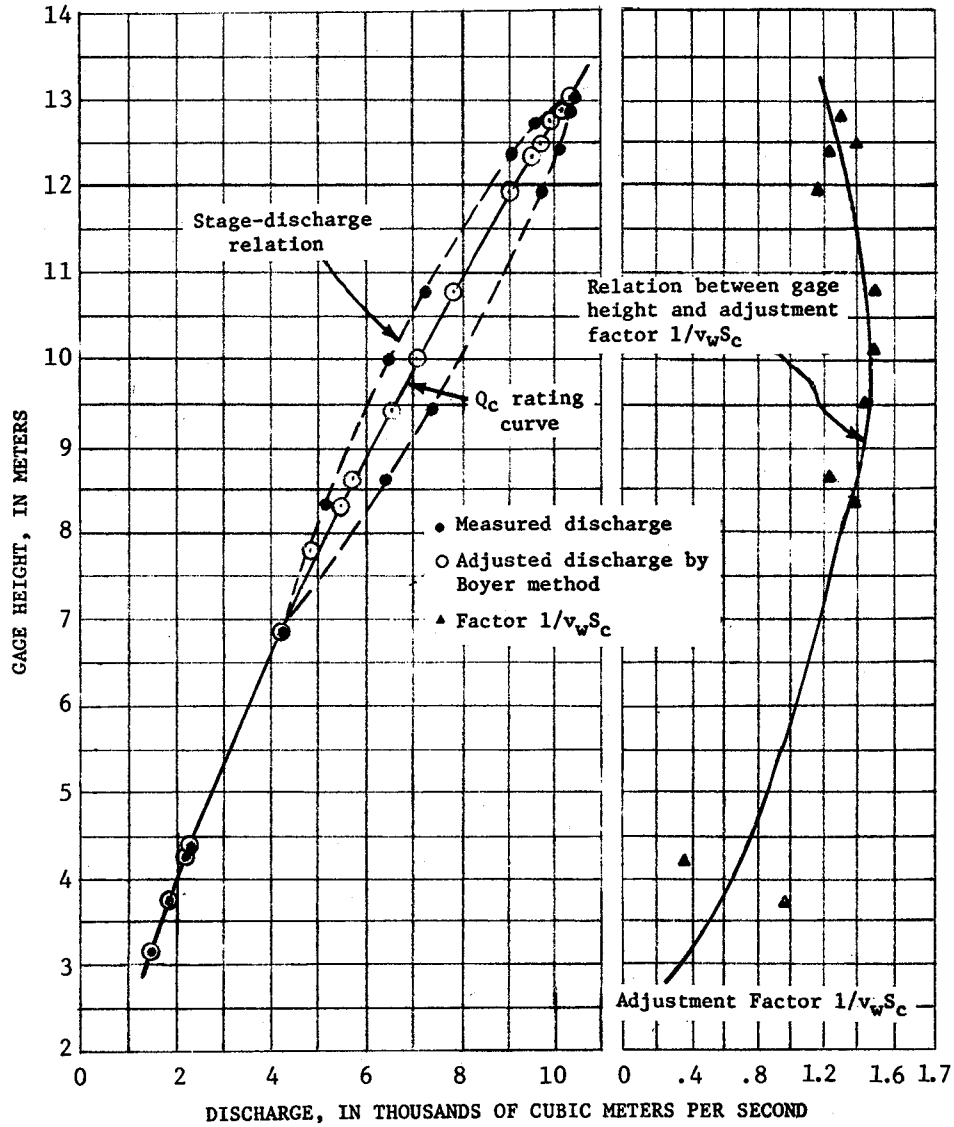


Figure 1-27.—Adjustment of discharge measurement for changing discharge of Ohio River at Wheeling, W. Va., during the period March 14-27, 1905 (from Corbett and others, 1945, Plate 17).

1.C.1.b.6. AQUATIC VEGETATION

Aquatic growths on the control and vegetal growth along the banks and in the overflow areas affect the capacity and the coefficient of roughness of the channel and therefore the stage-discharge relation, by amounts that will vary with the stage and the season. These growths are generally greatest in polluted streams that carry large quantities of organic waste. Aquatic growths at the control may have greater effects on stages at low discharges than at high discharges and except for their seasonal characteristics, the effects will resemble in many respects those produced by fill or scour. In northern regions, the effects, if any, from aquatic growths in rivers are generally noticeable during late May, increase gradually until the early part of July, then remain fairly constant until late October, and diminish rapidly after the first subfreezing temperatures. In milder climates, the effects may begin earlier in the spring and last until later in the fall. A knowledge of this general sequence of conditions is not sufficient for the determination of discharge without additional supporting data, including discharge measurements made at frequent and regular intervals of time. Abnormally low

temperatures may retard aquatic growths, and high temperatures later in spring and early summer may increase them. Floods or high velocities may remove part or all of the effect of backwater from such growths either by flattening them out or by cutting them entirely away from the bed. In some chemically polluted streams, aquatic growths may thrive during periods of high discharges when the chemicals are diluted but may die at times of lower discharge when the pollution is more concentrated.

Vegetal growth along the banks within the reach of channel that forms the control will tend to decrease the effective area of the cross section enough to become noticeable, especially at high stages. The presence of vegetal growths in the overflow areas will have a similar effect, particularly if the flow over such areas is controlled by elements not applicable to the main channel.

Shifting control corrections (adjustments) to the stage-discharge rating must be used when computing flow records during periods of variable backwater from aquatic and/or vegetal growth.

1.C.1.b.7. ICE FORMATION AND MELTING

Ice at the control may affect the normal stage-discharge relations. Its effects vary with the quantity of ice and its nature—whether surface ice, frazil, or anchor ice. Ice may also affect the stage-discharge relation if it forms a jam in the channel below the control sufficient to cause submergence of the control, or if it forms or collects between the gage and the control in sufficient amounts to cause additional resistance to flow, thus changing the slope of the water at the gage. The magnitude of the effect of ice on the stage-discharge relation—the backwater caused by ice—may be determined by measuring the discharge, observing the corresponding stage, and computing the difference between the observed stage and the stage for the measured discharge corresponding to the open-water stage-discharge rating curve. Such a procedure is based on the assumption that the open-water control remains permanent with respect to its physical features during the time when the stage-discharge relation is affected by ice. This assumption is generally true for streams of fairly stable beds and banks except for such scouring as may occur during the period of ice break-up, which is generally accompanied by high stages and correspondingly high velocities. Complete ice cover at the control and for some distance upstream may, in some instances, produce a closed conduit in which the characteristics of flow are different from those that prevail in a normal open-water channel.

Ice cover increases the frictional resistance to flow by the additional resistance introduced by the surface of the ice that is in contact with the flowing water. Also, the increase in the length of wetted perimeter causes reduction of the hydraulic radius. As a result of these changes in hydraulic conditions, a greater effective slope is needed for the same discharge. Many studies have been made to determine the effect of ice on the open-water ratings of a stream that is completely covered with ice for long reaches of channel except for a short distance at the rapids or riffle of the low-water control. These studies have shown in general that if the gage is located reasonably close to the control the presence of ice cover above or below the open control has little, if any, effect on the open-water stage-discharge rating. However, when the channel is partly or completely covered with ice at the control, the amount of backwater for a given stage will increase with the amount and thickness of ice and with the amount of snow on top of the ice which may, by its weight, cause additional displacement of water.

Ice may form so gradually that there may be little to indicate the time when the stage-discharge relations began to be affected. On the other hand, a decided rise in stage caused by an ice obstruction or a sharp drop in stage caused in part by impounding of water in the form of ice and in part by channel storage above the gage at places where ice has retarded the flow, may be the first indication that the stage-discharge relation is affected. On small streams in which a large part of the winter flow is derived from ground-water, it is not uncommon for the minimum flow of the year to occur just after the first extremely cold period, when the discharge from ground water is temporarily checked. Under such conditions, if water is being impounded above the gage in the form of ice and

channel storage, a period of extremely low flow may occur, which will usually be followed by a partial recovery. If a continuous record of the stage is made by a water-stage recorder, a steeper slope of the graph on a falling stage than on a rising stage usually indicates that the stage-discharge relation is affected by ice.

Of the three varieties of ice—surface, frazil[1], and anchor[2]—surface ice is the most common, and its effect is evident at more gaging stations than either of the other two. Although the different kinds of ice often occur in combination, each one by itself will produce the same general effect on the stage-discharge relation, that is, an increase in stage above that of normal open-water conditions. The major stream-gaging problems that result from any form of ice are related to the amount of backwater and its variation from day to day and the length of time when the stage-discharge relation is affected.

1.C.1.c. REVERSALS-COMPLEX CONTROLS

Stage-discharge relations at gaging stations, as discussed throughout 1.C.1., are affected by so many channel features and other variables that reversals in the stage-discharge relationship caused by complex control situations are commonplace. Probably the best way to demonstrate these effects is through a theoretical discussion of rating curves plotted on logarithmic graph paper.

A rating curve that plots as a straight line on logarithmic paper has the equation,

$$Q = p(G-e)^b \qquad \text{(in English or metric units)} \qquad (1\text{-}66)$$

where

Q = discharge
$(G-e)$ = head or depth of water on the control
G = gage height of the water surface
e = gage height of zero flow for a control of regular shape or effective zero flow for a control of irregular shape
p = the discharge (intercept) when the head $(G-e)$ equals 1.0 foot or 1.0 meter, depending on whether the English or metric units are used.
b = slope of the rating curve. This slope is the ratio of the horizontal distance to the vertical distance. This unconventional way of measuring slope is necessary because the dependent variable Q is always plotted as the abscissa.

Assuming that a segment of an established logarithmic rating is linear, various effects on the rating due to changes to the control will have various effects on the ratings. If the width of the control increases, p increases and the new rating will be parallel to and to the right of the original rating. If the width of the control decreases, the opposite effect occurs; p decreases and the new rating will be parallel to and to the left of the original rating. If the control scours, e decreases and the depth $(G-e)$ for a given gage height increases; the new rating moves to the right and will no longer be a straight line but will be a curve that is concave downward. If the control becomes built up by deposition, e increases and the depth $(G-e)$ for a given gage height decreases; the new rating moves to the left and is no longer linear, but is a curve that is concave upward.

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[1]*frazil ice*—fine spicules of ice formed in water too turbulent for the formation of sheet ice and formed in supercooled water when the air temperature is far below freezing. In some cases the number of spicules per cubic foot is very large and resembles a mass of snow. Frazil ice may extend to the bottom of the stream and dam its flow.

[2]*anchor ice*—ice formed below the surface of a stream or other body of water, on the stream bed, or upon a submerged body or structure.

When discharge measurements are originally plotted on logarithmic paper, no consideration is given to values of *e*. The gage height of each measurement is plotted using the same ordinate scale provided on the printed logarithmic paper or, if necessary, an ordinate scale that has been transposed as illustrated in fig. 1-28. Now referring to rating curve shapes resulting from different effective zero-flow elevations, it is possible to see that the same rating appears radically different when it is plotted with slight changes in *e* (see fig. 1-29). In fig. 1-29, the inside scale ($e = 0$) is the scale printed on the logarithmic paper. Assume that the discharge measurements have been plotted to that scale and that they define the curvilinear relation between gage height *(G)* and discharge (Q) that is shown in the topmost curve. For the purpose of extrapolating the relation, a value of *e* is sought, which when applied to G, will result in a linear relation between ($G - e$) and Q. If the control is a section control of regular shape, the value of *e* will be known; it will be the height of the lowest point of the control (point of zero flow.) If the control is a channel control or section control of irregular shape, the value of *e* is the gage height of effective zero flow; it may be determined by successive approximations.

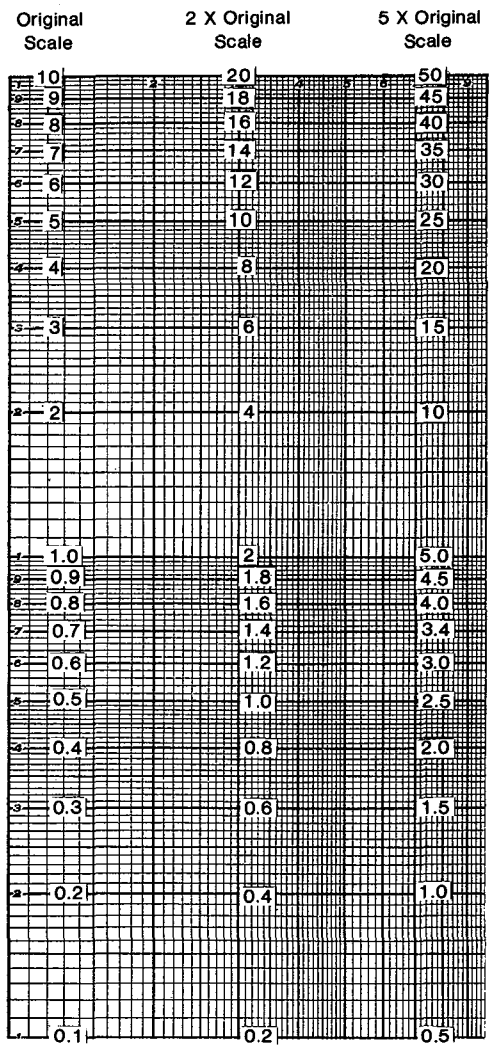

Figure 1-28. – How the logarithmic scale of graph paper may be transposed.

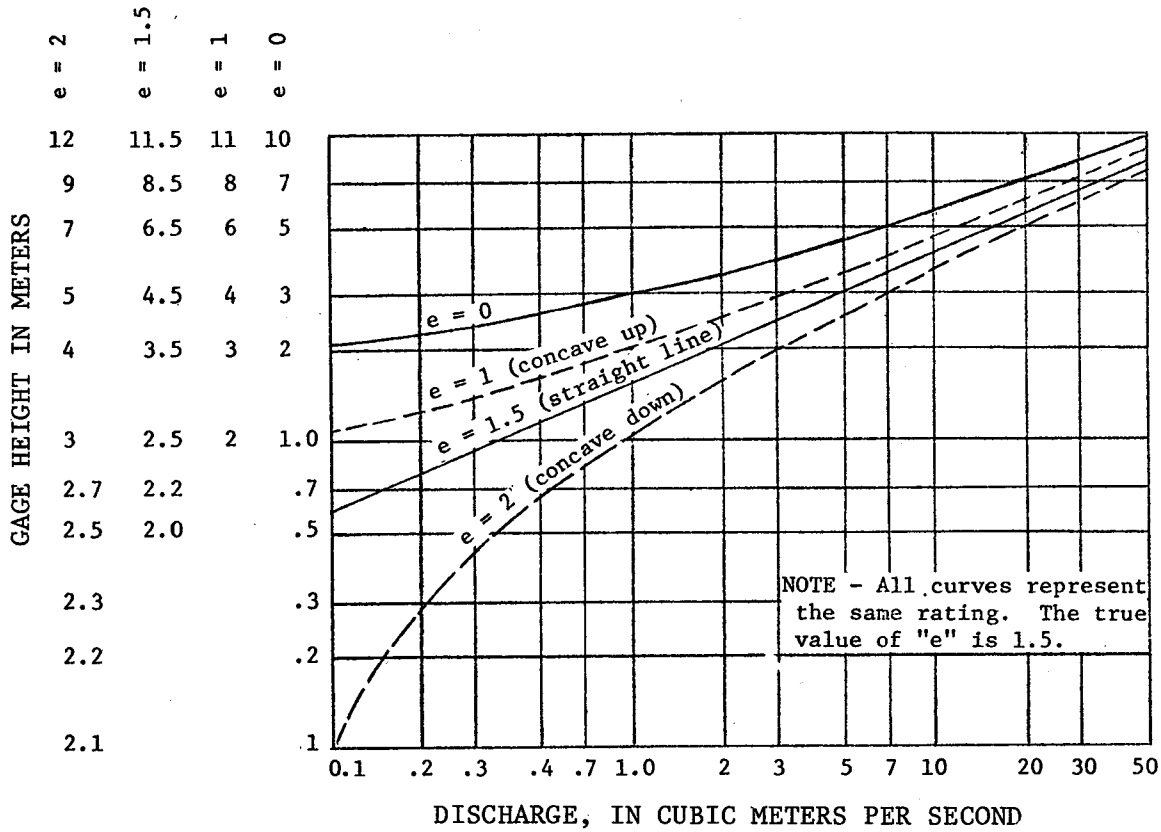

Figure 1-29.—Rating-curve shapes resulting from different effective zero-flow elevations.

In successive trials, the ordinate scale is varied for e values of 1, 2, and 3, each of which results in a different curve, but each of which still represents the same rating as the top curve. The true value of e is 2, the value with which the rating plots as a straight line if the ordinate scale numbers shown on the logarithmic paper are increased by this value. If smaller values of e are used, the curve will be concave upward; if higher values of e are used, the curve will be concave downward. The value of e for a rating curve or a segment of a rating curve can thus be determined by adding or subtracting trial values of e to the numbered scales on the logarithmic plotting paper until a value is found that results in a straight-line plotting of the rating. It is important to note that if the logarithmic ordinate scale must be transposed by multiplication or division to accomodate the range of stage to be plotted, that transposition must be made before the ordinate scale is adjusted for values of e.

A more direct graphical solution for e is illustrated by rectification of a curve on logarithmic paper as shown in fig. 1-30.

The gage height (G)-discharge (Q) plot shows a solid-line curve which can be rectified by subtracting a value e from each value of G. The part of the rating between points 1 and 2 is chosen, and values of G_1, G_2, Q_1, and Q_2 are picked from the coordinate scales. A value of Q_3 is next computed, such that $Q_3^2 = Q_1 Q_2$. From the solid-line curve, the corresponding value of G_3 is picked. By the properties of the straight line,

$$(G_3 - e)^2 = (G_1 - e)(G_2 - e), \tag{1-67}$$

from which e is solved for directly by the equation

$$e = \frac{G_1G_2 - G_3^2}{G_1 + G_2 - 2G_3} \tag{1-68}$$

A logarithmic rating curve is seldom a straight line or a gentle curve for the entire range in stage. Even where a single cross section of the channel is the control for all stages, a sharp break in the contour of the cross section, such as an overflow plain will cause a break in the slope of the rating curve. Commonly, however, a break or reversal in slope is due to the low-water control being drowned out by a downstream section control or by channel control becoming effective. Whenever the controls become complex so that the effects of downstream sectional and/or channel controls drown out or submerge the previously effective controls upstream, reversals in the slope of the stage-discharge relationships and rating curve are affected.

It can be demonstrated nonrigorously that straight-line rating curves for section control almost always have a slope greater than 2.0 and that those for channel control have a slope less than 2.0. It has been shown that the equation for a straight line rating on logarithmic paper is $Q = CH^b$, where b is the slope of the line. The first derivative of this equation is a measure of the change in discharge per tenth of a foot change in stage. The first derivative is:

$$\frac{dQ}{dH} = CbH^{b-1} \tag{1-69}$$

Second differences are obtained by differentiating again. The second derivative is:

$$\frac{d^2Q}{dH^2} = Cb(b-1)H^{b-2} \tag{1-70}$$

Examination of the second derivative and the second difference shows that the second differences increase with stage when b is greater than 2.0 and decrease with stage when b is less than 2.0.

A hypothetical rating for a compound control is shown in the fig. 1-31. This rating represents the condition of section control at the lower stages and channel control at the higher stages. Experienced hydrographers will recognize this table as being a typical one. Inspection of the second difference column shows the second differences to be increasing at the low-water end (section con-

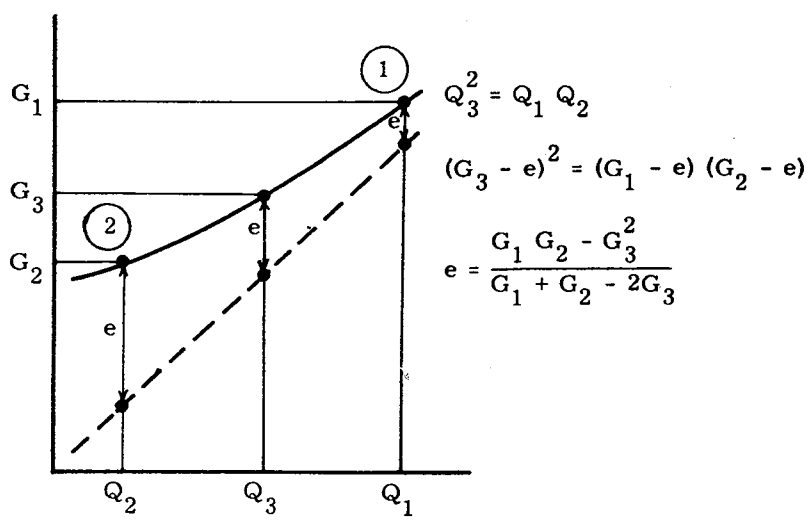

Figure 1-30.—Rectification of a curve on logarithmic paper.

trol, $b>2$) and decreasing at the high-water end (channel control, $b<2$.) These are the results that would be predicted from the discussion in the preceding paragraph. The use of rectangular-coordinate paper for rating analysis has certain advantages, particularly in the study of the pattern of shifts in the lower part of the rating. Changes in the low-flow rating at many sites may be represented by a constant shift in gage height because the rating curves are roughly parallel on rectangular-coordinate paper. Thus, the pattern of shifts with time is more apparant on rectangular-coordinate paper because the shape of the rating is more consistent than on logarithmic paper. A further advantage is that the point of zero flow can be plotted directly on rectangular-coordinate paper.

Logarithmic plotting should always be used initially in developing the general shape of the rating. The final curve may be displayed on either type graph paper and used as a base curve for the analysis of shifts. A combination of the two types is frequently used with the lower portion of the rating plotted on rectangular-coordinate paper.

1.C.1.d. DEVELOPMENT AND EXTENSION OF RATING CURVES

Most of sec. 1.C.1. (above) has been devoted to the discussion of channel features and controls affecting the stage-discharge relations in open-channel flow. Certain aspects in the plotting and development of rating curves were also covered. Procedures used for making indirect determinations of discharge for defining extremes of rating definitions are explained in sec. 1.B.2.d.3.

For the development of the rating curves the general shape and slope may be anticipated from consideration of equations which describe open-channel flow. For instance, many low-flow section controls approximate a broad-crested weir or overflow dam with an equation of the form:

$$Q = CL(G-e)^b \tag{1-71}$$

where L is the width of the weir, C the discharge coefficient and b is the slope of the rating curve (line).

The discharge coefficient is a function of the physical properties of the control and the head. If as with most natural controls, width increases with stage, the exponent of $(G-e)$ may approach a value of 3.0, whereas the exponent of $(G-e)$ for the broad-crested weir is only 1.5.

The discharge equation for the condition of channel control is represented by the familiar Manning equation where

$$Q = \frac{1.00}{n} A R^{2/3} S^{1/2} \qquad \text{(in metric units)} \tag{1-72}$$

or

$$Q = \frac{1.486}{n} A R^{2/3} S^{1/2} \qquad \text{(in English units)} \tag{1-73}$$

However,

A (area) is approximately equal to H (depth) times W (width),
S (slope) at high stages approaches a constant,
R (hydraulic radius) is considered equal to H, and
W is considered a constant.

Therefore,

$$Q = CH^{5/3} = CH^{1.67} \qquad \text{(approximately)} \tag{1-74}$$

and

$$Q = C(G-e)^{1.67} \qquad \text{(approximately)} \tag{1-75}$$

Gage height (m)	Discharge (m^3/s)	Difference per two-hundredths of a meter	Second Difference
0.30	2.74		
		0.37	
0.32	3.11		0.01
		0.38	
0.34	3.49		0.01
		0.39	
0.36	3.88		0.01
		0.40	
0.38	4.28		0.02
		0.42	
0.40	4.70		0.02
		0.44	
0.42	5.14		0.03
		0.47	
0.44	5.61		0.03
		0.50	
0.46	6.11		0.03
		0.53	
0.48	6.64		0.04
		0.57	
0.50	7.21		0.04
		0.61	
0.52	7.82		0.04
		0.65	
0.54	8.47		0.04
		0.69	
0.56	9.16		0.03
		0.72	
0.58	9.88		0.04
		0.76	
0.60	10.64		0.03
		0.79	
0.62	11.43		0.03
		0.82	
0.64	12.25		0.01
		0.83	
0.66	13.08		0.02
		0.85	
0.68	13.93		0.02
		0.87	
0.70	14.80		0.02
		0.89	
0.72	15.69		0.01
		0.90	
0.74	16.59		0.01
		0.91	
0.76	17.50		0.01
		0.92	
0.78	18.42		0.01
		0.93	
0.80	19.35		

Figure 1-31.—Hypothetical stage-discharge rating table.

However, unless the stream is exceptionally wide, R is appreciably smaller than H. This has the effect of reducing the exponent in the last equation, although this reduction may be offset by an increase of S or W with discharge. Changes in roughness with stage will also effect the value of the exponent. The net result of these factors is the discharge equation of the form

$$Q = C(G - e)^b \tag{1-76}$$

where b will commonly vary between 1.3 and 1.8 and practically never reach a value as high as 2.0.

The foregoing equation development confirms statements made in sec. 1.C.1.c., that "straight-line rating curves for section control almost always have a slope greater than 2.0 and those for channel control have a slope less than 2.0."

Rating curves, more often than not, must be extended beyond the range of measured discharges. Some of the preceding material explained the principles governing the shape of logarithmic rating curves to guide the hydrographer in developing the shape of the extrapolated segment of the rating. However, even with knowledge of those principles, there is an element of uncertainty in extrapolation. The purpose of the following section is to describe the methods of analysis that will reduce the degree of uncertainty.

1.C.1.d.1 LOW-FLOW RATING EXTENSIONS

Low-flow rating extensions are best performed on rectangular-coordinate graph paper because the coordinates of zero flow can be plotted on such paper. (Note: Zero discharge cannot be plotted on logarithmic graph paper.) An example of this low-flow extension is shown in fig. 1-32 where the circled points represent discharge measurements plotted on the coordinate scales of gage height versus discharge. The rating curve in the example is defined by measurements down to a gage height of .090 m, but extrapolation to a gage height of 0.039 m is required. Field observation has shown the low point on the control (point of zero flow) to be at a gage height of .027 m.

The method of extrapolation in fig. 1-32 is self-evident. A curve has been drawn between the plotted points at gage heights .027 m and .090 m, to merge smoothly with the rating curve above .090 m. There is no assurance that the extrapolation is precise—low flow discharge measurements are required for that assurance—but the extrapolation shown appears to be a reasonable one. When extrapolation must yield and accurate definition of the rating curve at lower stages is required, a hydraulic analysis considering the changing channel geometry, roughness and low flow channel controls may be required to define the relationship.

1.C.1.d.2. HIGH-FLOW RATING EXTENSIONS

As mentioned earlier (sec. 1.C.1.), the problem of high-flow extrapolation of rating curves can be avoided if the unmeasured peak discharge at the gaging station is determined by the use of indirect methods (sec. 1.B.2.d.3.). However, in the absence of such indirect peak-discharge determinations, estimates of the discharges corresponding to high values of stage may be made by using one or more of the following four techniques:

a. Conveyance-slope method—which has supplanted old velocity-area and Q vs $Ad^{1/2}$ methods. (See Corbett, 1943, p. 91-92 for description of these two supplanted methods).
b. Areal comparison of peak-runoff rates.
c. Step-backwater method.
d. Flood routing.

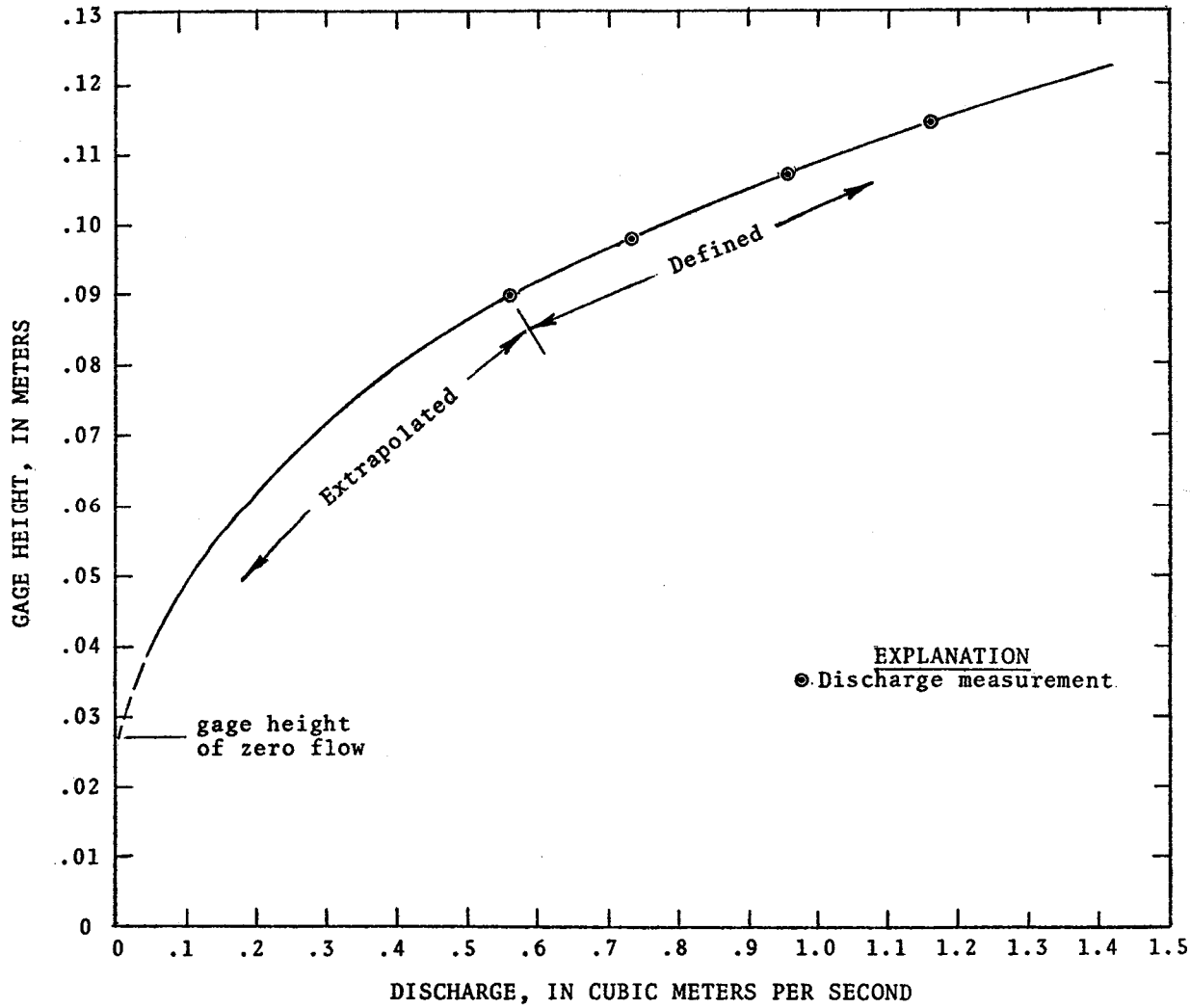

Figure 1-32.—Low-flow extrapolation on rectangular-coordinate graph paper.

These four recommended methods for high-flow rating extension are briefly described below:

Conveyance-slope.—This method is based on equations of steady flow such as Manning or Chezy where

$$Q = KS^{1/2}, \tag{1-77}$$

and for Chezy the conveyance, K, is

$$K = CAR^{1/2}, \tag{1-78}$$

and for Manning is

$$K = \left(\frac{1}{n}\right)AR^{2/3} \qquad \text{(in metric units)} \tag{1-79}$$

Values of A and R corresponding to any stage can be obtained from a field survey of the discharge-measurement cross section, and values for the coefficient C or n can be estimated. Thus, the value of K can be computed for any given stage. These computed values of K, covering the complete range-in-stage up to the required peak gage height are plotted versus gage height on rectangular

graph paper. (See fig. 1-33). A smooth curve is then fitted through the plotted points. (Note: It should be pointed out that the errors in estimating n or C usually are not critical in the computational procedure.)

Values of slope, S (which is actually the energy gradient), are not normally determined as part of a discharge measurement. However, $S^{1/2}$ can be computed by dividing each measured discharge by its corresponding K value; hence, S can be obtained by squaring the resulting value of $S^{1/2}$. Values of gage height versus S for the measured discharges are plotted on rectangular graph paper, a curve is fitted to the plotted points, and the curve is extrapolated to the required peak gage height. (See fig. 1-33.) The extrapolation is guided by the knowledge that S tends to become constant at the higher stages. That constant slope is the normal slope, or the slope of the streambed. If the upper end of the defined part of the curve of gage height versus S indicates that a constant or near-constant value of S has been attained, the curve can be extrapolated with confidence. However, if the upper end of the defined part of the curve of gage height versus S has not reached the stage where S has a near-constant value, the extrapolation will be uncertain. In that situation, the general slope of the streambed, as determined from a topographic map, provides a guide to the probable constant value of S that should be attained at high stages. The likelihood of a decrease in slope at high stages is greatest when overbank flows occur.

The discharge for any value of gage height is obtained by multiplying the corresponding value of K from the K curve by the corresponding value of $S^{1/2}$ from the S curve. (See fig. 1-33.) Errors in estimating C or n will have minor effect, because the resulting percentage of error in computing K is compensated by a similar percentage of error in the opposite direction in computing $S^{1/2}$. In other words, the constancy of S is unaffected, but if K is about 10 percent high, $S^{1/2}$ will be about 10 percent low, and the two discrepencies are cancelled upon multiplication.

Areal comparison of peak-runoff rates. — When flood stages are produced over a large area by an intense general storm, the peak discharges can often be estimated at gaging stations where they are lacking from the known peak discharges at surrounding stations. Usually each known peak discharge is converted to peak discharge per unit of drainage area before making the analysis. In other words, peak discharge is expressed in terms of cubic meters per second per square kilometer or cubic feet per second per square mile.

If there has been relatively little difference in storm intensity over the area affected, peak discharge per unit area may be correlated with drainage area alone. If storm intensity has been variable, as in mountainous terrain, the correlation will require the use of some index of storm intensity as a third variable. Fig. 1-34 illustrates a multiple correlation of that type where the independent variables used were drainage area and maximum 24-hour basinwide precipitation during the storm of December 1964 in north coastal California.

The peak discharge estimated by the above method should be used only as a guide in extrapolating the rating curve at a gaging station. The basic principles underlying the extrapolation of logarithmic rating curves are not to be violated to accommodate peak-discharge values that are relatively gross estimates, but the estimated discharges should properly be given consideration in the extrapolation process.

Step-backwater. — The step-backwater method is a technique in which water-surface profiles for selected discharges are computed by successive approximations. The computations start at a cross section where the stage-discharge relation is known or assumed, and then proceed to the study site whose rating requires extrapolation. If flow is in the subcritical regime, as it usually is in natural streams, the computations must proceed in the upstream direction; computations proceed in the downstream direction where flow is in the supercritical regime. In the discussion that follows, the usual situation of subcritical flow is assumed.

Under conditions of subcritical flow, at a given discharge, water-surface profiles converge upstream to a common profile. For example, the stage for a given discharge at a gated dam may have any of a wide range of values depending on the position of the gates. At a study site far enough

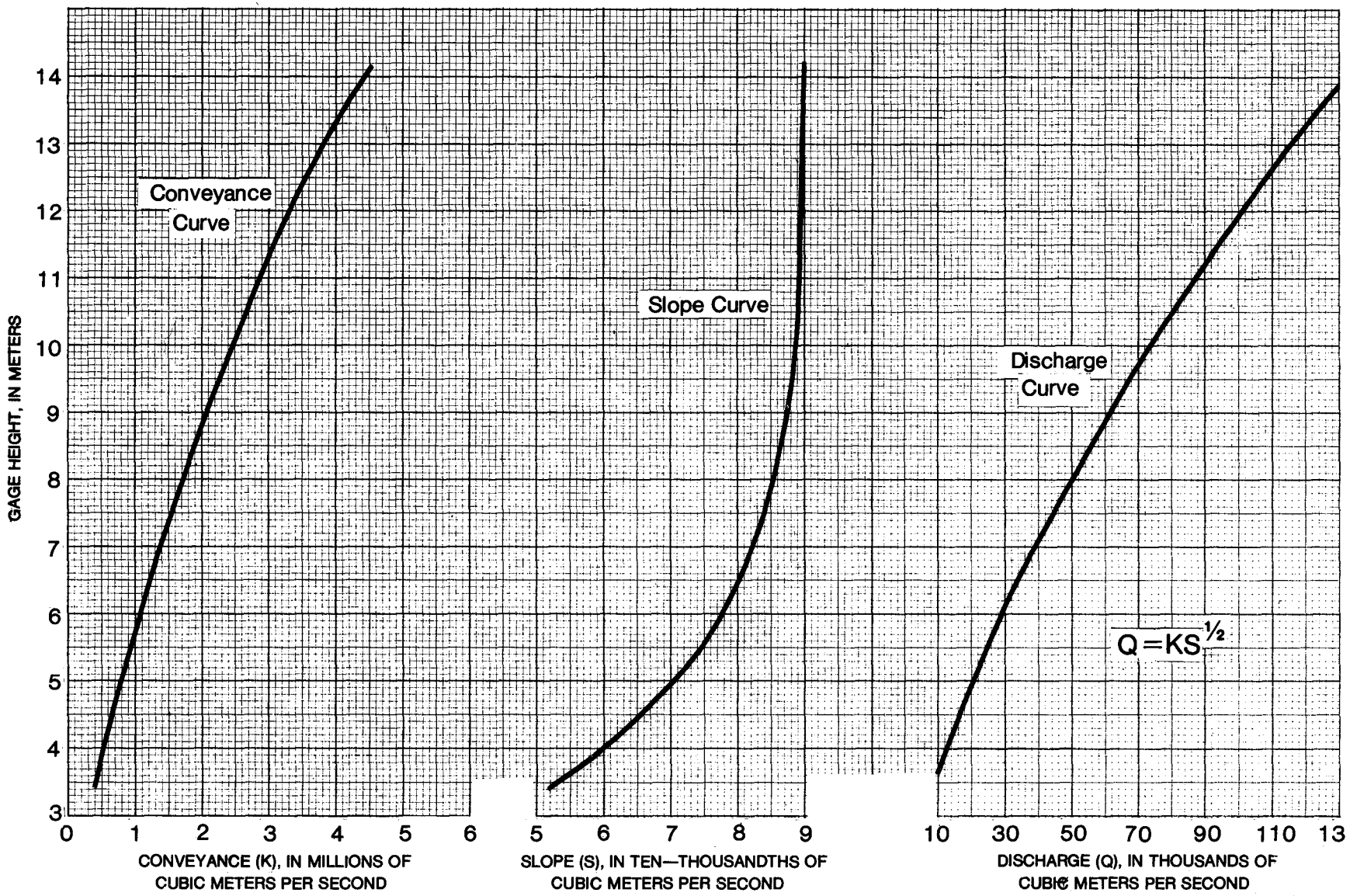

Figure 1-33 – High-flow extrapolation by use of conveyance-slope method.

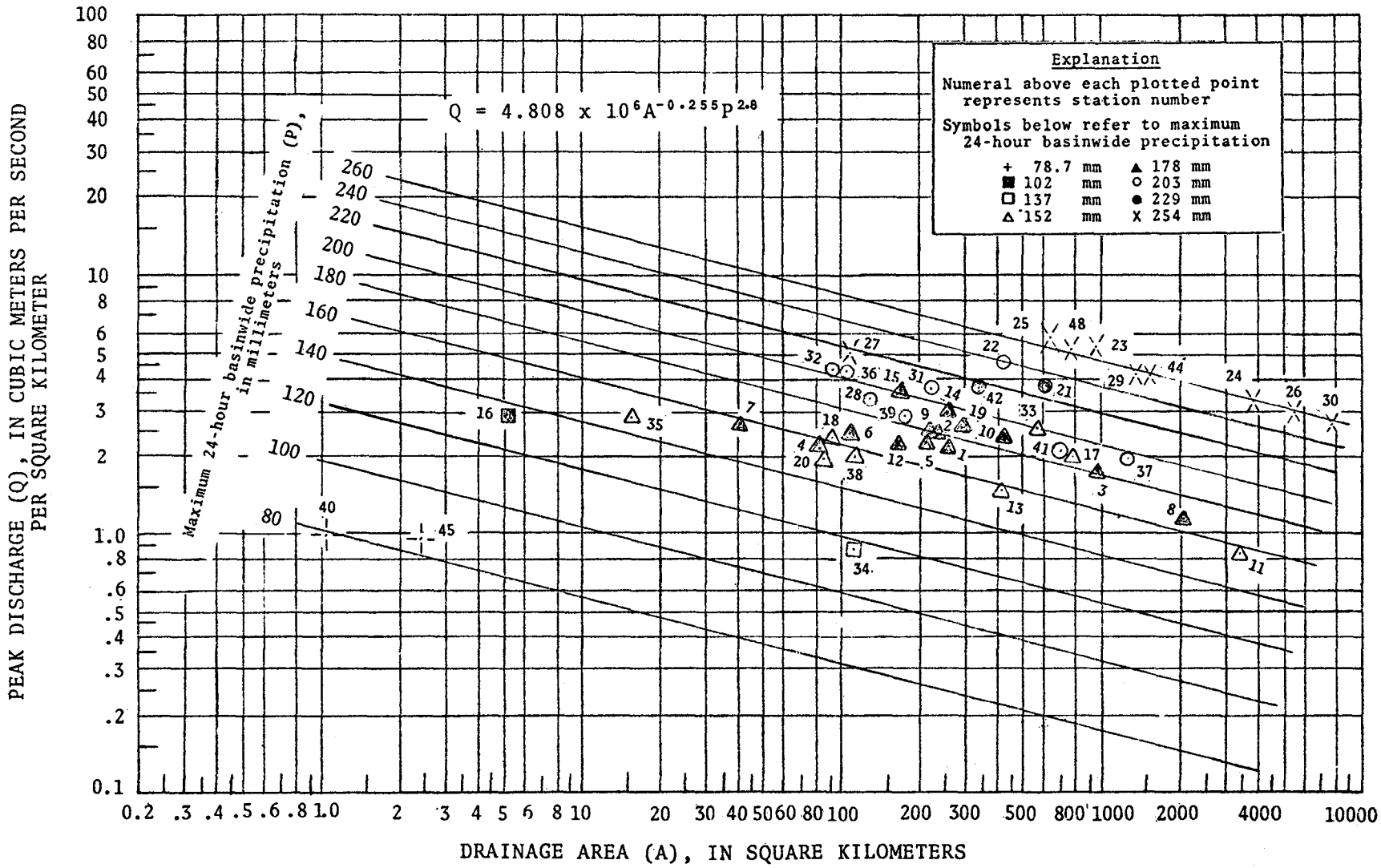

Figure 1-34.—Relation of peak discharge to drainage area and maximum 24-hour basinwide precipitation in north coastal California, December 1964.

upstream to be out of the influence of the dam, the stage for that discharge will be unaffected by the gate operations. Consequently, the water-surface profile may be computed for a given discharge in the reach between the dam and an upstream study site, and if it is far enough upstream, the segment of the computed profile in the vicinity of the study site will be unaffected by the value of stage that exists at the dam. However, it is necessary that the computations start at the dam and proceed upstream in "steps," subreach by subreach. If the initial cross section computing the water-surface profile is selected far enough downstream from the study site, the computed water-surface elevation at the study site corresponding to any given discharge will have a single value regardless of the stage selected for the downstream site.

The convergence of water-surface profiles computed for a subcritical discharge is illustrated in fig. 1-35. If flow is uniform, the true profile will be parallel to the bed slope, and the depth will be normal at all points in the reach. If the starting elevation for computations is estimated too high, the profile marked M1 will be computed; if the initial starting elevation is estimated too low, the profile marked M2 will be computed. Both the M1 and M2 profiles converge on the true profile and, thus, at a distance L upstream, the error caused by assuming an incorrect initial elevation virtually disappears.

A guide for determining the required distance L between study site and initial section is found in the dimensionless graph in fig. 1-36. The M2 curve shows that a good approximation of L could be:

$$L = 0.4\frac{\bar{d}}{S} \tag{1-80}$$

where

$$\left(\frac{S_o C^2}{g}\right) = F^2 = 0.2 \tag{1-81}$$

and the Froude number $F = .45$ (approx.)

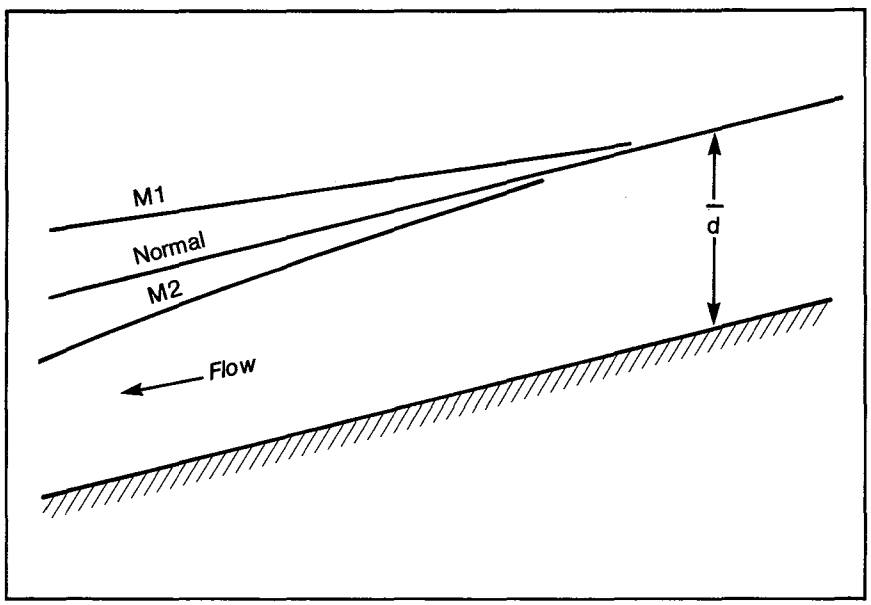

Figure 1-35.—Normal, M1, and M2 profiles.

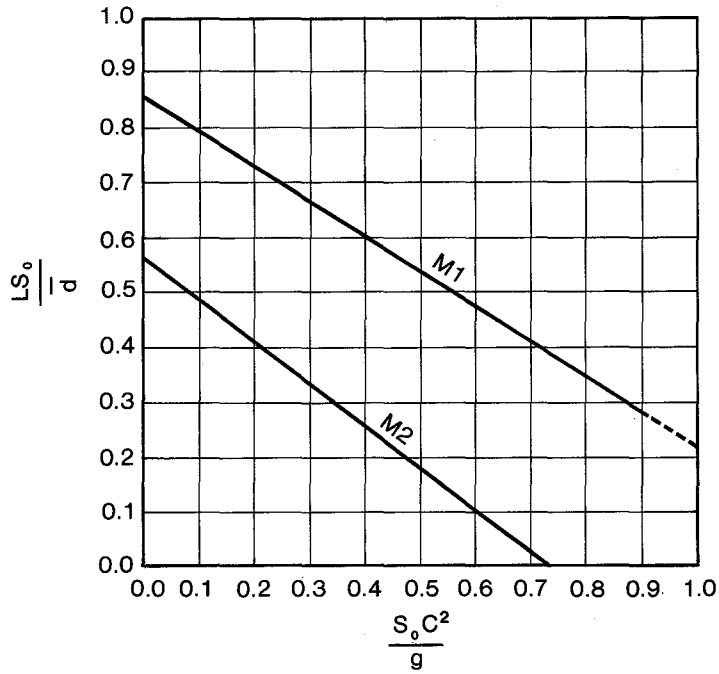

Figure 1-36.—M1 and M2 curves for determination of distance required for convergence of backwater profiles.

The graph, which is used in the USA (Bailey and Ray, 1966), has for its equations,

$$\frac{LS_o}{\bar{d}} = 0.86 - 0.64\left(\frac{S_oC^2}{g}\right) \text{----M1 Curve} \tag{1-82}$$

$$\frac{LS_o}{\bar{d}} = 0.57 - 0.79\left(\frac{S_oC^2}{g}\right) \text{----M2 Curve} \tag{1-83}$$

where L is the distance required for convergence,
S_o is bed slope,
g is the acceleration of gravity,
$\bar{d}$ is the mean depth for the smallest discharge (uniform flow) to be considered,
and C is the Chezy coefficient.

For an infinitely wide rectangular channel, it can be shown that

$$\left(\frac{S_oC^2}{g}\right) = F^2, \tag{1-84}$$

where F is the Froude number.

If a rated cross section is available downstream from the study site that cross section should be used as the initial section and there would be no need to be concerned with the above computation of L.

After the initial site is selected, the next step is to divide the study reach, that is, the reach between the initial section and the study site, into subreaches. That is done by predicting where major breaks in the high-water profile would be expected to occur because of changes in channel geometry or roughness. Representative cross sections are surveyed and roughness coefficients are selected for each subreach.

Various step-backwater computer programs use different assumptions in computing friction-head loss and selecting cross sections. See 1.B.2.d.3.e. for reference to some of the more widely used programs.

The assumption of constant discharge through the study reach must be checked. The discharge downstream of the study site at the time of the selected discharge may be higher or lower depending upon tributary inflow, storage in the reach, or flow bypasses. If a variable flow is indicated, a flood-routing technique (see end of this section) may be used to estimate the downstream starting discharge and each subreach discharge if necessary.

The first step in the step-backwater computations after selection of the discharge, Q, is to obtain a stage at the initial section for use with that value of discharge. If the initial section is a rated cross section, that stage will be known. If the initial section is not a rated cross section, an estimated stage there is computed from the estimated mean depth ($\bar{d}$) for discharge Q; $\bar{d}$ in turn is estimated by cut-and-dry computations from a variation of the Chezy equation,

$$\bar{d} = \frac{Q^2}{(CA)^2 S_o} \tag{1-85}$$

where

C is the Chezy coefficient,
A is the cross-sectional area corresponding to $\bar{d}$, and
S_o is the bed slope (or water-surface slope).

Step-backwater computations are then applied to the subreach farthest downstream. We have a known or estimated stage at the downstream cross section compatible with the value of Q being studied; the object of the computations is to determine the stage at the upstream end of the subreach that is compatible with that value of Q. The computation for each subreach is based on a steady-flow equation, such as the Chezy or Manning equation, after the equation has been modified for nonuniformity in the subreach by the use of the difference in velocity head at the end cross sections. It will be recalled that the Chezy equation is related to the Manning equation by the formulas,

$$C = \frac{1.486}{n} R^{1/6} \qquad \text{(in English units)} \tag{1-86}$$

$$C = \frac{1}{n} R^{1/6} \qquad \text{(in metric units)} \tag{1-87}$$

where n is the Manning roughness coefficient and R is hydraulic radius.

By shifting terms in the modified Chezy equation, the following equation is obtained for the difference in water-surface elevation (Δh) between the upstream (subscript 1) and downstream (subcript 2) cross sections.

$$\Delta h = h_1 - h_2 = \frac{L\, V_1 V_2}{C^2 R_1^{1/2} R_2^{1/2}} + \left[\frac{(\alpha_2 V_2^2 - \alpha_1 V_1^2)}{2g}\right](1+k) \tag{1-88}$$

Where

h = stage,
L = the length of the subreach,
V = the average velocity in the cross section,
g = the acceleration of gravity,
k = a constant whose recommended value is zero when $\alpha_2 V_2^2 > \alpha_1 V_1^2$, and whose recommended value is 0.5 when $\alpha_2 V_2^2 < \alpha_1 V_1^2$; and
α = the velocity-head coefficient whose value is dependent on the velocity distribution in the cross section.

In many nations, the value of α is assumed to be 1.1; in the USA its value is assumed to be 1.0 for cross sections of simple shape, but it is computed for cross sections of complex shape that require subdivision. The equation used for that purpose is

$$\alpha = \frac{\Sigma(K_i^3/a_i^2)}{K_T^3/A_T^2} \tag{1-89}$$

where the subscript i refers to individual subsections, and subscript T refers to the entire cross section. With regard to conveyance K,

$$K_i = C_i a_i R_i^{1/2}, \text{ and} \tag{1-90}$$

$$K_T = \Sigma K_i \tag{1-91}$$

We return to our computations for the downstream subreach. A trial value of stage for discharge Q is selected and values of A, V, and R are computed for the upstream and downstream cross sections. Those values are substituted in the equations for Δh and α in the two preceding paragraphs and after solving for Δh, the computed value of Δh is compared with the difference between the trial value of stage at the upstream cross section and the known or assumed stage at the downstream cross section. Seldom will the two values agree after a single trial computation; if they do not agree, a second trial value of stage is selected for the upstream cross section. The computational procedure is repeated and the newly computed value of Δh is compared with its corresponding trial value. The computations are repeated as many times as are necessary to obtain agreement between the computed Δh and the difference between the trial stage at the upstream cross section and the known or assumed stage at the downstream cross section.

After a satisfactory value of stage has been determined for the upstream cross section, that cross section becomes the downstream cross section for the next subreach upstream. Computations similar to those described in the preceding paragraph are repeated for that subreach, and for each succeeding subreach, to provide a water-surface profile extending to the study site that is applicable to the discharge value (Q) being studied.

If the stage corresponding to discharge Q at the initial cross section was known, the stage computed for the study site is satisfactory. If the stage at the initial cross section was estimated from the equation

$$\bar{d} = \frac{Q^2}{(CA)^2 S_o} \tag{1-92}$$

it is necessary to repeat the above computation twice using other values of stage at the initial cross section for the same discharge Q. That is done to assure convergence of the water-surface profiles at the study site. The computations are repeated, first using an initial stage about 0.25 m (0.8 ft.) higher than that originally used, and then using an initial stage about 0.25 m lower than that originally used. All three sets of computations for discharge should result in almost identical values of stage at the study site for discharge Q. If they do not, the initial cross section for the step-backwater computation should be moved farther downstream so that all computations give water-surface profiles that converge at a common stage at the study site. The entire procedure is repeated for other discharges until enough data are obtained to define the high-water rating for the study site.

From the preceding discussion, it should be evident that the computations will be expedited if, in a preliminary step, the three relations of stage versus area (A), hydraulic radius (R), and the conveyance (K), are computed for each cross section. Even then, the computations will be laborious and the use of a digital computer is therefore recommended.

The step-backwater method can be used to prepare a preliminary rating for a gaging station before any discharge measurement is made. A smooth curve is fitted to the logarithmic plot of the

discharge values that are studied. The preliminary rating can be revised, as necessary, when subsequent discharge measurements indicate the need for such revision. If the step-backwater method is used to define the high-water end of an existing rating curve, the discharge values investigated should include one or more of the highest discharges previously measured. By doing so, selected roughness coefficients can be verified, or can be modified so that step-backwater computations for the measured discharges provide stages at the study site that are in agreement with those observed. The computations for the high-water end of the rating can then be made with more confidence, in the knowledge that reasonable values of the roughness coefficients are being used. There will also be assurance of continuity between the defined lower part of the rating and the computed upper part.

Flood routing.—Flood-routing techniques may be used to test and improve the overall consistency of records of discharge during major floods in a river basin. The number of direct observations of discharge during such flood periods is generally limited by the short duration of the flood and the inaccessibility of certain stream sites. Through the use of flood-routing techniques, all observations of discharge and other hydrologic events in a river basin may be combined and used to evaluate the discharge hydrograph at a single site. The resulting discharge hydrograph can then be used with the stage hydrograph for that gage site to construct the stage-discharge relation for the site; or, if only a peak stage is available at the site, the peak stage may be used with the peak discharge computed for the hydrograph to provide the end point for a rating curve extrapolation. The many practicable hydrologic flood-routing techniques are based on the principle of the conservation of mass—inflow plus or minus change in storage equals outflow. Some hydrologic flood routing techniques that also consider the dynamics of flood flow (momentum), are extremely complicated and considered rather impracticable. It is beyond the scope of this chapter to treat adequately the subject of flood routing; it is discussed in most standard hydrology texts.

1.C.1.e. DATUM CORRECTIONS

The datum of the gaging station is the elevation of the zero point of the reference or base gage. The reference or base gage is the gage to which the recording instrument is set at a recording station and the daily gage readings reported by the observer at a nonrecording station. Levels are run periodically to all reference marks, reference points, and gages to determine whether any datum changes have occurred as a result of settlement, frost heaving, or other movement. If significant movement is indicated, the gage or bubble orifice is reset to its original datum. If a change in datum has occurred and the gage or bubble orifice is reset, it is necessary to determine the effective data of the change. Appropriate corrections to station records must be made to reflect datum changes. In the absence of any evidence indicating the date when the datum change occurred, the change is assumed to have occurred gradually from the time the last levels were run, and the correction is prorated with time.

It is recommended that a documented summary of levels be kept over the life and period of operation at the gaging station showing the dates levels were run, the periods and magnitudes of datum corrections required, and the dates and times when the original datum was restored.

See also section 1.B.2.a.1. Gage Datum.

1.C.2. DAILY MEAN DATA

Daily mean data are the elements of the most thoroughly studied time series in the hydrology of open channel flow. The daily mean is the average of a group of measured values of a hydrologic variable. It is obtained by adding together all values obtained for a calendar day and dividing by the total number of values used. Accordingly, the daily mean computed from 15-minute digital punch readings would represent the average of 96 readings for the day; whereas the daily mean computed from an analog chart or hydrograph might represent the average obtained by integration, by sub-

division, or by visual balancing of sub-areas along the analog graph for the day. In any case, the daily mean represents the average value for that hydrologic parameter over a 24-hour period.

1.C.2.a. GAGE HEIGHT

Daily mean gage height represents the average gage height for a 24-hour day. This gage height is the daily mean water-surface elevation referred to some arbitrary gage datum. Gage height is often used interchangeably with the more general term "stage," although gage height is more appropriate when used with a reading on a gage.

Records of gage height or stage are obtained from direct readings on a nonrecording gage, from a water-stage recorder that gives a continuous graph of the fluctuations, or from a recording tape punched at selected time intervals.

At some stream-gaging stations the records of stage may be as important to the local community as the record of discharge. Accordingly, the daily mean gage height of record should be the true water surface elevation which exists at the site as a result of all influences such as ice, backwater, drawdown, etc. There will be periods when, due to recorder or clock malfunction, the only record of gage height may be a recorded range-in-stage or no record at all. At other times, the recorded gage-height record may be distinctly erroneous due to plugged intakes, float frozen in ice, float sitting on mud in well, or any of many possible probems affecting the water level in the gage well or in translating and recording the water level (stage). Sometimes a few hours of missing gage-height record for a particular day may be estimated from data on recorded range-in-stage, observers' readings, levels, engineers' notes, or similar information; however, use of estimation of gage heights to replace missing or erroneous record of gage heights for an extended period of time is not recommended.

1.C.2.b. DISCHARGE

Daily mean discharge represents the average discharge for a 24-hour day. This discharge, by definition, represents the daily mean volume of total fluids (including dissolved solids and suspended sediments) passing the gaging station.

The basic data collected at gaging stations consist of records of stage and measurements of discharge of streams and canals. In addition, observations of factors affecting the stage-discharge relation, weather records, and other information are used to supplement basic data in determining the mean discharge. Measurements of discharge are generally made with a current meter, using the recommended methods described in sec. 1.B.2.d.

For stream-gaging stations, rating tables giving the discharge for any stage are prepared from stage-discharge rating curves. If extensions to the rating curves are necessary to express discharge greater than measured, they are made on the basis of indirect measurements of peak discharge (such as slope-area or contracted-opening measurements, computation of flow over dams or weirs), step-backwater techniques, velocity-area studies, and logarithmic plotting. The daily mean discharge is computed from gage heights and rating tables, then the monthly and yearly mean discharges are computed from the daily figures. If the stage-discharge relation is subject to change because of frequent or continual change in the physical features that form the control, the daily mean discharge is computed by the shifting-control method, in which correction factors based on individual discharge measurements and notes by engineers and observers are used in applying the gage heights to the rating tables. If the stage-discharge relation for a station is temporarily changed by the presence of aquatic growth or debris on the control, the daily mean discharge is computed by what is basically the shifting-control method.

At some stream-gaging stations the stage-discharge relation is affected by the backwater from reservoirs, tributary streams, or other sources. This necessitates the use of the slope method in which the slope or fall in a reach of the stream is a factor in computing discharge. The slope or fall is ob-

tained by means of an auxiliary gage set at some distance from the base gage. At some stations the stage-discharge relation is affected by changing stage; at these stations the rate of change in stage is used as a factor in computing discharge.

At some stream-gaging stations the stage-discharge relation is affected by ice in the winter, and it becomes impossible to compute the discharge in the usual manner. Discharge for periods of ice effect is computed on the basis of gage-height record and occasional winter discharge measurements. Consideration is given to the available information on temperature and precipitation, notes by gage observers and hydrologists, and comparable records of discharge for other stations in the same or nearby basins.

There may be periods when no gage-height record is obtained or the recorded gage height is so faulty that it cannot be used to compute daily mean discharge. This happens when the recorder stops or otherwise fails to operate properly, intakes are plugged, the float is frozen in the well, or for various other reasons. For such periods, the daily discharges are estimated on the basis of recorded range in stage, prior and subsequent records, discharge measurements, weather records, and comparison with records for other stations in the same nearby basins.

Probably the most common records at gaging stations on streams and other open channels are tables showing the daily mean discharge and the monthly and yearly discharge, along with a general description of the station. Tables of daily mean gage heights are also included for some steamflow stations.

When the stage at a gaging station changes considerably during a day, the stage-discharge rating applied to the daily mean gage height may give a value for average discharge for the 24-hour period that is slightly in error. Such an average discharge would be accurate if the stage-discharge relation (curve) were a straight line; however, as the relation is curved, an error occurs when a straight-line average is used. If the maximum error between the straight line and the curve is 5.0 percent or more, the discharge should be subdivided or averaged for intervals of the day. The computer program used for discharge calculation automatically subdivides the day in accordance with the number of recorded gage-height readings for the day; however, the reverse of the above problem may occur.

The calculated equivalent gage height (rating table gage height for the computed daily mean discharge) may differ from the measured daily mean gage height because of the rating curve's nonlinearity.

Where manual computation or subdivision is performed it is recommended that range tables be computed for every rating curve giving allowable range-in-stage values. Mechanically-integrated records, like digital records, would not require such range tables. Shifting-control corrections should be taken into consideration when using the range tables.

1.C.3. MISSING OR INCONSISTENT RECORDS

The digital or analog chart should be examined routinely for abnormalities. This practice will prevent much missing and inconsistent record where equipment, well, or intake problems are to blame. Sudden increases or decreases in the recorded stage, unless caused by local rain, should not occur except on regulated streams (and regulation usually follows a set pattern). Sudden vertical changes in stage may denote erratic clock action or temporarily plugged intakes; whereas, a prolonged or constant recorded stage may indicate intake, float or ice problems (see sec. 1.C.2.a.). Vertical or horizontal changes in recorded stage may also indicate faulty recorder action and may affect the eventual distribution of time or gage-height corrections needed.

There are so many possible problems which cause missing or inconsistent records at a gaging station that only a brief mention of the general problems is possible.

1.C.3.a. EQUIPMENT MALFUNCTION

One of the main causes of missing records due to equipment malfunction is stoppage of the clocks in the analog and digital water-stage recorders. The float-operated analog recorder continues to record the overall range-in-stage during a period of clock stoppage. The digital-punch recorder does not provide comparable supplemental data. It is highly recommended that all field personnel carry replacement clocks and be schooled in making replacements routinely. Failure to replace a clock which has stopped for no apparent reason will undoubtedly compound future problems with lost record.

If the clock stopped at any time, then the date and time listed by the person servicing the recorder in the field becomes very important in computing the resultant discharge record. Sometimes the clock will stop and restart; later data may be used if the times of stopping and restarting can be determined. Clear, accurate and complete documentation of information by field personnel is essential.

Another major reason for loss of record is plugged intakes. This can either be by plugged water intake pipes into the well from the stream or by plugged pressure transmission tubes to the manometer inside the gage shelter. In either case, the recorded stage in the gage shelter is not the true stage of the water in the stream. Flushing of the water intake lines and purging of the pressure transmission tubes is essential.

The continuously operating gas-purge system used for bubble-gage sensors is recommended. Channel fill buries the intakes and causes the pipe intakes to be totally plugged or sluggish. If the orifice is buried in mud or sand, the recorded stage will be greater than that in the stream due to increased pressure.

Other equipment malfunctions which cause loss of considerable analog record either directly or indirectly due to maintanance and/or servicing include insufficient chart supply, float-wire slippage on the float-wheel, slippage of the float-wheel, float sitting in mud in well, and float hung-up or fouled on well or shelf equipment. Records requiring corrections for paper shrinkage, recorder reversals, or poorly running clocks, although complete for the period, detract from overall reliability.

Minor equipment malfunctions peculiar to digital recorders include items such as tape catching in punch blocks, paper failing to advance, punch pins sticking, or sprocket wear causing bad spacing. Recorders with malfunctions should be repaired or replaced immediately.

1.C.3.b. EFFECTS OF BACKWATER OR ICE

Usually the effects of backwater and/or ice make the reliability of the published and computed record inconsistent and somewhat suspect. Backwater (see sec. 1.C.1.b.) from ice, vegetation, changing control, beaver activity, dune and riffle formation, or jamming or tributary inflow, complicates record processing. A rational method of evaluating the relative affects of changing backwater for all situations is not possible. Each occurrence is unique and must be handled and processed according to the situation and its merits. Common sense and experience provide the only reliable methods and/or rationale that can be recommended for use. The loss of record due to ice in the well, the float frozen in ice, frozen intakes, etc., is a totally different problem than backwater from ice. The use of weather records, hydrographic comparison of records of flow upstream or downstream or on similar drainages in the area, or calculation of ground water effluent to the stream, are reliable and consistent methods for estimating flow during periods of missing record and for computing the relative backwater from ice during a period of recorded gage height. Documentation of ice and/or backwater conditions in the field by field personnel adds immeasurably to confidence one places in the data.

1.C.3.c. ANOMALOUS PERIODS

Anomalous periods or periods of extremes of gage height and/or discharge are a problem if recorded data are missing or inconsistent. Field methods have been established for recovering these extreme events and the missing data and information (See 1.B.2.a.4. on Stage Related and/or Datum Related Measurements; 1.B.2.a.4.a. on High-Water Marks and Point of Zero Flow; and 1.B.2.d.3. on Indirect Methods for measurement of discharge). Office procedures for establishing discharge values for extreme events are also covered in sec. 1.C.1.d.1. on Low-flow Rating Extensions and 1.C.1.d.2. on High-flow Rating Extensions.

1.C.4. YIELD DATA

Yield from an open channel is defined as the volume of water per unit of time. Yield may be expressed as continous flow, for instance in cubic feet per second, or as larger units such as acre-feet per year. Yield is total runoff from the upstream surface or groundwater sources in a watershed. Streamflow in a given interval of time derived from a unit area of watershed can be expressed as unit streamflow, determined by dividing the observed streamflow at a given location by the drainage area upstream from that location.

Daily yield data (see 1.C.2.) represent the daily mean discharge (average discharge over a 24-hour period). Daily mean discharges for thousands of stream-gaging stations throughout the United States and the world are routinely published.

It is recommended that published yield data be uniform. Daily mean discharge should be computed to the nearest 0.01 ft^3/sec for discharges of less than 1 ft^3/sec; to 0.1 between 1.0 and 10 ft^3/sec; to whole numbers between 10 and 1000 ft^3/sec; and to 3 significant figures above 1000 ft^3/sec. Publication of daily mean discharge in the International System (SI) units in the United States is still a few years away. Because the constant for conversion from cubic feet per second to cubic meters per second is only .02832, a totally different range of significant figures will be needed for publishing daily mean discharge in SI metric units.

1.C.4.a. MONTHLY YIELD

The monthly yield represents the summary or total of the daily mean discharges for the month. Machine-produced daily tables will show the sums of the daily figures for complete months and years unrounded, unless the number of characters exceeds the column width, in which case, there may be truncation.

It is recommended that significant figures and rounding limits for month and yearly means, and average discharge be computed to 0.001 ft^3/sec below 0.10 ft^3/sec; to 0.1 between 10.0 and 99.9; to whole numbers between 100 and 999 ft^3/sec; and to 4 significant figures above 1000 ft^3/sec.

Runoff in cubic feet per second per square mile (csm) is often used to expressed yield. It is recommended that for uniformity the significant figures for discharge per square mile be to 1 significant figure below 0.10 $ft^3/sec/mi^2$; to hundredths from 0.10 to 9.99 $(ft^3/sec)/mi^2$; and to 3 significant figures above 10.0 $ft^3/sec/mi^2$. See 1.C.4.d. regarding natural yield.

It is recommended that discharge in acre-feet (monthly and yearly) be computed as the sum of the daily discharge figures multiplied by 1.9835. Significant figures should be reported to 0.01 below 0.01 acre-feet; to 0.1 from 0.1 to 9.9 acre-feet; to whole numbers from 10 to 999 acre-feet; to tens from 1000 to 9999 acre-feet and to 4 significant figures over 10000 acre-feet.

It is recommended that runoff in inches (monthly and yearly) be computed as the total cfs-days times 0.0372 and divided by the drainage area. The figures should be listed to 0.01, except below 0.10 inch, when only 1 significant figure will be shown. Note that the yearly total should not be computed by adding the 12 monthly figures. See 1.C.4.d. regarding natural yield.

1.C.4.b. ANNUAL YIELD

The annual yield represents the summary of the daily mean discharges for the years. Separate computations are usually made for the water year and the calendar year.

Recommended significant figures and rounding limits for annual values are included with the monthly yield values in 1.C.4.a. The water year represents the period from October 1 through September 30.

1.C.4.c. MAXIMUM AND MINIMUM YIELD VALUES

The published values for "MAX" and "MIN" yield values, for both the months and the year, give the maximum and minimum daily mean discharge, respectively, for the period. Significant figures are in accordance with those recommended for daily mean discharges in 1.C.4.

1.C.4.d. YIELD ADJUSTMENTS

Records of yield at a site may sometimes require adjustments based on the affect of regulation, storage, diversion, use, or return flow in order to present a realistic yield value at that site. It is recommended that figures of monthly and yearly unit discharge (in cubic feet per second per square mile) and runoff (in inches) be published only if these figures represent natural yield without gross error—whether adjusted or unadjusted. The term "gross error" may be considered 10 percent or more. If the flow past a stream-gaging station is subject to considerable day-to-day variation because of regulation, but the effect on monthly and yearly unit discharge and runoff is minor, these figures should be published without adjustment.

If the streamflow is subject to regulation and storage in a single reservoir a short distance upstream from the station, and if the effect on monthly and yearly unit discharge and runoff is considerable (more than 10 percent), monthly and yearly mean discharge may be adjusted for change in reservoir contents. Monthly and yearly unit discharge and runoff, computed from the adjusted mean discharge, may be published. For stations farther downstream it is probable that unit discharge and runoff should not be published.

Where streamflow is adjusted for storage in a single reservoir, for which the contents figures are published elsewhere, no reservoir data will be given with the discharge record. The monthly and yearly summary will show adjusted mean, unit discharge, and runoff after the observed data. If the reservoir contents figures are not important enough to be published elsewhere, the month-end contents figures will be given as supplemental data between the observed and the adjusted discharge figures.

If the flow is subject to regulation and storage in several reservoirs, so that adjustments for change in reservoir contents—without additional adjustments for evaporation, time of travel, bank and channel storage, and seepage gains or losses—would not result in natural yield without gross error, unit discharge and runoff should not be published.

Adjusted unit discharge and runoff may be published for a stream-gaging station, if a single measured diversion bypasses it. Where the flow is affected by several diversions above a station, and the amounts of the diversions and return flows cannot be determined precisely, no adjustments should be made, and unit discharge and runoff should not be published.

Where steamflow is adjusted for a single diversion, no diversion figures need be published with the adjusted figures because the amount of the diversion may be determined as the difference between the observed and mean discharge. If the diversion is important enough in itself, the figures should be published.

Where discharge is adjusted for both storage and diversion, enough information should be given to separate the effect of one from the other; figures of month end contents and diversions may be given.

When yield adjustments are made, or could be made, adequate footnotes and qualification of the record should let the user of the record know exactly what situation exists.

1.C.5.a. EXTREMES-INSTANTANEOUS VALUES

1.C.5.a. MAXIMUM (PEAKS)

Instantaneous maximum stage and flow data are of importance to a variety of problems. Such data are essential to flood-frequency analysis and flood-inundation studies. Outstanding flood events are often referred to as reference floods and used as a basis for planning and management decisions regarding flood plains.

Peak-stage records are usually the basis for calculating peak-flow data. Peak stages may be obtained directly from high-water marks or from recording gaging stations or crest-stage gages. At times, the recorded stage in a recording gage may lag that in the stream, especially during rapidly changing stage. Where possible, the stage should be checked from high-water marks or by other indication of the stream's maximum stage.

Downstream obstructions such as ice, effects of construction activity, or backwater from a downstream tributary may create a peak stage without a corresponding peak flow. The maximum stage may be of importance and should be recorded. However, it should also be qualified and the cause of the peak should be described.

At times, a peak flow may be the result of an unusual and unnatural event such as a dam failure. The flow and stage should be recorded and the data qualified, giving the cause of the peak. Such data should not normally be used in frequency analysis.

When the stage is obtained from a different site or is referenced to a different datum, that fact should be noted and the differences should be described. The user will then be warned to make adjustments for the differences.

Some gages are installed to record only stages above a selected gage height. Peak flows may not reach this stage every year. Records should show when the annual peak stage is less than the selected gage height and when the annual peak discharge is less than the discharge corresponding to the selected gage height. This data will be quite useful in a variety of types of analysis, such as flood-frequency analysis. Of course if the annual peak stage can be identified from outside highwater marks, such data should be used.

A peak-flow measurement, either direct or indirect, may have been made at a location some distance from the gage or point of interest. Adjustments should then be made for inflow, if any, between the measurement site and the gage. The records should show what adjustments are made to the peak-flow data.

Peak discharges are often determined by using a peak stage and the stage-discharge relation. If a defined stage-discharge relation and a measurement of flow are used on the same peak, the peak flow should be determined from the established stage-discharge relation unless there is sufficient difference to support a rating (stage-discharge relation) change. If the peak-flow measurement is the basis for extending the rating, the rating should be drawn right through the measurement unless there is good evidence to show that the measurement was unreliable.

When long extensions of a rating have been made without using any direct flow measurement, the basis of the extension should be included with the peak-flow record. If the rating was extended on the basis of the analyst's judgement, the record is not considered as reliable as if an indirect measurement of the peak flow had been made to support the extension. A rating which is based on indirect measurements would not generally be considered as reliable as one supported by direct measurements of flow. Discussion of such extensions can greatly aid the user in evaluating the accuracy of peak-flow data determined from the extended rating.

Peak information obtained on the basis of an observer's stage readings may need to be qualified unless the observer's readings are known to be right on the instantaneous peak. Sometimes, only a partial record is available; if there is any uncertainty as to whether a higher peak occurred during periods of no record, that information should be part of the record for that site.

Where historical peak data, that is, data not included with the regularly collected data, are available, they should be included with the peak data for a site. Also, any data which might indicate the magnitude of the historic peak, such as its being the largest flood for the period since some specific date, will help in the analysis of the record.

Upstream reserviors, diversions, and perhaps other conditions on the watershed may have a significant effect on peak discharges. Such information should also be made a part of the peak record.

1.C.5.b. MINIMUM (LOW FLOWS)

Instantaneous minimum-flow data are used for determining compliance with low-flow releases, as indicators of water-quality problems, as indicators of reliability of streams for various water uses, or for fish studies.

Generally, the minimum water-level stage has little value as it is often subject to shifting control conditions and it is not very useful except for rating analysis. However, if the minimum stage has importance for a site study, is should be in the records. Datum and location changes should be indicated and described.

When the minimum flow occurs on several days of a year, all of the days should be indicated in the record so that data users can know when minimum flow may be expected. If the stream goes dry for just a few days, all of the days should be shown. However, if the stream is dry many days throughout the year or most of the time, it may be adequate to indicate such a condition in a more general statement such as "no flow many days during the year.".

If the minimum flow occurs during a period when the record is affected by ice or during missing record, an estimated minimum daily flow may meet data needs for that site. Otherwise, the lowest observed flow and the period of record during which a lower flow may have occurred should be indicated in the site record. If record was obtained for only a part of a year, the period of record should be indicated and the minimum observed flow should be recorded.

1.C.5.c. SELECTION OF BASE

Peaks above a base should be shown only for streams which are not subject to substantial control by man during peak flows. At sites where control is minor or only occasional, either all of the peak above a base or none of the peaks should be recorded, regardless of the regulation on any one peak. Neither should peaks above a base be recorded if the stream's crests are generally so flat that the peak is not more than 5 percent greater than the daily mean discharge.

The base discharge should be chosen so that an average of about three peaks above the base per year are recorded. For sites with less than 5 years of record, a base should be selected on judgement and a comparison of records at other nearby stations. It is better that the selected base be too low rather than too high so that all peaks above the base are identified. Some peaks may be missed if the base is initially selected too high then revised downward. If such is the situation, past records should be examined and all peaks above the revised base identified.

For sites at which more than 5 years of record have been collected, list the annual flood peaks and compute their probability interval by the formula:

$$P = m/(n+1) \tag{1-93}$$

where P = probability,
n = number of years of record, and
m = order number of peak beginning with the largest peak or number 1.

Next, plot the points on log probability paper and draw a curve through the points. Then choose as the base the discharges having a probability of 0.87.

Changes in the base are not generally desirable. However, if there are more than about 40 peaks above a base in a 10-year period, the base should be revised upward. If there are less than 20 peaks for the ten years, the base should be revised downward and peaks missed in previous years should be added to the peak-above-a-base record.

1.C.5.d. TIME DIFFERENCES BETWEEN EXTREMES

Only the highest peak of two or more occurring within 48 hours of each other should be shown as a peak above a base unless it is fairly clear that the peaks in that time period are independent. If two independent peaks occurring within 48 hours are equal, show only the first peak.

A fair indication of independence of peaks may be made if the discharge of the trough between peaks is 25 percent or more below the discharge of the lower peak. If independence is indicated, record the peaks, otherwise, show only the higher one.

During periods of diurnal snowmelt, show only the highest peak occurring during each distinct snowmelt period. The determination of a distinct snowmelt period is usually a matter of individual judgement.

1.C.5.e. FREQUENCY OF OCCURRENCE (PEAKS AND LOW FLOWS)

The U.S. Water Resources Council (1977) recommends the use of the log-Pearson Type III distribution as the base method for analysis of annual flood peak discharge series data using a generalized skew coefficient. The basic log-Pearson Type III equations are computed using the logarithms to the base 10 of the annual peak data. The equations are:

$$\text{Log}\, Q = \overline{X} + KS \tag{1-94}$$

where Q = peak discharge,
K = a factor which is a function of the skew coefficient and selected exceedance probability. Values of K are given in the U.S. Water Resources Bulletin 17A (1977, appendix 3), and
$\overline{X}$ and S are variables which are defined below.

The mean, standard deviation and skew coefficient of station data may be computed using the following equations.

$$\overline{X} = \frac{\Sigma X}{N} \tag{1-95}$$

$$S = \left[\frac{\Sigma(X-\overline{X})^2}{(N-1)}\right]^{0.5} \tag{1-96}$$

$$= \left[\frac{(\Sigma X^2) - (\Sigma X)^2/N}{(N-1)}\right]^{0.5} \tag{1-97}$$

$$G = \frac{N\Sigma(X-\overline{X})^3}{(N-1)\,(N-2)\,S^3} \tag{1-98}$$

$$= \frac{N^2(\Sigma X^3) - 3N(\Sigma X)\,(\Sigma X^2) + 2(\Sigma X)^3}{N(N-1)\,(N-2)\,S^3} \tag{1-99}$$

where X = logarithum of annual peak flows,
N = number of items in data set,
$\overline{X}$ = mean logarithm,
S = standard deviation of logarithms, and
G = skew coefficient of logarithms.

Flood information outside that in the systematic record can often be used to extend the record of the largest events to a historic period much longer than that of the systematic record. For such a situation Bulletin 17A (U.S. Water Resources Council, 1977) has developed techniques and formulas to compute a historically adjusted log-Pearson Type III frequency curve.

The reader is referred to Bulletin 17A for recommended procedures for refining the basic flood-frequency curve by incorporating historic flood data, by information gained from comparisons with similar watersheds, and by using flood estimates obtained from precipitation. The Council recommends that at least 10 years of data need to be available to warrant statistical analysis.

The low-flow frequency curve may be made up of several segments, each of which may belong to a different distribution. This variety of distributions can occur as a result of a variety of geologic and other controls on low flows. Therefore, it is recommended that low-flow frequency analysis be performed using graphical methods.

For graphical methods, the annual instantaneous low-flow data is ordered so that the lowest annual flow has an order of one. The recurrence interval is then computed using the formula:

$$T=(n+1)/m \tag{1-100}$$

where T = recurrence interval, in years
n = number of years of record, and
m = order number of the annual low flow value.

For plotting purposes it may be desired to determine the probability, P, of occurence of each flow value or else to convert the probability scale of the plotting paper to recurrence interval. This is done as:

$$P=\frac{1}{T} \tag{1-101}$$

The data should then be plotted on log-probability paper and a curve drawn through the data points. Because of the possibility of various distributions being involved in the frequency curve, the curve may not be one continuous smooth curve as might be expected with most flood-peak analysis.

It may be desirable, because of the ready availability of a log-Pearson Type III computer program, to compute a log-Pearson Type III frequency curve for low-flow data. Because the lower end of the curve is of greatest importance, the fit at the lower end is critical. If the log-Pearson Type III analysis fits the data, especially at the lower end, the analysis may be used. However, the analyst should be ready to use graphical means if the computer analysis does not fit the data well.

Extrapolation of low-flow frequency curves may produce misleading information unless there is supplementary data. Generally, there is little need for low-flow frequencies greater than 20 years. At least 10 years of record should be available to determine the 20-year low-flow discharge. Riggs (1972) presents recommended procedures for obtaining frequency curves from short records. Riggs (1968) also provides a good deal of background on frequency curves for both peak and low flows.

1.C.6. MISCELLANEOUS FLOW DATA

1.C.6.a. AVERAGE DISCHARGE FOR PERIOD OF RECORD

1.C.6.a.1. DAILY VALUE

The average discharge of a stream is an indicator of the availability of water in the stream. The variability of flow must also be considered for development purposes.

The average daily discharge for a year is computed by summing the daily discharges for the year and dividing by the number of days in the year. If a small period of record is missing during a year, the missing record should be estimated if possible. Because of seasonal variability of flows, the average discharge for a part of a year will have little meaning unless means are computed for specific months or seasons.

Average flows for periods longer than a year generally have little meaning unless at least 5 years of record are available. Multiyear averages are obtained by summing the average annual flows and dividing by the number of years of available records. Only complete years of record should be used. The years of record need not be consecutive years but they should represent homogeneous flow conditions.

Average flows occurring after any development in a basin which significantly affects annual flows should not be used with average flows determined prior to development unless the flows are adjusted for the effect of development. If adjustments are made, that information should be made a part of the record. If adjustments are not made, 5 years of stable record after the development should be collected for computing mean flows for that flow condition. The period of record used to compute the mean flow should be identified.

Dams on a stream do not necessarily significantly affect the mean annual or long-term average flow. If losses from the reservoirs are of significant magnitude relative to the average flow, the records should not be considered homogeneous.

On some streams where runoff is low and the variability is high, there may be considered differences between the mean and median flows. The mean flow may be relatively high because of a few exceptionally high flow years. Therefore, in some situations it may also be desirable to determine the median flow of a stream. Generally medians should be computed only if there are 10 or more years of record and then only if there is generally a 10 percent or greater difference from the mean. The median is determined as the mid-value or the average of the two mid-value annual flows.

1.C.6.a.2. YEARLY VALUE

When the flow represents the natural runoff from the basin, it may be desirable to determine the equivalent runoff in millimeters per year, M. This indicates the depth to which the drainage area would be covered if the average annual runoff were uniformly distributed over the basin. The runoff, in millimeters per year, can be computed as:

$$M = 31{,}560\,\overline{Q}/A \qquad (1\text{–}102)$$

where $\overline{Q}$ = average annual discharge, in cubic meters per second, and
A = drainage area above the measured site, in square kilometers.

The average volume of flow for a year can be computed as:

$$\mathcal{V} = 31.56\,\overline{Q} \qquad (1\text{–}103)$$

where $\mathcal{V}$ = volume of flow in cubic hectometers per year, and
$\overline{Q}$ = average annual discharge in cubic meters per second.

1.C.6.b. CONSECUTIVE DAY MEAN FLOW VALUES

Often, extreme flows for other than instantaneous times are of value in describing the characteristics of a stream. Some of these low-flow characteristics are used in indices for the adequacy of a stream to meet the needs of waste disposal, to supply various water demands by industry, municipalities, and agricultural interests, and to evaluate the suitability of a stream for fish.

Often these flow indices involve annual maximum or minimum flows of 1, 3, 7, 14 or more consecutive days. Some agencies have computer programs which are designed to determine the 1-, 3-, 7-, 14-, 30-, 60-, 120-, and 183-consecutive day maximum and minimum flows on a stream for each year of daily-flow data.

1.C.6.b.1. MINIMUM OR MAXIMUM FLOW FOR SELECTED DURATION

The minimum or maximum consecutive-day flow for any year of record is determined from the daily records of flow for a station and represent the minimum or maximum mean flow of the year for the selected number of consecutive days. For any duration longer than a year, only complete years of record should be used unless it can be determined that the minimum or maximum flow did not occur in the period of no record for the year. The minimum or maximum flow of record is usually determined from the annual values regardless of whether or not a lower or higher value could be obtained by using a time frame which overlaps into two adjacent years.

Minimum or maximum consecutive-day flows can be manually selected from the flow records. However, computer determination is generally more efficient, especially if many years of data are considered.

1.C.6.b.2. ANNUAL, SEASONAL, OR MONTHLY PERIOD OF CONSIDERATION

Sometimes it may be desirable to describe the flow characteristics of a stream using consecutive day mean flow values for specific periods of time such as for a snowmelt or irrigation season or for each month. Consecutive day values for annual, seasonal, or monthly time periods are determined in the same manner as described in sec. 1.C.6.b.1. For seasonal values, the season should be consistently defined for each year and not be dependent on, for example, the actual snowmelt period or time of irrigation each year. Again only complete data for the selected time period should be used unless it can be determined that the particular flow characteristic did not occur during the time of missing record.

1.C.6.b.3. PROBABILITY OF OCCURRENCE

Frequency curves for consecutive-day flows should initially be computed using the log-Pearson Type III distribution described in section 1.C.5.e. However, the data should also be plotted as described in the same section and examined for goodness of fit.

The frequency curves for a variety of consecutive day periods generally should have shapes that are consistent with one another and generally should be parallel with each other. The upper ends of the high-flow curves and the lower ends of the low-flow curves should be made especially to fit the data. The reader is referred to Riggs (1968 and 1972) and to the U.S. Water Resources Council report (1977) for further details on methods of computations and methods of handling problem situations.

1.C.6.c. FLOW DURATION CURVES

The flow-duration curve is a cumulative frequency curve that shows the percentage of time during which specified discharges were equalled or exceeded in a given period (Searcy, 1959). The lower end of the duration curve is an expression of the low-flow characteristics of a stream, but it provides less information than a low-flow frequency curve, because the duration curve applies to the period of record rather than to a year (Riggs, 1972, p. 15). Prolonged drought for one year may have a significant effect on the duration curve. The period used for a duration curve should represent homogeneous basin characteristics and should not be used where changing basin conditions are affecting the flows.

In a strict sense, the flow-duration curve applies only to the period for which data were used to develop the curve. If flow during the period is representative of the long-term streamflow, the curve may be considered a probability curve and used to estimate the percent of time that a specified discharge will be equaled or exceeded in the future.

The flow-duration curve is prepared by arranging daily flows according to magnitude and computing the percent of time during which the flow equaled or exceeded specified flows. Data points of "discharge" versus "percent of time indicated discharge was equaled or exceeded" are plotted on log-

probability paper and a smooth curve drawn through the points. The computer can be used to great advantage in computing duration curves.

Complete years of record should generally be used. The data may be broken into 20 to 30 well-distributed class intervals for easier handling of the data. The reader should refer to Searcy (1959) and Riggs (1972) for special considerations in the development of flow-duration curves and in the interpretation.

1.C.7. SUPPLEMENTARY DATA FOR INTERPRETATION

1.C.7.a. CONTRIBUTING WATERSHED AREA

The drainage area of a stream at a specified location is that area measured in a horizontal plane, enclosed by a topographic divide, from which direct surface runoff from precipitation normally drains by gravity into the stream above the specified point.

The national topographic series of quadrangle maps of the U.S. Geological Survey are the standard maps for determining drainage areas. These maps are usually on scales of 1:62,500 or 1:24,000. For those areas not yet covered by standard USGS topographic maps, or if other topographic maps of longer scale or later data are available, the most accurate maps available should be used. For small watershed, drainage areas should be verified by aerial photographs or field checks. Drainage-area boundaries should be established with utmost care. At times, much personal judgement must be utilized for determining the location of the basin divide. The fundamental requirement for accurate drainage-area determination is an accurate boundary traced on a map of precise scale. When no maps with suitable ground contours are available, drainage area boundaries should be checked on aerial photographs or by a visit to the area.

Drainage areas for reservoir sites should be determined above the dam. Coordination of drainage-area boundary lines with other agencies should be made when feasible.

When a portion of the basin is known to be noncontributing, that is, when no direct surface runoff is contributed to the overall drainage system, the size of both the contributing and noncontributing area should be determined and noted. When it is uncertain in which basin the noncontributing area belongs, the determination should be based on the lowest point in the boundary of the noncontributing area.

When the headwaters of two or more streams lie in the same swamp or other depression, each respective stream should be assumed to drain that portion of the depression lying closer to it than to any other stream unless there is other information which might better define the boundary. When drainage areas are interconnected at high flow by flow from one basin into another, the flow records should be adjusted or qualified but the drainage areas should not be changed.

When all or nearly all of the flow from one basin is continuously discharged into another basin by man-made diversions, the drainage area of the respective basin should be adjusted and adequately noted. When the flow is only partially or intermittently diverted, the drainage areas should not generally be adjusted but notes should be made of the diversion.

If several maps are used to determine a drainage area, the same horizontal datum must be used on all maps. The area contained in the gap or overlap between adjacent quadrangle sheets on different horizontal control datums may be computed by multiplying the amount of the datum shift by the length of the common boundary of the maps within the limits of the drainage area.

The drainage area of some streams is so indefinite that the drainage area must be qualified as "approximately" or perhaps not determined at all and the drainage area labeled as "indefinite." Well developed karst areas can be examples of this situation.

1.C.7.b.1 TOPOGRAPHY AND DRAINAGE SYSTEM

A number of indices are used for describing topographic and drainage characteristics which may be significantly related to various streamflow characteristics. A number of these indices are described below. The method for determining all topographic and drainage indices used should be well documented. (See chap. 7 on Physical Basin Characteristics for Hydrologic Analysis.)

1.C.7.b.1.a. Elevation

Although elevation itself may not directly cause streamflow variations, elevation may serve as an index to other factors that cause basin-to-basin streamflow variation but that are difficult to evaluate. Radiation, temperature, wind, vegetation, and basin ruggedness, for example, may vary with elevation. Mean basin elevation is most easily computed by laying a grid over a topographic map of the basin and determining the mean of the elevations under each grid intersection. The grid spacing should be such that there are 50 to 100 points at the grid intersections within the basin boundary. (See chap. 7, sec. 7.B.2.a.8.b.)

1.C.7.b.1.b. Main-Channel Length

Main-channel length is an indicator, among other things, of the distance water is required to travel to the gage and hence is related to time of concentration and of the characteristics of peak flow. This variable is often highly related to drainage area size.

The main channel length is measured upstream from the gaged point or other point of interest along the main channel to the ridge forming the basin divide. The main channel above each stream junction is defined as the channel of the stream draining the largest area above the junction (Benson, 1964, p. 22-23).

Main-channel length is measured using a pair of dividers set at 0.1 mile chords (.2 kilometer) and stepping off the distance in 0.1 mile steps. (See chap. 7, sec. 7.B.2.c.1.a.).

1.C.7.b.1.c. Main-Channel Slope

Channel slope should also have an effect on time of concentration and hence on peak-flow characteristics. Channel slope should also have an effect on flow turbulence and velocity. This variable is often related to drainage area and elevation. (See chap. 7, sec. 7.B.2.c.2. for computational equations).

1.C.7.b.1.d. Basin Length

The basin length is often highly related to main-channel length. Long basin lengths should, on short-duration storms, produce smaller peaks than a basin of the same area but shorter. Basin length is defined as the longest straight line that can be drawn from the gaged point to the watershed boundary (Benson, 1964, p. 24-25; chap. 7, sec. 7.B.2.a.2.).

1.C.7.b.1.e. Basin Width

Basin width is computed as drainage area divided by basin length (chap. 7, sec. 7.B.2.a.3.).

1.C.7.b.1.f. Shape Factor

The shape factor is a measure of the departure of the basin from a circular shape and should have an effect on peak discharges. The shape factor is defined as the basin length divided by the average basin width (chap. 7, sec. 7.B.2.a.10.).

1.C.7.b.1.g. Stream Density

Stream density should be related to the efficiency of a basin in removing water from the basin. It is related to geologic conditions in the basin. The density of a stream system is expressed as total stream length in the basin divided by the basin drainage area. For consistency, all streams within a basin shown in blue on standard topographic maps are measured for total stream length (Benson, 1962, p.30). (See chap. 7, sec. 7.B.2.b.5. on drainage density).

1.C.7.b.2. LAND USE

Watersheds which are largely urbanized will likely have different hydrologic characteristics than those of largely forested or agricultural basins.

Forests have characteristics that can increase and decrease runoff. Many topographic maps are available showing forested areas. The percent of a basin area covered by forest relative to the entire basin upstream from a point of interest is sometimes used to relate to various flow characteristics.

Urbanization can have a significant effect on flow characteristics and especially on the extremes of flow. These are the result of increased impervious areas, improved drainage conditions, and various water uses within the river basin. The effect of urbanization in a basin should be studied in relation to the location of the urban area relative to the point of interest.

Two watershed characteristics that have been widely used in the analysis of peak flows from urban areas have to do with channel improvement and the amount of impervious area in the basin. Areas in which channel improvements have been made are called sewered areas. The index often used for sewered areas is a percentage of the basin which has improved stream channels and storm sewers. An index for imperviousness is the percentage of area covered by impervious material. This can best be accomplished by the use of a grid overlaying aerial photos of the area. The reader is referred to Anderson (1968) for uses made of these indices and for further analysis of floods in urban areas.

1.C.7.b.3. STORAGE (NATURAL AND ARTIFICIAL)

Reservoirs, lakes, channels, banks adjacent to water bodies, and valleys can all provide storage of water. Storage can either absorb an upstream change of flow or attenuate the flow pattern downstream from the storage. Water losses also occur as a result of storage, by evaporation from the surface of the stored water, by increased infiltration due to pondings, or by evapo-transpiration along the banks of the water body. Water gains can also occur as a result of storage where 100 percent of the precipitation falling on a ponded surface becomes surface runoff.

Reservoirs have an effect on downstream flows which will be dependent on, among other things, the storage prior to the flow event and on the way in which the reservoir is operated. A small reservoir which is full prior to a large peak flow may have very little effect on the peak. However, if there is sufficient storage and the water is not immediately released, a peak flow upstream from the reservoir may not be seen downstream. Much of the flow entering a reservoir may be diverted and will result in major modifications to flow patterns below the reservoir.

The primary effect of natural lakes is generally to attentuate the inflows. When a large flow enters the lake, the water goes into storage, thereby raising the head only a relatively small amount in the lake. This small head elevation produces a relatively small increase in the outflow. The surface area of the lake and the discharge control characteristics of the lake are important in assessing the effect of lake storage on downstream flows. The greater the surface area, the greater the storage and the narrower the control, the greater will be the attenuating effects. Lakes may also have large marshy areas and associated mud flats from which evapo-transpiration may take place.

Storage in stream channels is a function of the length and width of the stream. A stream having more storage capacity causes an upstream flow change to be more attenuated than one with a

smaller amount of available channel storage. Evaporation is a function of the total surface area of the stream and of the amount of shade which the stream receives from adjacent vegetation or other obstructions to sunlight.

Bank storage can occur along all types of bodies of surface water. The amount of storage available is a function of length of shoreline, type of bank material, and the effective volume of bank material. Ground-water gradients adjacent to the stream are a major factor in how much of the water going into bank storage on a rise returns to the water body on a falling stage and how much goes into ground-water. Where the water body is bordered with fairly solid bedrock there will be little or no significant bank storage. However, when there are broad areas of unconsolidated material adjacent to the water body, there may be considerable bank storage. If the bank material is fairly tight and changes of stages fairly rapid, then little effect may be expected from storage. Considerable evapo-transpiration can occur from banks which are fairly flat for some distance back from the water body, but steep banks may not provide much opportunity for evapo-transpiration.

Valley storage usually occurs during high flows when a stream overflows onto the flood plain. The storage effect is a function of the area overflowed and the gradient of the valley. If the water can flow back into the channel quickly on the recession, the attenuating effect may not be very great. Water can be lost to the stream during high-flow events by being trapped in depressions, by recharge to the ground water, and by evapo-transpiration from the soil surface and the vegetation on the flood plain.

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Chapter 2

Ground Water

CHAPTER 2–GROUND WATER

Prepared by
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CHAPTER 2—GROUND WATER

This chapter identifies ground-water data acquisition and interpretation methods that are widely used. The principal criteria used to justify the relative amount of detail given for any method of data collection or interpretation were: (1) the degree of standardization that has been achieved for the method and (2) the adequacy of the description of the method in readily available references. New and improved methods are being developed continuously. Future updates and additions will keep the chapter current and broaden the scope of coverage.

The type and distribution of field measurements depend on the purpose for the data collection, the complexity of the geohydrologic environment, and practical constraints such as time and, in some cases, by the economic loss that probably would be incurred by various levels of imperfection in evaluating problems of interest using the data.

In some cases, data are collected and analyzed as part of a study that focuses on the design and/or operation of a facility at a particular site. In other cases, data are collected and analyzed by an agency whose responsibility includes the collection of factual information on ground water that will permit efficient development and intelligent management of ground-water resources throughout a large region. In the first case, the purpose of the data collection activity is specific and limited in scope. In the latter case, the purpose of the data collection activity is general in that the data are used to characterize regional properties of the ground-water system.

Point data are not an end in themselves. They are a component of a network wherein information on the ground-water system is developed, recognizing the desirability to establish a basis for extrapolating information to areas where measurements of the parameter(s) of interest have not been made and/or in predicting the effects of natural and manmade stresses on the ground-water systems.

At each ground-water data collection site some information is necessary for the data collected to be most useful. For example, the aquifer tapped by a well, the depth of the well, the type of construction, and the well elevation should be known.

Field measurement is used in this chapter to include directly measured quantities such as water level, as well as derived quantities such as volume rate of flow from a pumping well.

2.A. WATER-LEVEL MEASUREMENTS

Water-level measurements are fundamental to ground-water studies. Some of the major uses of water-level data are to indicate the directions of ground-water flow and areas of recharge and discharge, to evaluate the effects of manmade and natural stresses on the ground-water system, to define the hydraulic characteristics of aquifers, and to evaluate stream-aquifer relations. Table 2-1 gives other uses of water level data.

2.A.1. MEASUREMENT SITES

Water-level data can be obtained from wells, piezometers, or from surface-water manifestations of the ground-water systems such as springs, lakes, and streams. An observation well for obtaining water-level data is basically a large manometer tube for measuring the hydrostatic pressure of the water in an aquifer. Aquifers occur either under artesian (confined) or water table (unconfined) conditions. The water level in an artesian well stands above the top of the water body it taps, and in some cases, above land surface. The water table is the surface in a ground-water body at

which the water pressure is atmospheric. The water table is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells that penetrate to greater depths within the aquifer, the water level may be above or below the water table depending on whether an upward or downward component of flow exists.

Table 2-1.—*Some uses of ground-water level data*

1. Indicate the status or change in ground-water storage.
2. Indicate the change in water level due to distribution or rate of regional ground-water withdrawal.
3. Show the relationship of ground water to surface water.
4. Estimate or forecast the baseflow of streams and/or irrigation drainage systems.
5. Provide long-term records that can be used to evaluate the effect of management and conservation programs.
6. Estimate the amount, source, and area of recharge and estimate discharge.
7. Estimate the hydraulic characteristics of an aquifer.
8. Provide data base for water management needs.
9. Identify areas where the water table is near the land surface (areas which may become waterlogged).
10. Identify the optimum sites for collecting streamflow data.
11. Estimate evapotranspiration.
12. Estimate rate and direction of ground-water movement.
13. Delineate reaches of losing or gaining streams or canals.
14. Monitor the effect of mining or subsurface disposal operations.
15. Monitor earthquakes.
16. Assist well owners and drillers in planning well construction depths and pump settings, and determine pump lifts and total head that can be used to calculate energy costs of pumping.

Ideally, observation wells should be constructed specifically and solely for that purpose. However, because often it is not economically feasible to specially construct observation wells, the majority of observation wells in the United States are privately owned and some are used for water supply.

Some items that should be considered in the selection of wells for measuring water levels are location, accessibility, use, physical condition, and construction. Table 2-2 gives a list of basic information that should be obtained at each observation well site.

Basic information concerning the well, such as that given in Table 2-2, should be recorded on a well schedule. The schedule should include a sketch of how to find the well and a drawing or a photograph to show location of access to the well and reference points (see also sec. 2.A.6.a.1).

Ease of access (to the well itself and to the well casing) also is a consideration in selecting an observation well site. Wells that are difficult to find, to reach in bad weather, or to measure may not always be measured at the desired time.

Table 2-2.—*Information recommended for each observation-well site*

1. Aquifer(s) tapped.
2. Aquifer hydrologic characteristics.
3. Lithologic and geophysical logs.
4. Well depth, size and type of casing or finish, location and type of perforations.
5. Elevation of land surface and measuring point.
6. Diagram and photograph of well, showing access to well, and measuring point.
7. Date drilled.

8. Well response data for unpumped wells (specific capacity test).
9. Local well name and owner.
10. Location by legal description such as latitude and longitude coordinates.
11. Significant features near well that could affect the water level.
12. Use of well.

2.A.1.a. EXISTING WELLS

An existing well can provide a convenient measuring site at low cost. However, a reliable and detailed description and a test of its effectiveness to provide accurate water levels are needed of any well before it can be used to obtain reliable hydrologic information. A well that is pumped occasionally is generally more suitable than one that has been abandoned. Abandoned wells, irrigation wells, industrial and public supply wells, stock wells, and domestic wells are examples of existing wells.

Abandoned or unused wells are often in poor condition because of damaged or leaky casings, corroded pumping equipment, or rotting wooden structures near or around the wells, which make the wells difficult to measure and safety hazards. An unused well with the pump removed offers greater ease and perhaps greater reliability of measurement than a well with the pump intact. Safety hazards also exist at used wells—pumps on an automatic cycle may unexpectedly start up while the observer is present, and high voltage lines near electric pump motors always should be considered a safety hazard. The depth of an unpumped well should be measured periodically to determine if part of the well has caved. This is especially important for uncased or dug wells. It would be useful to know why the well was abandoned.

Irrigation wells that are pumped on a regular schedule generally are satisfactory observation wells during the nonpumping season.

Measurements of water levels in industrial and public supply wells can be useful if adequate information is available on their operation prior to the measurement. It is desirable for the well to have quit pumping long enough for the levels to stabilize. This requires that the operation of nearby wells pumping from the same aquifer be nearly uniform for a period before the measurement is made.

Wells used seasonally for stock water will furnish good records during most other parts of the year.

Domestic wells are generally less satisfactory for water-level observations because the pumping schedule is usually not known.

2.A.1.b. OBSERVATION WELLS

Wells drilled especially for observation purposes are desirable because all pertinent details on lithology, well construction, depth and other features of the well may be accurately determined and the site selected to fill recognized data needs. In addition, these wells are easier to measure because of the lack of the pump.

It is important to determine during well development if the observation well is connected to the aquifer. A check measurement can be made by pouring a known volume of water into the observation well and recording the change in water levels at short time intervals until the original level is reached. However, if the well is to be used to collect water-quality samples, it may be more desirable to test the well by monitoring the water level response to the removal of a known volume of water from the well.

2.A.1.c. PIEZOMETERS

A piezometer is specially designed to measure the hydraulic head within a zone small enough to be considered essentially a point—as contrasted with a well that reflects the average head of the aquifer for the screened interval. Piezometers must be carefully constructed and tested to make sure they accurately represent the water level in the material. They are commonly used to measure the water level in fine-textured materials where caution is required because the response to water-level changes may be slow. Further information on piezometers are given in Johnson (1965), Wolff (1970), and Weeks (1978).

2.A.1.d. PITS, PONDS, SPRINGS, AND STREAMS

Construction pits, ponds, lakes, streams, and quarries may contain water surfaces that represent local ground water conditions. Such sites can be used where no wells are readily available for making measurements. A permanent reference mark must be established so that future measurements will have a reference point.

2.A.2. WELL-INTEGRITY CHECKS

The depth to the bottom of observation wells should be measured at least once a year. Corrosion can cause collapse of the casing. Check the well periodically for proper aquifer response by methods described in 2.A.1.b. Corrosion can cause the casing to leak, which could lead to erroneous or misleading water-level measurements. Corrosion and silting can also clog well screens causing a sluggish response or no response to water-level change.

2.A.3. SUPPLY-WELL ACCESS

Access into the well for measuring water levels varies with the type of pump and well construction. For example, access may be through an observation pipe built into the base of the pump, a hole in the casing, a vent pipe constructed at the well head or a hole in the base of the pump. The discharge pipe may be a possible access, but should be used as a last resort and only under specified conditions (see following sections). If there is no tape access hole, with the owner's permission, one can possibly be made by drilling or cutting a hole through the casing, threading the hole and inserting a threaded plug in the hole. An accurate drawing on the well schedule should be made of the well, pump, and point of access to the well. The following descriptions summarize various types of pump installations and possible points of access.

2.A.3.a. TURBINE-PUMP WELLS

Numbers refer to figure 2-1. Some wells have a breather pipe or other access in the side of the casing (1). Do not confuse with gravel pack access openings betwen dual casings on large capacity wells. Turbine pumps usually have access between the pump column and the casing (2). Sometimes the space between the casing and the pump is very small and an unweighted tape should be used. Some pumps have an opening between the base plate and the casing (3). In these pumps, the tape should be flexed and inserted cautiously into the well. This is not a desirable situation for water-level measurements but may be used on a temporary basis until a better access is found. Some pumps have access through the discharge line or pipe (4). Accurate water-level measurements through the discharge line or pipe are possible only when the pump does not have a foot valve. Below the intake, some wells are equipped with a screen that may become plugged with silt and clay, resulting in an improper connection between the water in the well and in the discharge pipe. Use extreme care when measuring in this type well because anything dropped into the well could damage the pump impellers. These measurements are best made with an electric tape. In either case, extreme caution

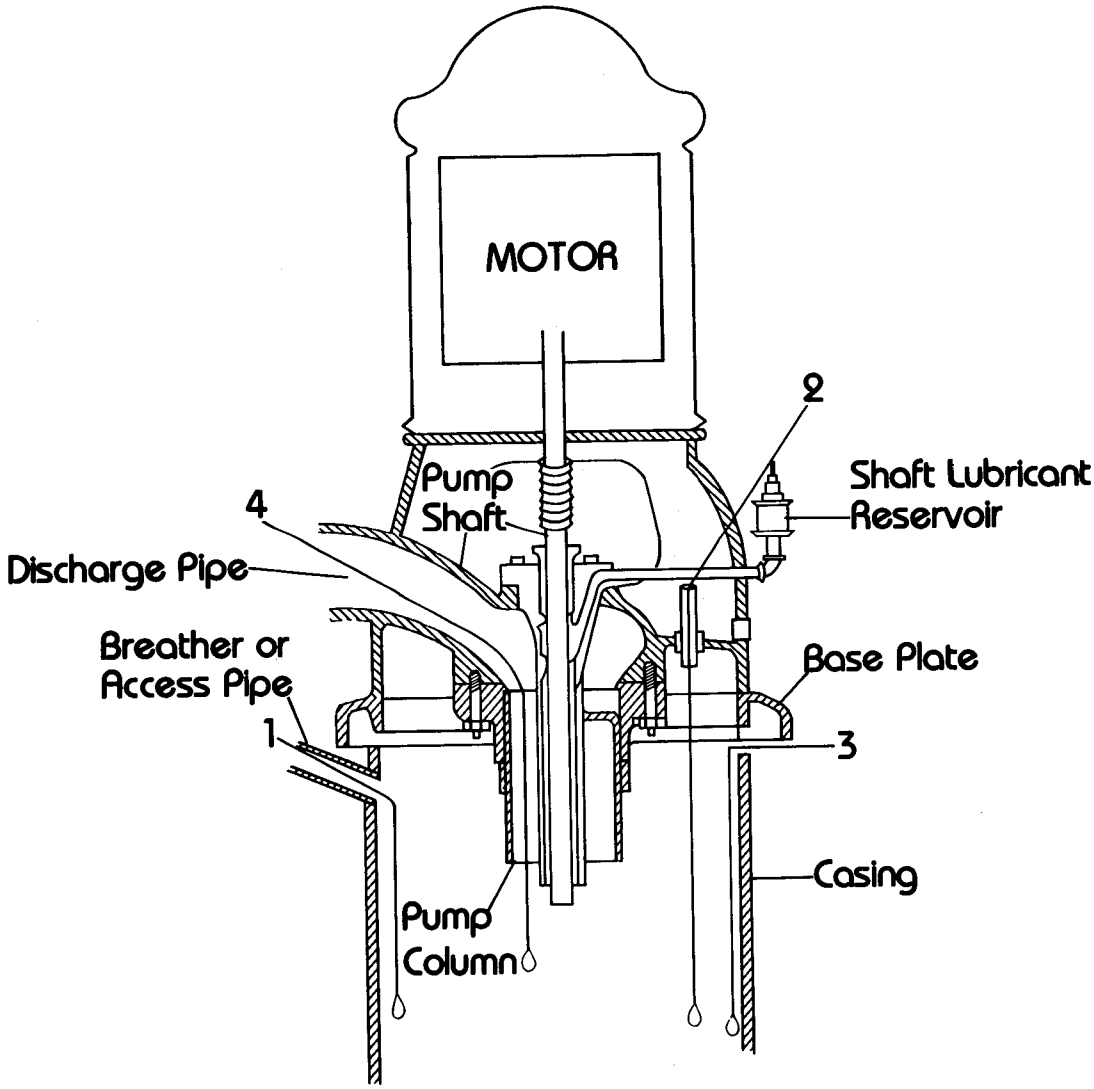

Figure 2-1. — Well with turbine pump.

must be taken when measuring pumping levels to avoid the electric or steel measuring tapes becoming entangled in the impellers.

2.A.3.b. SUBMERSIBLE-PUMP WELLS

A well with a submersible pump (Fig. 2-2) generally has a plug in the top of the sanitary seal (1). Because the opening may only be about ¼ inch, an unweighted tape may be necessary. Care is required not to get entangled in the electrical cable that is commonly strapped to the discharge pipe.

2.A.3.c. JET-PUMP WELLS

In a single pipe jet pump, the water level cannot be measured without removal of the pump works. In a two-jet pump the pump can be lifted and access gained through openings at the top of the casing (1), or an access hole or plug in the side of the casing (2).

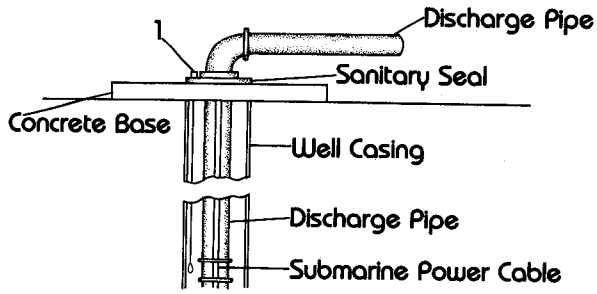

Figure 2-2. – Well with submersible pump.

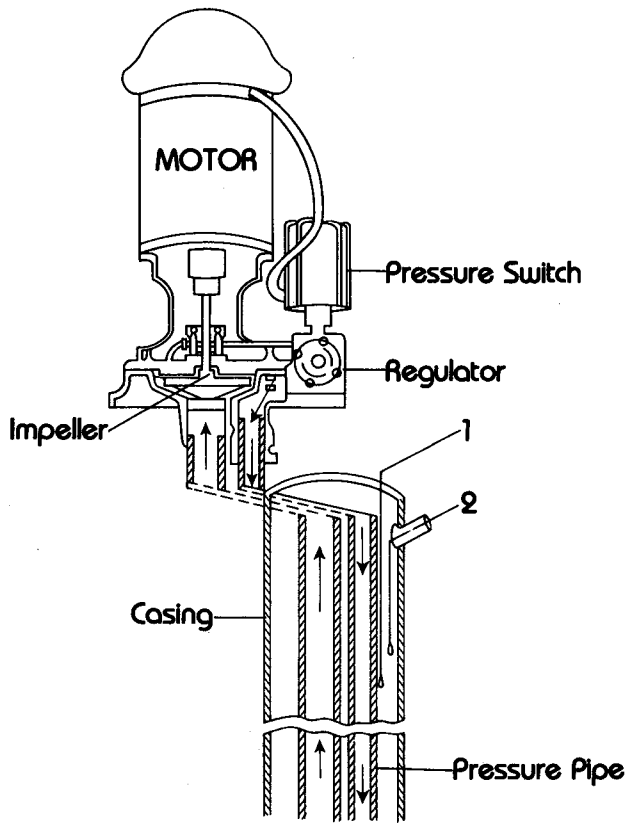

Figure 2-3. – Well with jet pump.

2.A.3.d. WINDMILLS AND HANDPUMP WELLS

Water levels must be measured between the well casing and the pump column because of the foot valve at the base of the pump column. For a windmill pump, measurements can be made at B by slipping the tape between the collar and the cover plate, through a hole in the cover plate, under the cover plate, or through a hole in the casing. In some cases, it may be necessary to jack up the entire pump column to provide an opening past the cover plate. For a handpump, measure at B by removing the plug (if there is one), by slipping the tape under the pump base and into the well casing, or by jacking the pump-column assembly.

Extreme care should be used in jacking the pump column to prevent cracking or breaking the column collar or discharge tee. Also, the piston should be at the top of the stroke and the pump col-

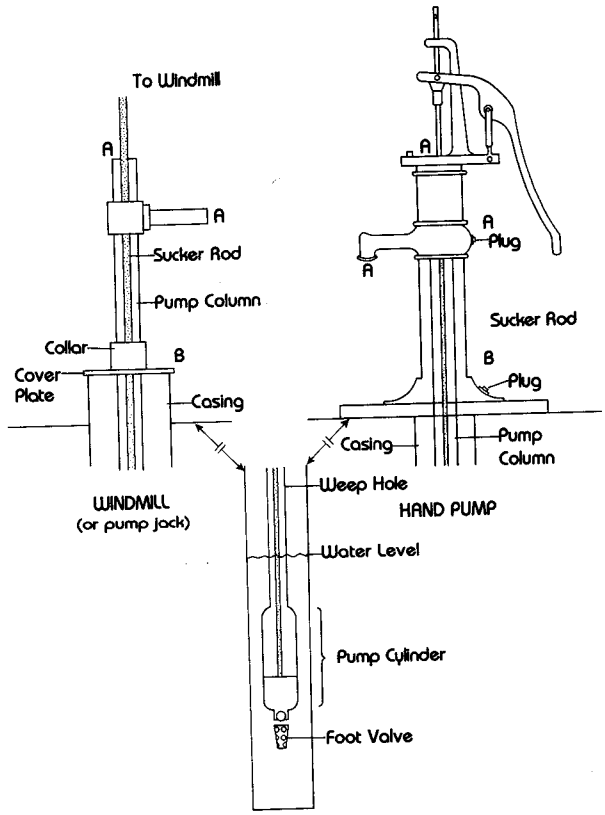

Figure 2–4.—Windmill and handpump wells.

umn raised less than the stroke length to assure that the piston does not ram into the cylinder bottom. The end of a short tapered square (½ to 1 inch cross-section) pry bar should be wedged or gently driven into the opening between the raised column cover-plate and the well casing to prevent injury and loss of measuring equipment if the jack and blocks slip.

Openings labeled A in the diagrams are not accesses to the water level in the well.

2.A.4. MEASURING POINTS AND REFERENCE POINTS

For comparability, water-level measurements must be referenced to the same datum (elevation). The measuring point is measured in reference to land surface datum and is the most convenient place to measure the water level in a well. Measurement points change from time to time, especially on private wells. The measuring-point correction of a water-level measurement converts the measurement to a distance above or below land surface at the well.

The measuring point must be as permanent as possible, clearly defined, marked, and easily located. If at all possible, position the point so that a leveling rod can be set on it directly over the well and the measuring tape can hang freely when it is in contact with the measuring point. Frequently, the top of the casing is designated as the measuring point; because the top of the casing is seldom smooth and horizontal, a particular point should be designated and marked clearly with paint and, if permitted, the letters MP with an arrow.

The reference point for water-level measurements is an arbitrary datum established by permanent marks set on or near the well. It is used to check the measuring point, and its greatest value is in re-establishing a measuring point if one is destroyed or changed.

2.A.5. LOCATIONS AND IDENTIFICATIONS

The records of an observation well, including the field sheets, should contain a detailed narrative description of the well, permanent landmarks, and the best route to the well. In addition, two sketches should be provided, one of the general location of the well, and one of a detailed sketch of the site. It may be desirable to have the well number or other identification painted, or otherwise marked, on the well, or on some conspicuous permanent object near the well.

2.A.6. TECHNIQUES

2.A.6.a. NONFLOWING WELLS

The graduated steel tape (wetted-tape method), the electrical measuring line, and the air line are the most common tools for manually measuring water levels in nonflowing wells.

2.A.6.a.1. GRADUATED STEEL TAPE METHODS

The graduated steel tape method is considered to be the most accurate method for measuring the water level in nonflowing wells. Steel surveying tapes in lengths of 100, 200, 300, 500, and 1,000 feet are commonly used. A black tape is better than a chromium-plated tape. The tapes are mounted on hand-cranked reels up to 500-ft lengths; for greater depths a motor-driven tape drive is usually required. A slender weight, usually made of lead, is attached to the ring at the end of the tape to insure plumbness and to permit some feel for obstructions. Lead weights are used so that if the weight should fall off the tape in a pumped well, the soft lead would be less likely to damage the pump. The weight is attached in such a way that if the weight becomes lodged in the well, the tape can still be pulled free. Attach the weight with wire strong enough to hold the weight but not as strong as the tape.

The lower few feet of tape is chalked by pulling the tape across a piece of blue carpenter's chalk. The wet chalk mark identifies the portion of the tape that was submerged. Lower the graduated steel-tape from the measuring point at the top of the well until a short length of the tape is submerged. The weight and tape should be lowered into the water slowly to prevent splashing. Submergence of the weight and tape may temporarily cause a water-level rise in wells or piezometers having very small diameters. This effect can be significant if the well is in materials of very low hydraulic conductivity. Under dry surface conditions, it may be desirable to pull the tape from the well by hand, being careful not to allow it to become kinked, and reading the water mark before rewinding the tape onto the reel. In this way, the water mark on the chalked part of the tape is rapidly brought to the surface before the wetted part of the tape dries. In cold regions, rapid withdrawal of the tape from the well is necessary before the wet part freezes and becomes difficult to read. Read the tape at the measuring point, and then read the water mark on the tape. The difference between these two readings is the depth to water below the measuring point.

Garber and Koopman (1968, p. 3–6) describe corrections for effects of thermal expansion of tapes and of stretch due to the suspended weight of the tape and plumb weight. Errors resulting from these effects can become significant at high temperatures and for measured depths in excess of 1,000 feet.

As a standard of good practice, the observer should make two measurements. If two measurements of static water level made within a few minutes do not agree within about 0.01 or 0.02 foot (generally regarded as the practical limit of precision) in observation wells having a depth to water of less than a couple hundred feet, continue to measure until the reason for the lack of agreement is determined or until the results are shown to be reliable. Where water is dripping into the hole or covering its wall, it may be impossible to get a good water mark on the chalked tape.

Unless the well is equipped with an access pipe that is placed to eliminate the possibility of lowering the tape into the pump impellers, the graduated-tape methods should not be used to measure pumping levels in a well.

In some pumped wells, a layer of oil floats on the water. If the oil layer is only a foot or so thick, read the tape at the top of the oil mark and use this data for the water-level measurement. The measurement will not be greatly in error because the oil surface in this case will differ only slightly from the water level that would be measured if the oil was not present. If several feet of oil are present in the well, or if it is necessary to know the thickness of the oil layer, a water-detector paste for detecting water in oil and gasoline storage tanks is available commercially. The paste is applied to the lower end of the tape that is submerged in the well. It will show the top of the oil as a wet line and the top of the water as a distinct color change.

After each well measurement, that part of the tape measure that was wetted should be disinfected to avoid contamination of other wells.

2.A.6.a.2. ELECTRICAL METHODS

Many types of electrical instruments have been devised for measuring water levels; most operate on the principle that a circuit is completed when two electrodes are immersed in water. Some instruments consist of a single conductor that is lowered into the well where the metal well casing is used as the second conductor. More commonly, a two-conductor cable and special probe are used. Various forms of electrolytic cells using two electrodes of dissimilar metals have been used, but current is more commonly supplied by batteries.

Ordinarily, two-conductor electric tapes are 500-ft long and are mounted on a hand-cranked reel that contains space for the batteries and some device for signaling when the circuit is closed. Electrodes are generally contained in a weighted probe that keeps the tape taut while providing some shielding of the electrodes against false indications as the probe is being lowered into the hole. The electric tapes generally are marked at 5-ft intervals with clamped-on metal bands.

Before lowering the probe in the well, the circuitry can be checked by dipping the probe in water and observing the indicator. The probe should be lowered slowly into the well until contact with the water surface is indicated. The electric tape is marked at the measuring point and partly withdrawn; the distance from the mark to the nearest tape band is measured and added to (or subtracted from) the band reading to obtain the depth to water. It is good practice to take a second or third check reading before withdrawing the electric tape from the well.

The tape should not rub across the top of the casing because the metal bands can become displaced; consequently, placement of the bands should be checked frequently with a steel tape.

Portable electrical instruments have been used to determine water levels as great as 2,600 feet below land surface (Weir and Nelson, 1976). Garber and Koopman (1968, p. 6–11) describe in detail various types of water-sensing probes used with an electric-cable device and the possible sources of inaccuracy. They also describe a calibration procedure for use with electrical tapes to measure at depths of several hundred feet or more.

Electric tapes are more cumbersome and inconvenient to use than the wetted-tape method, and they normally give less accurate results. In some situations, however, they are superior. Where water is dripping into the hole or covering its walls, it may be impossible to get a good water mark on the chalked tape. In wells that are being pumped, particularly with large-discharge pumps, the splashing of the water surface makes consistent results by the wetted-tape method impossible. Where a series of measurements are needed in quick succession, such as in pumping tests, electric tapes have the advantage of not having to be removed from the well for each reading. Electric tapes are also safer to use in pumping wells because the water is sensed as soon as the probe reaches the water surface and there is less danger of lowering the tape into the pump impellers.

Independent electric tape measurements of static water levels using the same tape should agree within ±0.04 foot for depths of less than about 200 feet. At greater depths, independent measurements may not be this close. For a depth of about 500 feet, the maximum difference of independent measurements using the same tape should be within ±0.1 foot. Garber and Koopman (1968, p. 11) note that the repeatability of measurements with deep-well electrical cable devices they tested was within ±0.5 foot for any one device in the 2,000 foot depth range.

In pumped wells having a layer of oil floating on the water, the electric tape will not respond to the oil surface and, thus, the fluid level determined will be different than would be determined by a steel tape. The difference depends on how much oil is floating on the water. A miniature float-driven switch can be put on a two-conductor electric tape that permits detection of the surface of the uppermost fluid. The electric tape should be disinfected after measurements in each well.

It is especially important to check the electric line length by measuring with a steel tape after the line has been used for a long time or after it has been pulled hard in attempting to free the line. Some electric lines, especially the single line wire, are subject to considerable permanent stretch. In addition, because the probe is larger in diameter than the wire, the probe can become lodged in a well. Some operators attach the probe by twisting the wires together by hand and using only enough electrical tape to support the weight of the probe. In this manner, the point of probe attachment is the weakest point of the entire line. Should the probe become "hung in the hole," the line may be pulled and breakage will occur at the probe attachment point, allowing the line to be withdrawn.

2.A.6.a.3. AIR LINE METHODS

The air line method is especially useful in pumped wells where water turbulence may preclude using more precise methods. A small diameter air-type tube of known length is installed from the surface to a depth below the lowest water level expected. Compressed air (compressor, bottled air, or tire pump) is used to purge the water from the tube. The pressure, in pounds per square inch (psi), needed to purge the water from the air line multiplied by 2.31 (feet of water for one psi) equals the length in feet of submerged airline. The depth to water below the center of the pressure gage can be easily calculated by subtracting the length of air line below the water surface from the total length of air line (assuming the air line is essentially straight). Accuracy depends on the precision to which the pressure can be read (Garber and Koopman, 1968). Kazmann (1965, p. 147) notes that:

> The accuracy of an air-line or pressure gage measurement depends primarily on the accuracy and condition of the gage but is normally within one foot of the true level as determined by means of a steel-tape measurement. The air lines themselves, however, have been known to become clogged with mineral deposits or bacterial growth or to develop leaks and consequently yield false information. A series of air-line measurements should be checked periodically by the use of a steel tape or an electric water-level indicator.

The air line and any connections to it must be airtight throughout its entire length. If the line is broken or leaky, large errors may occur. A long-term increase in air line pressure may indicate a gradual clogging of the air line. A relatively sudden decrease in air line pressure may indicate a leak or break in the air line. Air line pressures that never go above a constant low value may indicate that the water level has dropped below the outlet orifice of the air line. To minimize the effect of turbulence, the lower end of the air line should be at least five feet above or below the pump intake (UOP, Johnson Division, 1974, p. 90–91).

Garber and Koopman (1968, p. 11–14) describe procedures to correct for fluid temperatures much different from 68°F (20°C) and to correct for vertical differences in air density in the well column for cases where the depth to water is very large.

2.A.6.b. FLOWING WELLS

Because the water level in a flowing well is above the land surface, it is necessary to close off the flow in order to measure the static water level or head. Some flowing wells are equipped with valves so that the flow can be shut off, but many are open at the top and flow freely. Such wells can be shut-in by using a soil-pipe test plug, also known as a sanitary seal, which is available from most plumbing-supply houses in sizes to fit pipes from 2 to 10 inches in diameter. These plugs consist of a length of small-diameter pipe, generally ¾ inch, surrounded by a rubber packer that can be expanded by means of an attached wingnut to fit tightly against the inside of the well casing or discharge pipe. The end of the small pipe is threaded for the attachment of a valve, hose, or pressure gage. Shutting off small-diameter wells with these plugs, even when the pressure is relatively high, is relatively easy. As a safety precaution against blowouts, large-diameter plugs should be clamped to the casing when they are used in high-pressure wells.

A valve or a test plug on a flowing well should be closed and opened gradually. If pressure is applied or released suddenly, the water-hammer effect may permanently damage the well by cave in of the aquifer material, breakage of the casing, or damage to distribution lines or gages. A pressure snubber installed ahead of the gage can reduce the effect of the water hammer. The time required for the well to reach static pressure after it is shut in is variable, ranging from hours to days. Shut-in time (elapsed time since well was shut in) long enough to reach true static pressure may be impractical or impossible for some wells. In all cases, the shut-in time should be recorded for each pressure gage reading. Readings should be made frequently starting immediately after shut in; longer intervals may be used as the shut-in time increases. During subsequent visits to the well, it is desirable to duplicate the previously used shut-in time. (NOTE: This is analogous to recording recovery data of an aquifer test.)

2.A.6.b.1. LOW-PRESSURE HEAD MEASUREMENT

In flowing wells where the head is only a few feet above the ground, it is often practical and convenient to measure the head directly. A short length of hose can be connected tightly to the well and the free end of the hose is raised until the flow just stops, or a transparent plastic tube in which the water level can be observed directly against a measuring rod can be used. Heads can be measured to an accuracy of 0.1 foot or better by this method. Again, shut-in times should be recorded as indicated above.

2.A.6.b.2. HIGH-PRESSURE HEAD MEASUREMENT

Where the static water level is more than 5 or 6 feet above land surface, the foregoing method is generally impractical. Indicating pressure gages are commonly used in this case, although a mercury manometer designed for field use gives somewhat greater accuracy. If an indicating pressure gage is used, it should be periodically checked and calibrated with a mercury manometer or by some other standardized method, because the unavoidable jarring in the field decreases the gage's accuracy.

Mercury manometers for field use are commonly calibrated to read directly in feet and tenths of feet of water, and if handled and used carefully are accurate to 0.1 foot. Indicating gages may be calibrated to read either in feet of water or in pounds per square inch; in either case, they are probably not accurate to within 0.5 foot although they can be read to a tenth of a foot.

Pressure gages are delicate instruments that can be broken easily and can give wrong readings if dropped or otherwise mishandled. The pressure gage used should be selected so that the anticipated water pressure falls within the middle third of the gage range because if the well pressure exceeds the gage limits, the gage may be ruined. If in doubt, a wide-range gage should be used to make an initial estimate of the pressure, followed by use of a gage with the proper range for a more accurate measurement. A pressure gage should not be connected to a well that has a booster pump in the system because if the pump starts, the pressure surge may ruin the gage. In addition, the locations of any check valves should be carefully noted. Connecting the pressure gage to the wrong side of the check valve may give only the reading for a pressure in the distribution line or in a storage tank. The pressure indicated by a gage usually refers to the pressure at the center of the gage, and this point should therefore be held on a level with the measuring point or at a measurable distance above or below it.

2.A.7. INDIVIDUAL AQUIFERS IN BOREHOLES INTERSECTING MULTIPLE AQUIFERS

The water level in a well in hydraulic connection with more than one aquifer is a composite level that is affected by the heads and the hydraulic properties of the aquifers and the materials separating and/or bounding them. Bredehoeft (1965), Shuter and Pemberton (1978), Garber and Koopman (1968), and Blankennagel (1968) describe the use of hydraulically inflatable straddle packers to measure heads and make hydraulic tests of selected intervals in a borehole.

2.A.8. RECORDING DEVICES

Devices for recording changes in water levels may be mechanical, electronic, or electromechanical. A further distinction is the manner in which the device detects changes. A float or an electromechanically actuated water-seeking probe may be used to detect vertical changes of the water surface in the hole, or a mechanical or electrical pressure gage submerged several feet below the water surface may be used to detect changes in fluid pressure resulting from water-level changes. The principal advantage of pressure-sensing devices is that they may be used in packed or otherwise sealed-off zones in a well. In addition, their response to rapid changes of fluid pressure is generally better than that of mechanical devices (Garber and Koopman, 1968). An increasing number of digital punched-tape recorders that record levels at prescribed times are being used on observation wells. However, the simplest recording device commonly in use consists of a recording chart drum rotated mechanically by a free float that follows the water level, while a clock drive moves a recording pen horizontally across the chart (Garber and Koopman, 1968). Leupold and Stevens (1978) describes the various errors involved in float operated devices.

Where depth to water is more than a few feet below the top of the casing, special care must be taken to minimize friction between the float cable and the walls of the well. The float selected should be the largest diameter that can be accomodated by the casing. Shuter and Johnson (1961) indicate that the error resulting from float-line drag along the well casing is larger than the error caused by float drag. Shuter and Johnson (1961) describe a number of devices for improving the performance of recorders in wells of very small diameter. If the clearance between the float and the casing is small, the float cable should be arranged so that the counterweight does not have to pass the float, but is always above or below the water level. When the counterweight is immersed, a little extra weight should be used to counteract the water's bouyancy.

Water-level recorders should be protected from the weather and vandalism by a suitable shelter that is solidly anchored. The part of a recorder most susceptible to malfunction is the clock. To insure continuous records, field personnel who visit recorders should carry spare clocks. Malfunctioning clocks should be sent to a reliable clock-repair service for maintenance, and all clocks should be cleaned and adjusted periodically.

During each visit to a recorder installation, the water level should be measured (preferably by the wetted-tape method) and the measurement compared with the recorded value and the appropriate adjustments made.

In flowing wells where the static water level is above the top of the casing, float-activated recorders cannot be used. If the well can be shut in, however, a pressure recorder can be used.

2.A.9 FREQUENCY OF MEASUREMENTS

The following section is from Leggette and others (1935).

> The factors that should determine the frequency of water-level measurements are the types of fluctuation to be observed, the nature of the studies contemplated, and the available personnel. The principal factors that produce fluctuations in water-table wells are recharge, withdrawal of water from wells, transpiration, and other natural discharge. In wells that extend to confined water-bearing beds, the fluctuations in the water levels or pressure heads are relatively large and rapid and are produced by discharge of other wells or by other pressure effects, such as changes in atmospheric pressure and the effects of tides. In some localities, there are seasonal fluctuations produced by recharge and discharge.
>
> Automatic recorders afford the best means of observing the rapid and irregular water-level fluctuations in areas of heavy withdrawal, especially where pumps or flowing wells are turned on and off at irregular times. Figure 2-5 shows the comparison between daily measurements taken from automatic-recorder sheets on a well in an area of heavy withdrawal and weekly and monthly measurements taken from the same recorder sheets. The weekly measurements show only part of the fluctuations caused by change in rates of withdrawal, and the monthly measurements show even fewer changes. For instance, the daily record shows that the water level continued to rise through March to about the middle of April, although increased withdrawal has lowered the water level twice. The weekly measurements happen to record this in part. The monthly record begins to decline two weeks earlier and does not show the peaks.
>
> Recharge from rain or percolation from streams may reach the water table slowly and at a more or less uniform rate, or in large amounts during short periods. Weekly, monthly, or even semiannual measurements may suffice to show uniform recharge, but nothing less than daily or continuous records will show the more rapid recharge. Wells 1 and 2 in figure 2-5 show moderate types of fluctuations. Well 1 is about 15 miles from a heavily pumped district, and the decline is caused by the general effect of this withdrawal. The decline is slower during the winter, probably owing to a slow recharge. Monthly or semiannual measurements in

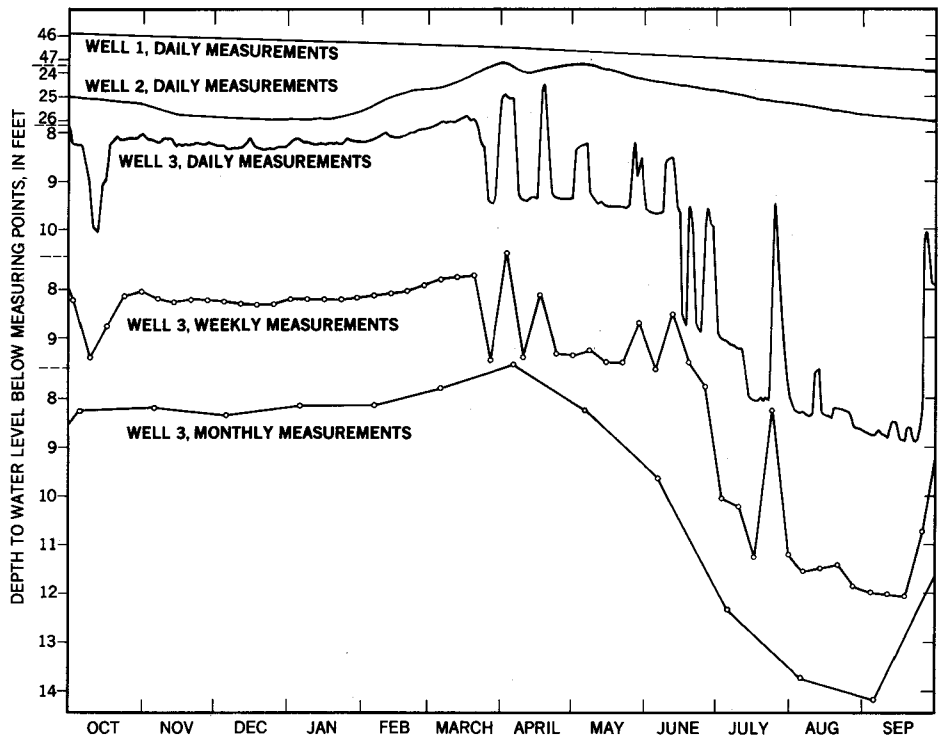

Figure 2-5.—Graphs showing different types of water-level fluctuations in three observation wells and a comparison between the graphs plotted from daily, weekly, and monthly water levels in the same observation well.

this well would suffice. Well 2 is not affected by pumping, and the fluctuations are caused by slow recharge following winter precipitation, withdrawal by plants, and summer evaporation. Weekly or monthly measurements in this well would be adequate. Obviously, more frequent measurements and a greater use of automatic recorders are required for intensive investigations than for the determination of annual, secular, or long-term fluctuations.

In summary, the frequency of measurements must be tailored to the purposes for collecting the data within the constraints of funds and personnel.

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2.B. WELL-DISCHARGE MEASUREMENTS

Measurements of well discharge are used to determine well yield, relation of discharge rate to drawdown (specific capacity), aquifer response to pumpage, aquifer characteristics; to obtain basic data for quantitative analysis of the well-aquifer system; and to determine withdrawal volumes and rates from an aquifer or a ground-water basin. Measurement of discharge as used here refers to measurement of instantaneous flow rates. Measurement or estimate of withdrawal refers to long-term flow rates and implies indirect methods.

Requirements of accuracy in flow measurement vary with the purpose for which data are collected. For example, accuracy to within 5 percent is desirable if the data are to be used to determine aquifer characteristics. In contrast, in an inventory of ground-water withdrawal over a large area, it may be necessary to accept an estimate without knowing its accuracy.

Some wells flow at the surface, but removing water from most wells requires a pump. Pump type, capacity, and head requirements vary with the type of application, and range from a few gallons per minute for domestic supplies to thousands of gallons per minute for municipal, agricultural, and industrial supplies. Some of the more widely used means of lifting water from wells are described below.

2.B.1. PUMP TYPES

2.B.1.a. CENTRIFUGAL PUMPS

2.B.1.a.1. SHALLOW-WELL CENTRIFUGAL PUMPS

Pump and drive motor are both located at the surface in shallow-well centrifugal pumps. An impeller rotating inside the pump chamber discharges water by centrifugal force. The resulting pressure drop in the chamber creates a suction which causes water to enter the intake pipe in the well.

Since entrance of water into the intake depends on atmospheric pressure, the height of intake lift is limited to about 20 feet (6 meters) at sea level and less at higher altitudes. Very high discharge rates can be attained and water can be lifted as high as 150 feet (46 meters) above the pump.

2.B.1.a.2. DEEP-WELL (VERTICAL-LINE-SHAFT) TURBINE PUMPS

In the deep-well turbine pump, the pump is submerged and the drive motor or engine is at the surface. The impellers are driven by a vertical shaft, mounted inside the discharge pipe, which allows water to be lifted at high rates against high heads.

2.B.1.a.3. SUBMERSIBLE PUMPS

In submersible pumps, both pump assembly and electric drive motor are suspended from the discharge pipe and submerged in the well. The intake is located between the motor and the pump assembly. Horsepower, head, and lift capacity range widely.

2.B.1.a.4. JET PUMPS

Jet pumps consist of a centrifugal pumphead at the surface that circulates water through a Venturi tube and nozzle in the well. As the circulating water flows through the Venturi, pressure is reduced (suction) and additional water flows from the well annulus into the intake. Two pipes are necessary, one for downward flow, the other for upward return flow. This design allows water to be lifted from the well against a much higher head than surface-mounted centrifugal pumps can accommodate. Most jet pumps are used for relatively small supplies that require less than 25 gpm (1.6 L/s).

2.B.1.b. RECIPROCATING-PISTON PUMPS

These pumps are positive-displacement pumps consisting of a piston in a submerged cylinder operated by a rod connected to the drive mechanism at the surface. A flap valve or ball-check valve is located immediately above or below the piston cylinder. This pump is capable of lifting water from the well at relatively small rates against high head. It is used mostly for stock water supplies.

2.B.1.c. ROTARY PUMPS

Rotary pumps are also positive displacement pumps. In one design, water is moved by squeezing between gear-like, intermeshing teeth; in another, flexible vanes are rotated on an offset shaft inside a shaped chamber. As the vanes flex during rotation, displacement volume decreases, forcing the water out. Since these are normally suction-intake pumps, height of lift from the intake is limited to about 20 feet. Height of lift on the discharge side may be 200 feet or more.

2.B.1.d. AIR-LIFT PUMPS

Air-lift pumps move water by releasing compressed air through an air pipe inside a larger diameter discharge or eductor pipe. Mixing air bubbles with the water results in a lower water density inside the discharge pipe, allowing the water to be driven to the surface. This method is most efficient when about two-thirds or more of the air pipe is submerged, but efficiency in any case is low, and this method is not generally used as a permanent installation. High pumping rates can be attained, depending on compressor size, height of lift, etc.

2.B.2. FLOW MEASUREMENTS

Ground water discharge from wells (instantaneous flow measurement) should be measured directly where possible. Use indirect methods (long-term withdrawal measurements or estimates) with care, where necessary.

2.B.2.a. INSTANTANEOUS FLOW MEASUREMENTS

Numerous methods are useful for obtaining instantaneous flow measurements. Below are listed the most useful methods.

2.B.2.a.1. TIMED VOLUME

A stopwatch can be used to measure the time to fill a container of known volume with water. The stopwatch is a simple and accurate method (Johnson, 1966 and U.S. Departments of the Army,

the Navy, and the Air Force, 1971) provided a sufficient period of time elapses so any error in measuring time is negligible.

2.B.2.a.2. BAILER

Water is removed from the well by bailing with a container of known volume, being sure to measure water levels before and after bailing. This method is most often used when the well is completed in order to obtain preliminary well yield and drawdown information.

2.B.2.a.3. CIRCULAR ORIFICE (FREE DISCHARGE ORIFICE)

A steel plate with an accurately-cut, centered, circular, and beveled-edge hole is attached to the end of a pump discharge pipe. The plate restricts the flow through the orifice and creates a pressure head in the discharge pipe. The head in the discharge pipe is measured in a piezometer tube set back at least three discharge pipe diameters from the orifice. Head is correlated with discharge by use of appropriate tables or curves calibrated for the particular ratio between orifice diameter and discharge-pipe diameter. This method yields an accuracy within 2 percent. This method assumes that the discharge pipe is level, the water falls freely, and there are no air bubbles in the piezometer tube or any flow disturbances within 10 pipe diameters of the piezometer tube (Jorgensen, 1969; Layne and Bowler, Inc., 1958; and Johnson, Inc., 1966).

2.B.2.a.4. PIPE ORIFICE

A pipe orifice is a circular orifice enclosed in the discharge line and mounted between two pipe flanges. Full-pipe flow is measured by observing head differential ahead and behind the orifice by means of a differential manometer. Manometer readings are correlated with discharge by formulas, curves, or tables. Flow requirements and accuracy are similar to those for circular orifices (U.S. Departments of the Army, the Navy, and the Air Force, 1971).

2.B.2.a.5. CURRENT METER

Discharge can be computed using the mean velocity of open-channel flow through a measured cross-sectional area. Velocity and depth are measured at several points across the channel. Velocity is measured by use of one of several types of current meters; the most common is the vertical-axis meter such as the pygmy meter, or for large flows, the Price AA meter. Mean velocity is multiplied by cross-sectional area to find discharge. This method yields a maximum accuracy of about 5 percent and is often used to double check flow measurements made by other methods, such as by weirs or flumes (Buchanan and Somer, 1969; King and Brater, 1963; and U.S. Bureau of Reclamation, 1967).

2.B.2.a.6. WEIR OR FLUME

Discharge can be computed by measuring the head of water as it flows through weir and flume openings of various shapes.

Tables or curves have been prepared for determining discharge-head relatioinships for various shaped openings. The most common weir opening shapes are triangular (V-shaped), rectangular, or trapezoidal. These and other types of weirs require low approach velocities, attained by pooling water above the weir. The most common flume is the Parshall flume, which has the advantages of not requiring low approach velocity and of being self-cleaning. Weirs and flumes are advantageous in accurately measuring large to very large flows (King and Brater, 1963; Smoot and Novak, 1968; and U.S. Bureau of Reclamation, 1967).

2.B.2.a.7. PIPE-FLOW CURRENT METER APPLICATIONS

Discharge from an open pipe, flowing full and having free fall of water, may be measured by a modified horizontal-shaft propellor-type current meter. Velocity of flow is measured inside the end of the pipe, at the center of flow. Discharge is the product of the velocity reading and a constant for the size of discharge pipe used.

A propellor-type meter may be mounted inline in a short length of portable pipe attached to the end of the discharge pipe or inline in the discharge pipe. The pipe must flow full. Some portable assemblies are equipped with a riser gooseneck on the downstream side of the meter to maintain full pipe flow.

These methods yield an accuracy within 5 percent (Rohwer, 1942).

2.B.2.a.8. PITOT TUBE

Full pipe flow in a closed system may be determined by use of pitot tubes inserted in the discharge pipe. The tubes are used to measure pressure head at different points in the pipe cross section. Head is related to velocity at each point, and average velocity is multiplied by pipe area to obtain discharge (King and Brater, 1963; U.S. Bureau of Reclamation, 1967; U.S. Departments of the Army, the Navy, and the Air Force, 1971).

2.B.2.a.9. WATER METER

Discharge can be computed by using a water meter that totalizes volume of flow during a timed interval (Johnson, Inc., 1966).

2.B.2.a.10. ORIFICE BUCKET

This device consists of a cylindrical tank having one or more holes drilled through the bottom. Water flowing into the container rises to a head sufficient to balance outflow through the holes. Head is read in a piezometer tube attached to the bucket, and is converted to flow rate by use of a table or curve. The Illinois State Water Survey uses such a device for measuring flow rates up to about 150 gpm (9.5 L/s) (Johnson, Inc., 1966).

2.B.2.a.10.a. Pressure gage with pitot adapter

This pressure gage may be used to measure inline discharge through a sprinkler system. Flow of water through a sprinkler head is a function of pressure and nozzle diameter. Ratings for various types of sprinkler nozzles are avilable from manufacturers.

2.B.2.a.10.b. Venturi meter

The venturi meter can be installed in the discharge pipe almost anywhere along the pipe. Flow through this meter is proportional to pressure head difference between that at the entrance to the meter and that at the point of maximum constriction of the venturi throat. Piezometers for low pressures or a differential mercury manometer for high pressures may be used. Pressure readings are correlated with flow by use of appropriate tables or curves (U.S. Bureau of Reclamation, 1967; and U.S. Departments of the Army, the Navy, and the Air Force, 1971).

2.B.2.a.10.c. Free fall or jet flow

Trajectory free fall or jet flow of water from a horizontal pipe flowing full can be used to provide a fair estimate of flow. The distance, in inches, from the end of the discharge pipe to a point one foot above the falling stream of water, multiplied by the cross-sectional area of the pipe, in

square inches, is approximately equal to the discharge in gallons per minute (U.S. Departments of the Army, the Navy, and the Air Force, 1971).

2.B.2.b. INDIRECT DETERMINATIONS OF LONG-TERM WITHDRAWAL

2.B.2.b.1. FUEL OR POWER CONSUMPTION

Records of fuel or electric power consumption for pumping over a period of time, pump efficiency ratings, and height of lift may be used to estimate ground-water withdrawal. In most cases, loss of efficiency by pump wear must be taken into account.

2.B.2.b.2. METERED WATER SALES

Records of metered water sales obtained from water companies whose supply is from ground water are useful. Water sales revenues may also be useful, but these records are complicated by flat rates, minimum charges, and sliding scale arrangements.

2.B.2.b.3. PUMP-OPERATION DURATION

Where the pumping rate is known, long-term withdrawal is the product of rate and duration of pump operation. Otherwise, pump head capacity, efficiency, and height of lift must be known in order to estimate withdrawal.

2.B.2.b.4. FINISHED-PRODUCT VOLUME

If the quantity of water required to manufacture one unit is known, the volume (or number) or finished product of factory output can be used to estimate long-term withdrawal.

2.B.2.b.5. AGRICULTURAL DEMAND

In areas where irrigation is practiced and where no other data are available, agricultural demand may be used as a very coarse estimate of ground-water withdrawal. The estimate is based on seasonal crop requirements by acreage and variety of crop. Water requirements for other agricultural practices, such as beef, dairy, or poultry farming, may also be used to estimate withdrawal.

2.B.2.b.6. WELLS

Where irrigation practices are similar, an estimate of withdrawals may be made by assigning a reasonable average annual or seasonal pumpage per well and multiplying this figure by the number of irrigation wells.

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2.C. MULTIAQUIFER-WELL INTERNAL FLOW

Data on inhole flow is related to well construction, differences in head, and the relative magnitude of permeability of the water-bearing units open to the well.

2.C.1. PRINCIPLES

Devices used to measure the vertical component of flow in a single well include impeller flowmeters and various systems for injecting and detecting chemical tracers. The impeller flowmeter transmits pulses, which indicate the number of impeller revolutions per unit time. In tracer tests, various tracers are injected into the column of water, and the tracer's movement is timed.

Interpreting all types of vertical fluid-movement logs is similar, regardless of whether they are made with impeller or tracer probes.

2.C.2. INSTRUMENTATIONS

Patten and Bennett (1962) discuss various methods of flow measurement in wells, with the exception of radioactive tracers. Their discussion and new developments are summarized here. The most widely used devices for measuring flow in water wells use impellers, rotors, or vanes housed inside a protective cage or basket.

Pulses can be coded so that the direction of rotation can be ascertained without moving the flowmeter. Pulses from the flowmeter can be integrated into a standard gamma-logging module, and the time constant adjusted so a smooth integrated trace, or an integrated trace with pulses superimposed, can be recorded. Loggers with time drive on the recorders also permit the graphic recording of pulses per unit time. In this manner, all data from either continuous or stationary flowmeters is automatically recorded. Some flowmeters have a number of interchangeable baskets and impellers of different diameters. The chief advantages of an impeller flowmeter are its simplicity and its relatively low cost. Disadvantages include nonlinear response, lack of sensitivity at low velocity, and poor accuracy at high velocity; also, none are available for very small diameter holes.

A significant improvement can be made in the performance of any type of flowmeter by adding a device to force all or most of the flow through the cage or basket. The performance of most flowmeters can be improved with a simple centralizing flange. A thick rubber flange and an annular bristle-type brush have been used successfully. The rubber flange can be cut to fit the hole diameter.

2.C.3. APPLICATIONS

One of the most common applications of the measurement of vertical-fluid movement is in wells that are open to a multiaquifer artesian system (Bennett and Patten, 1960). If there are differences in head between aquifers, flow will occur within the well (figure 2–6).

An example of the measurement of natural flow in a well with an impeller-type flowmeter is shown in figure 2–7. The left side of figure 2–7 shows continuous integrated flowmeter logs made to locate the zones of flow. In this mode of operation, the logs were run with the sonde moving down and up the hole at a relatively constant logging speed.

The individual pulses on these logs are caused by rotation of the impeller. The pulses are integrated, so a deflection of the trace to the right indicates an increase in revolutions per unit time. If it were possible to maintain the same constant logging speed up and down a hole, and if the position of a symmetrical sonde in the hole were consistent, logs made up and down in a stagnant column of water would be the same. Therefore, the zone of maximum curve separation in figure 2–7 represents a zone of upward flow. The impeller revolutions increased when the sonde was moving against the upward flow and decreased when the sonde was moving in the same direction as the flow. The deflections on one log not matched by deflections in the opposite direction on the other log were probably caused by changes in logging speed or by the probe bouncing off the casing. When the logs were repeated, only the curve separation between 259 and 272 feet were duplicated. By moving the flowmeter, flow can be detected that is too slow to detect with a stationary flowmeter. When the velocity of flow is equal to the logging speed, the impeller ceases to rotate.

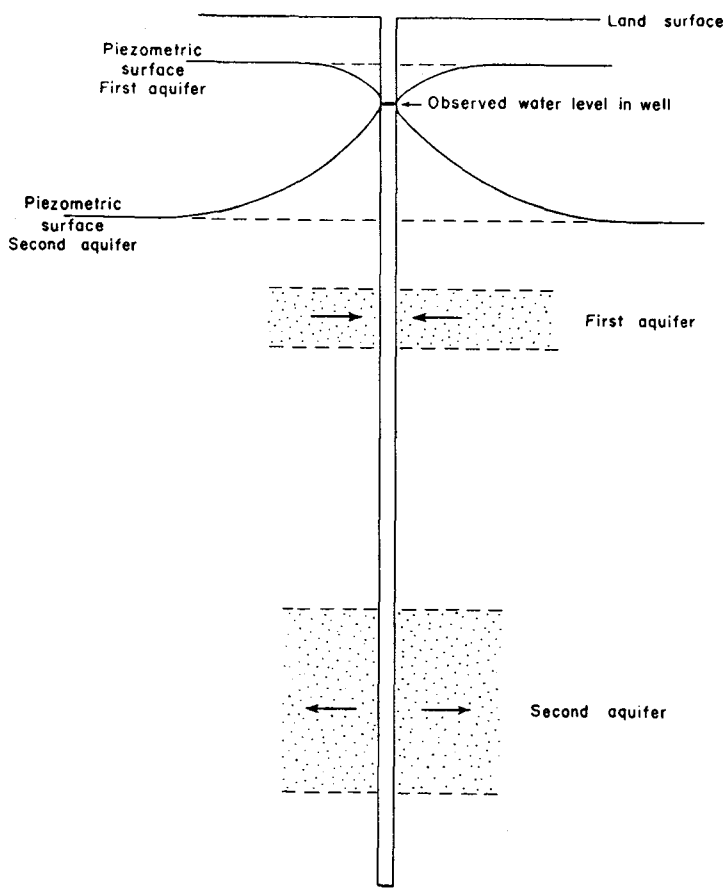

Figure 2–6.—Internal flow in a multiaquifer well.

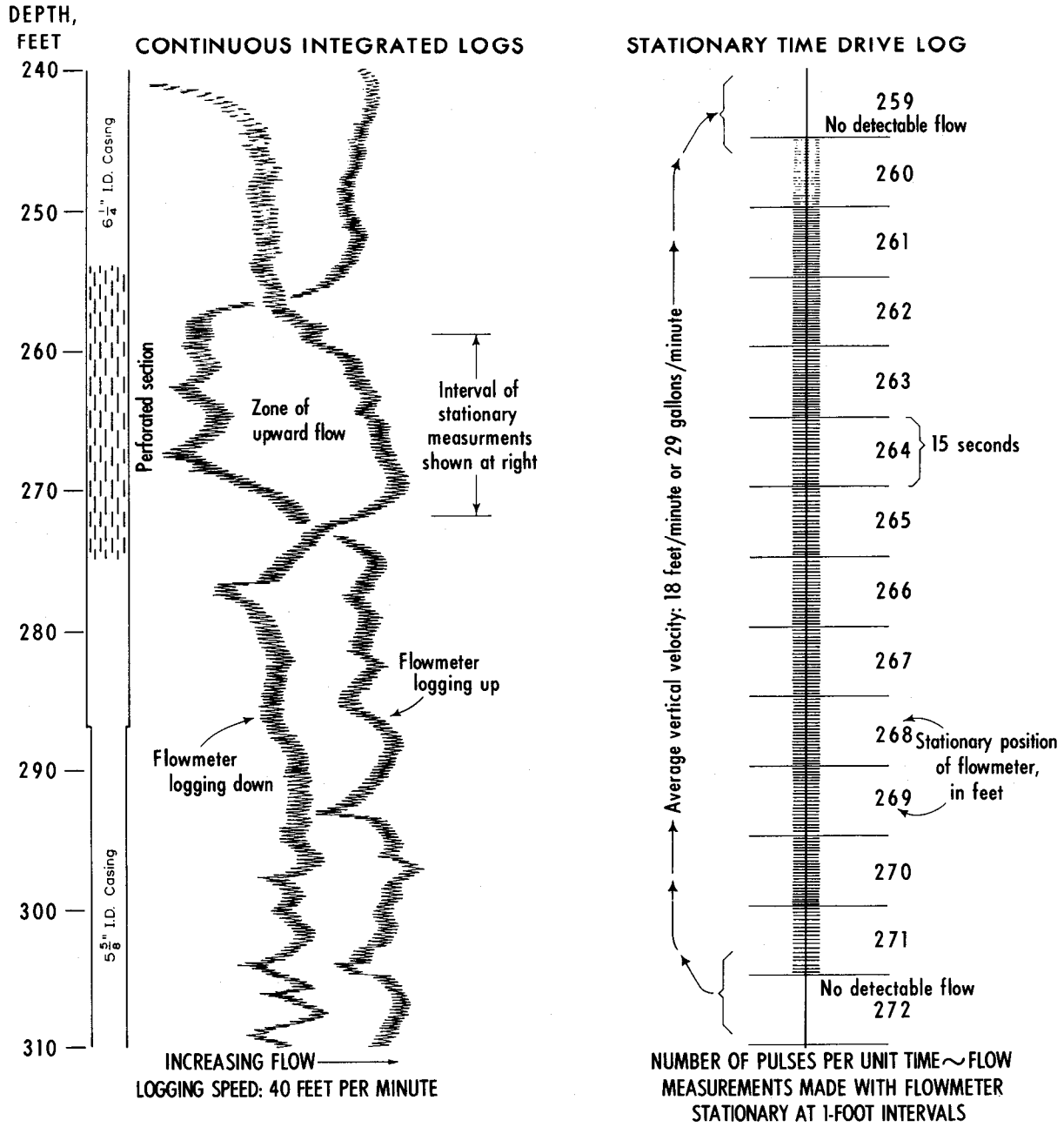

Figure 2–7.—Continuous flowmeter logs, used to locate the zone of flow (left) and to determine stationary time-drive measurements across that interval (right).

The right-hand log in figure 2–7 shows stationary-flowmeter measurements made through the same zone. In this mode, the recorder on the logger is set to operate on time drive—4 inches per minute on this log—and individual pulses caused by rotation of the impeller are recorded. Note on this log that only minor changes in velocity occurred across the zone of interest.

Apparently, all the water was entering and leaving the screen in two very thin zones separated by relatively impermeable material. Such flow lowers the head in the contributing aquifer and may

result in either thermal or chemical pollution of the aquifer having the lower head. Vertical flow in a well may invalidate pump-test data if not detected. Vertical flow will also complicate sampling for water quality of zones of lower head.

In addition to impeller flowmeters, brine-tracer techniques for inhole flow surveys are widely used in ground-water investigations. Basically, the downhole equipment consists of a device for injecting a brine solution in the well and one or several fluid conductivity detectors. A common type of tracejector used consists of a positive-displacement piston-type pump that will eject from a fraction of a milliliter to 20 milliliters of a water-soluble tracer.

The ejector is operated by direct current from the surface. The module for operating a motor-driven caliper may be used. The fluid conductivity probes may be attached to the ejector in any one of a number of combinations.

When direction of flow is not known, they may be placed above and below the ejector. When direction is known, they may both be attached above or below the ejector to increase the accuracy of measurement.

The recorder is operated on time drive, and an event marker is automatically triggered when the switch is depressed to eject the brine solution.

A brine ejector-detector system has the advantage of using a less expensive, more readily available tracer that does not require licensing. However, chemical tracers have disadvantages in that results are affected more by the specific gravity of the solution; they have a lower detection sensitivity; and they are not detectable through casing. Figure 2–8 shows the tool that is set up to measure downward flow. On the left are actual time-drive logs of three different salt tracers within the same flow system. Some solutions (in this case the NH_4I solution) show higher downward velocity than the true water velocity because the solution has greater specific gravity than the well water. An event marker records the instant of ejection, and a plot of fluid conductivity versus time is made automatically. After the slug of tracer has passed the detector, the tool may be moved to follow it, but this causes some mixing and disturbance in the flow system.

Tools using two sets of electrodes for tracer detection above or below the ejector are more desirable. This method is inherently accurate and usable at low velocities and is proabably the most useful flowmeter available for a variety of borehole conditions.

2.C.4. CALIBRATIONS AND EXTRANEOUS EFFECTS

All the flow-measuring devices described are subject to extraneous effects; hence, all of the devices should be calibrated by empirical methods. Aside from the disadvantages mentioned for each tool, a problem common to all is the apparent change of fluid velocity caused by varying the probe position radially within the borehole. The velocity of a fluid moving through a smooth cylinder is lowest near the wall, and is fairly constant across most of the central part of the conduit. Thus, a flow-measuring device that measures the velocity of only a small part of the total cross-sectional area can give low results if it is located near the wall. For this reason, using centralizing devices, channelling flanges, or packers improves the accuracy of flow measurement.

Lateral dispersion of the tracer into the central zone of maximum velocity occurs with vertical movement. The directional effect on the output of a flow-measuring sonde is significant if the upper and lower parts of the sonde are not mirror images. Generally, a symmetrical tool is not feasible to construct because of the cable connector. Directional errors due to specific-gravity differences between tracers and water are only significant at low velocities and can be checked in a stationary column.

Tools that have a large diameter in relation to the diameter of the well will cause the greatest vertical dispersion when they pass through a slug of tracer.

Flow-measuring devices should be calibrated in the size of casing or hole in which they are to be used. Open-hole flow surveys should be checked against caliper logs.

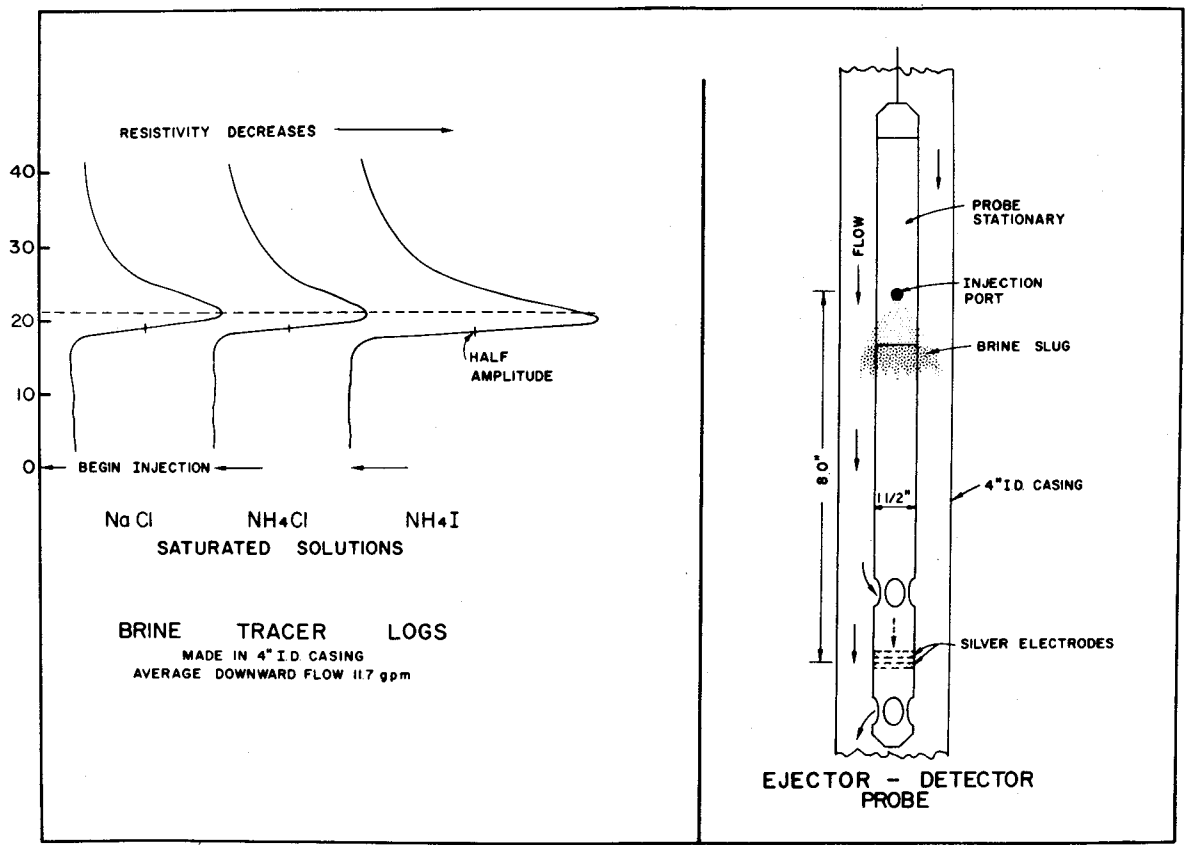

Figure 2-8.—Brine ejector-detector probe (right) and logs of three different salts used as tracers (left).

In addition, the equipment should be calibrated for both flow directions, if possible. Field-standardizations, or calibrations for one size can be done either when a well is being pumped or when water is being injected into the well at a known rate. By careful calibration and field standardization, errors at low-flow velocities can be reduced to 10 percent, and at high velocities, to as low as 1 percent.

2.C.5. REFERENCES

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2.D. GEOPHYSICAL MEASUREMENTS

2.D.1. SURFACE METHODS [1]

Geophysical surveys can be useful in the study of many subsurface geologic and hydrologic problems. However, geophysical surveys are not always the most effective method of obtaining the needed information. For example, in some areas, auger or drill holes may be a more effective way of

[1] This section is a condensed revision by A. A. R. Zohdy, edited by H. E. Gill and others, of the report "Zohdy, A. A. R., Eaton, G. P., and Mabey, D. R., 1974, Application of surface geophysics to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chap. D1, 116 p.

obtaining near-surface information than geophysical surveys. In some investigations, a combination of drilling and geophysical measurements may provide the optimum cost-benefit ratio. Geophysical surveys are not practical in all ground-water investigations, but this determination usually can be made only by someone with an understanding of the capabilities, limitations, and costs of geophysical surveys.

Some simple geophysical surveys can be made by individuals with little previous experience and with an investment in equipment of only a few hundred dollars. Other surveys require highly skilled personnel working with complex and expensive equipment. Good equipment and technical expertise are essential to a high quality survey.

Some geophysical data can be used directly in geologic interpretations. Other geophysical data require considerable processing before the data can be interpreted, and the cost of data reduction is a major part of the total cost of the survey. Many data processing operations in use today require the use of electronic computers.

Interpretation of geophysical data can be completely objective or highly subjective. It can range from a simple inspection of a map or profile to a highly sophisticated operation involving skilled personnel and elaborate supporting equipment. Some interpretations require little understanding of the geology, but the quality of most interpretations is improved if the interpreter has a good understanding of the geology involved. Although some individuals are both skilled geophysicists and geologists, a cooperative effort between geologists and geophysicists is usually the most effective approach to the interpretation of geophysical data.

2.D.1.a. ELECTRICAL METHODS

The electrical properties of most rocks in the upper part of the Earth's crust depend primarily on the amount, salinity, and distribution of water in the rock. Saturated rocks have lower resistivities than unsaturated and dry rocks. The higher the porosity (percent void space) of the saturated rock, the lower its resistivity; the higher the salinity of the saturating fluids, the lower the resistivity. Clays and conductive minerals also reduce the rock's resistivity.

Two properties are of primary concern in applying electrical methods: (1) the ability of rocks to conduct an electric current, and (2) the polarization which occurs when an electrical current is passed through the rocks (induced polarization). The electrical conductivity of earth materials can be studied by analysis of the electrical potential distribution produced at the Earth's surface as a result of passing a direct current through the Earth. Conductivity may also be measured by analysis of the electromagnetic field produced by passing an alternating electric current through the Earth. Measuring natural electric potentials (spontaneous polarization, telluric currents, and streaming potentials) has also been useful in geologic investigations. The principal methods using natural energy sources are telluric current, magnetotelluric, spontaneous polarization, and streaming potential.

2.D.1.a.1. TELLURIC-CURRENT METHOD

Telluric currents (Cagniard, 1956; Berdichevskii, 1960; Kunetz, 1957) are natural electric currents that flow within the Earth's crust in the form of large sheets. These currents constantly change intensity and direction.

It is believed telluric currents originate in the ionosphere and are related to ionospheric tidal effects created by the continuous flow of charged particles from the sun that become trapped by the Earth's magnetic field.

If the ground in a given area is horizontally stratified and the surface of the basement rocks is also horizontal, then at any given moment the density of the telluric current is uniform over the entire area. In the presence of geologic structures, such as anticlines, synclines, and faults, the distribu-

tion of current density is not uniform. Current density is a vector quantity, and the vector is larger when the telluric current flows at right angles to the axis of the structure.

By plotting these vectors, we obtain ellipses over anticlines and synclines and circles where the basement rocks are horizontal. The longer axis of the ellipse is oriented at right angles to the axis of the geologic structure.

The measurement of telluric field intensity is relatively simple. Four electrodes, M, N, M′, and N′ are placed on the surface of the ground at the ends of two intersecting perpendicular lines, and the potential differences are recorded on a potentiometric chart recorder or on an *x-y* plotter (Yungul, 1968). From these measurements two components, E_x and E_y of the telluric field can be computed, and the total field obtained by adding E_x and E_y vectorially.

The intensity and direction of the telluric current field vary with time; therefore, measurements must be recorded simultaneously at two stations to compensate for this variation. One station is kept stationary (base station), and the other is moved to a new location in the field (field station) after each set of measurements. The ratio of the area of the ellipse at the field station to the area of a unit circle (Keller and Frischknecht, 1966) at the base station is calculated mathematically. When a contour map of equal elliptical areas is prepared (Migaux, 1946, 1948; Migaux and others, 1952; Migaux and Kunetz, 1955; Schlumberger, 1939), it reflects the major geologic structures of the basement rocks in much the same manner as a gravity map or magnetic map. However, a telluric map delineates rock structure based on differences in electrical resistivity rather than on differences in density or magnetic susceptibility.

2.D.1.a.2. MAGNETOTELLURIC METHOD

The magnetotelluric method (Berdichevskii, 1960; Cagniard, 1953) of measuring resistivity is similar to the telluric current method, but it has the advantage of providing an estimate of the true resistivity of the layers. Measurements of amplitude variations in the telluric field E_x, and the associated magnetic field H_y, determine Earth resistivity. Magnetotelluric measurements at several frequencies will provide information on the variation of resistivity with depth because the depth of penetration of electromagnetic waves is a function of frequency. This method is limited by the instrumental difficulty of measuring rapid fluctuations of the magnetic field. Interpretation techniques usually involve comparisons of observed data with theoretical curves. The magnetotelluric method is useful in exploring depths greater than can be reached effectively by methods using artificially induced currents.

2.D.1.a.3. AUDIO-MAGNETOTELLURIC METHOD

The AMT (Audio-magnetotelluric) method uses electromagnetic energy from distant sources, and this permits a plane-wave assumption. Although artificial or natural sources may be used, most work has been done with natural sources because of the convenience of not having to provide a strong source field. This method is not without problems, however, because of the vagaries of natural signals. The system used by Hoover and Long (1976) used natural sources, with the exception of the upper end of their operating frequency spectrum. The frequency range covered by their system goes from the first Schumann resonance at about 8 Hz to 18,600 Hz where a convenient source was available from a Navy VLF (Very Low Frequency) broadcast station.

The usable natural energy for AMT exploration originates in worldwide lightning storms, with the principal energy coming from tropical storm cells that occur most frequently during the summer months. The method has been well-described by Strangway, Swift, and Holmer (1973) in relation to mineral exploration.

The apparent resistivity at a given frequency is determined by measuring the mutually orthogonal electric and magnetic fields of the distant lightning.

The maximum exploration depth varies with the square root of the resistivity of the section and with the inverse square root of the frequency.

From the experience of Hoover and Long (1976), Strangway, Swift, and Homer (1973), and Strangway and Vozoff (1970), evidence for lateral resistivity changes is common on AMT sounding curves.

As a reconnaissance technique, AMT surveys are made in conjunction with regional gravity, magnetic, and telluric surveys. The exploration depth is a function of the resistivities of the lithologic section, but it typically ranges from the surface to 0.2 kilometer in low-resistivity areas and to greater than 2 kilometers in high-resistivity regions. Results of reconnaissance AMT surveys provide a rational basis for deciding the extent of costlier follow-up surveys.

Spontaneous polarization or self-potential methods involve measuring electric potentials developed locally in the Earth by electrochemical activity, electrofiltration activity, or both. The most common use of self-potential surveys has been in searching for ore bodies in contact with solutions of different compositions. The result of this contact is a potential difference and current flow which may be detected at the ground surface. Of more interest to ground-water investigations are the potentials generated by water moving through a porous medium (streaming potentials). Measurements of these potentials have been used to locate leaks in reservoirs and canals (Ogilvy and others, 1969).

Spontaneous potentials generally are no larger than a few tens of millivolts, but in some places potentials may reach a few hundred millivolts. Relatively simple equipment can be used to measure the potentials, but spurious sources of potentials often obscure these natural potentials. Interpretation is usually qualitative, although some quantitative interpretations have been attempted.

2.D.1.a.4. DIRECT-CURRENT RESISTIVITY METHOD

The resistivity of a material is defined as being numerically equal to the resistance of a specimen of the material of unit dimensions. The unit of resistivity in the SI metric system is the ohm-meter (ohm-m).

2.D.1.a.4.a. Rock Resistivities

Rocks and minerals display a wide range of resistivity (ρ). For example, graphite has a resistivity of the order of 10^6 ohm-m, whereas some dry quartzite rocks have resistivities of more than 10^{12} ohm-m (Parasnis, 1962). No other physical property of naturally occurring rocks or soils displays such a wide range of values.

In most rocks, electricity is conducted electrolytically by interstitial fluid, and resistivity is controlled more by porosity, water content, and water quality than by the resistivities of the rock matrix. Clay minerals, however, are capable of conducting electricity electronically, and the flow of current in a clay layer is both electronic and electrolytic. Resistivity values for unconsolidated materials commonly range from less than 1 ohm-m for certain clays or sands saturated with saline water, to several thousand ohm-m for dry basalt flows, dry sand, and gravel. The resistivity of sand and gravel saturated with fresh water ranges from about 15 to 600 ohm-m. Field experience indicates that values ranging from 15 to 20 ohm-m are characteristic of aquifers in the southwestern United States, whereas in certain areas in California the resistivity of fresh-water-bearing sands generally ranges from 100 to 250 ohm-m. In parts of Maryland, resistivities have been found to range between about 300 and 600 ohm-m, which is about the same range as that for basaltic aquifers in southern Idaho. The geophysicist should be familiar with the resistivity spectrum in the survey area before he draws conclusions about the distribution of fresh-water aquifers.

2.D.1.a.4.b. Principles of Resistivity Method

In making resistivity surveys, a commutated direct current or very low frequency (<1 Hz) current is introduced into the ground via two electrodes. The potential difference is measured between a second pair of electrodes. If the four electrodes are arranged in any of several possible patterns, the current and potential measurements may be used to calculate resistivity.

For a semi-infinite medium, which is the simplest Earth model, and with both current and potential point-electrodes placed at the Earth surface,

$$V=\frac{\rho I}{2\pi \overline{AM}}$$

where V is the electric potential at any point ρ caused by a point electrode emitting an electric current I in a homogeneous and isotopic medium of resistivity ρ and where $\overline{AM}$ is the distance on the Earth's surface between the positive current electrode A and the potential electrode M.

The value of the apparent resistivity measured in the field is a function of several variables: the electrode spacings, the geometry of the electrode array, and the true resistivities and other characteristics of the subsurface materials, such as layer thicknesses, angles of dip, and anisotropic properties. The apparent resistivity, depending on the electrode configuration and on the geology, may be a crude average of the true resistivities in the section, may be larger or smaller than any of the true resistivities, or may even be negative (Al'pin, 1950; Zohdy, 1969b).

2.D.1.a.4.c. Electrode Configurations

Zohdy and others (1974) describe the design of commonly used electrode array configurations.

2.D.1.a.4.d. Electrical Soundings and Horizontal Profilings

Electrical sounding is used to investigate depth, and horizontal profiling is used to detect lateral variations in resistivity. However, the results of electrical sounding and of horizontal profiling are often affected by both vertical and horizontal variations in the electrical properties of the ground.

If the ground is comprised of horizontal, homogeneous, and isotropic layers, electrical sound data represent only the variations of resistivity with depth. In practice, however, the electrical sounding data are influenced by both vertical and horizontal heterogeneities. Therefore, the execution, interpretation, and presentation of sounding data should be such that horizontal variations in resistivity can be distinguished easily from vertical ones.

The basis for making an electrical sounding, irrespective of the electrode array used, is that the farther away from a current source the measurement of the potential or the potential difference the electric field is made, the deeper the probing will be.

In horizontal profiling, a fixed electrode spacing is chosen (preferably on the basis of studying the results of electrical soundings), and the whole electrode array is moved along a profile after each measurement is made. The value of apparent resistivity is plotted, generally, at the geometric center 0 of the electrode array. Maximum apparent resistivity anomalies are obtained by orienting the profiles at right angles to the strike of the geologic structure. The results are presented as apparent resistivity profiles (fig. 2-9) or apparent resistivity maps (fig. 2-10), or both. In making horizontal profiles, it is recommended that at least two different electrode spacings be used, in order to aid in distinguishing the effects of shallow geologic structures from the effects of deeper ones (fig. 2-11). In figure 2-11, the effect of shallow geologic features is suppressed on the profile made with the larger spacing, whereas the effect of deeper features is retained.

The interpretation of horizontal profiling data is generally qualitative, and the primary value of the data is to locate geologic structures such as buried stream channels, veins, and dikes. Quan-

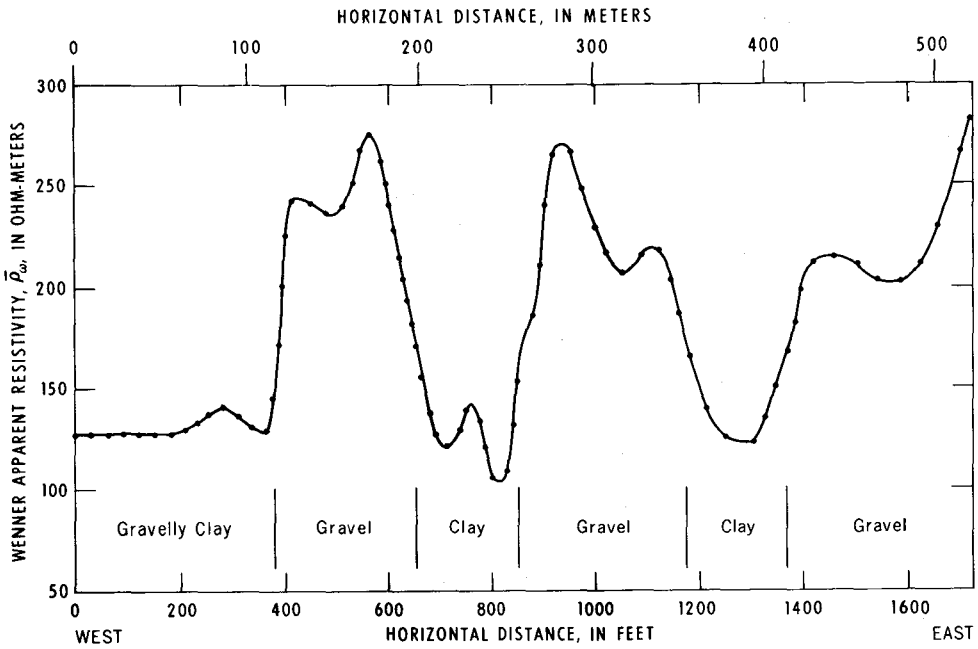

Figure 2-9. —Horizontal profile and interpretations over a shallow gravel deposit in California (Zohdy, unpub. data, 1964; Zohdy, 1964) using Wenner array at a = 9.15 meters.

titative interpretation can be obtained by making a sufficient number of profiles with different electrode spacings and along sets of traverses of different azimuths. Best interpretive results are obtained generally from a combination of horizontal profiling and electrical sounding data.

2.D.1.a.4.e. Problems of Defining Probing Depth

A misconception in electrical prospecting is that the electrode spacing is equal to the depth of probing. This leads to erroneous interpretations. When using direct current in probing a homogeneous and isotropic semi-infinite medium, there is a definite relation between the spacing separating the current electrodes and the depth to which any particular percentage of the current penetrates. For example, 50 percent of the current penetrates to a depth equal to one-half the current electrode separation and 70 percent to a depth equal to the current electrode separation. Therefore, the greater the current electrode separation, the greater amount of current that penetrates to a given depth.

The current-depth relation for a homogeneous and isotropic Earth cannot be used to establish a depth of penetration or probing depth that also applies to a stratified or an inhomogeneous Earth. For an inhomogeneous medium, the percentage of the total current that penetrates to a given depth Z depends not only upon the electrode separation but also upon the resistivities of the Earth layers. This fact was discussed by Muskat (1933), Muskat and Evinger (1941), Evjen (1938), Orellana (1960), (1961), and others. Furthermore, the current-depth relation used does not include the apparent resistivity nor the true resistivity (or resistivities) of the medium. Consequently, it is of no value in interpreting apparent resistivity data. In fact, in resistivity interpretation we do not care about the percentage of current that penetrates to a given depth or the percentage of current that exists at a given distance as long as we can make measurements of the total current and of the potential difference from which the apparent resistivity can be calculated.

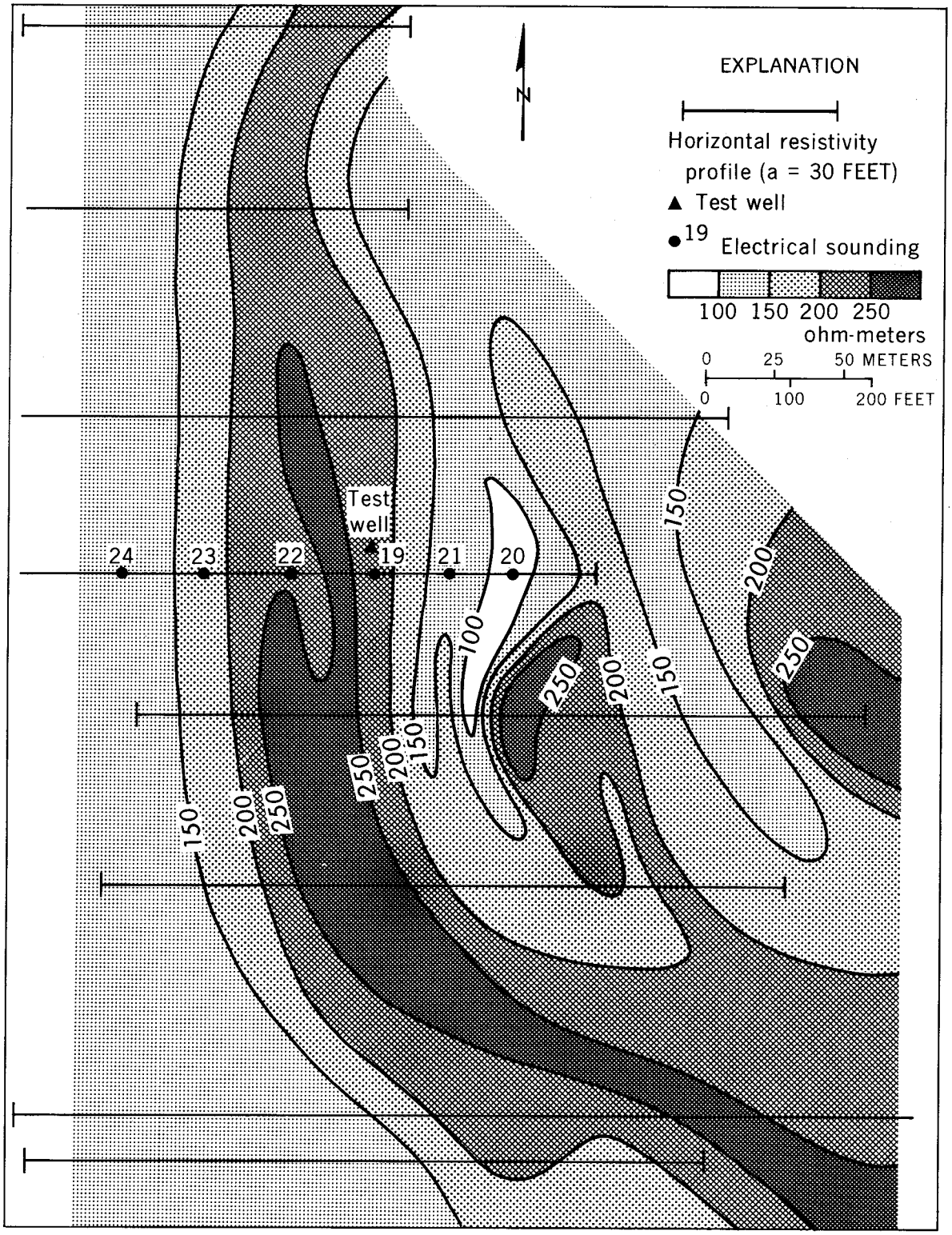

Figure 2-10. – Apparent-resistivity map near Campbell, Calif. Unpublished data obtained by Zohdy (1964) using Wenner array. Cross-hatched areas are buried stream channels containing thick gravel deposits. Stippled areas are gravelly clay deposits.

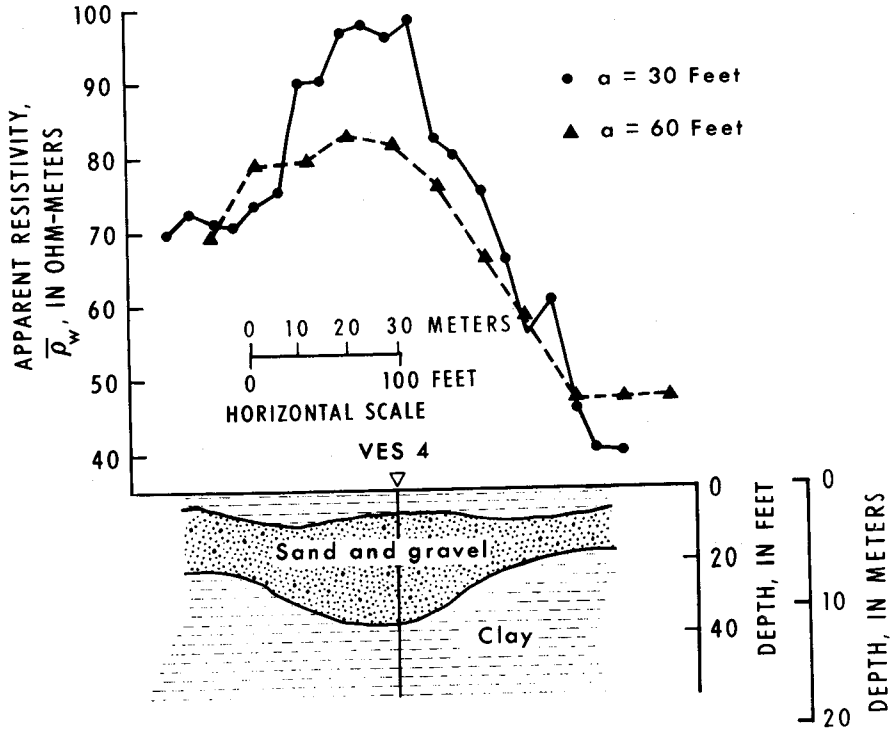

Figure 2-11.—Horizontal profiles over a buried stream channel using two electrode spacings: a = 9.15 m (30 ft) and a = 18.3 m (60 ft) (after Zohdy, 1964). VES 4 marks the location of an electrical sounding used to aid in the interpretation of the profiles.

2.D.1.a.4.f. Geoelectric Parameters

The electric boundaries separating layers of different resistivities may or may not coincide with boundaries separating layers of different geologic age or lithologic composition. For example, when the salinity of ground water in a given type of rock varies with depth, several geoelectric layers may be distinguished within a lithologically homogeneous rock. In the opposite situation, layers of different lithologies or ages, or both, may have the same resistivity and, thus, form a single geoelectric layer.

A geoelectric layer is described by two fundamental paramenters: its resistivity, ρ_i, and its thickness, h_i, where the subscript i indicates the position of the layer in the section ($i = 1$ for the uppermost layer).

Other geoelectric parameters are derived from its resistivity and thickness. These are:

1. Longitudinal unit conductance, $S_i = h_i/\rho_i$
2. Transverse unit resistance, $T_i = h_i\rho_i$
3. Longitudinal resistivity, $\rho_L = h_i/S_i$
4. Transverse resistivity, $\rho_t = T_i/h_i$
5. Anisotropy, $\lambda = \sqrt{\rho_t/\rho_L}$

For an isotropic layer $\rho_t = \rho_L$ and $\lambda = 1$. These secondary geoelectric parameters are particularly important when they are used to describe a geoelectric section consisting of several layers. (See Zohdy and others, 1974.)

In the interpretation of multilayer electrical sounding curves, the evaluation of S or T is sometimes all that can be determined uniquely. There are simple graphic methods for determining these parameters from sounding curves. The study of the parameters S, T, ρ_L, ρ and λ is an integral part of analyzing electrical sounding data and is also the basis of important graphic procedures for interpreting electrical sounding curves (Kalenov, 1957; Orellana and Mooney, 1966; Zohdy, 1965).

2.D.1.a.4.g. Electrical Sounding Curves Over Horizontally Stratified Media

The form of the curves obtained by sounding over a horizontally stratified medium is a function of the resistivities and thicknesses of the layers, as well as of the electrode configuration. (See Zohdy and others, 1974.)

2.D.1.a.4.h. Electrical Soundings Over Laterally Inhomogeneous Media

Lateral inhomogeneities in the ground affect resistivity measurements in different ways. The effect depends on (1) the size of the inhomogeneity with respect to its depth of burial, (2) the size of the inhomogeneity with respect to the size of the electrode array, (3) the resistivity contrast between the inhomogeneity and the surrounding media, (4) the type of electrode array used, (5) the geometric form of the inhomogeneity, and (6) the orientation of the electrode array with respect to the strike of the inhomogeneity.

The effects of dipping, vertical and horizontal contacts, and pipelines have been described in the literature for different electrode arrays (Kunetz, 1966).

2.D.1.a.4.i. Limitations of the Resistivity Method

The interpretation of a multilayer sounding curve generally is not unique. This means that a given electrical sounding curve can correspond to a variety of subsurface distributions of layer thicknesses and resistivities. Furthermore, several other limitations are inherent in the conventional methods of electrical sounding, and these are discussed in Zohdy and others (1970, p. 28).

These limitations do not mean that the interpretation of sounding data is an entirely hopeless endeavor. In practice, it is by correlation of several sounding curves, by making crossed soundings, by sounding with different arrays, by traversing the area with horizontal resistivity profiles, by knowledge of its general geology, and by recognition of the electrical properties of the rocks in the studied area that correct interpretations are achieved. When drilling information is available, it is advisable to make parametric electrical soundings near the wells in order to determine the resistivity parameters of the layers using accurately determined layer thicknesses. Then using these known resistivity parameters, the layer thicknesses can be determined in areas where drilling information is lacking.

2.D.1.a.4.j. Electrical Sounding Curves Analyses

Sounding curves generally may not be interpretable in terms of horizontally stratified media. This section discusses some of the qualitative and quantitative methods of interpreting electrical sounding data.

2.D.1.a.4.j.1. Qualitative Interpretation—The qualitative interpretation of sounding data involves the following:

1. Studying the types of sounding curves obtained and noting the areal distribution of these types on a map of the survey area.

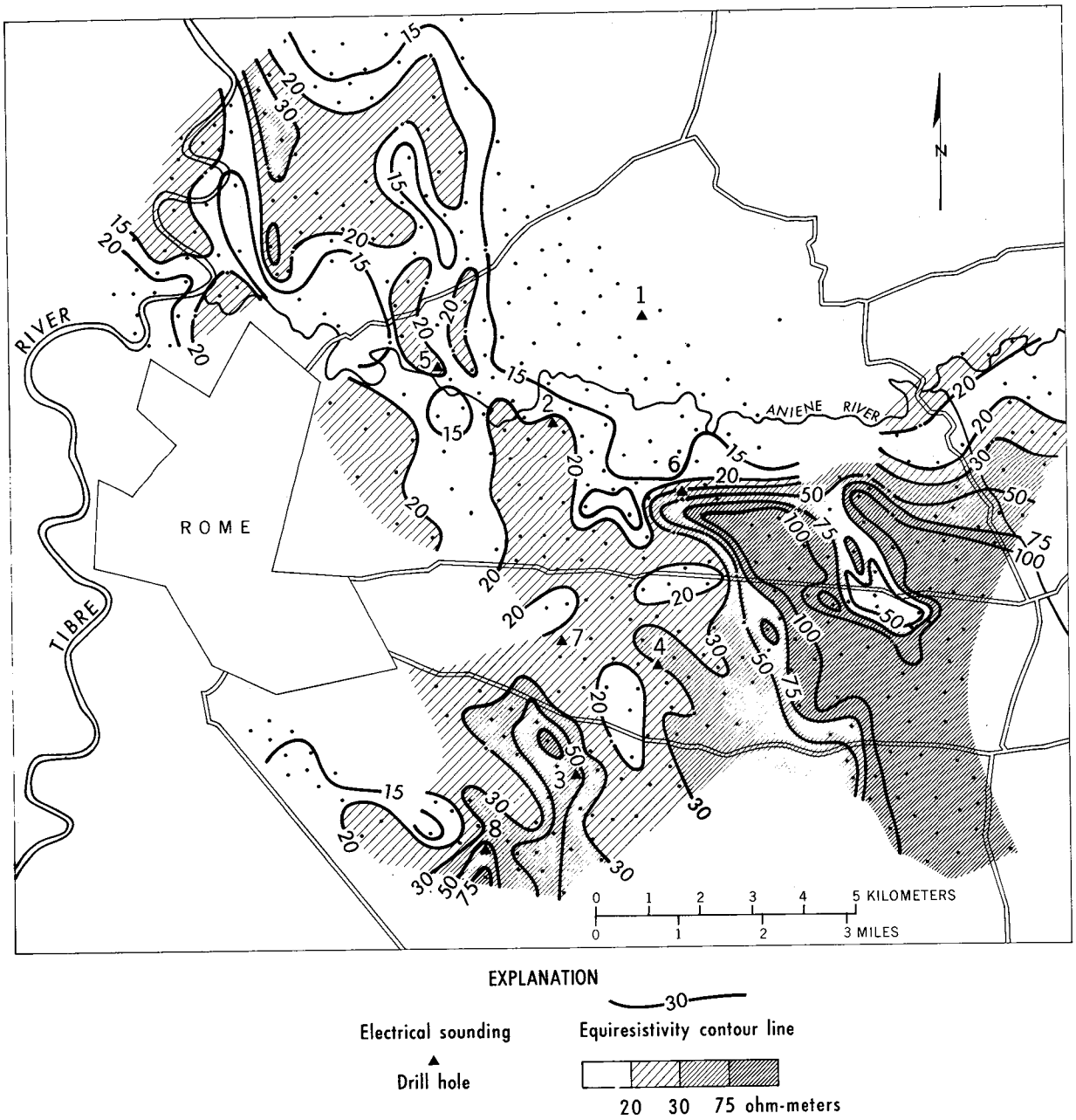

Figure 2-12.—Map of apparent resistivity near Rome, Italy (after Breusse, 1961).

2. Preparing apparent-resistivity maps. Prepare each map by plotting the apparent resistivity value, as registered on the sounding curve, at a given electrode spacing (common to all soundings) and contouring the results (fig. 2-12).
3. Preparing apparent-resistivity sections. Construct these sections by plotting the apparent resistivities, as observed, along vertical lines located beneath the sounding stations on the chosen profile. The apparent resistivity values are then contoured (fig. 2-13). Generally, a linear vertical scale is used to suppress the effect of near-surface layers.
4. Preparing profiles of apparent-resistivity values for a given electrode spacing, profiles of ρ_L values, and profiles of S and T values, among others.

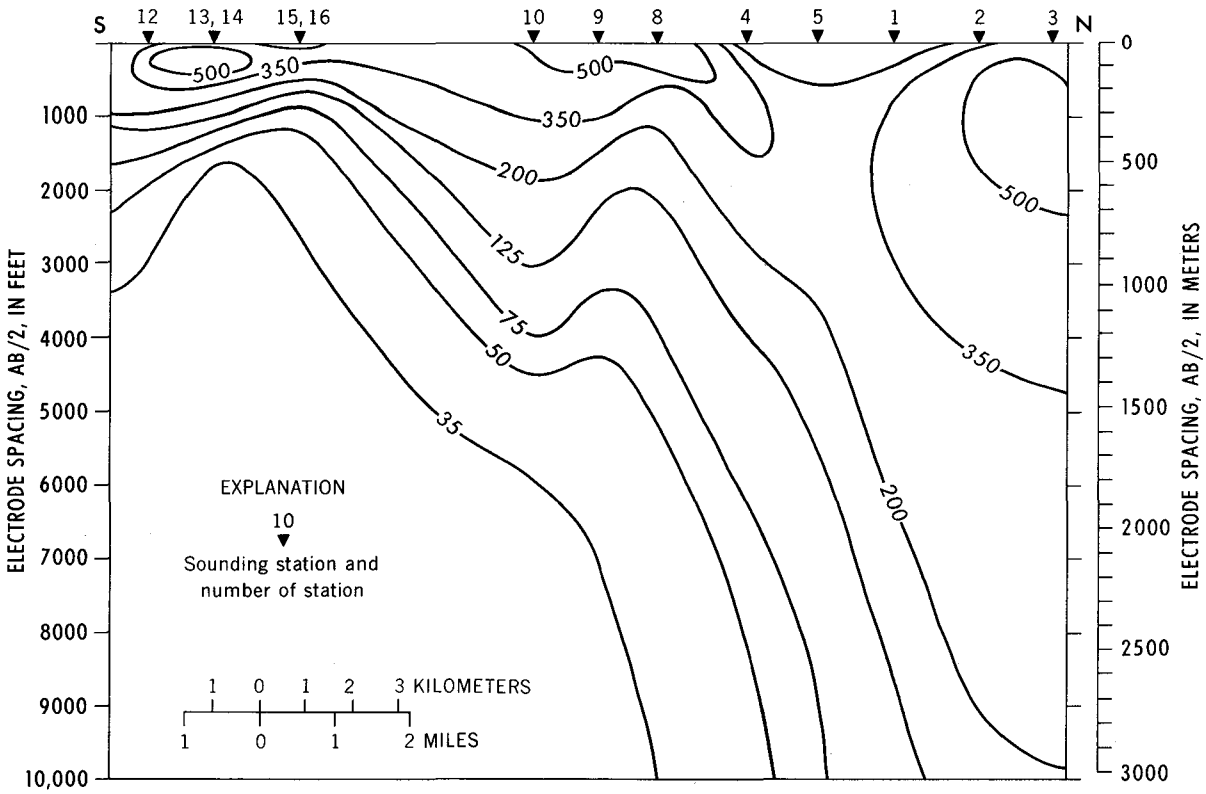

Figure 2-13.—Section of apparent resistivity near Minidaka, Idaho. Values on contour lines designate apparent resistivities in ohm-meters. Snake River basalt thickens toward the north.

These maps, sections, and profiles constitute the basis of the qualitative interpretation which should precede quantitative interpretation of the electrical sounding data.

Note, however, that an apparent resistivity map for a given electrode spacing (fig. 2-12) does not represent the areal variation of resistivity at a depth equal to that electrode spacing; it merely indicates the general lateral variation in electrical properties in the area. For example, an area of the map having high apparent resistivity values may correspond to a shallow high resistivity bedrock, it may indicate thickening in a clean sand and gravel aquifer saturated with fresh water, or it may indicate the presence of high resistivity gypsum or anhydrite layers in the section.

Electrical sounding curves may be distorted by lateral inhomogeneities in the ground, by errors in measurements, or by equipment failures. Zohdy and others (1974) discuss the causes of cusps, sharp peak values, and curve discontinuities on sounding curves.

2.D.1.a.4.j.2. Quantitative Interpretation—Zohdy and others (1974) indicate that of the analytical, semiempirical, and empirical methods of quantitative interpretation of electrical sounding curves, in most cases the analytical methods are preferred. The analytical methods are based on the calculation of theoretical sounding curves that match the observed curves.

Before interpretation is made with the master sets of sounding curves for horizontal layers, the interpreter must be satisfied with the form of the sounding curve, in that it is sufficiently smooth and not severely distorted by sharp cusps or discontinuities. A certain amount of smoothing generally is required. The type of curve and the minimum number of layers it seems to represent can be determined by visual inspection.

Computer programs have been developed for the automatic interpretation of some types of vertical electrical sounding (VES) curves (see Zohdy, 1974a; Zohdy and Bisdorf, 1975). These methods are intended for the processing of large numbers of VES curves on a digital computer in a very short time so that the interpreter may have a basic solution, and simplified solutions, for each observed VES curve. The basic solution may also be modified manually to obtain electrically equivalent solutions that will fit certain constraints on the layering in the survey area. The layering provided by the computer, moreover, may be considered as an interpretation made by an independent interpreter whose computations do fit the observed data and, therefore, may often point out a certain layering distribution which the interpreter may have overlooked.

These methods were designed so that positive, realistic, layer resistivities and thicknesses are always obtained, even if the VES curve is distorted by lateral heterogeneities. For these distorted VES curves, although a practically perfect match between observed and calculated curves may be impossible (because the solution is based on a horizontally stratified, laterally homogeneous earth model) the calculated curve will fit the observed points as closely as possible, except for those points near the distorted segment.

2.D.1.a.4.k. Resistivity Survey Applications

In ground-water studies, the resistivity method can furnish information on subsurface geology which might be unattainable by other geophysical methods. For example, electrical methods are unique in furnishing information concerning the depth of the fresh-salt water interface, whereas neither gravity, magnetic, nor seismic methods can supply such information. A thick clay layer separating two aquifers usually can be detected easily on a sounding curve, but the same clay bed may be a low velocity layer in seismic refraction surveys and cause erroneous depth estimates.

2.D.1.a.4.k.1. Mapping Buried Stream Channels—Buried stream channels, which often can be mapped accurately by the resistivity method, are favored targets for exploration. Horizontal profiling, electrical soundings, or both are used in their mapping. More details may be found in reports by Zohdy (1965b) and Hansen (1966).

Horizontal profiling has been used to furnish information on the presence or absence of shallow buried stream channels and electrical soundings for the determination of depth preceding and following the horizontal profiling survey.

2.D.1.a.4.k.2. Mapping Fresh-Salt-Water Interfaces—Zohdy and others (1969, 1974), Zohdy (1969a), Breusse (1950), Flathe (1967), Flathe and Pfeiffer (1964), van Dam and Meulenkamp (1967) discuss the use of resistivity methods for mapping fresh-salt water interfaces.

2.D.1.a.4.k.3. Mapping the Water Table—Determination of the depth to the water table is generally a more difficult problem than mapping the fresh-salt water interface. Deppermann and Homilius (1965) investigated the geoelectric conditions where the water table can be detected on an electrical sounding curve. Wherever the water table is overlain and underlain by several layers of different resistivities, its detection on a sounding curve may be virtually impossible. Under favorable conditions, the water table can be detected on a sounding curve as a conductive layer.

2.D.1.a.5. ELECTROMAGNETIC METHODS

Electrical surveys also are made using a time-varying electromagnetic field as an energy source. These electromagnetic or induction methods generally use frequencies in the range between 100 and 5,000 Hz, but radio waves of higher frequencies are also used.

The magnetic field is produced by passing an alternating current through a wire loop. When this primary field is imposed on Earth materials, a flow of electrical current results. The amount of current flow, as in other electrical surveys, depends on the conductivity of the layers. The current flow produces a secondary magnetic field which has the same frequency as the primary field, but not the same phase or direction. The secondary magnetic field can be detected at or above the ground surface by measuring the voltage induced in another loop of wire, the receiver.

Electromagnetic surveys can be made either on the ground or from low-flying aircraft. The effective depth at which conductive bodies can be detected with electromagnetic methods is dependent upon both the frequency and spacing between the transmitter and the receiver loops. Thus, electromagnetic measurements can be used in the same manner as resistivity measurements to obtain horizontal profiles and depth soundings. In general, electromagnetic surveys lack the resolution and depth penetration of resistivity surveys, but have the advantage of being rapid and less expensive. Results of electromagnetic surveys generally are presented in profile form. Measurements may be made at one or several frequences. Interpretation usually is accomplished by curve matching or modeling. The technique is very effective in locating conductive bodies within a few hundred feet of the surface, but has found only limited use in regional ground-water investigations. The induced pulse transient (INPUT) system differs from continuous-wave airborne electromagnetic systems in that the current waveform consists of half-sine pulses of alternating polarity. The primary magnetic field induces currents in the earth whose magnitudes are a function of earth resistivities. The secondary magnetic field that arises from the earth currents is measured by the receiver coil system during the transmitter off-time.

The airborne electromagnetic data are obtained 120 meters above the surface and are flown in a series of profiles several kilometers apart. The technique has been used effectively in mapping buried channels where the channel-filling material has a resistivity contrast with the enclosing medium (Collett, 1967, Gales and Stanley, 1976).

In recent years, several powerful radio transmitters have begun broadcasting at frequencies of a few tens of kilo-Hertz (kHz). Radio waves at these frequencies penetrate the earth to sufficient depths to be of use in geophysical exploration. Both ground and airborne detection systems have been developed. The measurements consist of one or more components of the electrical and magnetic fields. This method, which is undergoing rapid development, has proved effective in detecting near-surface highly conductive deposits, but quantitative interpretation techniques are not yet available.

A description of inductive methods is contained in Keller and Frischknecht (1966).

2.D.1.a.6. INDUCED POLARIZATION METHOD

The induced electrical polarization method is widely used in exploration for ore bodies, principally of disseminated sulfides. Its use in ground-water exploration has been limited. The origin of induced electrical polarization is complex and is not well understood. This is primarily because several physico-chemical phenomena and conditions are responsible for its occurrence.

Conrad Schlumberger (Dorbin, 1976) probably was the first to report on the induced polarization phenomenon. While making conventional resistivity measurements, he noted that the potential difference, measured between the potential electrodes, often did not drop instantaneously to zero when the current was turned off. Instead, the potential difference dropped sharply at first, then gradually decayed to zero after a given time interval. Certain layers in the ground became electrically polarized, forming a battery when energized with an electric current; on turning off the polarizing current, the ground gradually discharged and returned to equilibrium.

The study of the decaying potential difference as a function of time is now known as the study of induced polarization (IP) in the time domain. This type of study requires heavy and generally bulky equipment in the field; to avoid this limitation, mining geophysicists began to study the effect

of alternating currents on the measured value resistivity. This is known as IP in the frequency-domain. Ground-water studies have generally been made with time-domain IP.

The techniques of sounding and profiling, used in resistivity measurements, are also used in the IP method. The IP sounding curve is interpreted by curve matching procedures using sets of IP sounding master curves. An IP sounding curve can be of significant value in complementing a resistivity sounding curve.

Only a few IP surveys have been made for ground-water exploration, but there are three noted examples in the literature: Vacquier and others (1957); Kuzmina and Ogilvy (1965); and Bodmer and others (1968). Kuzmina and Ogilvy reported on work done near the Sauk-Soo river in Crimea and in the Kalinino region of Armenia. In Crimea, the IP work consisted essentially of IP sounding (time domain). The alluvial deposits in the studied area were poorly differentiated by their resistivities, but three horizons were clearly distinguished by their polarizabilities. The section consisted of a top layer of weak polarizability, which represents a 2-4 m (6.5-13 ft) dry loamy layer; a second layer, 18-20 m (60-64 ft), of strong polarizability which represented a clayey sand layer saturated with fresh water; and an effective infinitely thick third layer of weak polarizability which represents impervious siltstones. The survey in this area demonstrates that the IP work provided more complete information about the occurrence of ground water than did the resistivity soundings alone.

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2.D.1.b. SEISMIC MEASUREMENTS

Applied seismology has, as its basis, the timing of artificially-generated pulses of elastic energy propagated through the ground and picked up by electromechanical transducers operating as detectors. These detectors, or geophones as they are more commonly called, respond to the motion of the ground, and their response, transformed into electrical signals, is amplified and recorded on magnetic tape or film on which time is also recorded. The geophysicist is interested in two parameters which affect the elapsed time of transmission of this pulse—the propagation velocity (or velocities) and the geometry of the propagation path. Determination of these parameters is a complex task, both in practice and in theory. Energy generated at the source travels in several types of waves simultaneously, and each wave has a different transmission velocity. Furthermore, each of these waves may travel to the geophones by more than one path. For example, the first energy to arrive at a geophone near the source may arrive via the direct wave; that is, the energy travels parallel to the surface in the layer in (or on) which the source and receiver are located. Another geophone, located farther away, may record the arrival of a refracted wave first. When such a wave impinges on a subhorizontal discontinuity where there is an abrupt change in elastic properties, reflection or refraction of the wave will lead to the generation of additional waves. Thus, a compressional wave can give rise to both a reflected and refracted compressional wave and a shear wave. Lastly, energy

travelling into the ground may return to the surface via reflections or refractions from several different interfaces of varying depth. The geophysicist must be able to recognize and sort out from the complex wave train arriving at the geophones those impulses in which he is interested and must translate their times of transmission into geological information. The times required for the reflected and refracted waves to reach the detectors are the basis for the most widely used seismic methods. These waves have the highest velocity of the waves discussed, and, therefore, the shortest travel time for a given propagation path.

Elastic wave energy can be imparted to the ground in a variety of ways. The most commonly used method is that of firing a charge of explosives with high detonation velocity in a tamped hole. Such charges may be fired on the surface or a short distance above it. The amount of charge used depends on the length of the propagation path and the attenuation characteristics of the earth materials along the path. Although crude rules-of-thumb for estimating the explosives requirements for a given shot have been formulated, there is enough variation in attenuation characteristics from area to area that the requirements at a given locale are best determined by trial and error; so also are the depth-of-shot requirements. In some areas, and for some kinds of records, the seismologist may require a drilled or augered hole below the water table. In others, he may be satisfied to place the charge in a shallow, hand-dug hole and tamp it with a shovelful of soil. In still others, he may wish to excavate a hole of intermediate depth, say 3-5 m (10-15 ft), with a backhoe and then refill the hole with earth. In general, the deeper the target, the larger the charge; and the larger the charge, the greater the depth of implantation. The bulk of the explosive energy should be consumed in producing elastic waves. If much energy is spent in the process of venting, the shot will probably not be efficient, and the desired results will not be obtained. For shallow work—20 m (65 ft) or less—adequate energy sometimes can be generated by a hammer blow on a steel plate. Analogous sources of energy in larger amounts are produced by weight dropping or by impacting the ground with a plate driven hydraulically.

2.D.1.b.1. REFLECTION AND REFRACTION METHOD COMPARISONS

The differences between reflection and refraction methods go far beyond differences in ray-path geometry. These differences include geophone array (the refraction method uses much longer spreads), accuracy, resolution, depth, size and shape of the target, number of discontinuities to be mapped, vertical succession of velocity values, and cost. The great bulk of all applied seismic work done today is done by the reflection method—especially in petroleum exploration. It offers higher accuracy and resolution, allows the mapping of a larger number of horizons, requires smaller amounts of energy, uses shorter geophone spreads (simplifying their layout and minimizing problems associated with the communication of the shot instant), and is more suited to routine field operation. In addition, it does not require, as does the refraction method, that each succeeding layer have a velocity higher than that of the layer above it. In light of all these advantages, it is reasonable to inquire why the refraction method is used at all. This is an especially relevant question here, because most seismic measurements made in hydrogeology are refraction methods.

The reasons for use of the refraction method are several. In some areas it is almost impossible to obtain good reflection records. A typical example is an area of thick alluvial or glacial fill. In this setting, optimum reflection prospecting would require the drilling of deep shot holes. Such an area lends itself to the refraction method and is precisely the kind of setting in which the hydrogeologist might be interested. A downward increase in velocity can be reasonably expected in such an area, and abrupt increases in velocity might be encountered both at the water table and at the base of the sediments, if they overlie consolidated bedrock. No prior knowledge of velocity is required in reconnaissance refraction measurements, and the velocity information obtained in the course of the work may help in identifying the rock types involved. In reflection shooting, special measurements of

velocity need to be made, either by greatly expanding an occasional geophone spread or by shooting at a well into which a geophone has been lowered.

The reflection method works best when continuous line coverage is possible and when the line or lines can be tied to a few points of velocity control. A single reflection profile, or a series of them individually isolated and spread over many square kilometers of an alluvial basin, are not as useful as a series of isolated refraction profiles. Seismic reflection profiling from boats has proved useful in distinguishing lithologic zones under water-covered areas. See Missimer and Gardner (1976) and Hersey (1963) for a description of this technique in water-covered areas.

In areas where steeply dipping boundaries are encountered, the refraction method is better suited for exploration than the reflection method. Typical examples include a fault-bounded valley or a buried valley with steeply sloping sides.

2.D.1.b.2. COMPUTER ANALYSES OF SEISMIC DATA

Computer models have been developed for two-dimensional, layered earth models as an aid in interpreting seismic-refraction field data. The program requires input data consisting of shot-point and geophone location, refraction travel times, and identification of the refraction layer associated with each travel time. The program results in a model designed to minimize the discrepancy between field-measured travel times and computed travel times of rays traced through the model. (Scott, J. H. and others, 1972 and 1973).

2.D.1.b.3. ACCURACY OF SEISMIC REFRACTION MEASUREMENTS

A value commonly quoted in the literature concerning the magnitude of error involved in seismic refraction depth calculations is 10 percent. Eaton and Watkins (1970) appear to substantiate this oft-quoted value with a comparison between seismically predicted depths and drilled depths at 97 drill-hole sites (fig. 2-14). It is notable, however, that there are 8 points in this plot which represent errors of at least 30 percent, and three of these represent errors in excess of 100 percent. Such data do not reflect incompetence on the part of the geophysicists who published them, rather they represent an attempt at intellectual honesty and a willingness to reveal how far off some geophysical predictions can be. Because there is a general tendency on the part of most investigators to publish only their successful results, the data shown in figure 2-14 may be regarded as representing a biased sample. It is probable that the average error in most seismic refraction work is somewhat greater than 10 percent.

There are, on the other hand, published examples in which average errors in depth prediction are as small as 5 percent. The difference between these extremes of 5 and 100 percent stems, in part, from the availability of independent geologic information or other kinds of geophysical data. It should be emphasized that the more information of a stratigraphic nature the hydrogeologist can give to the seismologist, the better the seismic interpretations will be. The geophysicist, like the surveyor, benefits from being able to close on one or more control points in the form of a bore hole or a well. In the total absence of independent geologic or geophysical information, the interpretations can be no better than the assumptions made concerning probable conditions below the surface.

Inspection of figure 2-14 indicates that those depth measurements which are in error by 30 percent or more are all on the high side; the seismic method overestimated depths to the refractors. A common cause of depth overestimation is unrecognized velocity inversions in the section. The thickness of the slow layer and the velocity difference between it and the layer above determine the magnitude of the error.

Other sources of error pertinent to hydrogeologic studies include (1) discontinuous and abrupt lateral variations of velocity, (2) pronounced velocity anisotropy, (3) blind zones, (4) a highly fractured or weathered bedrock surface, and (5) hydrologically significant interfaces that do not display velocity contrasts large enough for seismic detection.

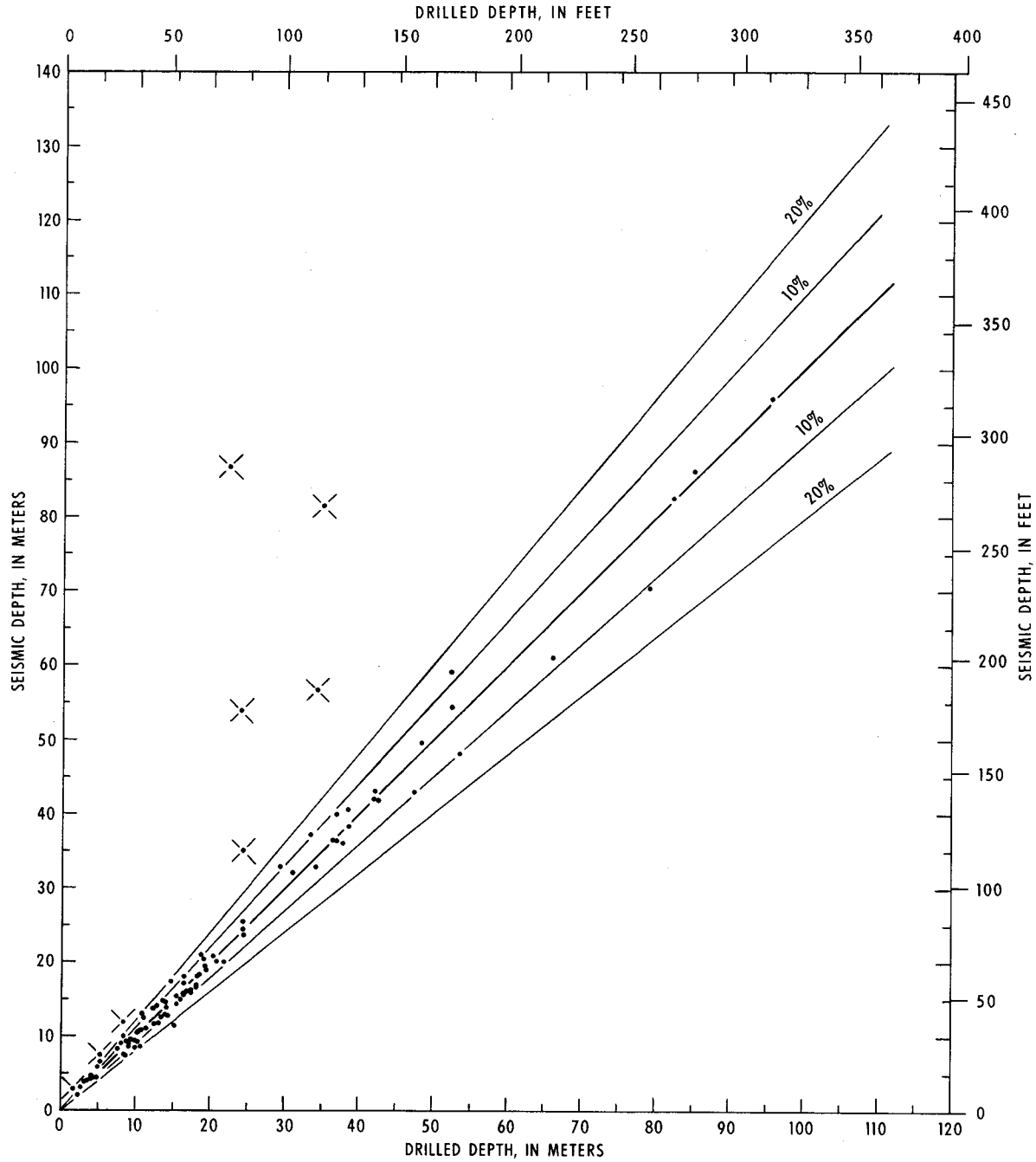

Figure 2-14.—Comparison of 97 seismic refraction depth determinations versus drill-hole depths at the same localities. Heavy line represents envelope of error-free determinations; labelled lines represent envelopes for errors of 10 percent and 20 percent (after Eaton and Watkins, 1970). Reproduced by permission of "Information Canada."

2.D.1.b.4. APPLICATIONS OF SEISMIC REFRACTION MEASUREMENTS

2.D.1.b.4.a. Mapping Buried Channels

The most common use of the seismic method in hydrogeology is in the determination of the thickness of sediments which overlie essentially non-water-bearing consolidated bedrock. The surface of the bedrock may be plane or irregular, but it is of special hydrologic interest where it occurs

in the form of a channel filled with silt, sand, and gravel. Typical examples include the fluvial sediments of present-day river valleys and valley-train deposits in old water courses. Models of this type are particularly well adapted for seismic study if there is an appreciable contrast in velocity between the sediments and the bedrock. Zohdy and others (1974) describe the results of seismic surveys to define buried bedrock channels in northern New Jersey and California.

2.D.1.b.4.b. Measuring Depths to the Water Table

Seismic refraction measurements of semiconsolidated or unconsolidated elastic deposits reveal that compressional wave velocities increase abruptly at the water table. The velocity in saturated continental sediments generally is about 1.50 km/sec (0.92 miles/sec) and is sufficiently higher than that in unsaturated sediments so that the zone of saturation acts as a refractor. Observed velocities in unsaturated sediments generally are less than 1.00 km/sec (0.6 miles/sec), but rarely may be high as 1.40 km/sec (0.9 miles/sec). According to Levshin (1961) the minimum observed difference in velocity across the water table occurs in fine-grained sediments and exceeds 100 to 150 meters/sec (330 to 500 ft/sec). In aquifers composed primarily of gravel, he noted differences as large as 1.00 km/sec (0.6 miles/sec).

Whether or not the water table can be recognized seismically depends on the thickness of the saturated zone above the bedrock. If the saturated zone is too thin in relation to its depth, it will not appear as a separate branch on a traveltime curve prepared from first arrivals only.

2.D.1.b.4.c. Determining the Gross Stratigraphy of an Aquifer

If some of the velocity discontinuities in unconsolidated or semiconsolidated deposits represent stratigraphic breaks in the sedimentary section, seismic refraction measurements can be used under optimum conditions to unravel the gross stratigraphy of a deposit. If these breaks further represent significant hydrologic boundaries, such as those between water-producing formations and non-water-producing formations, the seismic work may have special hydrogeologic interest.

2.D.1.b.4.d. Mapping Lateral Facies Variations in an Aquifer

Seismic refraction measurements in areas where a large number of geophone spreads and shot points are employed may reveal systematic lateral variations in the velocity of unconsolidated deposits. These variations reflect measurable variations in the physical properties of the deposits, which in turn stem from fundamental variations in lithology. Many geologic factors contribute to variations in the compressional wave velocity of unconsolidated and semiconsolidated sediments. Among these are geologic age, average particle size, particle-size distribution, composition, degree and nature of cementation, confining pressure, degree of saturation, and porosity.

2.D.1.b.4.e. Estimating Porosity from Seismic Wave-Velocity Values

Many investigators have noted a pronounced correlation between porosity and compressional wave velocity in clastic sediments, velocity increasing with decreasing porosity (fig. 2-15). Similarly, there is a correlation between velocity and density, velocity increasing with increasing density. These correlations of porosity and density with seismic wave velocity are interdependent, as bulk density can be defined by three parameters: porosity, particle density, and pore-fluid density. For a group of sediments with the same average mineralogical composition, variations in bulk density are a function primarily of variations in porosity. If a small amount of cementing material is present in the pores, it would diminish total porosity but at the same time increase bulk density. Assuming the composition, and more particularly the particle density, of the cement to be approximately the same as that of the clastic constituents, its presence would not materially affect the relationship between density and porosity. In such a situation, the cement could be regarded macroscopically as one of

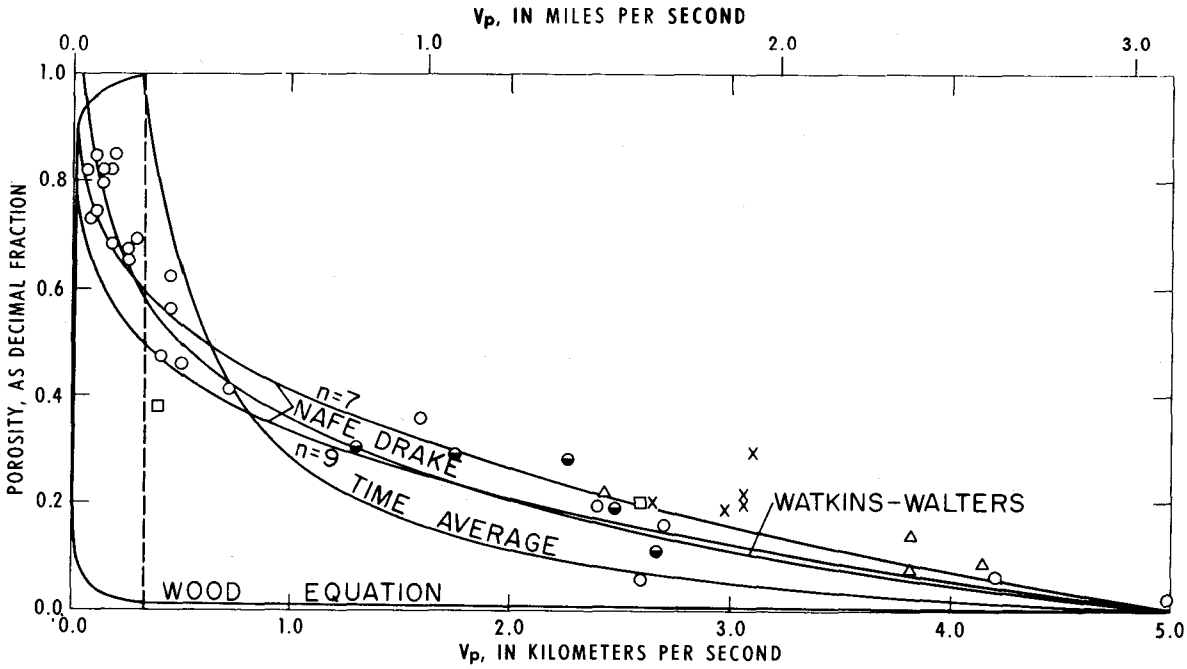

Figure 2-15.—Plot of observed porosity versus compressional wave velocity for unconsolidated sediments (after Eaton and Watkins, 1970). Reproduced by permission of "Information Canada."

the mineral constituents of the sediment. If its composition is grossly different from that of the clastic particles, however, variations in the degree of cementation would result in variations in the average particle density of the sediment, and the simple relationship between porosity and bulk density would not hold. Neither would that between porosity and velocity. Other factors, such as the degree of fracturing in a semiconsolidated rock, also influence velocity; the greater the volume density of fractures, the lower the velocity. To some extent, however, fractures contribute to the total porosity, so their effect on the velocity-porosity relationship is not always pronounced. The net result is that velocity values can be used to predict total average porosity, within certain limits, for unconsolidated sediments and weakly consolidated sedimentary rocks.

Experimental data bearing on the systematic relationship between velocity and porosity (fig. 2-15) include rocks and sediments of a wide variety of compositions. The smooth curves drawn through the data points are empirically derived mathematical functions relating the two properties. Curves such as these could be used in conjunction with mapped velocities to produce maps illustrating areal variations in porosity for uniform sediments in a given area. Although the standard deviation of porosity determined in this way would be high, the maps might nevertheless serve a useful purpose in evaluating the relative water-storage potential of the sediments.

2.D.1.b.5. REFERENCES

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2.D.1.c. GRAVIMETRY

Gravimetry is the geophysical measurement of the acceleration of gravity and has, as its basis, two well-known laws of elementary physics. The law of universal gravitation states that every particle of matter exerts a force of attraction on every other particle that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. The other law is Newton's second law of motion, which may be stated in the form: when a force is applied to a body, the body experiences an acceleration that is directly proportional to the force and inversely proportional to the body's mass.

Because the Earth is approximately spherical and because the mass of a sphere can be treated as though all of it were concentrated at a point at the center, any object with mass m_o, resting on the Earth's surface, will be attracted to the Earth by a force.

$$F \cong G \frac{m_o m_e}{R^2} \tag{2–2}$$

where m_e is the mass of the Earth and R, its average radius, and G is the gravitational constant. This force of attraction between the object and the Earth is the object's weight.

If the object is lifted a short distance above the Earth and allowed to fall, it will do so with a gravitational acceleration,

$$g \cong F/m_o = G \frac{m_e}{R^2} \cdot \tag{2–3}$$

This acceleration is the force per unit mass acting on the object. It is a function of both mass of the Earth and the distance to its center. The principle is the same, however, when the attracting body is something other than the Earth as a whole, and it is on this principle that gravimetry, as a geophysical method, is based.

In gravimetric studies, the local vertical acceleration of gravity (the standard metric unit of which is the gal, after Galileo) is measured. A gal is equivalent to an acceleration of 1 cm/sec/sec. Most gravity variations associated with geologic bodies in the outer several miles of the Earth's crust are measured in milligals (mgals). The maximum gravity difference between the Earth's normal field (the main gravity field of the reference spheroid) and that actually observed on the surface and corrected for altitude and latitude is of the order of several hundred mgals. This difference, known as a gravity anomaly, reflects lateral density variations in rocks extending to a depth of several tens of miles.

The gravity meter, or gravimeter, is the instrument most used in making gravity measurements in the field. It is a highly sensitive spring balance with which differences in acceleration are measured by weighing at different points a small internal mass suspended from a spring. Because this mass does not change, differences in its weight at different points on the Earth reflect variations in the acceleration of gravity (eq. 2-3). It is light in weight, easily portable, highly accurate, and rapidly read. The modern gravity meter measures, with great accuracy and precision, differences in gravity between points, but does not measure the absolute value of gravity itself at any point. What is measured is the vertical component of the acceleration of gravity rather than the total vector, which may depart slightly from the vertical.

The total gravitational attraction of a body M, at point P, can be calculated by subdividing it into a series of vanishingly small elementary masses (fig. 2-16). One of these is shown in figure 2-16 as dm.

The summed effect of all of the elemental masses contained within body, M, represents the total attraction.

A summation of dm over the entire body yields the vertical component of the total attraction due to M at point P:

$$g_z = G \int_m \frac{dm}{r^2} \cos \theta. \tag{2-4}$$

If the density of body M is homogeneous and has the value ρ, we can rewrite equation 2-4 as:

$$g_z = \rho G \int_v \frac{dv}{r^2} \cos \theta. \tag{2-5}$$

where dv represents the volume of dm and the integration is peformed over the entire volume. Equation 2-5 is the basic equation of gravimetry. An exact solution for the integral can be obtained

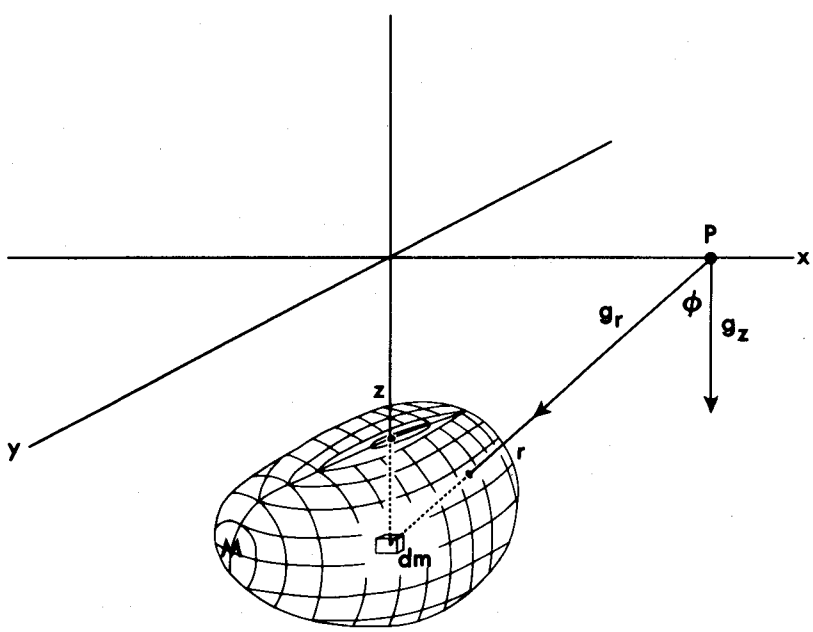

Figure 2-16.—Gravitational attraction at point P due to buried mass dm.

if the body has a simple analytical shape such as a sphere, a right circular cylinder, or an infinite, uniformly thick plate. If, however, the body is irregular in shape, as most geologic bodies are, then the total attraction must be calculated by graphic integration or by numerical summation, using a digital or analog computer.

Although the gravitational attraction of any geologic body is a function of its mass, the total gravitational attraction measured by a gravimetric device on the surface above it represents the sum of the attractions of both the body and the rest of the Earth, as a whole. In geophysical prospecting, we are interested only in that part of the gravity field due to the body; therefore, we generally need be concerned only with the excess or deficiency of mass that the body represents, rather than with its absolute mass. Under these circumstances, the body can be described quantitatively in terms of its density contrast with its surroundings. Observed gravity variations, when corrected for nongeologic effects, reflect contrasts in density within the Earth. The symbol ρ in equation 2-5 can be taken to represent the density contrast between a geologic body and its surroundings, rather than the actual density of the body.

2.D.1.c.1. REDUCTION OF GRAVITY DATA

The theoretical foundations for gravity data reduction have been worked out in rigorous detail. See Dobrin (1960) or Grant and West (1965) for the details and mathematical derivation of the corrections.

The observed gravity data are corrected to account for departures of field conditions from what would be expected if the Earth were in the shape of a perfectly uniform spheroid fitted to a fixed datum and if the vertical distribution of density with depth would be the same everywhere. Corrections are functions of latitude, Earth tides, station elevation, and irregularities in nearby topography.

All the corrections described thus far are designed to eliminate nongeologic effects. The resulting contoured gravity field is known as a complete Bouguer gravity anomaly map and displays features that theoretically are due only to lateral variations in rock density below the elevation datum. An analysis of the gravity field in terms of this geology is presumably the reason for making the survey in the first place. From a practical standpoint, things are not quite so simple. Usually a target of geologic interest is quite specific at the outset and the gravity field arising from it is the objective sought. The problem results from the fact that rarely does the geophysicist see the gravity field of a given geologic body in isolation. Usually, the anomaly of interest is distorted or partly masked by the gravity fields of other bodies. As a result, the geophysicist must sort out those parts of a total gravity field caused only by the object of immediate interest. Basically, he knows only the magnitude and shape of the total Bouguer gravity field, but he hopes to be able to subtract from it the contributions caused by geologic bodies of unknown shape, density, and location, in order to isolate the residual anomaly of interest. To make a quantitative interpretation of the anomaly caused by the target alone, we must subtract the effect of regional deep-seated structural features. Nettleton (1954) gives a nonmathematical discussion of the methods used to filter out these regional effects.

2.D.1.c.2. INTERPRETATION OF GRAVITY DATA

2.D.1.c.2.a. Ambiguities

In its simplest form, the interpretation of gravity data consists of constructing a hypothetical distribution of mass that would give rise to a gravity field like the one observed. Models are constructed graphically or mathematically and their gravity effects calculated from equation 2-5 by numerical summation or graphical integration. The difficulty lies in the fact that a large number (theoretically, an infinity) of hypothetical models will produce the same gravity anomaly. The

known quantity g_z is a complex function of three unknowns: density, shape, and depth of the causative body. It is apparent, even without knowledge of an exact solution for the volume integral in equation 2-5, that one could substitute, simultaneously, a variety of values for the parameters ρ, r, ϕ, and $\int_v dv$ in such a way as to maintain a constant value for g_z at point P on the surface.

If there were enough information in a given situation to know that the body was spherical and its center buried at a specific depth, we still could not make a unique interpretation of the gravity anomaly in terms of size and density (fig. 2-17A). The gravity anomalies for these four spheres are identical. This results from the fact that the mass of a sphere can be treated as though it were concentrated at a point at the center. In figure 2-17A, the radius and density of the spheres have been adjusted to keep the total mass constant.

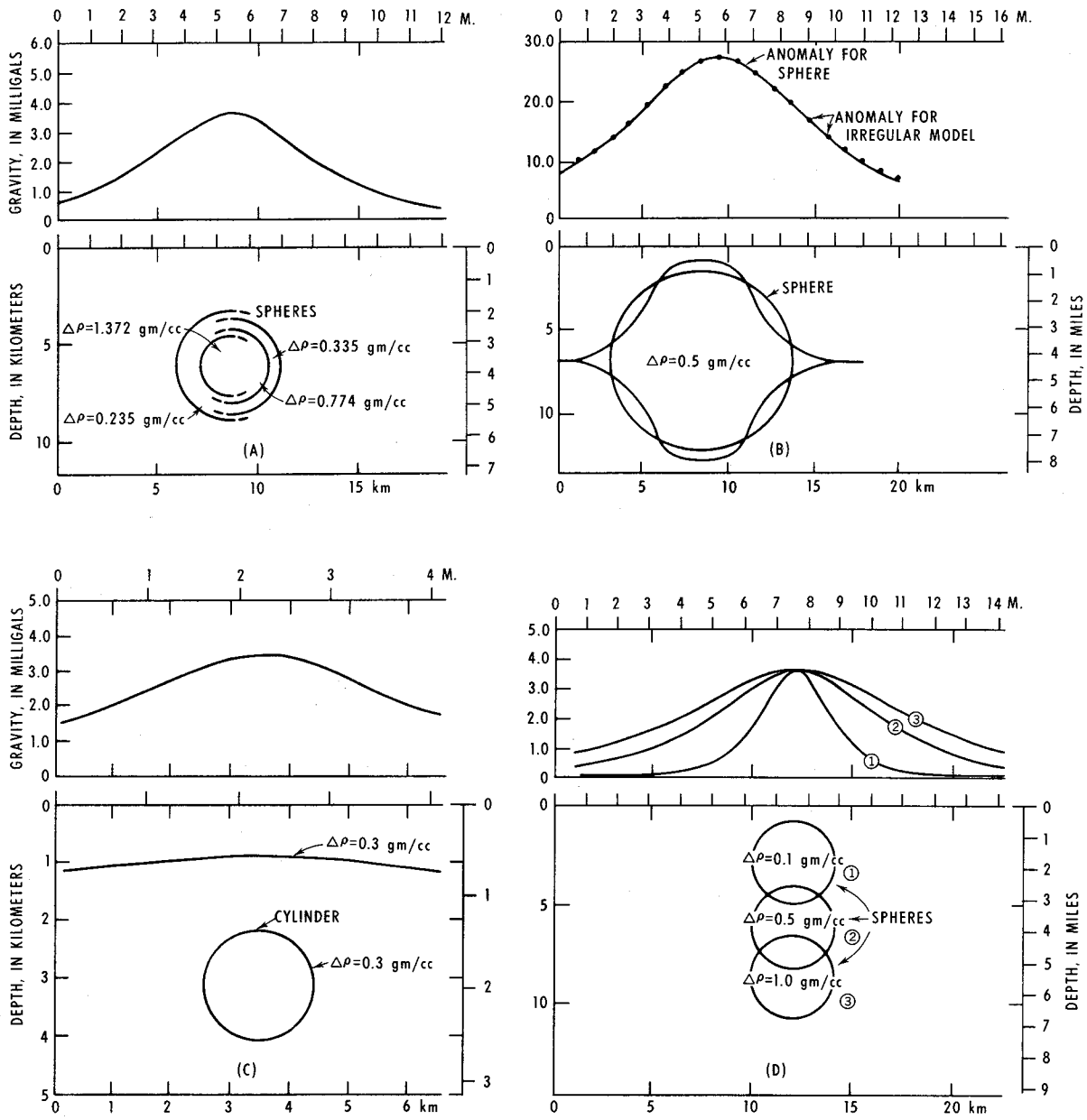

Figure 2-17.—Schematic models and associated Bouguer gravity anomalies for idealized geologic bodies.

In addition, the gravity field of a sphere does not have a unique configuration (fig. 2-17B). Thus, the shape of a body cannot be determined from its gravity anomaly alone, even when the density contrast and center of gravity are known. In figure 2-17B, the anomaly arising from the sphere is shown as a smooth curve and the field due to an irregular body of different rotational shape with coincident center and density is shown by dots. The two curves match very closely.

Bodies of other shapes also produce non-unique anomalies (fig. 2-17C). The gravity anomaly of a horizontal right circular cylinder buried at a depth slightly in excess of 3 km (1.9 miles) can be matched by that of a gently convex basement surface at a depth of approximately 1 km (0.6 mile) when the density contrast between basement and overburden matches that of the sphere and its surroundings.

The nonuniqueness is pronounced. The fact that gravimetry has been successfully employed as an exploration techique for many decades indicates that ambiguity is not an insurmountable interpretation problem. For example, the individual masses and gravity fields of the spheres of different size shown in figure 2-17A were kept constant by holding the product ρR^3 constant. The maximum range of bulk densities for common, naturally occurring consolidated rocks and unconsolidated sediments is well known. Reference to Clark (1966, Sec. 4) and Manger (1963) indicates that the limits of the range are approximately 1.70 and 3.00 gm/cm^3. These limits represent well sorted, unconsolidated clastic sediments of high porosity and massive basalt, respectively. There are a few earth materials with densities outside this range, but they are not common. This range places an upper limit on the magnitude of the density contrast that one might expect to encounter in nature and constitutes the maximum density contrast (1.30 gm/cm^3) that can be used in modelling. In most geologic settings, the contrast is less than 1.00 gm/cm^3. Greater restriction can be placed on the density contrast in an actual setting from a knowledge of the local geology.

Other boundary conditions can be imposed as well. For example, a typical valley-fill aquifer consists of unconsolidated or semiconsolidated sediments resting unconformably on older, and usually more consolidated (and therefore denser), rocks. Geologic mapping determines the approximate surface location of the interface between the aquifer and the rocks on which it rests. If, in addition, the top of the aquifer is coincident with the surface of the ground, an additional boundary condition exists. Further limits on the interpretational model can be achieved by making measurements of the average bedrock density and the density of the uppermost part of the valley fill. It can be reasonably assumed that the fill density probably increases with depth and that the walls of the valley probably slope inward in the subsurface. Thus, severe limitations have been placed upon the conceptual model. Several different models that will produce the observed anomaly probably can still be constructed, but the differences between the models may not be significant. If they are, however, we might be able to bring other data to bear that would furnish still further constraints and, thus, allow a more nearly unique interpretation. The greater the amount of geologic data that can be used in establishing limits or constraints on the model, the more unique will be the interpretation.

Another facet of the interpretation process that aids in the early stages of data analysis is shown in figure 2-17D. Three spheres of the same size at different depths have had their densities adjusted to keep the maximum amplitude of their anomalies the same. At horizontal distances that are several times the depth of burial of the spheres, all three anomalies asymptotically approach zero because the vertical component of gravity at this distance is negligible. Between the regions of zero and maximum amplitude, however, the three curves are notably different. The greater the depth of burial of a given body, the gentler are the gradients of the flanks of its anomaly. The gradients of any anomaly are also a function of the shape of the producing body because two bodies at distinctly different depths may produce anomalies with the same gradients. There is, however, a limit to the depth to which we can push a model and still maintain anomaly gradients at or above a fixed value. For example, there is no infinitely long, horizontal body of any cross-sectional shape that can be

buried with its upper surface at a depth of 3 km (1.9 miles) or more and still produce an anomaly that has flanking gradients as steep as those shown in figure 2-17D. There are some general formulas, based on potential theory, that allow determination of the maximum possible depth to the top of anomaly-producing body from the ratio of the maximum amplitude to the maximum gradient of its flanks (Bott and Smith, 1958; Bancroft, 1960). These formulas are useful for a rough fix on maximum depth to the top of a body in the early stages of modelling.

2.D.1.c.2.b. Interpretation Techniques

The basic technique of gravity interpretation is field matching. A model is constructed and its gravity field calculated for comparison with the observed field.

Details of the various interpretation methods are given in Dobrin (1960, p. 253-262) and Grant and West (1965, p. 268-305). It should be stressed that: (1) The solution for a given gravity anomaly is never unique, and the use of highly sophisticated and elegant mathematical methods of interpretation does not make it so, and (2) the quality and uniqueness of the interpretation are, in part, a function of the kind and amount of geologic information available to the interpreter.

2.D.1.c.2.c. Significance and Uses of Density Measurements

The interpretation of gravity data necessitates accurate knowledge of rock densities in the area surveyed. Because variations in rock density produce the potential field differences we observe after data reduction, this property is of fundamental importance.

There are several ways in which density values may be obtained for use in handling the data for a given area.

The cost of the method selected should be in rough proportion to the significance of the problem. Methods described briefly below are listed approximately in order of increasing significance and accuracy.

1. Assumption of a constant density value of 2.67 gm/cm^3.
2. Assignment of density values on the basis of lithology. Because of the wide variability of rock composition and rock density within a lithologic classification, values assigned on this basis can be in error by as much as 40 percent.
3. Estimates of density based on sound-wave velocities in rocks. Compressional wave velocities and densities of rocks are a function of some of the same lithologic factors. Because of this, they show a pronounced correlation. Approximately three-fourths of the data points in figure 2-18 fall within 0.1 gm/cm^3 of the regression curve fitted to them.
4. In situ gamma-gamma logging. A gamma-gamma borehole logging device measures radiation that originates from a source in the sonde and travels through a shell of rock adjacent to the borehole. The decrease in strength of the returning signal is approximately proportional to the density of the rock. However, the borehole diameter, the presence of borehole fluids, mudcake on the hole walls, mud-filtrate invasion, and the roughness of the hole all adversely affect the results. A separation of the logging tool from contact with the rock by as little as 0.7 cm (0.3 in) can cause a significant error in the density value.
5. Density measurements on handspecimens collected at the outcrop. If taken to procure unweathered material, if the sampling statistics are adquate, and if the samples are large and geologically representative, the results of this method are usually quite accurate. This probably is the method most frequently used today.
6. Density profiling with the gravity meter. If a topographic feature such as a hill or valley is underlain by rocks of laterally homogeneous density and if the topography is not an expression of geologic structure, the data from a gravity profile can be used to measure the average bulk density. The advantage of this method is that it samples, in place, a very large volume of rock.

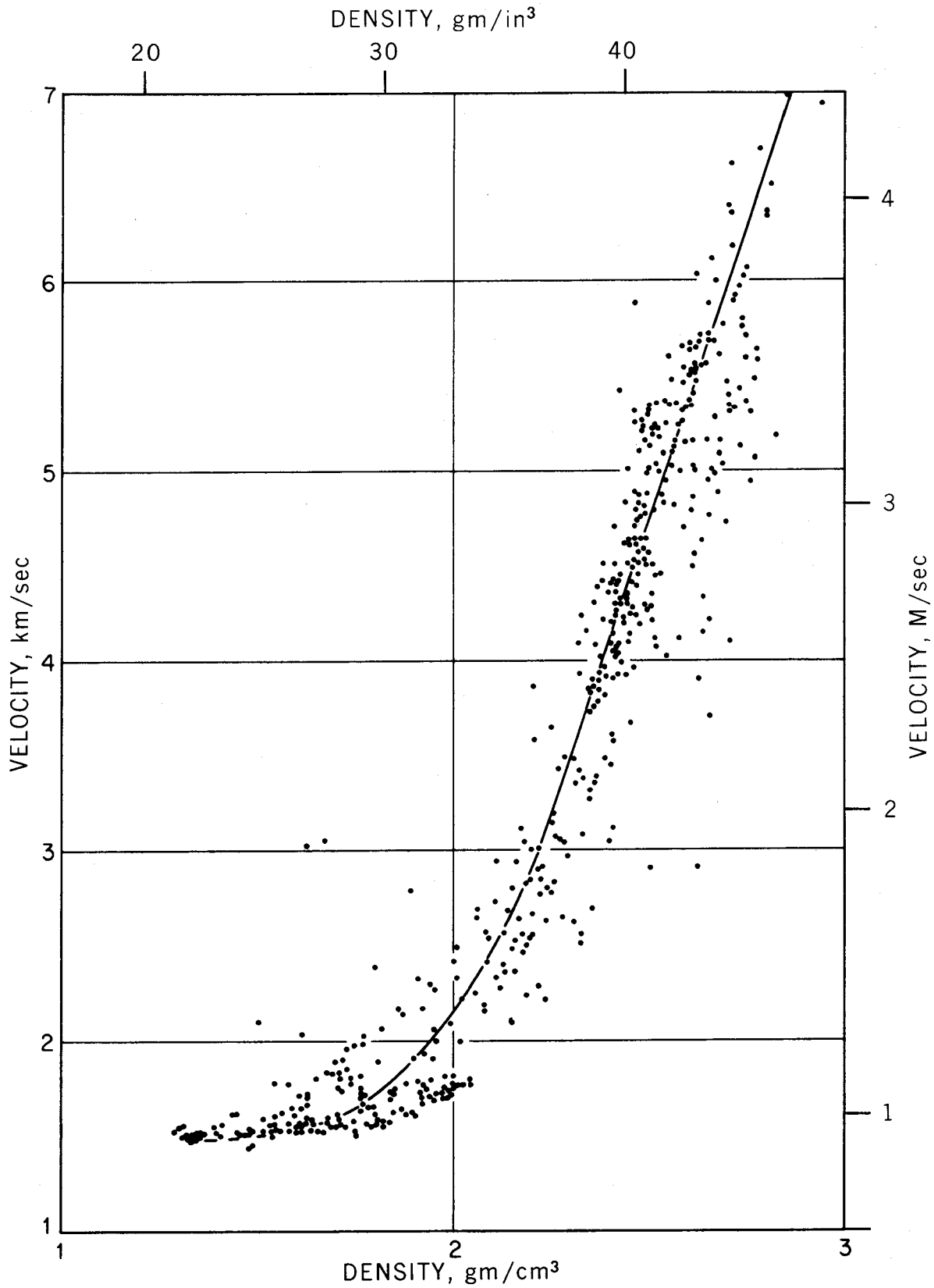

Figure 2-18. – Plot of observed compressional wave velocities versus density for sediments and sedimentary rocks (after Grant and West, 1965). Reproduced with permission of McGraw-Hill Book Company.

7. Laboratory measurements of drill-core samples of consolidated rocks. This method provides a means of sampling below the zone of weathering and, if recovery is good, it also provides the basis for computing geologically weighted means for the section. Recent tests (McCulloh, 1965) indicate that when proper care is taken in handling the cores, the accuracy of this method is high. However, a borehole represents a single vertical traverse of the rocks in an area. If there are pronounced lateral variations in density, cores from a single hole may not suffice.
8. Logging with a borehole gravity meter (Healy, 1970). A gravity meter lowered into a borehole can be used to measure the in situ density of rocks directly. The radius of the region of rock that is sampled is roughly five times the length of the vertical interval, *T*.

2.D.1.c.3. APPLICATION OF GRAVIMETRY

The gravity method is a rapid, inexpensive means of determining the gross configuration of an aquifer, providing an adequate density contrast exists between the aquifer and the underlying bedrock. This method is useful in locating areas of maximum aquifer thickness, in tracing the axis of a buried channel and in locating a buried bedrock high that may impede the flow of ground water. Eaton and Watkins (1970) and Zohdy and others (1974) describe selected field applications of gravimetry to such problems.

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2.D.2. BOREHOLE METHODS [2]

Geophysical well logs are an important means for the hydrologist to acquire data on the ground-water environment. Besides the obvious role that well cuttings, cores, and fluid samples play in defining the subsurface environment, geophysical logs run in the open or cased drill hole often provide the only practical measurement of the undisturbed subsurface sediments and fluids. Therefore, it is important to obtain an appropriate set of logs from each hole.

[2] This section has been abstracted from Keys and MacCary (1971).

Geophysical logs are used to determine geologic correlations, as well as to determine lithology, geometry, resistivity, formation-resistivity factor, bulk density, porosity, permeability, moisture content, and specific yield of water-bearing rocks. Further, logs can often be used to define the source, movement, and chemical and physical characteristics of water. Log data can be of considerable value in the evaluation of surface geophysical surveys.

Well-logging methods originally were developed by the petroleum industry to solve specific oil-related problems. Most of the techniques have been successfully adapted to ground-water studies. Geophysical well logging can provide continuous analog records with values that are consistent from well to well and from time to time, if the equipment is properly calibrated and standardized.

Although geophysical logging should complement rather than replace the driller's or geologist's log, some samples that are properly taken and analyzed are essential to the interpretation of logs in most geologic environments. One well that is adequately sampled and logged can serve as a guide for the horizontal and vertical extrapolation of data through borehole geophysics. Furthermore, well logging provides a means for obtaining information from existing cased wells for which there may be no data on rock properties and from wells where casing prevents sampling.

Geophysical logs can be digitized and are then amenable to computer analysis. Such logs are usually stored on, and retrieved from, magnetic tape.

Logging techniques also permit time-lapse measurements to observe changes in a dynamic system. Changes in both fluid and rock characteristics and well problems caused by pumping or injection can be determined by periodic logging. radiation logs are generally the only methods used for logging through casting.

2.D.2.a. LOGGING ENVIRONMENTS

Any change in the nature or thickness of material between the logging sensor and the rock being measured is likely to affect the log response, sometimes in a predictable manner. Therefore, the sensitivity of each logging device to hole diameter should be considered, and where necessary, a caliper log should be made. The walls of most drill holes are irregular and the diameter of the hole may range from inches to feet. Poorly consolidated or thin bedded sediments generally produce irregular boreholes, whereas highly consolidated or thick bedded formations usually produce more uniform boreholes. In sedimentary rocks the drilling technique is a major factor in hole diameter; for example, a rapidly drilled hole generally has the smoothest bore. The longer the drilling and sampling operations are continued in a hole drilled in poorly consolidated sediments, the larger and more irregular the bore becomes. Circulating drilling mud or water for long periods also tends to affect the diameter.

In rotary drilling, a natural or artificial mud is circulated down the drill stem to bring the cuttings back to the surface; the mud also keeps the hole open, cools the bit, lubricates the drill stem, coats the wall of the hole to reduce fluid loss, and serves as an electrical-coupling medium necessary for many logging operations. Because the pressure of the mud column exceeds the hydrostatic pressure in the formation being penetrated by the bit, the mud filtrate invades the rock and cavities adjacent to the borehole and displaces the native fluids. During this process, many of the particles suspended in the mud are filtered out and form a mud cake or filter cake on the wall of the hole. The invaded zone and mud cake may introduce unknown and, in general, undesirable factors in log interpretation (Doll, 1955). Improper mud control may cause the hole to have an irregular diameter, particularly where sands are likely to collapse or wash out and clays have a tendency to squeeze. Decreases in hole diameter to less than bit size are due either to mud cake build-up or to clay squeezing into the hole. Clay squeezes will generally continue to decrease diameter until the hole is closed. Mud cake or clay squeezes will affect the response of some logging devices. Scale and mineral deposits may decrease the hole diameter or increase the casing or screen thickness in pumped wells.

Thin-bedded units, fractures, and solution openings are responsible for most borehole rugosity. Correction of logs for rugosity where the tool spans thin washed-out zones is generally not possi-

ble even with the aid of a caliper log. Therefore, these zones should be eliminated from quantitative log analysis.

If a logging sensor is visualized to be within a volume of rock that is contributing to the recorded signal, the drill hole, the fluids in the hole, and the wall of the hole that has been invaded and caked with drilling materials are also within the volume investigated. Changes in any of these factors will alter log response even though the characteristics of the surrounding rocks are constant. Furthermore, sondes measuring similar parameters but having different volumes of investigation will record dissimilar logs. Therefore, several kinds of resistivity sondes having different volumes of investigation can be used to measure the thickness of the invaded zone which is related to formation porosity and permeability. Some resistivity sondes have a zone of maximum response at some arbitrary distance from the pickup electrodes. For most logging devices, however, the materials closest to the sonde contribute most of the recorded signal.

Other factors being equal, a change in bed thickness will produce a change in log response because logging sondes have a predictable volume of investigation. For a thin bed, the volume being investigated may include part of the adjacent rocks, so that the logging sonde does not measure the same value that it would in a thick bed of the same lithology. If a logging device has a volume of investigation that extends a considerable distance up and down the hole from the detector, a lithologic change will begin to affect the signal transmitted from the sensor before it actually reaches the depth at which the change occurs. The effect of the bed will also be seen on the log after the sensor has passed beyond the bed boundary. This phenomenon occurs during radiation-logging where a gradual change in log response is observed even though the lithologic change may be sharp. Thus, the common technique of drawing lithologic contacts through the half-amplitude point on radiation logs can be misleading, particularly for thin beds.

2.D.2.a.1. ELECTRIC LOGGING METHODS

The electric log includes measurements of natural potentials and resistivities, and except for the induction curve, can be run only in open holes that are filled with a conducting fluid such as mud or water. The chart paper used commonly for the electric log is divided into two vertical columns called tracks. The electric log usually includes the spontaneous potential (SP) in the left-hand track and one or more resistivity curves in the right-hand track. Some of the commonly used resistivity curves are the single point, short normal, long normal, lateral, microlog, microfocused log, induction, and guard or laterlog. The use of each curve depends on the lithology, depth of mud invasion, and other borehole conditions.

2.D.2.a.1.a. Spontaneous Potential

SP logs are records of the natural potentials developed between the borehole fluid and the surrounding rock materials. The SP is used chiefly for geologic correlation, determination of bed thickness, separating nonporous from porous rocks in shale-sandstone and shale-carbonate sequences, and for calculating formation water quality (Alger, 1966).

The SP log is a graphic plot of the small differences in voltage, measured in millivolts, that develop at the contacts between the borehole fluid, the shale or clay, and the water in the aquifer. One source of SP is the streaming potential caused by electrokinetic phenomena. This electromotive force (emf) develops when an electrolyte moves through a permeable medium. The emf appears in the borehole at places where mud is being forced into permeable beds; although, in water wells, streaming potentials may be generated in zones gaining or losing water. Streaming potentials can sometimes be detected on the SP curve by sudden oscillations or by departures from the more typical response in a particular environment.

A second source of SP arises in the electrochemical emf produced at the junction of dissimilar materials in the borehole as explained by Hallenburg (1971). The junctions are between the follow-

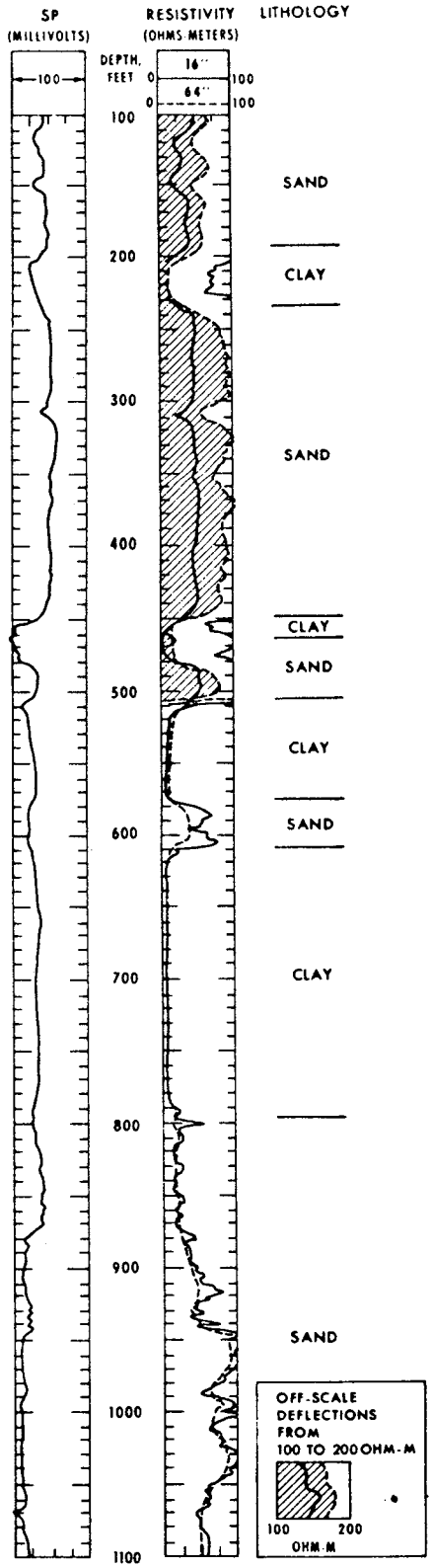

Figure 2-19.—Electric log showing reversed SP curve.

ing materials: Mud-mud filtrate, mud filtrate-formation water, formation water-shale, and shale-mud. Because the mud filtrate is derived from the mud, it generally has a similar electrochemical activity, and any emf developed across this junction will be minimal. The potential developed across the junction from formation water to shale to mud is called the membrane potential, and the potential developed across the junction from mud filtrate to formation water is called the liquid-junction potential. The potentials arising from these junctions cause a current to flow near shale-aquifer boundaries in the mud column in the borehole. The SP log, therefore, is a measure of the potential drop that occurs in the mud. When the drilling mud is fresher than the formation water, the SP will deflect to the left (negative direction) opposite water-bearing sands and to the right (positive direction) opposite the shales. If on the other hand, the formation water is fresh compared with the mud, the polarity of the SP curve is reversed. The SP is, therefore, more positive opposite the sands and is more negative opposite the shales. This condition occurs in hydrologic regimes where ground water contains low dissolved solids and, thus, both the SP and the resistivity deflect in the same direction. An example of this is illustrated in figure 2-19. The water in the formations above 500 feet contain dissolved solids of only 42 mg/L, whereas the formations below 800 feet have a dissolved-solids content of about 250 mg/L. The dissolved solids of the drilling mud lie somewhere between these two extremes. The resistivities above 450 feet are all off-scale to the right and lie between 100 and 200 ohm-meters.

When the resistivities of the borehole fluid and the formation water are approximately equal, the SP deflections will be small and the curve will lack detail. The hydrologist frequently encounters this situation when logging water wells after they have been developed or taken out of service. The well bore is filled with fluid of essentially the same ionic character as the producing formation, thus suppressing the SP. In a sand-shale sequence containing formation water that is more saline than the mud, a shale line can be constructed to fit through as many of the extreme positive deflections as possible, and a sand line to fit through as many of the extreme negative deflections as possible (fig. 2-20). If the ionic concentration of the borehole fluid and the aquifer water are constant throughout the length of the borehole, the shale line and the sand line will generally be parallel to the vertical axis of the log. The shale line is considered to be the base line, and all potential measurements are made perpendicular to this line, using the scale of SP, in millivolts, on the log heading. When carefully applied, this method can be used to estimate sand-shale ratios.

The following equation is useful to calculate the quality of the formation water when sodium chloride is dominant and the concentration is about 10,000 mg/L:

$$SP = -K \log \frac{R_{mf}}{R_w}, \tag{2-6}$$

where

SP = log deflection in millivolts;
$K = 60 + 0.133T$;
T = borehole temperature in degrees Fahrenheit;
R_{mf} = resistivity of borehole fluid, in ohm-meters; and
R_w = resistivity of formation water, in ohm-meters.

The SP deflection opposite a sand bed is read from the log, and the R_{mf} is measured with a mud kit or a fluid-resistivity tool. Inserting these values in the equation determines the resistivity of the formation fluid, R_w, which can be related back to milligrams per liter of NaCl from salinity-resistivity charts as outlined in Keys and MacCary (1971).

Alger (1966) discusses a method for finding the R_w of fresh waters by use of equation 2-6 . In order to correlate SP deflections with water resistivity and ionic concentration from salinity-resistivity charts, it is necessary to convert all anions and cations in the water to an equivalent sodium chloride solution. The relations between SP, R_w, and total dissolved solids—if determined

from a borehole having an electric log and water analyses—can be extrapolated to other boreholes in the regime exclusively from the *SP* deflections, assuming that the relative ionic concentrations and ratios are approximately constant.

2.D.2.a.1.b. Resistivity

Resistivity-logging sondes measure the electrical resistivity of a known or assumed volume of earth materials under the direct application of an electric current or an induced electric current. Depending on the sonde employed, resistivity logs can be used for geologic correlation, although this is not the most important application. Resistivity devices are generally used to determine the formation resistivity, formation porosity, mud cake resistivity, invaded zone resistivity and porosity, hydrocarbon and water saturation, and fluid resistivity.

Except for conductive minerals like graphite, metallic sulfides like pyrite and galena, and native metals such as silver, most minerals are good insulators when they are dry. However, completely dry rocks rarely occur, and subsurface formations have measurable resistivities because of formation water in rock pores and solution channels, and absorbed water on clay particles. The resistivity of a rock depends on the composition of the contained water, on the amount of water, and on the shape and length of the interconnected pores.

The spaced-electrode methods are most commonly used to measure resistivity in ground-water studies. These systems include the single point (also called point resistance), normals, and laterals. All these come under the general heading of multiple-electrode resistivity. The point resistance is a special case in which the current and potential electrode are at a single-point electrode. Although considered arachaic by the oil industry, these systems are useful to the hydrologist because they give good bed resolution, measure apparent resistivities to thousands of ohm-meters, and are inexpensive to buy and run.

The single point has a very limited depth of investigation and, furthermore, does not make its measurement on a fixed volume of rock.

For these reasons, it cannot be used for quantitative measurements. However, it is an excellent tool for determining formation tops and for ascertaining qualitatively that resistivities are relatively high or low with respect to one another.

Normal logs measure the apparent resistivity of a volume of rock surrounding the electrodes. The volume investigated is determined by the spacing between the principal current electrode and the potential electrodes (16 in for the short normal and 64 in for the long normal). The radius of investigation is approximately twice the electrode spacing. The short normal spacing was selected by the oil industry to give good vertical detail and record the apparent resistivity of the invaded zone. The long normal spacing was selected to record the apparent resistivity beyond the invaded zone. The normals give poor results in highly resistive rocks.

The lateral log measures the formation resistivity beyond the invaded zone by using electrodes spaced 18 2/3 feet apart. The lateral spacing was chosen by the oil industry to measure R_t beyond any invasion and gives best results in beds whose thickness exceeds twice the electrode spacing. Its efficiency is poor in highly resistive rocks.

Figure 2-20 gives an example of the response of the two normals and lateral in an invaded formation. Bed A in the figure exhibits a large negative excursion of the SP from the shale base line, indicating that the bed is sand. Both the short normal and the long normal have low values of resistivity opposite bed A, actually not much different in magnitude from the resistivities in the shales above and below. However, while the two resistivity curves are practically coincident in the shales, they are separated in the sand bed A. The short normal reads an average value of about 10 ohm-meters, and the long normal reads about 3 ohm-meters. The short normal is recording the resistivity of a zone that has been invaded by relatively fresh drilling fluid, whereas the long normal is responding to the much lower resistivities in a zone less affected by invasion.

The lateral curve records an average resistivity of about two ohm-meters in bed A, thus suggesting that the formation water may be even saltier beyond the zone investigated by the long normal.

Bed B in figure 2-20 is believed to be an oil sand. Petroleum is a nonconductor of electricity, and, thus, the resistivity increases.

Normal curves are usually symmetrical at each bed, but they also exhibit an artifact called cratering when the bed is equal to or less than the electrode spacing. For example, a 30 in resistive bed would be recorded as a deflection to the right on the short normal and as a deflection to the left on the long normal. A bed less than 16 in thick would cause deflections to the left on both normals.

A characteristic of the lateral curve is its lack of symmetry about a given bed. The curve is badly distorted by adjacent beds and by thin-bed affects. Not only do the apparent resistivities depart from the actual value, but shadow peaks and dead zones show up near thin resistive beds whose thickness is less than the 18 2/3 ft electrode spacing. Very salty muds and changes in hole diameter also affect the response of the lateral device.

The sonde used by many commercial services logs the SP, both normals, and the lateral curve. Commercial service tools are about 8 ft long and 3 5/8 in in diameter; they weigh up to 125 pounds and require a heavy rubber-covered bridle longer than 50 ft that carries the current and reference electrodes. Generally, a tower and A frame, or a derrick over the hole is needed for commercial service electric logging. The electric logging sondes of small water-well loggers are light enough in weight for one person to handle with ease and can be run over a small pulley attached to the well casing or a short portable tripod. Usually the normals and lateral cannot be run simultaneously on the small loggers.

A hole is generally logged from bottom to top, so that the long normal electrode, which is near the top of the sonde, is the first electrode to enter a given bed for formation. The long-normal pen deflects first; then when the sonde has moved 2 ft (the space between reference points), the short normal begins to "see" the same bed.

Both normals are calibrated at zero on the left edge of the resistivity side of the recorder chart. To distinguish one from the other when the curves cross or run nearly the same, the long normal is shown as a dashed trace. When present, the lateral curve occupies the right half of the resistivity track with zero at the center line.

One important application of the normal curves is in the estimation of water quality in clastic rocks from electric logs. A relation between ionic concentration of formation water and the long-normal resistivity reading can be established empirically. Field studies by Turcan (1966) show that once the relationship is established for a specific ground-water environment, water quality can be estimated at each new well solely from the electric log readings. These calculations, as well as many others, are based on the use of the formation factor. The formation factor (F) is defined as the ratio of the electrical resistivity of a formation 100 percent saturated with water to the resistivity of the formation water:

$$F = \frac{R_o}{R_w} \tag{2-7}$$

where R_o is the original resistivity of the formation where it is 100 percent saturated with water.

2.D.2.a.1.c. Induction

The induction log records the conductivity (reciprocal of resistivity) of rocks by inducing a current to flow in the rocks. Where invasion is shallow, the induction log measures true resistivity. The device has the advantage of working in either air- or oil-filled holes.

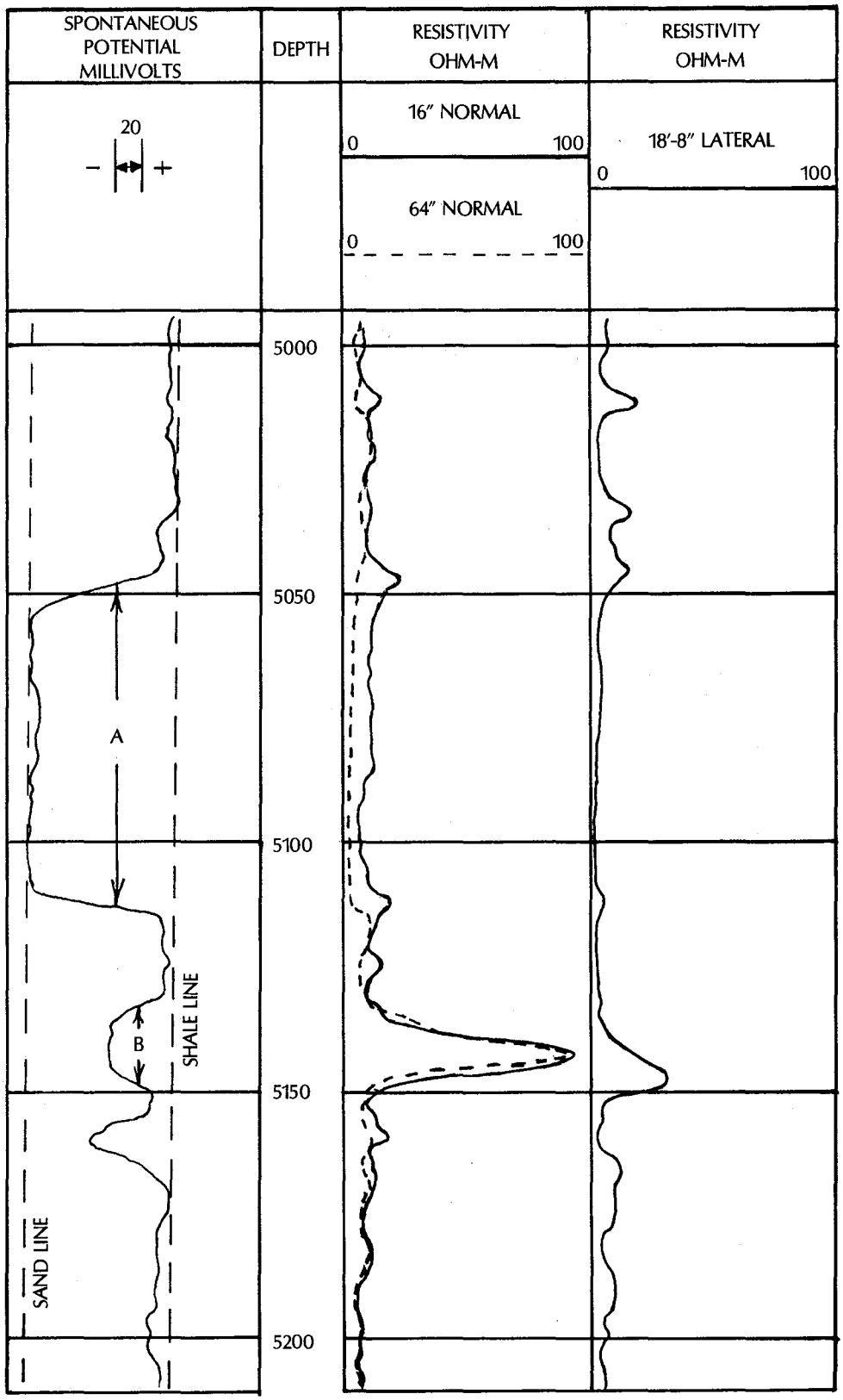

Figure 2-20.—Electric log showing sand line and shale line in the SP track.

The induction sonde transmits an alternating current field into the formation, and receives the signal returned from the formation. The electromagnetic field penetrates the formation in a torus-shaped pattern about the sonde and induces ground currents in the formation that flow along circular loops perpendicular to the axis of the borehole. The magnitude of the ground currents is proportional to the conductivity of the formation carrying this current, and a curve proportional to formation conductivity is developed. Because resistivity is the reciprocal of conductivity, it is customary to electronically invert the conductivity log and display both resistivity and conductivity curves. The induction curve samples a cylinder of rock of constant volume. The height of the cylinder is about 40 in, and the geometry is such that most of the signal is developed between radii of 40 and 120 in. This means that invasion depths of less than 40 in have a minimal effect on the induction reading.

For many situations, such as in oil-base mud, fresh mud, and in empty holes (air or gas filled), the induction log virtually measures true information resistivity. The induction log presents advantages and limitations when applied to the ground-water environment. The chief limitation is the inability of the induction method to give accurate readings when the formation resistivities are greater than about 50 ohm-meters. Thus, in clean formations saturated with very fresh water, the conductivities appear almost nil and the resistivities appear very large on the induction curve, whereas a standard electric log might read resistivities of a few hundred ohm-meters or less. Figure 2-21 compares an induction survey and a standard electric log in such an environment. The induction curve reads off scale (more than 200 ohm-meters) in the thick sand section from 1,270 to 1,400 ft; however, the lateral curve shows resistivities with peak values of about 120 ohm-meters.

The induction log has a distinct advantage over normals and laterals when resistivities are low, when invasion may be present, and particularly when the formation contains resistive beds less than 5 ft thick. Figure 2-22 shows the induction survey and a standard electric log. Thin resistive lime streaks occur within a sand section from 288 to 296 ft. The part of the sand section from 250 to 260 ft averages about 21 ohm-meters, as does the part from 275 to 282 ft. The middle section averages about 30 ohm-meters with a peak at 35 ohm-meters. The normals and lateral are adversely affected by the thin beds so the short normal reads nearly 60 ohm-meters and the lateral reads about 45 ohm-meters at the center of the sand section. The long normal exhibits cratering at the center and reads about 24 ohm-meters. It is difficult to arrive at an average resistivity for the sand section based on the electric log, but it is relatively simple to do for the induction curve.

2.D.2.a.1.d. Guard

The focused-resistivity devices were developed to overcome some of the limitations of the conventional resistivity systems. Focused devices include such electrode arrays as the guarded-electrode, laterlog, and the microfocused devices.

Guard systems use focused current methods to measure relatively high formation resistivities through conductive mud. These systems have good vertical resolution and enough horizontal penetration to measure resistivities beyond the invaded zone.

The normal and lateral resistivity devices discussed previously yield anomalous results when they are used to log formations that are much more resistive than the borehole mud column. Electric current tends to follow the path of least resistance, and under the above conditions, most of the current will flow in the mud column. For very high contrasts between the formation resistivity and the mud column, very little current enters the formation, which causes the resistivity curves to lack character, bed boundaries to be indistinct, and the apparent resistivities to depart radically from true resistivity.

The deeply-penetrating focused systems are of interest to the hydrologist because they enable beds as thin as one foot to be investigated. One use of the guard log is for computing the apparent formation-water resistivity, R_{wa}, by using a porosity log and the guard resistivity in the method described by Merkel and others (1976).

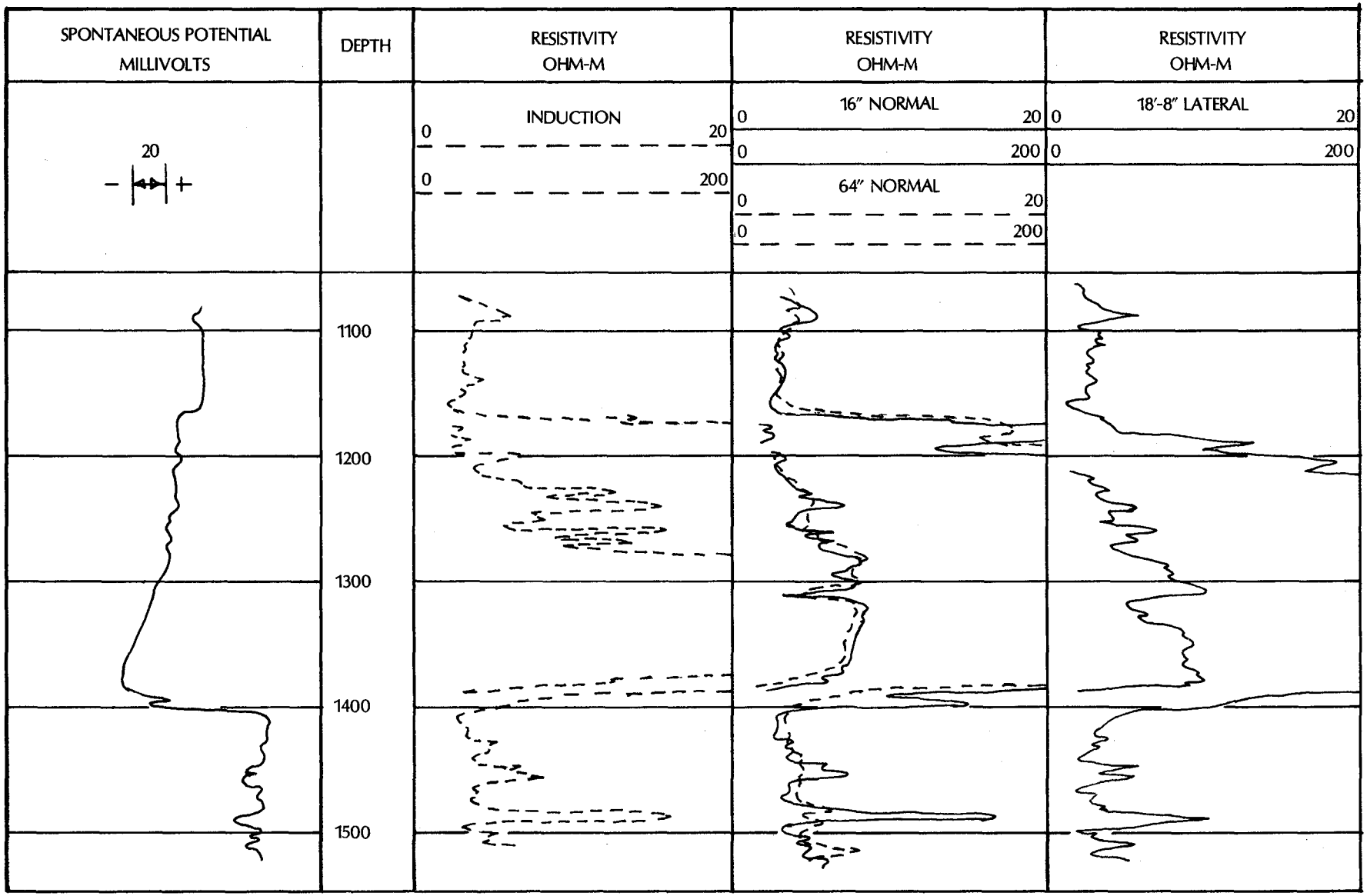

Figure 2-21.—Induction and electric logs in a resistive sand bed.

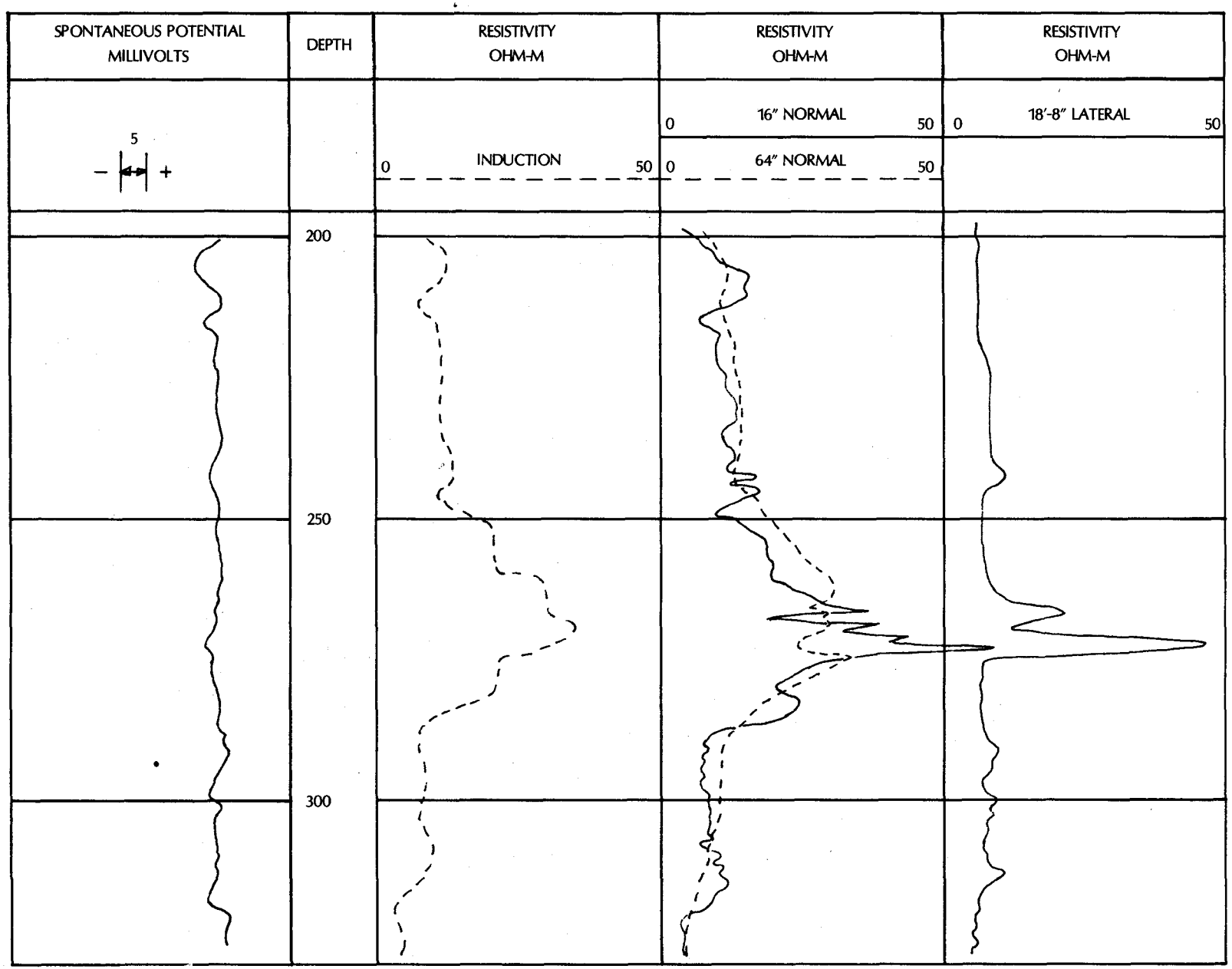

Figure 2-22. – Induction and electric logs in a sand bed containing thin resistive lime streaks.

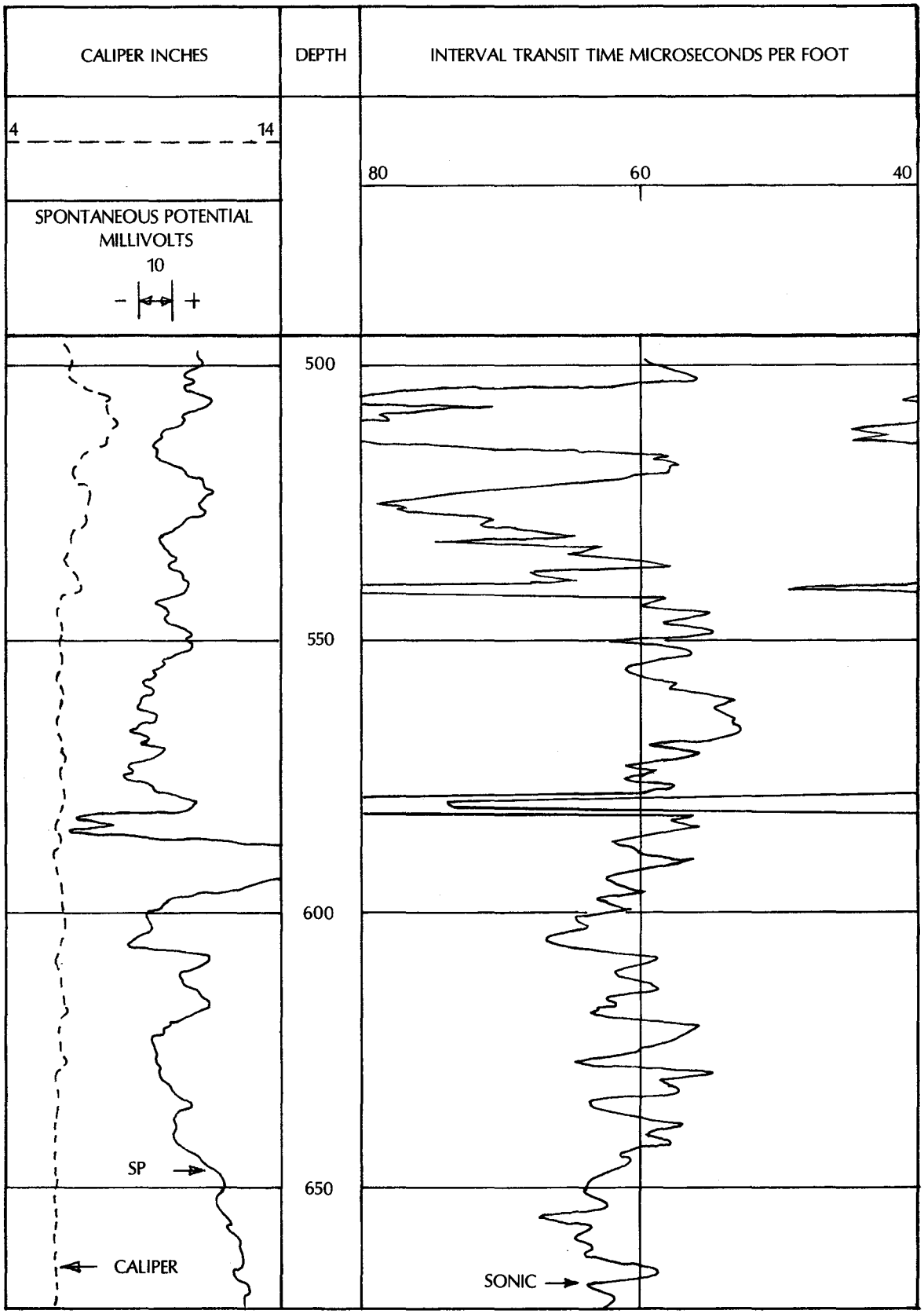

Figure 2-23. – Sonic log in a limestone formation.

Several logging systems are based on acoustic measurements and include the standard acoustic velocity (sonic log), the 3D or full-wave recording, and the televiewer systems.

2.D.2.a.2.a. Acoustic Velocity

The acoustic velocity or sonic log is one of the most important porosity measuring systems for borehole use. The acoustic log is a record of the interval transit time required for a pulse of acoustic energy to travel through a fixed length of rock. The interval examined depends on the spacing between the acoustic receivers, usually 1, 2, or 3 ft. Basically, all acoustic-velocity logging devices contain one or two transmitters that convert electrical energy to acoustic energy, which is then transmitted through the environemnt as an acoustic wave. Two or four receivers reconvert the acoustic energy sensed into electrical energy for transmission up the cable. The tool is constructed so the shortest path for the acoustic wave is through the rock surrounding the well and then along the borehole wall by refraction. The hole must be filled with water or mud to permit transmission of the clastic waves from transmitter to formation, and from formation to receiver.

Because the amplitude, frequency, and velocity of acoustic waves are affected by various rock properties, a great potential exists for determining in-situ lithologic properties by using acoustic techniques. Many useful data are available in the received-wave train. The types of acoustic waves received after transmission through the rock are classified as compressional (P waves), shear (S waves), and boundary (surface waves) (Guyod and Shane, 1969).

Acoustic-velocity logs are widely used for the measurement of porosity, based on a linear relationship between porosity and interval transit time:

$$\Delta t = \theta \Delta t_f + (1-\theta)\Delta t_{ma}$$

where

Δt = reading on the log in microseconds per foot (μs/ft),
Δt_f = interval transit time of acoustic pulse in formation fluid in μs/ft,
Δt_{ma} = interval transit time of acoustic pulse in matrix in μs/ft,
θ = porosity.

The time-average equation assumes there are two interval transit times in series, Δt_f and Δt_{ma}. The time through the fluid is equal to porosity θ, and the time through the rock is equal to $1-\theta$. A more useful version of the equation solves for porosity:

$$\theta = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma.}} \tag{2-9}$$

Because the equation is valid only for rocks with uniformly distributed intergranular pore spaces, it is a measure of total intergranular porosity. Secondary porosity, due to vugs and fractures, can not be accurately measured because the elastic waves that give the first arrival apparently travel through the matrix around the openings. Figure 2-23 is a sonic log in a water well drilled in limestone.

Usually the caliper and SP are run in the left hand track for borehole and lithologic control. In a uniform lithology, such as this, the time-average equation could be used to establish a porosity scale across the log heading. For example, the midpoint of this log scale is 60 μs/ft, the interval transit time for a limestone is 47.5 μs/ft, and that of fresh water is 200 μs/ft. Inserting these values in equation (2-9) and solving for porosity gives a ϕ equal to 8.2 percent at 60 μs/ft. Similarly, other points on the log heading can be converted to porosity for this particular rock matrix and fluid. If the rock type were to change to a sandstone and the fluid to a brine, then 55.5 μs/ft and 181 μs/ft would be used in the porosity equation for matrix and fluid values.

Several zones in figure 2-23 exhibit long interval transit times (slow velocity). The sonic log at

these places goes off scale to the left and comes back on at the right. At 580 ft, where the velocity is quite slow, the trace goes off the scale to the left and reappears on the right to give a reading of 114 μs/ft. Several similar offscale readings can be noted between 500 and 550 ft.

Until recently, the only acoustic logging systems available to the hydrologist were those using large-diameter, heavy sondes run by commercial service companies. The development of slim, flexible, lightweight sondes capable of working on small loggers has made sonic logging more attractive for ground-water studies. The acoustic log should be considered in any hydrologic logging program because it is one of the best porosity-measuring systems available.

2.D.2.a.2.b. Full Wave

The full-wave acoustic log is a recording, usually on film, of the entire acoustic waveform as it is received by the transducers on the logging instrument. Most sonic systems will work in this mode by disabling the time computing circuits and by suitably synchronizing a recording camera to the oscilloscope picture of the acoustic wave. The amplitudes and relative velocities and frequencies of the compressional (*P*) and shear (*S*) waves can be determined from a full wave recording and used to compute the elastic moduli of the rock. Another use of the full wave recording is to determine the degreee of cement bonding to the casing and formations. Unbonded pipe gives an acoustic signal of large amplitude whereas cement tends to dampen the signal received. In open holes, the full wave recording is used to locate fractures because decreases in amplitude in hard formations may be due to breaks in the rock. Decreases in amplitude may also be caused by the presence of gas.

2.D.2.a.2.c. Televiewer

The televiewer is an acoustic system much like sonar, which scans the borehole to yield an acoustic picture of the hole (Zemanek and others, 1970). An ultrasonic transducer rotates at 180 revolutions per minute while transmitting and receiving about 1,600 pulses of acoustic energy per second. The amplitude of the received signal is used for intensity modulation of the beam during the Z-axis deflection of an oscilloscope, while the X-axis deflection is proportional to the length of the borehole section logged and the Y-axis deflection represents a full 360° scan of the borehole wall. The system is oriented on the north azimuth by a magnetometer compass, and each scan of the borehole begins and ends at north. The succession of scans is gradually moved across the scope face as the logging tool is moved up along the borehole. A Polaroid or other type of camera photographs this succession of scans to produce a picture composed of successive scans closely stacked together. The intensity of the Z-axis information is proportional to the strength of the reflected signal—a hard, smooth borehole wall produces a bright area on the picture, and a washout or fracture produces a dark area. Borehole conditions between these extremes produce various shades of gray on the photograph.

Because it is an acoustic system, the televiewer must be run in a fluid-filled hole. The nature of the fluid is immaterial, and good televiewer logs can be run in holes filled with drilling mud, water, or oil.

Televiewer pictures appear as though the borehole were cut along the north edge and opened and flattened. The orientation of the picture is with north on the left edge, south up the center, and north on the right edge. East and west appear midway between north and south, and south and north, respectively. Figure 2-24 is a typical televiewer log in a hole drilled in crystalline rocks. Fractures appear as sinusoids of various amplitudes, the greater the amplitude the higher the angle of intersection with the borehole. A horizontal fracture would appear as a horizontal dark band. Fractures at several angles appear in the upper part of the picture at about 2,747 ft. A low angle fracture is indicated by the low amplitude sinusoid at about 2,752 ft. and part of a high-angle fracture occurs from 2,753 to the bottom of the picture at 2,755 ft. Numerous small openings in the rock can be seen as irregular dark areas, particularly at a depth of 2,751 ft. Zemanek and others (1970) give a method for calculating the direction and magnitude of dip of fractures from televiewer pictures.

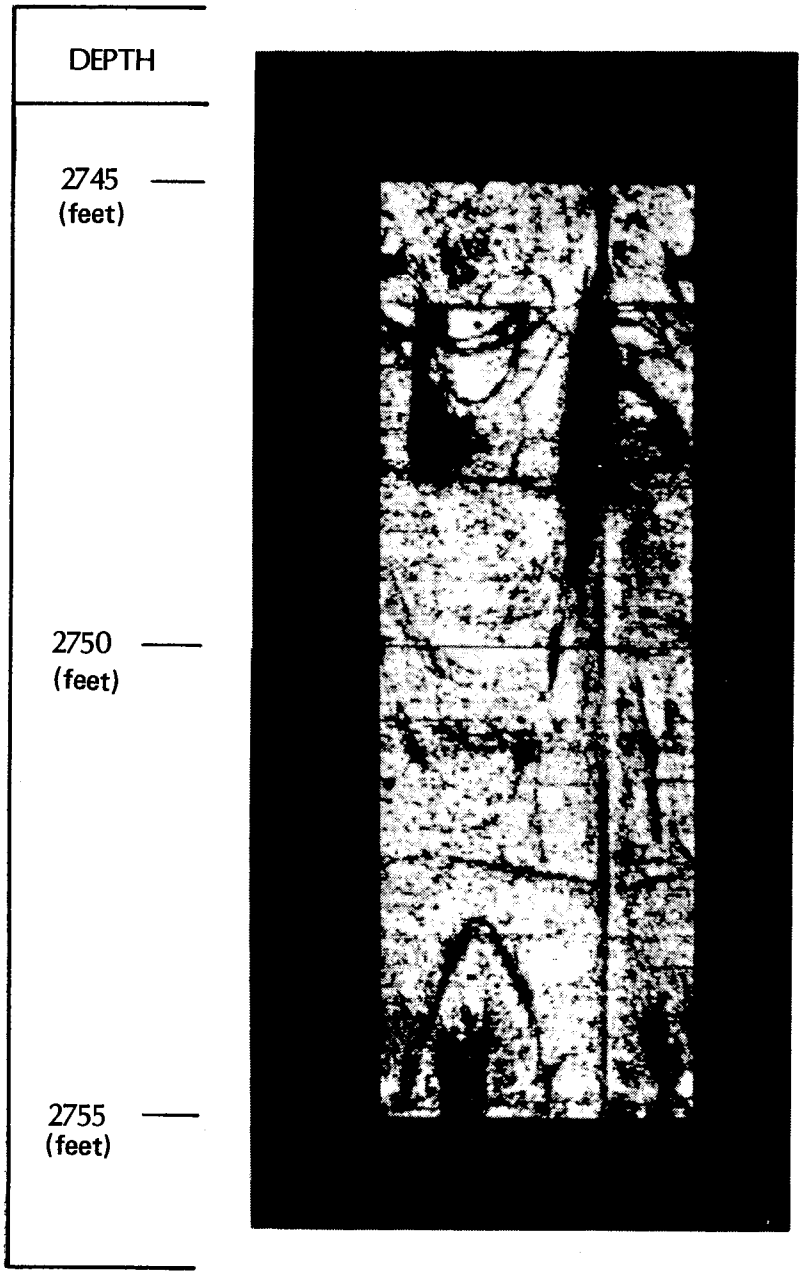

Figure 2-24.—Televiewer picture of a borehole drilled in crystalline rocks.

2.D.2.a.3. NUCLEAR LOGGING METHODS

Nuclear or radiation logs are all related to the measurement of fundamental particles or radiations from the nucleus of an atom. Commonly used nuclear logs are natural gamma (gamma ray), gamma-gamma, and neutron. Nuclear logs have an advantage over most other logs because they may be made in either cased or open holes that are empty or filled with any type of fluid. Before using these, the appropriate State agencies should be contacted, because some States prohibit the use of certain types of nuclear logging tools in holes hydraulically connected to freshwater-bearing zones. The criteria used concern the nature of any radioactive source materials used.

The radiation emitted during radioactive decay consists of alpha particles, beta particles, and gamma photons or rays. Of this group, only gamma rays are commonly measured in well logging because of their unique ability to penetrate high-density materials. Neutrons produced by an artificial source are also used for well logging. They have the ability to penetrate dense material, but are slowed in material containing hydrogen. Radiation energy is measured in electron volts (ev), thousands of electron volts (Kev), and millions of electron volts (Mev). Radiation intensity is related to the number of pulses detected per unit time.

Scintillation crystals are commonly used as gamma and neutron detectors where the expected borehole temperature does not exceed about 149°F (65°C). Commercial logging sondes generally use proportional gas counters for neutron logging because these detectors are less affected by the elevated temperatures frequently encountered in deep drill holes. Scintillation detectors, because of their great sensitivity to radiation, are often used as gamma detectors in commercial logging, but the detector must be protected from high temperatures by suitable thermal insulation. Both scintillators and gas-filled detectors produce electrical pulses proportional in number to the intensity of the radiation field. These pulses are amplified electronically in the probe and sent to the surface equipment. In the radiation-control module on a logger, the pulses are integrated over a selected time constant, and the resulting DC-voltage output is recorded. The sensitivity of a scintillation detector is mainly a function of crystal size and shape. More pulses are measured in a given radiation field if the crystal is larger.

Nuclear logging instruments can be used for logging through well casing, but their reponse is qualitative under these conditions because the casing and cement between the detector and the formations suppress the radiation being surveyed. For example, changes in bulk density on the gamma-gamma log can be seen in a cased hole, but rarely can a numerical scale in grams per cubic centimeter be applied with any confidence.

2.D.2.a.3.a. Natural Gamma

Natural-gamma logs are records of the amount of natural-gamma radiation emitted by all rocks. The chief use of the gamma ray log is identification of lithology and stratigraphic correlation in open or cased, liquid- or air-filled holes.

The gamma-emitting radioisotopes normally found in rocks are potassium-40 and the daughter products of the uranium- and thorium-decay series. The natural-gamma log run by most equipment does not use energy discrimination to distinguish the various radioiosotopes; therefore, only gross gamma activity above a detection theshold is recorded.

Even though the common gamma probe detects the several radio-active elements without distinguishing them, it does provide diagnostic lithologic information. Potassium, which contains about 0.012 percent potassium-40, is abundant in feldspars and micas, which weather to clay. Clays also tend to concentrate the heavy radioelements through the processes of ion exchange and adsorption. In general, the natural gamma activity of clay-bearing sediments is much higher than that of quartz sands and carbonates.

The logging-service companies have standardized the response of gamma ray logs by using the American Petroleum Institute (API) gamma unit. The API gamma unit is defined as 1/200 of the difference in log deflection between two zones of different gamma intensity in manmade pits. The average shale found in the U.S. midcontinent sediments will produce about 100 API gamma units. Gamma logs are calibrated in the field by means of a clip-on device or jig containing a small radioactive source. Most jigs are designed to simulate 100 or 200 API units on the recorder chart.

Small water-well loggers run the natural gamma as a separate log generally, but commercial logging companies run it for lithologic control along with the neutron or density (gamma-gamma) curves. Figure 2-25 is a natural gamma log in a water well drilled through a succession of limestones, chalks, and shales. The low gamma zone down to about 460 ft is in a chalk bed. The gamma high

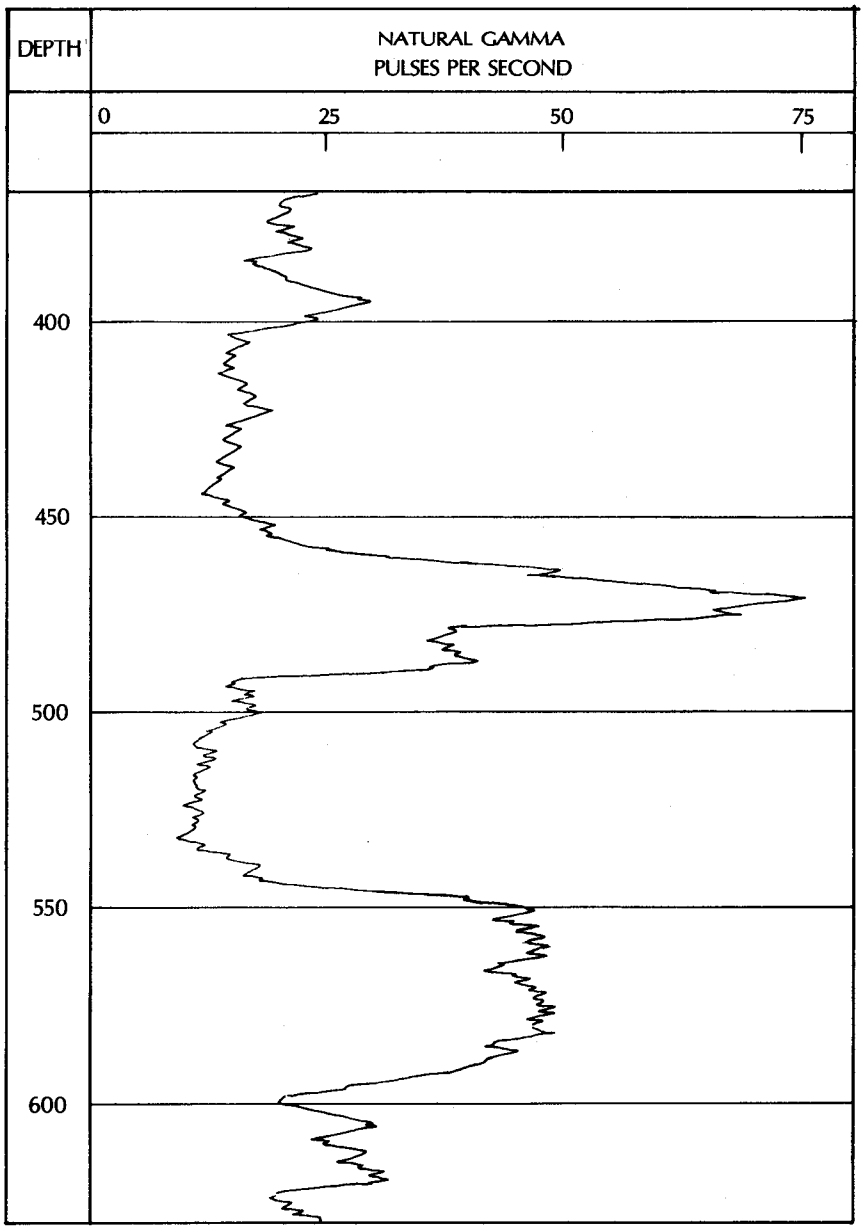

Figure 2-25.—Natural gamma log of a well drilled in limestone, shale, and chalk.

from 460 to 492 ft is in a shale section. From 492 to 546 ft another low occurs in a limestone and from 546 to 595 ft another high occurs in a clay section. This log is calibrated in pulses per second per unit of chart, but it could be related to API units with a suitable calibrator or with an established ratio between pulses per second and API gamma units.

One of the most frequent uses of the gamma log in hydrology is lithologic correlation between wells. The gamma log is suited because it will work in both cased and open holes. A semi-quantitative application relates gamma intensity to percentage of clay and hydraulic conductivity in sand-shale sequences (Keys and MacCary, 1973). Although the gamma log does work through casing, the response is subdued by casing and further reduced by cement or multiple strings of casing.

Most logging service companies publish charts to correct the gamma log for hole size, casing and cement.

In general, the gamma activity of clay-bearing sediments is much higher than that of quartz sands and carbonates. However, the gamma log does not have a unique response to lithology. Volcanic debris can greatly increase the gamma activity of clastic and carbonate sediments and the presence of heavy minerals such as monazite in quartz sand may cause the sand to be more radioactive than adjacent shales.

2.D.2.a.3.b. Neutron

The neutron log is one of the principal porosity measuring systems available to the hydrologist. A neutron source and detector are arranged in a probe so that the output is a function of the hydrogen content of the borehole environment. Water is the most common hydrogen compound in this environment, and, thus, the log indicates the total amount of water in the rock pores. Below the water table the tool measures porosity and above the water table, the tool responds to moisture content (soil moisture).

Neutrons are derived from the interaction of alpha particles impinging on beryllium. The alpha emitter is intimately mixed with beryllium inside a sealed source. A 3-curie, americium-241 beryllium source, having an emission of 8.62×10^6 neutrons per second, gives good logs under most conditions and is now standard on many oil- and water-well loggers. Americium-241 has a half life of 458 years, so the decay-correction factor is small. These sources emit fast neutrons (greater then 10^5 ev or 0.1 million electron volts).

The neutron curve used in well logging differs from that used in soil moisture logging, both in type of equipment and in the log response.

The neutron curve on most water-well loggers is run with an omni-directional tool, and the log is recorded in pulses per second per chart division. This type of tool responds to a spherical environment that includes the water in the borehole as well as the rock and fluid outside the well bore. These logs can be related to percentage of porosity if the logging system is calibrated in test holes of known porosity. Several holes of different sizes are required because this type of neutron system is sensitive to changes in well bore diameter. Regardless of these shortcomings, the neutron log commonly run in ground-water studies is very useful because the curve records high porosity zones by deflections to the left and low porosity zones by deflections to the right. The variations in rock porosity often can be used as a lithologic indicator with this curve because shales cause deflections to the left and low porosity rocks such as anhydrite cause deflections to the right. Most common sediments fall somewhere between these two extremes, however. Usually coal shows an apparent porosity much higher than shale because both hydrogen and carbon are present to moderate neutrons. Even water or crystallization will affect neutrons and, therefore, gypsum is logged as if it had a porosity of about 49 percent. Sediments containing boron, such as borax, will also record a high porosity on the nuetron curve.

The neutron logs run by logging-service companies differ from those run on water-well loggers in several important respects. Two basic tools are used, either the sidewall neutron (Tittman and others, 1966) or the compensated neutron (Alger and others, 1971). The source and detector of the sidewall neutron tool are housed in a pad which is pressed firmly against the borehole wall by a backup arm. The detector is shielded on the back so it is insensitive to neutron interactions in the borehole fluid, thus receiving most of its information from the side against the borehole; this tends to minimize the effects of borehole size and fluid effects on the curve. The backup arm is also used to actuate a caliper, from which the information is recorded on the log. More importantly, however, the backup arm corrects the neutron data for hole size changes. This computation is accomplished in the surface panel and the neutron curve is recorded in linear porosity units. Figure 2-26 is part of a neutron log of a water well drilled in limestone and dolomite. Three curves are shown—the gamma

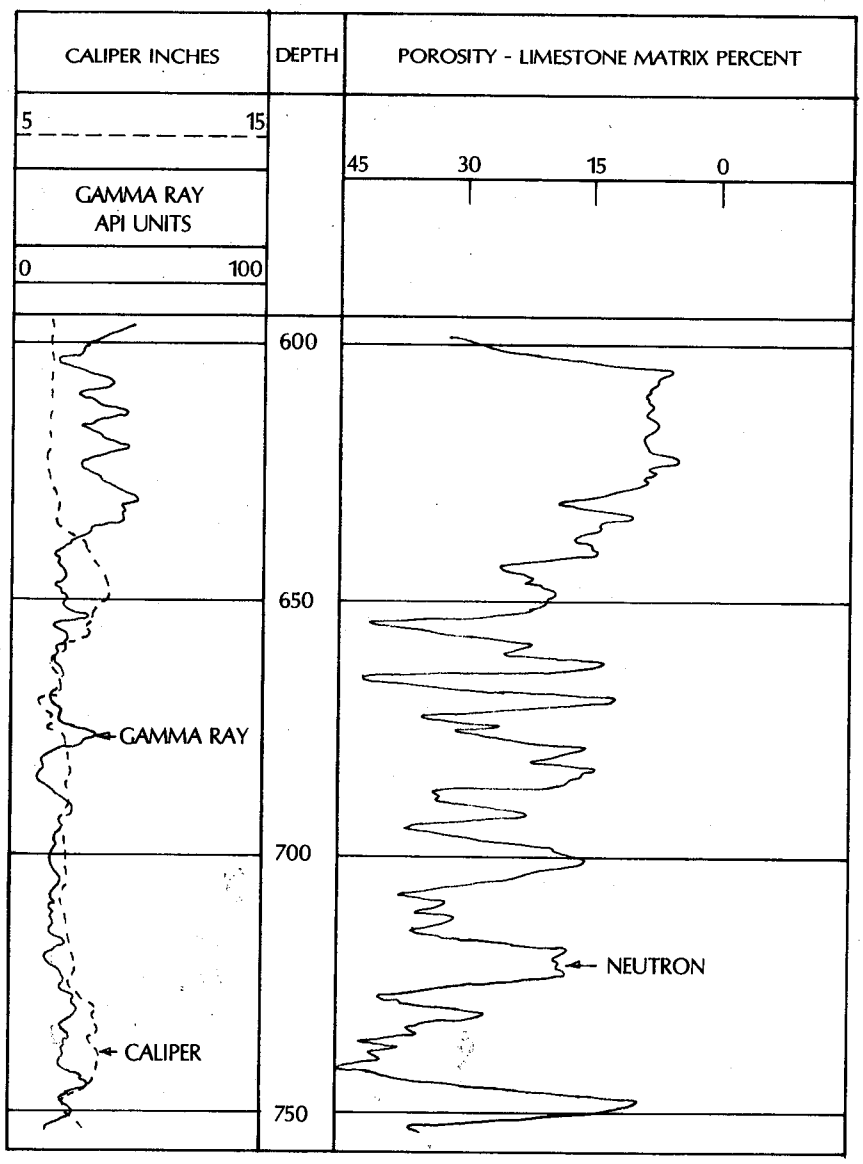

Figure 2–26.—Neutron log of a well drilled in limestone and dolomite.

ray and caliper in the left track, and the neutron porosity in the right. Most logging services run the gamma log along with the neutron for lithologic control and bed correlations.

Compensated neutron systems use two detectors and one source to self compensate for hole and fluid variations. The detector nearer the source is more sensitive to borehole variations such as roughness and mud cake. The detector farther from the source is sensitive to variations in the rock matrix and porosity. A computation using the output from both detectors is performed in the panel to produce a recording in linear porosity units.

Neutron logs run by commercial logging-service companies and the better water-well loggers are calibrated in terms of the API porosity unit. This unit is defined as 1/1000 of the difference between instrument zero and the deflection opposite a 19.0 percent porosity limestone block in a man-made test pit. The matrix lithology must be defined before porosity can be determined. At the well

site a portable calibrator is used to simulate 1000 API units so that the neutron tool and panel can be trimmed up before logging.

2.D.2.a.3.c. Density

Like the neutron and sonic systems, the density log is an important porosity measuring device. Density logs (also called gamma-gamma and scattered gamma) are records of the intensity of gamma radiation from a source in the probe after it is backscattered and attenuated within the borehole and surrounding rocks. The main response of the log is to the bulk density of the surrounding medium.

The gamma-gamma probe contains a source of gamma photons, generally cesium-137, shielded from a scintillation or Geiger-Mueller detector by heavy metal spacers. Gamma photons from the source penetrate and are scattered and absorbed by the fluid, casing, and formation surrounding the probe. Gamma radiation is absorbed and scattered by all material through which it travels; photon energy is degraded by several processes (Keys and MacCary, 1971). The absorbed gamma radiation is proportional to the electron density of the material penetrated, but it is affected by the chemical nature of the medium. Electron density is approximately proportional to the bulk density of most materials penetrated in logging. The count rate recorded on a gamma-gamma log is inversely proportional to the bulk density. A quantitative interpretation and correction for borehole factors is necessary to determine density from the gamma-gamma log.

The density log is widely used for determining total porosity using the following equation:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}, \tag{2-10}$$

where

ϕ = porosity as decimal value,
ρ_{ma} = matrix (particle) density in g/cm^3,
ρ_b = bulk density from log in g/cm^3,
ρ_f = fluid density in g/cm^3.

Matrix density can be derived from laboratory analyses of cores or cuttings or, for quartz sandstone, a value of 2.65 g/cm^3 is used. The fluid density in most water wells may be assumed to be 1 g/cm^3, or if the fluid is highly saline, laboratory measurement of fluid density may be necessary.

Bulk density may be read directly from a calibrated and corrected log or derived from a chart of correction factors. Errors in bulk density obtained by gamma-gamma methods are on the order of $\pm 0.03 - 0.04$ g/cm^3. Errors in porosity calculated from log bulk densities depend on the accuracy of particle and fluid densities used. Most commercial gamma-gamma logs are reversed, so that radiation increases to the left, rather than to the right as on natural-gamma and neutron logs. The purpose of this reversal is to make porosity increase to the left, as on long-spaced neutron logs.

Gamma-gamma probes are of two general types—an omnidirectional tool frequently used on small loggers, and a collimated tool used by logging-service companies and by small loggers to an increasing extent. The omnidirectional tool is generally contrived from a standard natural gamma probe by adding suitable spacers and a gamma source.

The omnidirectional tool is sensitive to the borehole environment as well as to the rock and fluids being investigated. Changes in borehole size and the presence or absence of fluid produce large deflections on the log. For these reasons, it is difficult to determine quantitative densities or porosities with this system. It is best used as a qualitative log.

The collimated tools described by Wahl and others (1964) are made of a skid or pad that houses the cesium source and two detectors. The skid is machined from heavy metal, so that both detectors and the source are shielded on the side toward the borehole and have slots or windows directed toward the wall of the hole. In operation, the caliper arm pushes the skid firmly against the borehole wall so the gamma energy is directed into the formation through the source window and returns to the detectors through similar windows. The detector nearer the source is more sensitive to borehole roughness and mud cake and the detector farther from the source is more sensitive to rock matrix and porosity. The surface panel computes density and porosity from a ratio of the counting rates of the two detectors. This ratio is continually compared to at least two calibration points present in the panel. The calibration points are usually preset by placing the pad on blocks of magnesium, aluminum, and sulfur which simulate known bulk densities.

Figure 2-27 is a density log of a water well penetrating carbonate rocks. The caliper trace was recorded from the backup arm which presses the pad against the borehole wall. As with most logging-service company density logs, a gamma ray log is included for lithologic control. In addition to the bulk density curve, there is also a dashed curve called compensation. This dashed curve is recorded from the detector closer to the gamma source and shows the extent to which the density curve was corrected because of borehole roughness and mud cake thickness.

2.D.2.a.3.d. Gamma Spectral

Gamma spectrometry is a means of studying the energy distribution of gamma photons and provides information not available on the natural-gamma lot. Both natural and artificial radioisotopes emit radiation with energies characteristic of the isotope. When dealing with the identification and quantitative analysis of potassium, uranium, and thorium, one must recognize that each of these constitutes a radio-active decay series.

The energies of emitted gamma rays are characteristic of a particular radioisotope. It is this characteristic that is utilized in gamma spectometry to identify elements. An important characteristic of scintillation detectors is that the intensity of each flash of light in the detector is proportional to the energy of the gamma photon that produced it. With the proper amplifying circuits, an electrical pulse proportional to the energy of the detected radiation is transmitted to the surface.

A single-channel, pulse-height analyzer blocks all pulses not within a preselected energy range and makes it possible to record a continuous log of a part of the energy spectrum or to eliminate unwanted energy levels from a log.

Figure 2-28 shows energy peaks for naturally occurring potassium-40 and daughter products of uranium and thorium as they might appear on the oscilloscope of a multichannel-spectrum analyzer. The abscissa represents energy, increasing to the right, and the ordinate is the number of counts, or photons, detected. Counts are accumulated on the abscissa in channels that are subdivisions of the energy range selected. Spectra of this type must be accumulated over a period of time. Because of low count rates, and because of statistical considerations, the length of time for accumulation depends on the gamma intensity.

The applications of inhole gamma spectometry are several. The relative distribution of potassium, uranium, and thorium can be determined by running successive logs with different "window" settings. Diagnostic ratios of natural radioisotopes can be a significant aid to stratigraphic correlation and lithology identification. One of the most important uses of gamma spectral logging is monitoring the migration of artificial radionuclides at radioactive burial grounds (Eggers, 1976). Spectral techniques can be used to identify various gamma emitting nuclides with a detection limit of about 0.2 picocuries per gram (this equals 0.2×10^{-12} curies per gram). An advantage of inhole spectral logging over coring or sampling techniques is that temporal changes can be monitored by repeat

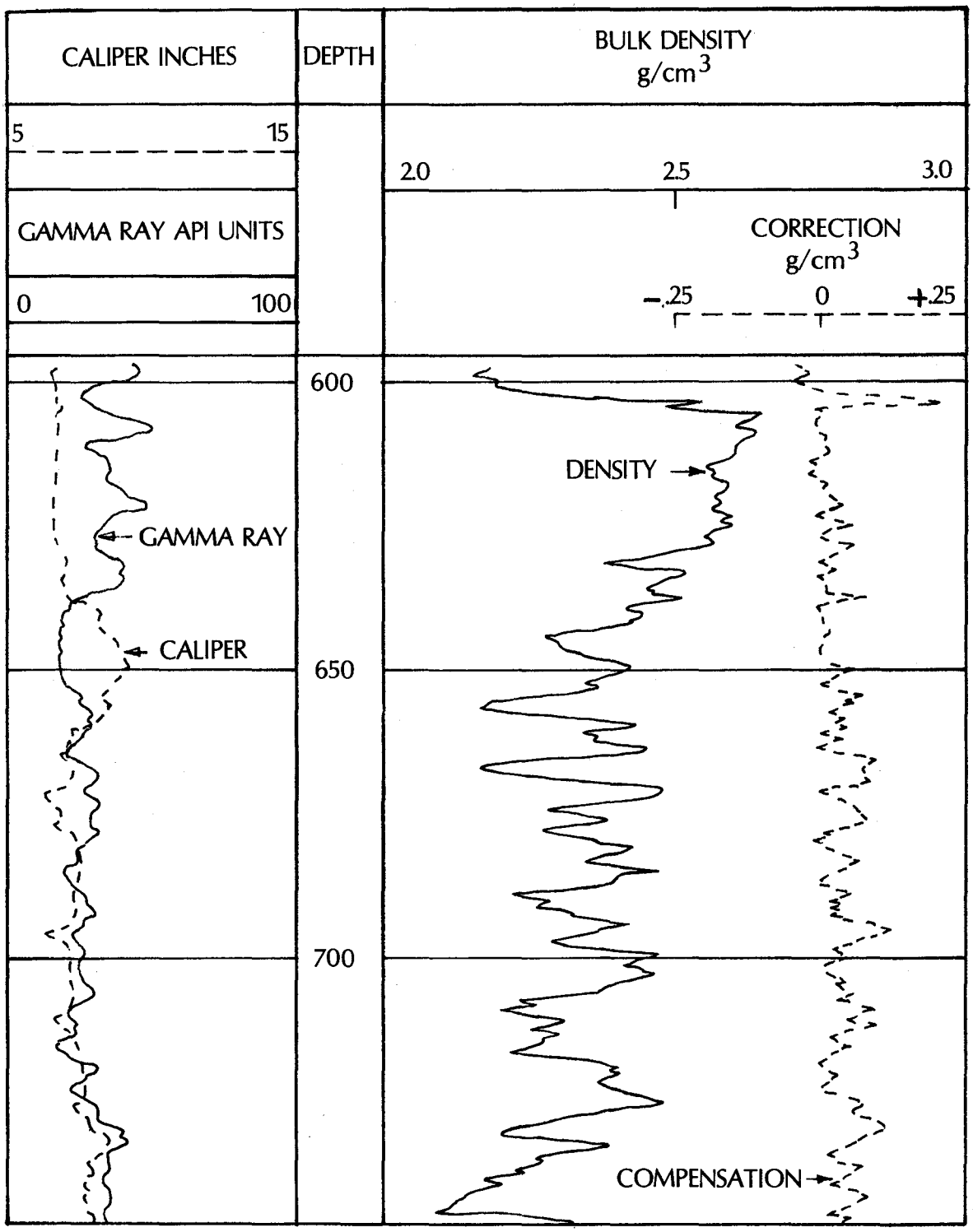

Figure 2-27. – Density log of a well drilled in carbonate rocks.

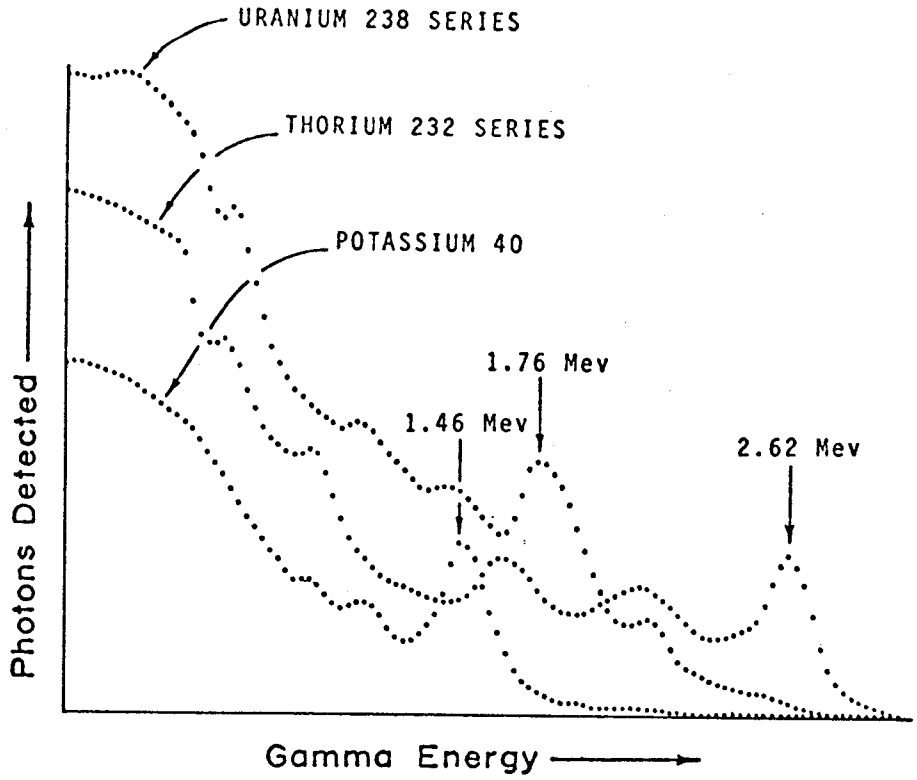

Figure 2-28.—Gamma spectra of naturally occurring radioisotopes.

logging (Eggers, 1976). By using a single channel detection system, a curve can be generated that represents the concentration of a specific nuclide at various levels in a well.

Figure 2-29 shows a natural gamma log and three spectra from a monitor well at a radioactive waste-disposal site. Only the lower spectrum appears to indicate an uncontaminated background.

2.D.2.a.4. ADDITIONAL LOGGING METHODS

In addition to the logging system already described, others are available that are useful to the hydrologist.

2.D.2.a.4.a. High resolution caliper

Caliper logs have already been discussed in connection with the nuclear logs; however, a high resolution caliper is also available. This caliper uses three arms to probe the walls of the borehole to detect openings or fractures less that one-half cm. In addition to furnishing data on the average hole size for the correction of other logs, the caliper also helps the hydrologist find solution and fracture zones, washouts, and mud squeezes. The caliper is occasionally useful in geologic correlation, particularly when one formation washes out more than those directly above or below. Some clay beds swell characteristically into the hole, and these can be correlated by searching for mud squeezes on the caliper curves.

2.D.2.a.4.b. Temperature

Temperature logs are available with most small water-well loggers. The temperature curve is usually run on the first trip in the well and logged from top to bottom to minimize effects of mixing

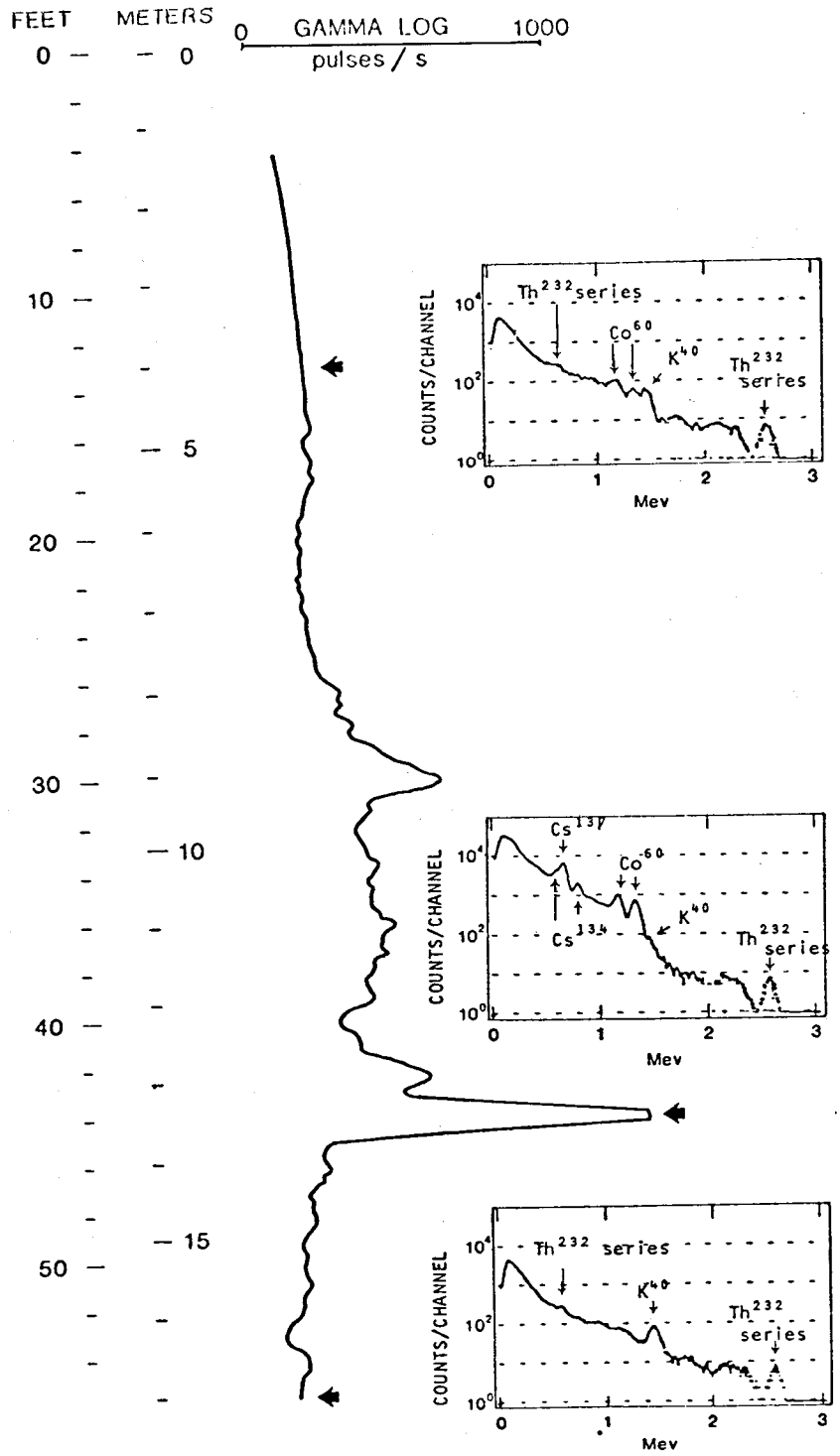

Figure 2-29.—Natural gamma log and spectra from a monitor well.

of the water in the well before measurement. The temperature sensor may be either a thermistor or a platinum wire resistor.

The geothermal gradient may be derived from a temperature log if the fluid in the well is in thermal equilibrium with the adjacent rocks, and if there is no vertical circulation of fluids in or adjacent to the well bore. Such static conditions are unusual, but where they occur, the temperature gradient is a function of the thermal conductivity of the rocks. In most wells, the geothermal gradient is modified considerably by fluid movement in the borehole and adjacent rocks.

Temperature logs can be used to locate points of water entrance or loss from the well bore. Temperature logs can also be used to trace the movement of recharge water through an aquifer system (Keys and Brown, 1973). Because cement gives off heat as it cures, temperature surveys can be used to find the position of cement behind casing for at least 24 hours after well cementing. Temperature logs are also used to correct resistivity and SP readings for the effects of borehole temperature in deep wells.

2.D.2.a.4.c. Fluid conductivity

Fluid conductivity logs are a record of the electrical conductivity of the borehole fluid. Some tools measure resistivity rather than conductivity. Unless the well has been cleared of drilling mud, a fluid conductivity log is little more than a record of drilling-mud conductivity with changing temperature down the borehole. If the well has been cleaned and pumped, often the conductivity log represents the formation water-qualtity changes with depth. If a temperature log is available, the fluid conductivity or resistivity can be converted to specific conductance using suitable graphs.

2.D.2.a.4.d. Others

Many other logging systems are available, such as casing inspection logs, dipmeter, cement bond, acoustic flow, neutron lifetime, and nuclear magnetism. Most of these logs are offered as a service and described in logging-service company literature furnished by Dresser-Atlas (1974), Schlumberger Limited (1969, 1974), and Birdwell (1976).

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2.E. SUBSURFACE MATERIALS

The environment of ground water is generally hidden from view and inaccessible, which precludes *in situ* examination of an aquifer. However, the drilling of a boring or well provides a means of access to an aquifer and permits the acquisition of important data. Such data may be acquired from the drilling procedure, the collecting and logging of samples, and the sample analyses. The data requirements may vary from a general survey of subsurface conditions to relatively precise knowledge of all major aspects of materials and conditions. In some instances, geophysical borehole logging may yield the required data. However, where certain types of precise data are required, holes must be drilled, samples must be taken, examined, logged and preferably analyzed.

Usually, the type and level of data required dictate the drilling and sampling methods used and the thoroughness of examining and logging the samples.

2.E.1. DRILLING

1. During the process of drilling, independent of other aspects of subsurface investigations, data on subsurface conditions may be obtained. These date are usually qualitative and may include:
    a. Material (rock or soil) type.
    b. Material (formation indentification).
    c. Ground-water presence.
    d. Ground-water level.
    e. Material permeability.
    f. Ground-water quality.
2. These data result from drilling conditions:
    a. Drilling equipment response (feel).
    b. Drilling rate.
    c. Drill bit wear.
    d. Hole stability.
    e. Drilling fluid response (loss or gain).
    f. Fluid appearance and condition.
    g. Ground water appearance and condition.

References that give more information: Campbell and Lehr (1973); Johnson, Inc., (1966); U.S. Department of the Interior (1977).

The method of drilling is a factor in acquiring data. The two principal methods are rotary and cable tool.

2.E.1.a. DIRECT ROTARY (HYDRAULIC ROTARY)

The direct rotary method involves drilling by continuous rotary action transmitted to a bit by a string of drill pipe. Circulating fluid (usually a clay-based mud) is pumped down the drill pipe and returns via the annulus between the pipe and hole carrying the rock cuttings to the surface for disposal. The fluid also cools and lubricates the bit and stabilizes the hole by hydrostatic pressure and mud (filter cake) buildup on the hole face to prevent caving.

The direct rotary method excels in drilling small to moderate diameter deep holes in sedimentary rock. However, it may yield minimum data (unless the hole is cored as it is drilled) because of rapid drilling action and the masking effect of the drilling fluid on geologic and ground-water conditions. Geophysical logging usually must follow direct rotary drilling to obtain maximum subsurface data.

References that give more information: Brantly (1961); Campbell and Lehr (1973); and Universal Oil Products, Johnson Division (1974).

2.E.1.b. REVERSE CIRCULATION (REVERSE ROTARY)

This method is similar to the direct rotary, except that the fluid (usually water) is circulated by gravity down the annulus and returns within the drill pipe. The fluid level is maintained at ground level to prevent caving. This requires an adequate supply of make-up water.

The reverse circulation method is most useful in drilling shallow- to moderate-depth holes in fine- to medium-grained, unconsolidated materials. It yields moderate to maximum geologic data because of use of clear water and minimum grinding of cuttings. However, ground-water conditions may be masked. This method may not be pratical for high-pressure artesian conditions.

References that give more information: Campbell and Lehr (1973); Universal Oil Products, Johnson Division (1974).

2.E.1.c. AIR ROTARY

The air rotary method is similar to the direct rotary method, except air (and often a foam-like additive) is used as a circulating fluid.

The air rotary method is most useful in drilling small diameter holes in hard rock or in arid regions. It yields minimum geologic data because of maximum grinding of cuttings and mixing of cuttings from various depths. However, in hard-rock terrains where water is encountered in fractures or similar openings, it can give moderate to maximum ground-water data.

References that give more information: Campbell and Lehr (1973); Universal Oil Products, Johnson Division (1974).

2.E.1.d. CABLE TOOL (CHURN DRILL)

This method drills by lifting and dropping a string of heavy cable-suspended drilling tools. A chisel-like bit at the bottom of the string of tools breaks or crushes the rock at the bottom of the hole into small pieces. Cuttings are removed by a bucket-like bailer suspended on a cable.

The cable-tool method is most useful in drilling small- to moderate-diameter, shallow- to moderate-depth holes in bouldery material, highly permeable rock, and where subsurface conditions are diverse. It yields moderate to maximum geologic and ground-water data because of slow discontinuous drilling action, lack of a circulating fluid and common use of casing.

References that give more information: Campbell and Lehr (1973); Gordon (1958); Universal Oil Products, Johnson Division (1974).

2.E.1.e. OTHER METHODS

Minor methods of borehole production include:

1. Augering.
2. Jetting.
3. Driving.

References that describe these methods: ASTM (1980b); Davis (1970); U.S. Department of the Interior (1974).

2.E.2. SAMPLING

Sampling of subsurface materials provides a source of quantitative data on many subsurface conditions. Such data may be required for a variety of purposes, including:

1. General knowledge of subsurface stratigraphic and other conditions.
2. Design of wells and well components, such as screens and gravel packs.
3. Laboratory testing for properties, such as permeability, moisture content, and specific yield.

Samples can be divided into two general types:

1. Those that are obtained coincidental with drilling—usually referred to as drill cuttings.
2. Those that are obtained alternately with drilling—true samples. Core samples are an exception because they are obtained coincidental with drilling.

Samples obtained from subsurface sources may vary greatly in their relationship to the materials in place. Some samples may represent only selected materials or general characteristics and, consequently, yield little or no specific characteristics, whereas other samples may be nearly true specimens. Generally, it is easier to sample fine-grained materials such as silts and clays than to sample loose, noncohesive materials such as sands and gravels.

The three generally accepted levels of samples and their degree of representation in declining order are:

1. Undisturbed sample.—Essentially an in-place specimen in which features such as structure, density, and moisture content are preserved. Suitable for most engineering testing and analysis.
2. Representative sample.—A disturbed sample in which some features do not survive but grain size and gradation are preserved. Suitable for mechanical analysis.
3. Nonrepresentative.—A sample that may consist only of drill cuttings or other incomplete or contaminated portions of subsurface materials. Generally not suitable for testing or analysis.

References that give more information: Acker (1974); Anon. (1967); ASTM (1980a); Hvorslev (1948); Mohr (1947); U.S. Department of the Interior (1974,1977); Universal Oil Products, Johnson Division (1974).

The field methods for obtaining samples vary according to the sample requirements, sampling equipment, subsurface conditions, and nature of the material to be sampled. The most common methods are discussed below:

Digging: This method yields undisturbed to nonrepresentative samples of all materials from shallow depths using hand tools or excavating equipment.

See U.S. Department of the Interior (1974) for more information.

Drive Coring: This technique yields undisturbed to nonrepresentative samples by driving an open ended cylindrical sampler into the material at the bottom of a drill hole. The sample can be obtained

using cable tool, rotary, reverse circulation, or air rotary equipment. Restricted to use in unconsolidated cohesive materials, sands, and small gravels.

References that give more information: Acker (1974); Anon. (1967); ASTM (1980a, c, d) Hvorslev (1948); Mohr (1947); U.S. Department of the Interior (1974); Universal Oil Products, Johnson Division (1974).

Rotary Coring: This technique yields undisturbed to representative samples of rock and cohesive unconsolidated materials by rotating and forcing a cylindrical sampler into the material using either rotary or air rotary equipment.

References that give more information: Acker (1974); ASTM (1980e); Brantly (1961); Hvorslev (1948); U.S. Department of the Interior (1974).

Circulating: This method yields representative to nonrepresentative samples of all types of materials from the circulating system of rotary, reverse-circulation, and air-rotary rigs.

References that give more information: Brantly (1961); Universal Oil Products, Johnson Division (1974).

Bailing: This method yields representative to nonrepresentative samples of all types of materials by bailing from the bottom of cable-tool drilled holes.

References that give more information: Anon. (1967); Gordon (1958); Universal Oil Products, Johnson Division (1974).

Augering: Augering yields representative to nonrepresentative samples of unconsolidated materials from flight or bucket augers operated by rotary or auger rigs.

References that give more information: Acker (1974); ASTM (1980a, b); Davis (1970), U.S. Department of the Interior (1974).

Jetting: This method yields nonrepresentative samples of unconsolidated materials from return jetting water.

References that give more information: Campbell and Lehr (1973); Universal Oil Products, Johnson Division (1974).

2.E.3. EXAMINING AND LOGGING

In order for samples to provide useful data, they must be examined and described in a logical, concise manner. In addition, factors involved in drilling, other than collecting samples, must also be described. This descriptive process is referred to as preparing a log or logging.

The completeness of logging may depend on several factors, including:

1. Type of samples or data.
2. Purpose of the hole, the sample, and the type of data required.
3. Technical capability of personnel involved in drilling, sampling, and logging procedures.

The general types of logs associated with ground-water investigations include geologic, lithologic, driller's, construction, drilling rate, and fluid loss.

2.E.3.a. GEOLOGIC (GEOLOGIST'S) LOG

The geologic log is a complete technical log of all conditions encountered in drilling and sampling, including lithologic, stratigraphic, mineralogic, paleontologic, hydrologic, drilling, and similar

conditions. Such a log may include results of laboratory analyses as well as field examinations and usually includes both descriptive text and graphic displays.

References that give more information: Johnson, White, and Page (1962); LeRoy and Crain (1949); Stevens (1963); U.S. Department of the Interior (1974).

2.E.3.b. LITHOLOGIC (STRATIGRAPHIC) LOG

This log is a technical log which concentrates on type, thickness, sequence, and identification of materials encountered. Such a log may include results of laboratory analyses as well as field examinations and usually includes both descriptive text and graphic displays.

References that give more information: Johnson, White, and Page (1962); LeRoy and Crain (1949); Stevens (1963); U.S.Department of the Interior (1974).

2.E.3.c. DRILLER'S LOG

The driller's log is a nontechnical field record which describes the general types of materials encountered, ground-water features, drilling conditions, major construction details, and other aspects.

References that give more information: Acker (1974); Gordon (1958).

2.E.3.d. CONSTRUCTION (AS-BUILT) LOG

This log is a record of the construction details of a well, piezometer or other facility. It details hole depths and diameters, casing and screen diameters, weights and settings, grout seal placement, water levels, and other similar data. It usually includes descriptive text as well as graphic displays.

References that give more information: Gordon (1958); U.S. Department of the Interior (1977).

2.E.3.e. DRILLING RATE LOG

This log is a record of drilling rate versus depth of drilling. It usually consists of an instrument-recorded graphic display. See Brantly (1961) for more information.

2.E.3.f. FLUID-LOSS LOG

This log is a record of rate of loss of drilling fluid from the hole versus depth of drilling. It usually consists of an instrument-recorded graphic display. See Brantly (1961) for more information.

2.E.4. IDENTIFYING AND PRESERVING SAMPLES

In order for a sample of subsurface material to be useful, it must be properly handled, identified, and preserved following collection. Major factors include:

1. Removal from the sampling equipment.
2. Identification of the sample.
3. Determination of depth interval that the sample represents.
4. Reduction to a reasonable volume where required.
5. Package for shipment.
6. Recordation of pertinent data.
7. Storage until needed.
8. Final disposition (permanent storage, etc.).

References that give more information: Acker (1974), U.S.Department of the Interior (1974).

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2.F. LABORATORY MEASUREMENTS

Laboratory tests related to flow, or storage, of fluids in porous soil and rock materials often made for one or more of the following purposes:

1. Engineering planning and design for construction of dams, canals, drainage works, etc.;
2. Land use and development, such as agricultural cropping;
3. Geologic interpretation and quantification; and
4. Quantitative ground water evaluation.

Laboratory tests usually are made, and probably should always be made where feasible, in conjunction with and correlated with field tests. Generally, tests made for engineering planning and design are made in a soil- or rock-mechanics laboratory. Tests for soil surveys and land use classification usually are made in an agricultural laboratory and geologic tests may be made in the geologic laboratories of agencies or universities. Generally, tests related primarily to ground-water quantitative evaluation, as well as most of the other tests mentioned above, can be made in a hydrologic laboratory. A correlation and interchange of data and information among these various disciplines and the expertise associated with them, is desirable and can be mutually beneficial. In

fact, the organization of all of these disciplines and objectives into one cohesive laboratory for hydrologic purposes is a desirable objective in order to help solve the wide range of hydrologic problems that can be assisted by laboratory data. The reference by Johnson (1964) lists a number of technical manuals, handbooks, papers, and reports that can provide additional details on field and laboratory test procedures appropriate to each of the above listed purposes.

2.F.1. TESTING AND ANALYSIS

For water-resources evaluation, laboratory tests are made to determine the hydrologic and physical quantitative properties of soil and rock materials. See Morris and Johnson (1967) for a summary of physical and hydrological properties for soil and rock materials derived from a variety of geologic origins.

2.F.1.a. GEOLOGIC ORIGIN PROPERTIES

Laboratory analyses must be evaluated in conjuction with a practical knowledge of the geologic origin and mineral content of the soil or rock under consideration. Publications by Kaye (1950), Legget (1967), Morris and Johnson (1967), and U.S. Soil Conservation Service (1969, 1978a, 1978b) are some that describe the soil and rock properties and some of their interrelationships with their water characteristics.

The mode of geologic origin of soil and rock materials can be used to divide them into three principal groups. These groups are the igneous rocks—formed by the solidification of molten material derived from great depths below the surface; the sedimentary rocks—formed by the accumulation of sediments in water, from air (eolian), or by gravity; and the metamorphic rocks—formed from other rocks that have undergone chemical and physical change by agencies of heat and pressure. These groups differ in mineral composition, texture, and structure, with a consequent difference in number, size, shape, and arrangement of the interstices. Pronounced differences in physical properties and the water-bearing characteristics result in the rocks as well as in the soils derived from those rocks.

Laboratory hydrologic property tests on igneous and metamorphic rocks have limited application. The matrix of most unweathered igneous and metamorphic rocks has low permeability, but the geologic units as a whole may have high permeability.

The more-productive water-bearing portions of igneous rocks—such as granite, diorite, and gabbro—are near the surface in the interstices of the disintegrated and decomposed weathered portions, or in joints and cavities extending to greater depths.

Although most igneous rocks are porous, their permeability and drainability can vary greatly according to the degree that the pore spaces, cavities, and joints are interconnected. Although laboratory analyses may show low permeability, porosity, and yield, igneous rock provides a prolific aquifer in some areas, especially where there are coarse interflow zones between successive lava sheets.

The weathered portion of metamorphic rocks—such as gnesis, schist, phyllite, and slate—is much like that formed upon igneous rocks. Ground water in these residually formed earth materials occurs much as in the weathered portion above igneous rocks. Ground water occurs in metamorphic bedrock along cleavage planes, joints, and fault zones.

Consolidated sedimentary rocks generally are overlain by residual material which may be water bearing. Water in consolidated sedimentary rock is generally limited to porous sandstones, to solution channels in carbonate rocks, or to joint openings or fault zones in those sedimentary rocks having little primary porosity.

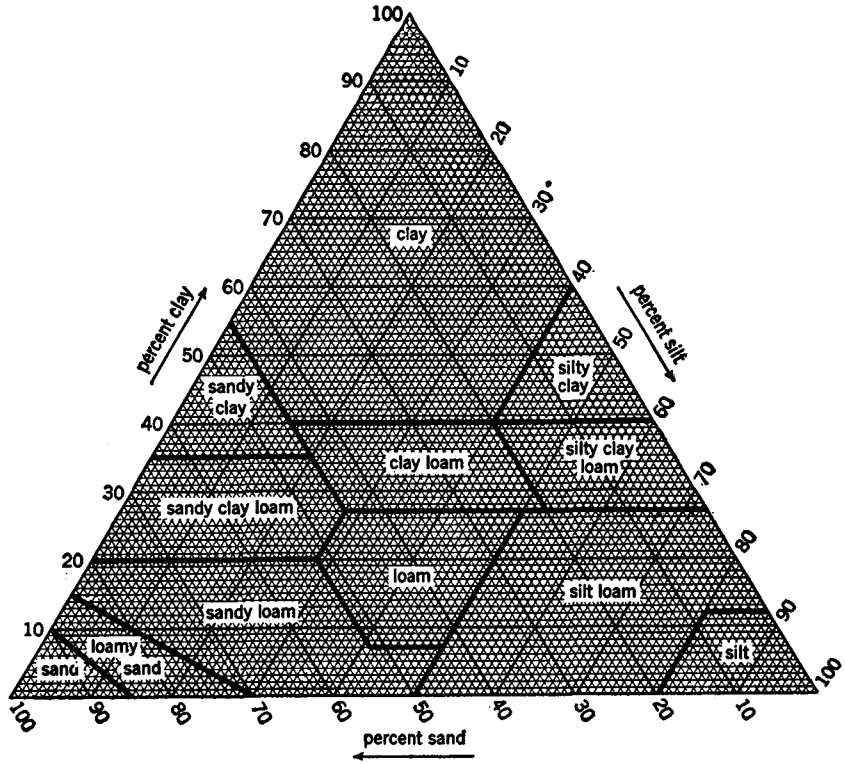

Figure 2–30a.—Example of a textural classification system.

Because of the characteristics of the various rock materials discussed above, laboratory testing related to their hydrologic properties is generally useful only for soils derived from the rocks, unconsolidated sediments, residual material, or porous sedimentary and volcanic rocks. Laboratory tests also are useful for estimating the amount of leakage through the dense matrix of confining beds where the beds are not breached vertically by short-circulating zones.

2.F.1.b. PARTICLE CHARACTERISTICS

Particle characteristics can be related to many other properties of soil and rock materials. Particle size and size distribution, shape, and mineral composition affect the movement, retention, and drainage of subsurface water (Morris and Johnson, 1967). These factors are important also in establishing the origin of the tested materials and in determining stratigraphy and structure of the sampled formations or soil materials.

2.F.1.b.1. SIZE

A variety of particle-size classification systems have been used for water-resource, engineering, agricultural, and other type studies. Many different ways of presenting such classifications have been published. Figure 2–30a presents several size-classification systems that include particles from clay-size to cobbles and boulders.

Field classification of particle size characteristics can be accurate when made by experienced personnel. Repeated checks of the field classification against that made in the laboratory on collected samples can be useful in maintaining accurate field descriptions. A textural-classification triangle chart, such as the U.S. Department of Agriculture chart shown in figure 2–30b, is especially useful in classifying materials into soil textural families.

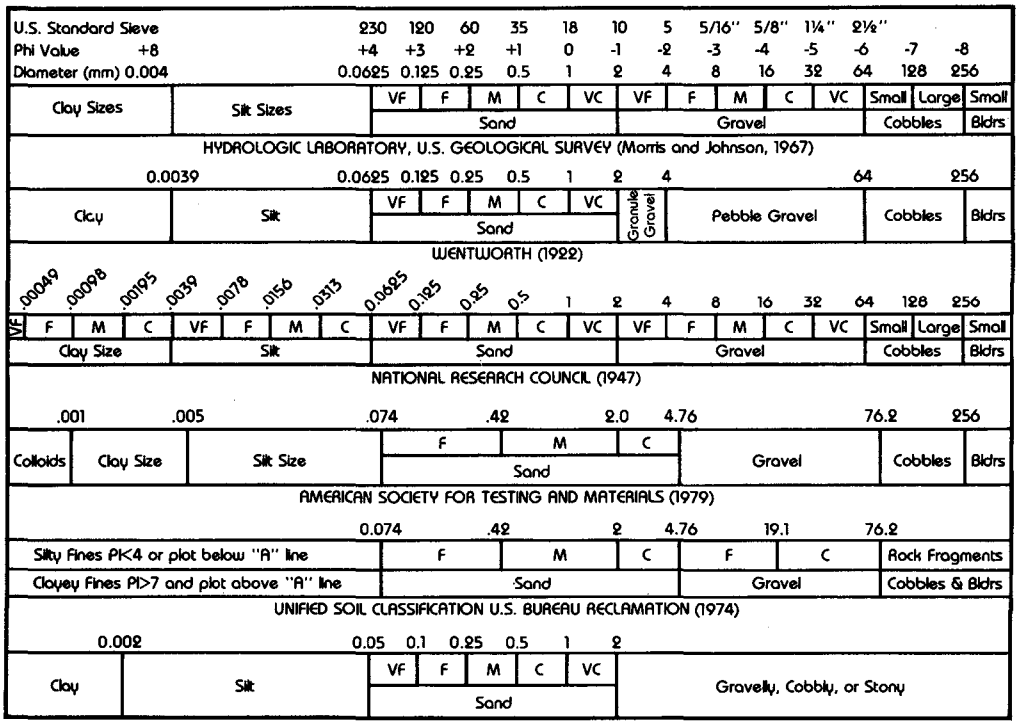

Figure 2–30b.—Examples of particle-size classification systems.

2.F.1.b.2. SHAPE

Figure 2-31 shows a comparison of degree of roundness and angularity which can assist in visual estimation and classification of roundness, this classification is useful primarily for particles of sand size or larger and only for equidimensional particles.

Normally roundness is not adequate for expression on non-equidimensional constituents either in coarse or fine-grained fractions of materials. Where flaky minerals are present these should be described on the basis of the mineral name instead of the shape, viz., biotite, muscovite, chlorite, etc. Where platy or prismatic rock fragments are present the rock type or structure controlling the shape such as bedding, cleavage, schistosity, etc., should be given as well as degree of rounding.

2.F.1.b.3. MINERAL COMPOSITION

The mineral composition of earth materials depends on the origin of the materials and the geologic processes involved. Coarse-textured materials are usually dominated by minerals which are more resistant to weathering, such as quartz. Rock fragments and unaltered rock-forming minerals—such as feldspar, calcite, and mica—may also be present.

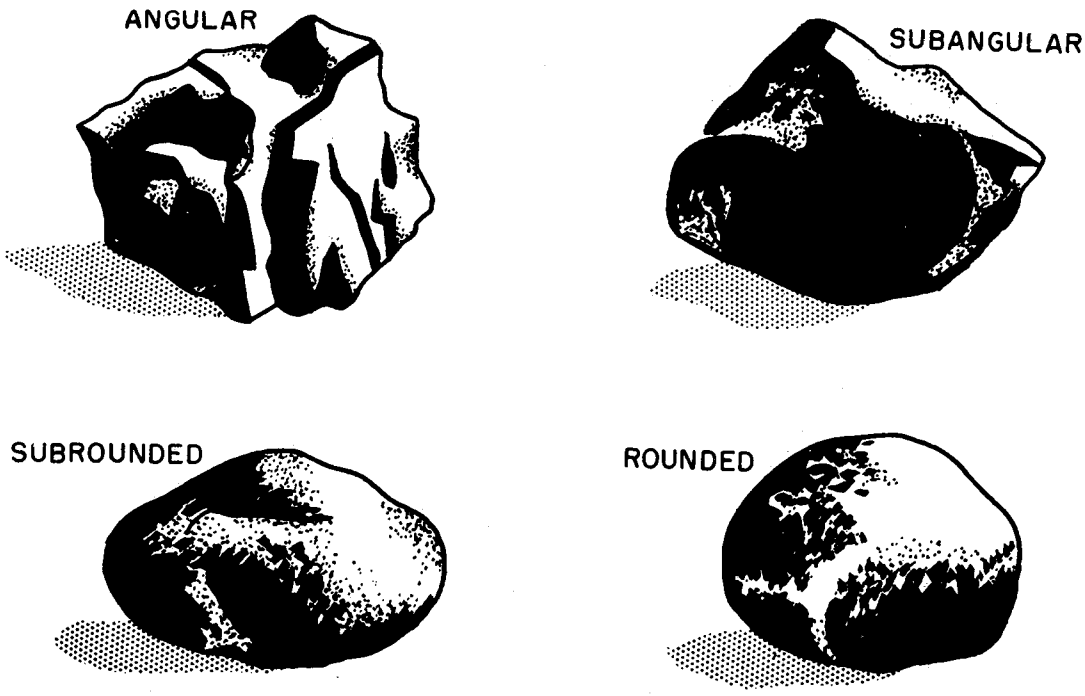

Figure 2-31.—Particle shapes (from U.S. Soil Cons. Serv., 1978a).

The fine-textured materials are the result of mechanical and chemical weathering processes. The mineral composition, as well as weathering, control the size and shape of fine-textured particles. Quartz, feldspar, and other minerals may be reduced to very small equidimensional particles, as in rock flour. Micas break down into platy particles. Other minerals may form tabular or prismatic particles.

Clay minerals require special consideration because of their influence on hydrologic and engineering properties of soils. The three principal groups of clay minerals are: (1) kaolinites, (2) montmorillonites, (3) illites. Because of variable influence each type of clay mineral may have on hydrologic and engineering properties of soils, it is recommended that the clay minerals be identified.

Kaolinite particles are larger than either illite or montmorillonite particles and are more stable. Montmorillonite clays expand when wet and shrink when dried. They are very plastic when wet and have low shear strength and high consolidation potential. Illite has the same molecular structure as montmorillonite but is less subject to expansion or contraction.

Knowledge of the local geology helps in identifying minerals. Consideration of parent materials helps to predict the minerals in the residual soils.

2.F.1.c. TEST TYPES

The type of test to be made on soil and rock materials depends upon the problems to be solved and the properties required to solve the problem. Some tests that can be found useful are as follows:

Acid solubility
Capillary rise and rate
Carbonate content
Centrifuge moisture equivalent
Consolidation
Degree of saturation
Density or unit weight
Direct shear

Effective hydraulic conductivity (capillary conductivity)
Effective porosity
Formation factor
Gypsum content
Heavy mineral analysis
Infilitration rate
Ion-exchange analysis
Mineral analysis
Moisture content
Moisture retention
Moisture tension (capillary pressure)
Particle shape
Particle-size distribution
Permeability (hydraulic conductivity)
Petrographic analysis
pH
Pore-size distribution
Pore-water quality
Relative density
Soil conductivity
Specific gravity
Specific retention
Specific yield
Total porosity
Triaxial compression

Definitions of these can be found in Lohman and others (1972) or in ASTM Standard Definitions D-653 (79) (Amer. Soc. Testing and Materials, 1979). The methods recommended for the listed tests may be found in the following publications presented in the reference list at the end of this section: Amer. Soc. Testing and Materials (1970, 1979); Bureau of Reclamation (1974); Corps of Engineers (1970); Soil Conservation Service (1972), and American Society of Agronomy (1965). Methods shown in these publications may be used with confidence provided all steps are followed and all limitations of the tests are duly noted.

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2.G. DETERMINATION OF CHEMICAL AND PHYSICAL CHARACTERISTICS OF GROUND WATER

A thorough understanding of the type of information needed and its intended use is a necessary preliminary to collection of ground water samples for analysis. Ground water samples are collected:

1. To determine chemical, physical, and bacteriological composition of ground water and suitability for domestic, industrial, and agricultural uses.
2. To aid in understanding geochemical and hydrologic relationships in natural systems and to evaluate the influence of man's activities on these systems (Brown and others, 1970).

Samples of ground water may be collected for subsequent analysis to meet one of several objectives. Most commonly, the purpose will be to determine the chemical and bacteriological suitability of the water derived from the well or spring for subsequent use. With adequate well development and careful sample treatment, the quality of ground water can be rather easily established. Because the rate of change in water quality parameters in most ground water sources is slow, the frequency of subsequent samples can be rather low. Monthly or semiannual quality tests are often adequate except in very shallow aquifers or under conditions of rapidly changing quality from the introduction of pollutants from outside sources.

Studies of the impact of outside influences that may affect the future use of ground water are different for each site. Various approaches have been tested to assess a wide variety of changing conditions. This section describes guidelines for sound sampling procedures applicable to all ground-water sampling and references detailed instructions where they are available. The importance of field measurements for certain parameters and the methods for these measurements are described.

Because samples are only a minute portion of a large ground-water body, each sample must be truly representative of the whole. Adequacy of the sample depends on the homogeneity of the water body sampled, the size of the individual samples, and the manner of sample collection.

Chapter 5, Chemical and Physical Quality of Water and Sediment, of the National Handbook discusses sample storage and preservation procedures.

2.G.1. SAMPLING METHODS

2.G.1.a. SITE SELECTION

Select sample sites to meet the specific needs of the sampling program. When possible, correlate sampling site selections to benefit basin-wide, regional, and national water quality network programs.

For a general evaluation of the quality of a ground-water resource, two approaches are equally satisfactory.

1. Determine a few constituents known to be most important in a large number of samples collected over the entire area, and from an evaluation of these data, develop an areal water-quality pattern to select sites for collecting samples to be analyzed comprehensively.
2. Where the key constituents are unknown, comprehensive analysis should be made early in the study to augment the data from the site in question. This analysis can be used with partial and comprehensive analyses from other sites.

Sites for repeated sampling to determine changes over time should be selected by analyzing the controlling variables. Outside influences, such as irrigation, that can obliterate natural recharge effects should be avoided unless the purpose of the study is to evaluate ground-water quality changes caused by outside influences.

Aquifer, well, and pumping-schedule information should be provided with each sample for maximum usefulness and applicability of data.

Sampling should be frequent enough to describe all important water-quality changes. First, important parameters and the smallest water-quality change of interest must be identified. Changes in pumping rate, chemical composition of recharge, and inflow from surrounding areas may influence ground-water quality. Changes in chemical and physical characteristics of ground water are generally slow, and often are adequately described by monthly, seasonal, or annual sampling schedules.

2.G.1.b. SAMPLE COLLECTION

2.G.1.b.1. EQUIPMENT LIST

Necessary items to be included are:

1. Sample containers.
2. Labels.
3. Notebook.
4. Filtration equipment.
5. Pump and power supply (if needed).
6. Down-hole sampler (if needed).
7. Water level measuring equipment.
8. Thermometer.
9. Meters for pH, DO, conductivity and ion determinations (as needed).
10. Preservative(s).

2.G.1.b.2. RECORDS

Obtain and record data in as complete a manner as possible and suitable to the study. Items to consider include:

1. Exact location of well or source of sample.
2. Point and method of collection.
3. Depth and diameter of well.
4. Casing record.
5. Screened, slotted, perforated, or louvered intervals.
6. Types of screens, slots, perforations, or louvers.
7. Water-bearing formation(s).
8. Water level.
9. Rate of discharge.
10. Duration of pumping prior to sampling.
11. Water temperature.
12. Other field measurements (including pH, conductivity, DO, etc.).
13. Date.
14. Time of collection.
15. Preservative type and amount.
16. Appearance and any other relevant data.
17. Filter size used and on which samples.
18. Use of water (if any).
19. Purpose of sampling.

2.G.1.b.3.a. Determination of Suitability of a Spring or Well

When the spring or well is in use, samples should be collected for subsequent determinations of water quality under normal operating conditions. A spring or well that is planned for future use should be tested under conditions approximating the anticipated future pumping rates and drawdown.

2.G.1.b.3.b. Determination of Ground-Water Quality

See Wood (1976) for detailed information.

2.G.1.b.3.b.1. Springs—For springs in unconsolidated deposits, drive a well point or a slotted pipe one meter or less into the ground adjacent to the spring. Collect from artesian flow or use a small pitcher pump. Use plastic pipe and plastic well screens for trace metal determinations.
Sample larger upwelling springs with a submersible electric pump having plastic housing, impellers, and tubing. Attach the pump to a pole and submerge it in the mouth of the spring.

2.G.1.b.3.b.2. Wells—Pump wells until temperature, specific conductance, and pH are constant before collecting representative samples. The sample should be collected near the wellhead before the water has gone through pressure tanks, water softener, or other treatment. When wells are not equipped with pumps, a submersible pump with outside power source is preferred. A pitcher pump may be used if the water level is within 7 meters of the surface. A small diameter point sampler may be used, but only after the well has been bailed until the temperature and other field measured parameters are constant. Bailers and point samplers usually contaminate the sample with oxygen.

Well packers can be used to sample from individual aquifers tapped by multi-screen or open-hole wells that receive water from several aquifers. Such wells often are avoided in sampling for geochemical studies because of the higher costs involved in the use of packers.

2.G.1.c. SAMPLE PREPARATION AND STORAGE

Chapter 5 of the National Handbook gives information on selecting the type of container, method of filtration, field treatment, preservation, and storage of samples—depending on the particular inorganic, organic and radioactive constituents to be determined. Chapter 4 of the National Handbook provides this information for biological samples.

2.G.2. ON-SITE MEASUREMENTS OF UNSTABLE CONSTITUENTS

Special collection procedures and field analyses are required immediately after collection for the following chemical and physical parameters: pH, temperature, carbonate, bicarbonate, specific conductance, Eh, and dissolved oxygen. Wood (1976) provides detailed directions for these determinations. Methods for collections and field determination of ammonia and hydrogen sulfide gas are given by Presser and Barnes (1974).

Samples used for determining temperature, dissolved oxygen, Eh, and pH should not be filtered. Do not use vacuum filtering prior to determining carbonate and bicarbonate concentrations because it removes dissolved carbon dioxide and exposes the sample to the atmosphere. Pressure filtration can be done using water pressure from the well. If gas pressure is required, use an inert gas such as argon or nitrogen.

2.G.2.a. SPECIFIC CONDUCTANCE

The specific conductance of a water sample is a measure of its ability to carry an electrical current under specific conditions. Specific conductance, which is a measure of the ionized salts, gives an indication of the concentration of dissolved solids in the water.

There are several reasons for determining the specific conductance of a sample in the field at the time of collection rather than waiting for a laboratory measurement. The field determination can be used as an aid in evaluating whether a sample is representative of water in the aquifer. For example, in new or little used wells, or in wells that have been recently drilled, grouted, or cemented, chemical changes in the pumped water may be rather large, and the well may require prolonged pumping to insure that the sample is representative of water in the aquifer. Specific-conductance determinations can be used to indicate that sufficient water has been pumped and that the quality of the water is stabilized.

A specific-conductance value that is markedly different from values obtained in nearby wells may indicate a different source of water, such as induced recharge, contamination from the surface, or leakage from a formation that contains water of different quality. Detection of an anomaly may indicate that more detailed sampling or reevaluation of the well is required. If so, the work can usually be done more economically at the time the original sample is collected rather than several weeks or months later.

Once the sample is in the container, its specific conductance may change with time as a result of precipitation of minerals from the water. A sample that has been acidified or otherwise treated will not yield an accurate representation of the specific conductance of the water in the aquifer; therefore, it is essential to obtain an accurate field determination.

2.G.2.a.1. METHOD SUMMARY

The ability of a solution to conduct an electrical current is a function of the concentration and charge of the ions in solution and of the rate at which the ions can move under the influence of an electrical potential. As the number of ions per unit volume of solution increases, the rate at which individual ions can move decreases because of interionic attraction and other effects. A graph of total ion concentration versus specific conductance, even for solutions of a single salt, is a straight line only for values below 1,000 micromhos/cm. As specific conductance increases to above 5,000 micromhos/cm, the regression line curves significantly; beyond 50,000 micromhos/cm, the specific conductance may be an unsatisfactory index of ion concentration.

The temperature of the electrolyte affects the ionic velocities, and consequently, the specific conductance. For example, the specific conductance of potassium chloride (KCl) solutions changes about 2 percent per degree Celsius near 25°C.

Specific-conductance meters used in the field should be battery operated, equipped with temperature compensator, and read directly in micromhos/cm at 25°C. The direct reading meter is recommended to save time in converting resistance values to specific conductance and to insure that the value is read in the field.

The cell should be checked before initial use and should be checked daily during regular use. A 0.00702 N potassium chloride (KCl) solution (dissolve 0.5234 g KCl dried at 180°C for 1 hour in distilled water and dilute to exactly 1 litre) has a specific conductance of 1,000 micromhos/cm at 25°C. Routine checks are made by using the 0.00702 N standard solution at the ambient temperature. The temperature control on the instrument is set at 25°C, and the ambient temperature of the standard KCl solution is recorded. A value of specific conductance is obtained and compared with the values given in figure 2–32 for the ambient temperature. The value obtained should be within 5 percent of that in figure 2–32.

Next, the temperature-adjustment knob is moved to the ambient temperature, and the meter is read. The value obtained should be 1,000 micromhos/cm, regardless of the ambient temperature.

This procedure checks the temperature compensator, the conductance cell, and the electrical circuit of the instrument.

If the value obtained for the standard solution is not within the specified precision, the cell must be reconditioned and replatinized according to the instructions given in Brown, Skougstad, and Fishman (1970) or in the literature supplied by the manufacturer of the instrument. The carbon-type electrode supplied with some conductance meters needs no platinizing and should be replaced if it fails to perform to the specified accuracy.

2.G.2.a.2. APPLICATION AND INTERFERENCE

2.G.2.a.2.a. Apparatus

1. Mark V Electronic Switchgear (Chemicon Co.)[1] with cell constants of 0.1 and 1.0, or equivalent direct-reading meter.
2. Thermometer, 0–50°C graduated in 0.1°C.

2.G.2.a.2.b. Procedure

The following general procedure is supplemental to the instructions supplied by the manufacturer:

1. Rinse measuring cell with several volumes of sample water.
2. Bring temperature of cell to that of the water being measured by immersing measuring cell in well discharge for at least 5 minutes. Some plastic cells have a high heat capacity and will cause drifting of the reading if not in thermal equilibrium with the sample.
3. Record reading, temperature, time, date, cell constant, and any meter constants.
4. Remeasure, with fresh sample, until reproducible readings are obtained.

2.G.2.b. TEMPERATURE

The temperature of ground water is important for numerous applications. For example, temperature measurements are critical in identifying recharge from nearby surface-water sources. For accurate geochemical evaluation of equilibrium thermodynamics, it is desirable to know the temperature of the water in the aquifer within ±0.1°C.

2.G.2.b.1. METHOD SUMMARY

The temperature is recorded by a mercury-filled thermometer that is permitted to equilibrate in a sample that is continuously pumped into a dewar flask. The well should be pumped continuously until three identical consecutive readings of temperature are obtained.

2.G.2.b.2. APPLICATION AND INTERFERENCE

The foregoing method may be used to measure the temperature of any ground water sample but is most accurate when the ambient temperature is within 20°C of the ground-water temperature. New or little-used wells may develop new producing zones during pumping, thereby varying the proportion of water entering the well from different depths and causing either an instantaneous change or continual drift in the temperature measurements. Drawdown may cause dewatering of certain beds and may cause a change in the temperature. Pumping time insufficient to allow equilibration of water temperature in the casing and pump column will also cause drifting of the temperature.

[1] The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

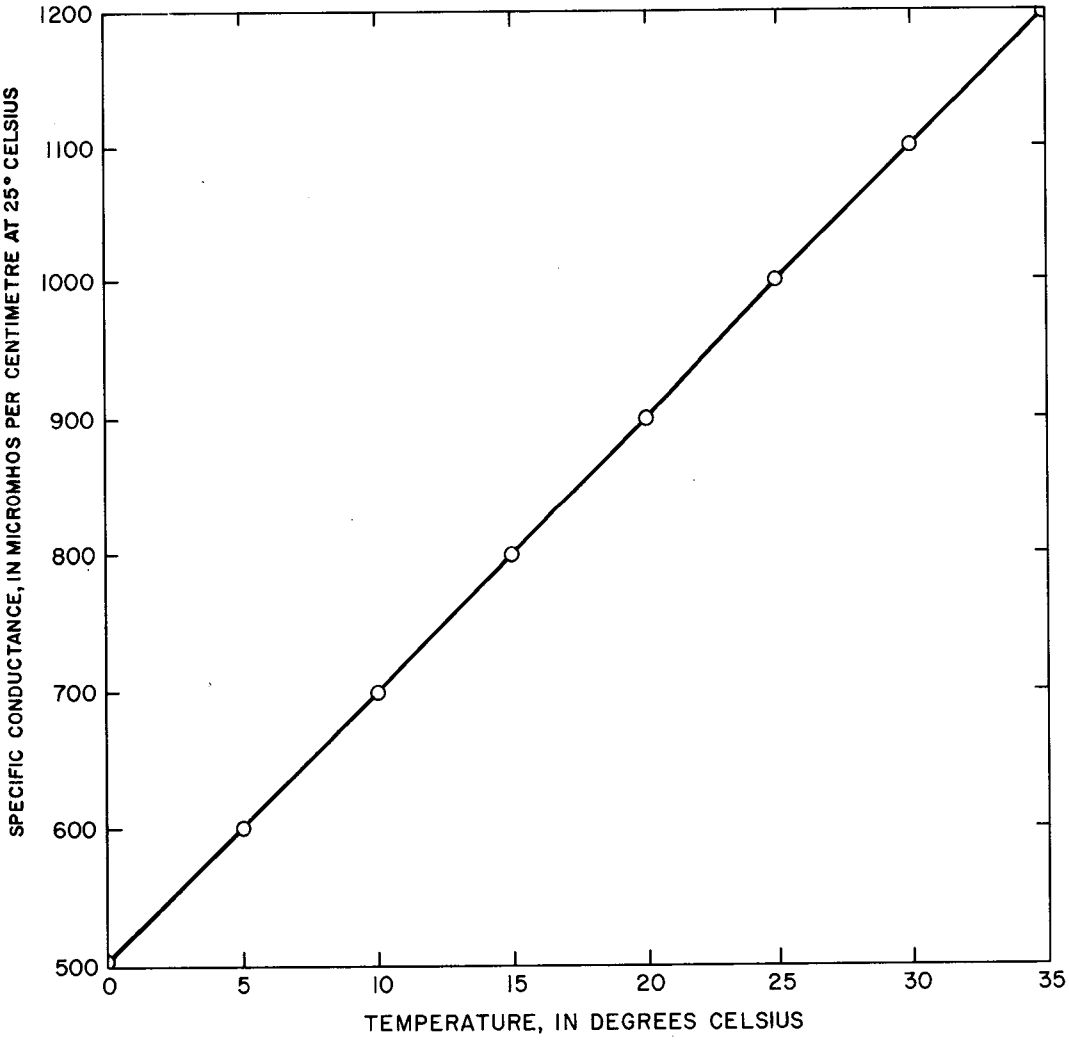

Figure 2–32.—Specific conductance of a 0.00702 N potassium chloride solution at various temperatures.

2.G.2.b.2.a. Apparatus

1. Dewar flask (a thermos bottle with a narrow mouth is adequate).
2. Partial immersion thermometer calibrated in 0.1°C or 0.2°F with the usual range of 0–50°C, or any range expected in the ground water in the study area. Steel or brass armor should be used to minimize breaking the thermometer. The thermometer should be accurate to ±0.1°C as checked against the Bureau of Standards calibrated thermometer.

2.G.2.b.2.b. Procedure

Samples should be collected as close to the wellhead as possible. A continuous stream of water should be conducted through a short plastic tube into the bottom of the flask, allowing a continuous flow of water from the flask. Readings should be taken after 5 minutes of flow at 1-minute intervals

and recorded until no change is observed. If collection by continuous flow is impossible, the sample should be collected in the dewar flask and stoppered, with the thermometer inserted through the access hole. The first sample should be allowed to equilibrate 1 or 2 minutes and should then be discarded. The flask should be quickly refilled, and the temperature should be recorded immediately. This process should be continued until three identical consecutive readings are obtained. A box similar to that shown in figure 2–33 is useful for carrying equipment and preventing breakage.

2.G.2.c. SOLUTION pH

The pH of a solution is a measure of effective hydrogen-ion concentration, or more accurately, it is the negative logarithm of the hydrogen-ion activity in moles per liter:

$$pH = -\log [H+]. \tag{2-11}$$

In aqueous solutions, pH is controlled by reactions that produce or consume H+, including practically all dissociations of acids, bases, and by hydrolysis. The primary control over pH in most potable ground water is the carbonate system including gaseous and dissolved carbon dioxide, bicarbonate, and carbonate ions. Other dissolved gases, such as hydrogen sulfide and ammonia, can also affect the pH of the solution.

2.G.2.c.1. METHOD SUMMARY

The pH is determined with a glass hydrogen ion electrode compared against a reference electrode of known potential by means of a pH meter or other potential measuring device with a high input impedance. A detailed description of pH and reference electrodes and their operations are given in Durst (1969), Garrels and Christ (1965), and Langmuir (1971). Because pH is exponentially related to concentration, great care must be exercised in making a measurement. Barnes (1964) gives details for measuring pH.

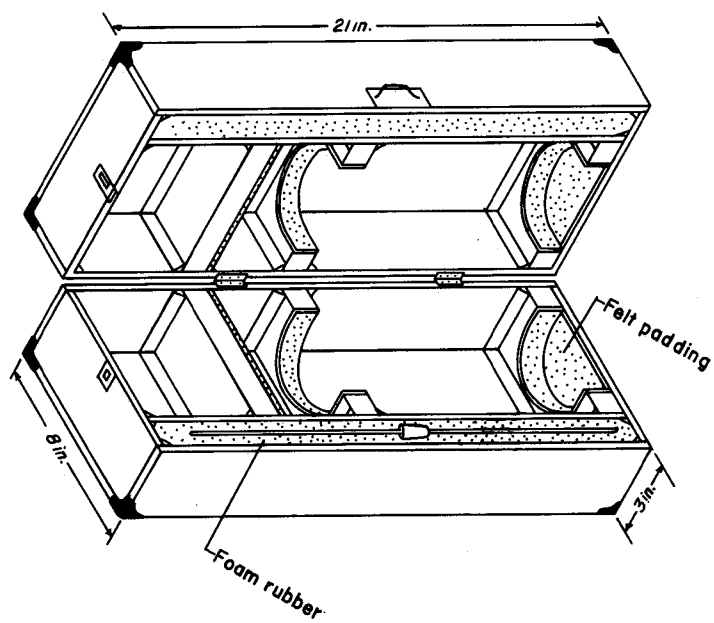

Figure 2–33. – Carrying box for thermometer, reading lens, and dewar flask.

A high sodium concentration will give an anomalous pH reading, which must be corrected according to the recommendation of the manufacturer of the pH electrode. This correction is usually necessary only if pH is greater than 11, and sodium concentration is more than 10 moles per liter. Measurement of pH is temperature sensitive, so the standard buffers should be within ±1°C of the sample solution for precise determinations.

2.G.2.c.2.a. Apparatus

1. Orion 401 pH meter or equivalent (a meter with a scale at least 15 cm long, is necessary for detailed work of ±0.02 pH units).
2. pH buffer solutions 4.00, 7.00, and 10.00; 500 mL each.
3. Corning triple-purpose pH electrode 476021, or equivalent.
4. Orion single-junction reference electrode 90–01, or equivalent.
5. Filling solution for reference electrode.
6. Holder for electrodes, Multiflex or equivalent.
7. Plastic pail.
8. Thermometer.
9. Distilled water.
10. 500-mL plastic squeeze wash bottle for distilled water (color coded so as not to be confused with other reagents in wash bottles).
11. Box of small Kimwipes or equivalent.
12. Mixed bed deionizer in a delivery tube, 16-ounce size Deeminac or equivalent (useful for final treatment if commercial distilled water must be purchased).
13. Three 100-mL plastic beakers.
14. One 250-mL plastic beaker.
15. Card table or other portable table on which to work.

2.G.2.c.2.b. Procedure

The following procedure has been found useful in supplementing the pH meter manufacturer's instructions:

1. Check and fill reference electrode with internal filling solution recommended by the manufacturer. On Orion reference electrode, press cap and permit some of the filling solution to drain from the electrode to insure complete electrolyte contact before inserting electrode in sample.
2. Adjust buffer solution and electrodes to ±1°C of the sample temperature by letting sample water flow over submerged bottles and electrodes. (Be careful not to let sample water enter the filling hole of the reference electrode.) To prevent floating of partially filled buffer bottles, epoxy heavy steel washers to the bottom of the bottles. An alternative is to construct a small water bath that holds two buffer bottles and sample beaker firmly in place during determination (fig. 2–34).
3. Record temperature of water.
4. Level meter and check to insure that the needle is properly adjusted.
5. Place pH 7.00 buffer in color-coded insulated beaker and place electrodes in the buffer, (Note-The pH of the buffer is equal to 7.00 only at 25°C; therefore, it is necessary to use the temperature-correction curve supplied by the manufacturer. Figure 2–35 is an example of a typical curve of temperature versus pH for a commerical buffer of pH 7.00). Turn on meter and adjust to correct pH value. If the electrodes have not been used recently, or have been allowed to dry for several days, it may take 10-20 minutes

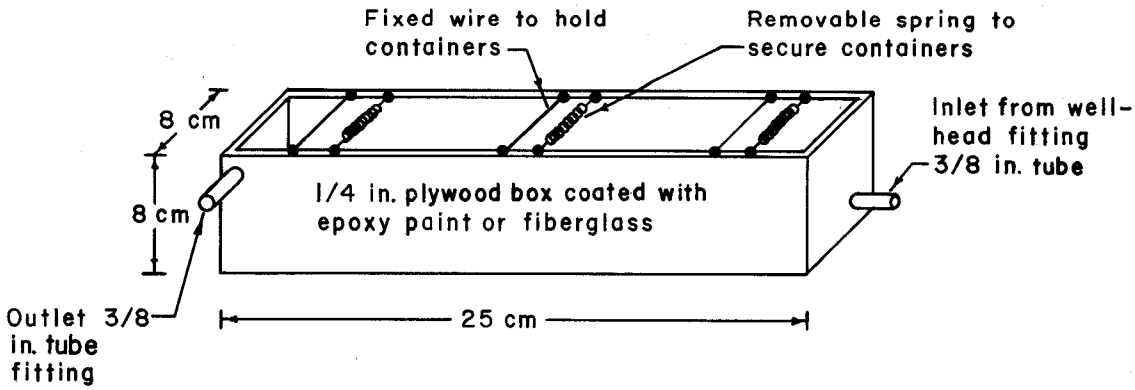

Figure 2-34.—Portable bath for maintaining buffers and sample at wellhead temperature.

for them to stabilize. If electrodes will not stabilize, try either a new reference or pH electrode. To keep electrode from drying out and ready for use, immerse the electrode tip in a rubber or plastic sack (such as the finger cut from a plastic glove) containing a few milliliters of buffer solution.

6. Switch meter off or to standby position and remove electrodes from pH 7.00 buffer. Rinse thoroughly with distilled water and blot dry. Place electrodes in either pH 4.00 or pH 10.00 buffer, bracketing the expected pH of the sample. Switch meter on and allow several minutes for stabilization before making final adjustment. Turn meter to off or standby position.
7. Check adherence of the response of the electrodes to the theoretical Nernst slope. According to manufacturer's instructions, and before adjusting meter with pH 7.00 buffer, set the slope indicator to 100 percent and the temperature compensator to the correct temperature (of water and buffer). After placing the electrode in the second buffer, adjust the temperature compensator until the correct value of the second buffer is obtained. Then adjust the slope indicator until the temperature compensator points to the temperature of the solution. Read the percentage of theoretical slope on the slope scale.

   Experience has shown that if the observed percentage differs from the theoretical value by ±10 percent, the reference electrode should be replaced and the slope rechecked by returning to step 5. The theoretical Nernst slope for temperatures commonly encountered in ground water is shown in figure 2-36. Comparison of electrode response to the theoretical response (Nernst equation) is a check on the efficiency of the electrode system. The lack of agreement between the observed electrode system and the Nernst equation does not indicate that the observed pH values are inaccurate. All that is indicated is a potential source of trouble and some part of the system is not operating as efficiently as it should. Generally, combination pH-reference electrodes do not conform to the theoretical curve as closely as do the individual electrodes.
8. Rinse electrode with distilled water and blot dry. Recheck value of pH 7.00 buffer. If value is within ±0.02 pH of the correct value, proceed with next step. If drift from original setting has occurred, repeat steps 5-8.
9. Thoroughly rinse electrode with sample water and then place electrodes in a sample collected in 250-mL plastic beaker. Turn on meter. Do not swirl or stir sample. Allow at least 2 minutes for equilibration. Record value. Turn meter to off or standby posi-

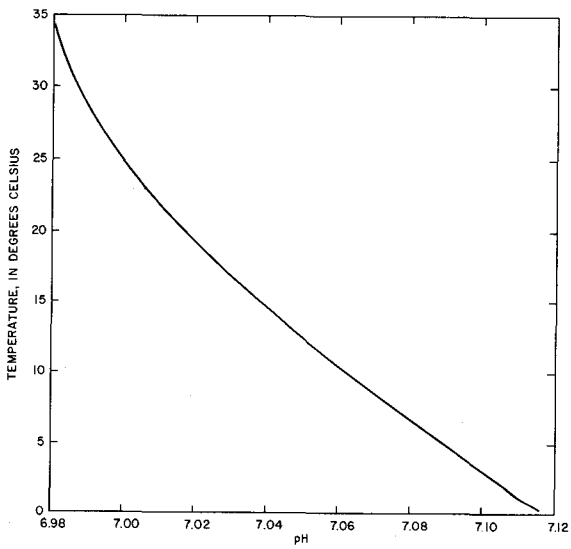

Figure 2-35.—Relationship between temperature and pH for a typical commercial buffer solution.

tion. Repeat step 9, using newly collected samples until three consecutive readings differ by no more than ±0.02 pH unit. If equilibrium is not attained in several minutes, outgassing of CO_2 may be occurring. In such cases, the initial reading may be the best. Outgassing may be reduced by placing the electrode system through a tightly fitting stopper into the water-filled beaker.

10. Place electrodes in temperature equilibrated buffer pH 7.00. Turn on meter. If reading is within ±0.02 of original buffer reading, then analysis is complete. Turn meter off or to standby position. If reading has changed from original value, repeat steps 5-10. NOTE: In dry windy climates, such as in the southwestern United States, a static charge tends to build on the plastic face of a pH meter, which causes erratic movement of the indicator needle. Antistatic spray, of the type used for phonograph records, sprayed on the meter face minimizes this interference. It is also desirable to keep the meter protected from extreme temperature changes during measurement, as this affects the stability of the electronic system and, consequently, the precision of the measurement. In cold waters, slow electrode response may occur from the precipitation of the saturated filling solution in the reference electrode, thereby reducing the fluid contact. This can be remedied by allowing the filling solution to reach ambient temperature before filling the reference electrode.

2.G.2.d. CARBONATE AND BICARBONATE

For chemical equilibrium calculations related to carbonate minerals, it is essential to have an accurate value for pH, carbonate, and bicarbonate concentrations. Carbonate and bicarbonate determinations for ground water must be made in the field at the time of sampling if the concentrations are to accurately represent those originally present in the water. These parameters are particularly subject to change if the sample is collected and stored in certain types of plastic bottles that are permeable to carbon dioxide.

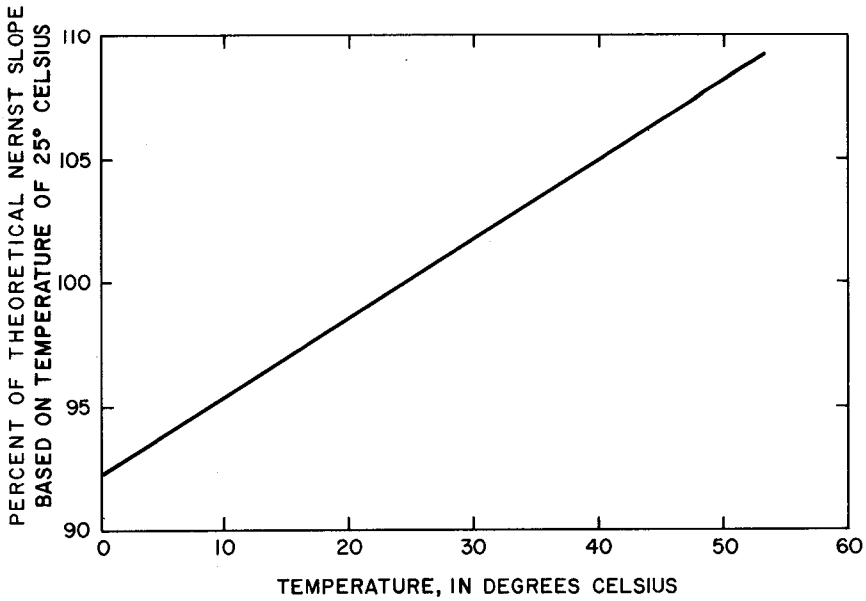

Figure 2-36.—Relationship temperature and the Nernst slope.

2.G.2.d.1. METHOD SUMMARY

Barnes (1964), Weber and Stumm (1963), and Brown, Skougstad, and Fishman (1970) give detailed descriptions of the theory and practice of potentiometric titration of carbonate and bicarbonate. In general, the carbonate (CO_3^{-2}) and bicarbonate (HCO_3^-) concentrations are determined by titration of the water sampe with a standard solution of strong acid. The following equations govern the reactions involved:

$$(1)\ CO_3^{-2} + H^+ \rightarrow HCO_3^- \quad \text{(This reaction is complete near pH 8.3)} \tag{2-12}$$

and

$$(2)\ HCO_3^- + H^+ \rightarrow H_2O + CO_2 \quad \text{(This reaction is complete near pH 4.5)} \tag{2-13}$$

The end point of the carbonate or bicarbonate titration process is determined by method A, a plot of pH versus titrant volume, where the end point corresponds to an inflection point of the curve (fig. 2-37) or by method B, a plot of

$$\frac{\Delta\ \text{pH}}{\Delta\ \text{mL of titrant}} \tag{2-14}$$

the rate of change in pH per unit volume of titrant versus the average titrant volume between two successive values. The end point is the value where the maximum rate of change of pH per volume of titrant added occurs (fig. 2-37).

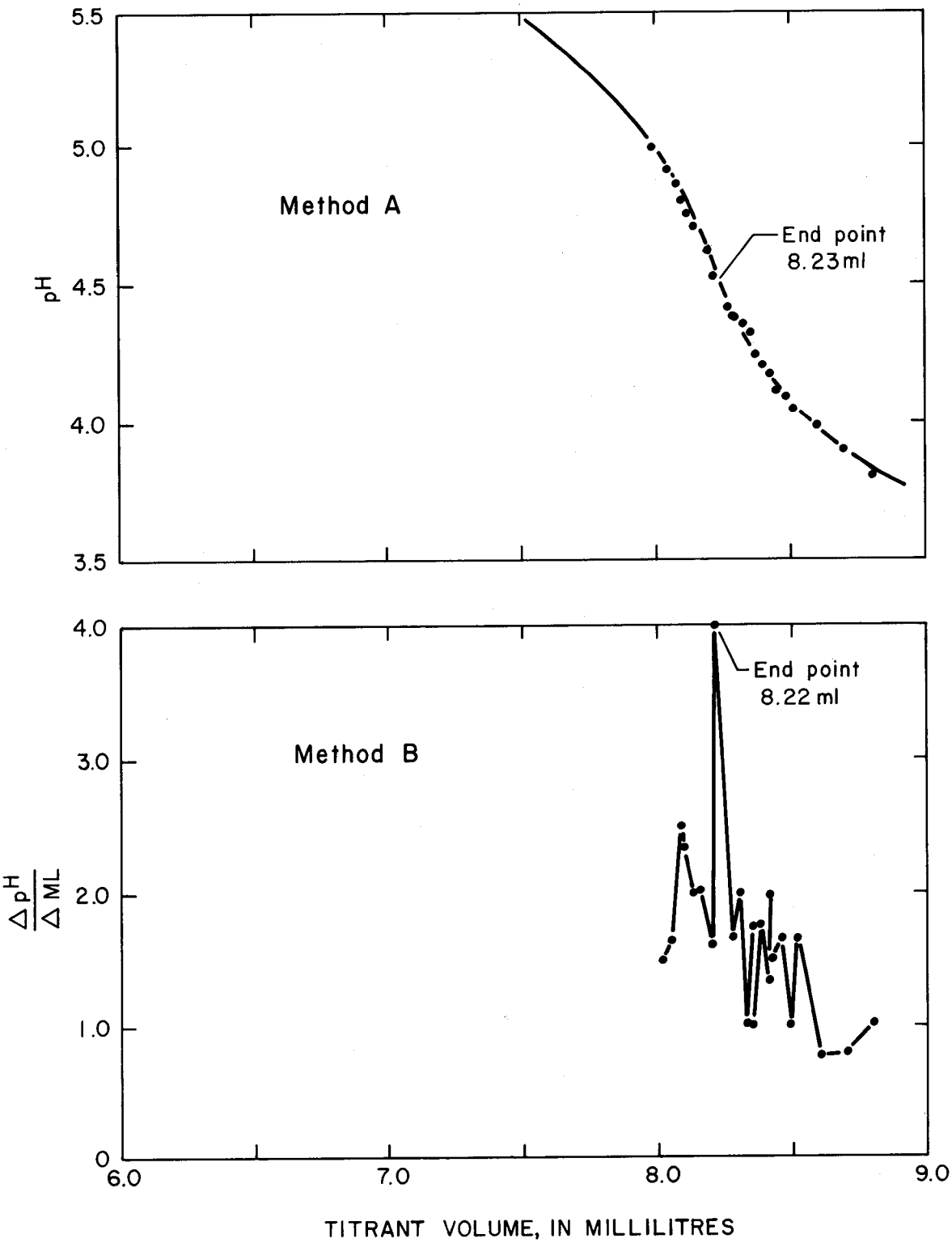

Figure 2-37.—Two methods of determining the end point for bicarbonate determinations.

The approach in method B is less subjective and permits consistent choice of the end point, but requires exacting analytical procedures and the assurance of complete equilibration of pH after each increment of acid is added.

Salts of weak organic and inorganic acides, such as silica, that cannot be corrected for, may yield erroneous results when present in large amounts. In addition, oils, greases, and colloidal material, if present, may tend to foul the pH electrode and prevent its proper operation.

2.G.2.d.2. APPARATUS

1. All equipment and reagents used for pH determinations. See section on pH determination.
2. Buret, 25-mL capacity with 0.1-mL graduation and Teflon stopcock.
3. Portable battery-powered magnetic stirrer, Lapine or equivalent with extra batteries.
4. Teflon-coated stirring bar, small size.
5. Ring stand, clamp holder, and universal V-jawed clamp.
6. 25- and 50-mL class A volumetric pipets.
7. 250-mL plastic-squeeze acid bottle with nozzle for filling buret (color-coded bottle to prevent confusion with distilled water bottle).
8. 1 liter of 0.01639 N sulfuric acid packaged in two 500-mL plastic bottles to prevent breakage. (Prepared according to Brown, Skougstad, and Fishman, 1970.)
9. Wire pen cleaner for dislodging foreign debris in buret tip.
10. Cap to prevent dust from entering buret.
11. Buret meniscus reader (useful for poor light conditions often encountered in the field).

A padded wooden box (fig. 2–38) is useful for carrying volumetric glassware and small accessories such as meniscus reader, stirring bar, wire pen cleaner, etc.

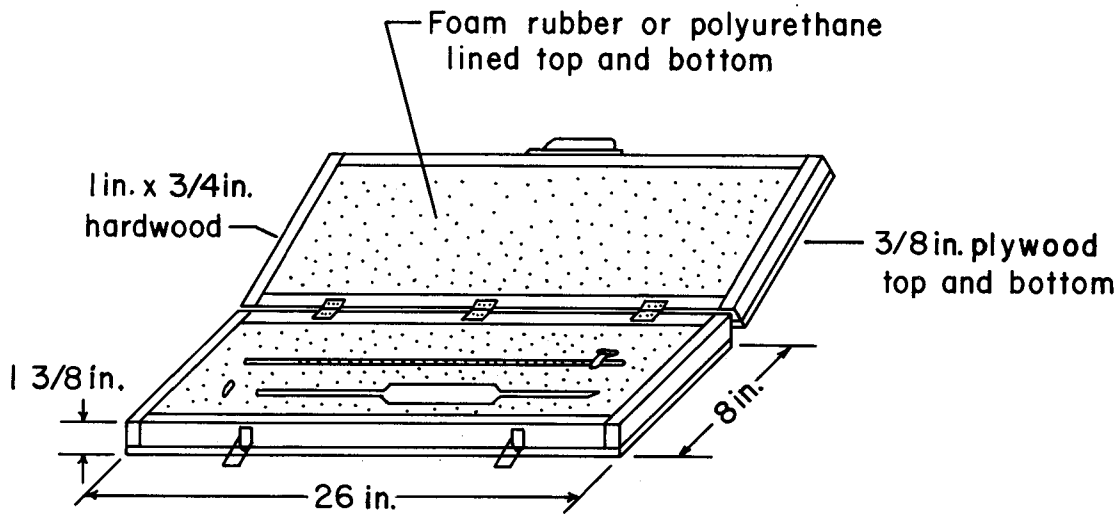

Figure 2–38.—Carrying box for volumetric glassware electrodes and other small fragile items.

2.G.2.d.3. PROCEDURE

1. Adjust temperature of titrant to ±2°C of the sample by immersion of securely stoppered acid-storage bottles in a water bath of the sample fluid; set up and fill buret to 0.00 mL; cap buret with dust cover.

2. From a pressure-filtered sample (see section on filtration) pipet 50 mL into a clean dry 100-mL beaker. Under no circumstances should the sample be diluted or concentrated in any way. The pipet is rinsed three times with the sample water before final sample is placed in the beaker. If

titration cannot be completed with one filling of the buret, discard sample and use a small sample size. There is a great chance for error in refilling a buret during a titration.

3. Insert pH and reference electrodes into the sample. Calibrate the electrodes in 7.00 and 4.00 buffer solutions at the temperature of the sample, then wash them in sample or distilled water and blot, not wipe, dry. (See section on pH determinations.) Insert the clean dry stirring bar and adjust stirrer to slow speed.

4. If pH is greater than 8.3, add sulfuric acid by drops, recording volume accurately with 0.05-mL increments and pH values to 0.02 pH units until pH is below 8.00.

When the pH of sample during titration declines below 8.00, or the initial value is less than 8.3, add acid increments of 1 mL and record pH value at each increment. Continue this procedure until pH declines to approximately 5.5. From pH 5.5 to pH 4.0, add acid by drops, recording pH at each volume increment. The most sensitive part of the titration is usually between 4.8 and 4.3. Adding acid in fractions of a drop is desirable in this range. (Carefully touch ¼ or ½ drop to sample surface and pull away from buret tip.) Allow 15–20 seconds for equilibration.

2.G.2.d.4. CALCULATION

Calculations for the carbonate content are made by using the equation (2–15)

$$CO_3 \text{ (in mg/L)} = \left(\frac{1{,}000}{mL_s}\right) \times (mL_a \text{ to end point near pH 8.3}) \times (0.9835).$$

Calculations for bicarbonate are made by using the equation

$$HCO_3 \text{ (in mg/L)} = \left(\frac{1{,}000}{mL_s}\right) \times (mL_a \text{ between end points near pH 8.3 and 4.5}) - (mL_a \text{ to end point near pH 8.3}),$$

where mL_a and mL_s are volumes of standard 0.01639 N sulfuric acid and samples, respectively, and end points are determined as in figure 2–37. Because of the relatively small amount of time required for this analysis, it is best to repeat titration to insure precision.

2.G.2.e. Eh (REDOX POTENTIAL OR OXIDATION-REDUCTION POTENTIAL)

A chemical reaction in which an element undergoes a loss or gain of orbital electrons is referred to as oxidation or reduction and may be represented by the following general expression:

$$\text{reduced species} \rightarrow \text{oxidized species} + ne^-, \tag{2–17}$$

where ne^- is the number of electrons involved per atom. The standard oxidation potential, $E°$, for a half-cell reaction of this type is the potential that would occur if the two species are both present at unit activity at 25°C and one atmosphere pressure. When the activities of participating species differ from unity, the potential observed at equilibrium is termed the redox potential (oxidation-reduction potential).

The redox potential, represented by the symbol Eh, is related to the standard potential and the activities of participating substances by the Nernst equation: (2–18)

$$\text{Eh} = E° + \frac{RT}{nF} ln \frac{\text{oxidized state}}{\text{reduced state}},$$

where $E°$ is the standard potential of the reaction, R is the universal gas constant, T is the absolute temperature in degrees Kelvin, F is the Faraday constant, n is the number of electrons involved in a half-cell reaction, and $\ln \frac{\text{oxidized state}}{\text{reduced state}}$, is the natural logarithm of the ratio of the products of the activities of oxidized species to that of the reduced species. The potential is reported as volts or millivolts, relative to the potential of the hydrogen electrode, taken as zero, and may be positive or negative (the greater the negative value, the more the reducing tendency of the system). Langmuir (1971) presents an excellent review article on Eh-pH determination.

Some writers have preferred the notation "pE," defined as the negative logarithm of the molar activity of the electrons, which avoids some of the unit conversion calculations required by the Nernst equation (Stumm, 1966).

Eh is generally a qualitative tool for the ground-water geochemist. However, it has been used very effectively in explaining the concentration of many minerals that exhibit more than one oxidation state under natural conditions. See, for example, the relation of iron in natural water to Eh as shown by Back and Barnes (1965).

2.G.2.e.1. METHOD SUMMARY

Eh is measured with a noble metal (usually platinum) and a reference electrode system using a pH meter than can read in millivolts. Reference solutions with known Eh are used to standardize and check the accuracy of the electrode system. Unlike pH buffer solutions, the Eh reference solutions are not used to adjust the system to the correct range of values. The potassium ferric-ferro cyanide solution described by ZoBell (1946), which has been proved satisfactory as a standard reference solution by many geochemists, is the standard recommended.

At 25°C, the potential of the ZoBell solution relative to the standard hydrogen electrode is +0.428 volts. The potential varies with temperature according to the following equation:

$$\text{Eh} = 0.428 - 0.0022\,(t - 25)\ \text{volt} \tag{2-19}$$

(Ivan Barnes, oral commun., 1972).

At 25°C, the saturated calomel (mercury-mercurous chloride) reference electrode, which is commonly used, has a reference voltage of +0.244 volts relative to the potential of the standard hydrogen electrode. The voltage varies with temperature according to the following equation:

$$\text{Eh} = 0.244 - 0.00066\,(t - 25)\ \text{volt} \tag{2-20}$$

(Garrels and Christ, 1965, p. 127),

where t is the temperature in degrees Celsius.

By combining the half-cell potentials for the platinum-calomel electrode system and ZoBell solution, and utilizing the equations for potential variation with temperature ($\text{emf} - \text{Eh}_{\text{ZoBell}} - \text{Eh}_{\text{Calomel}}$), the theoretical potentials for the system at different temperatures can be calculated. The relationship of theoretical potentials of this system to temperature is shown in figure 2-39. The relationship for a silver-silver chloride reference electrode and platinum electrode system to temperature is also plotted in figure 2-39.

The measurement of Eh of a system requires that the observed potential be adjusted to a potential relative to the standard hydrogen electrode.

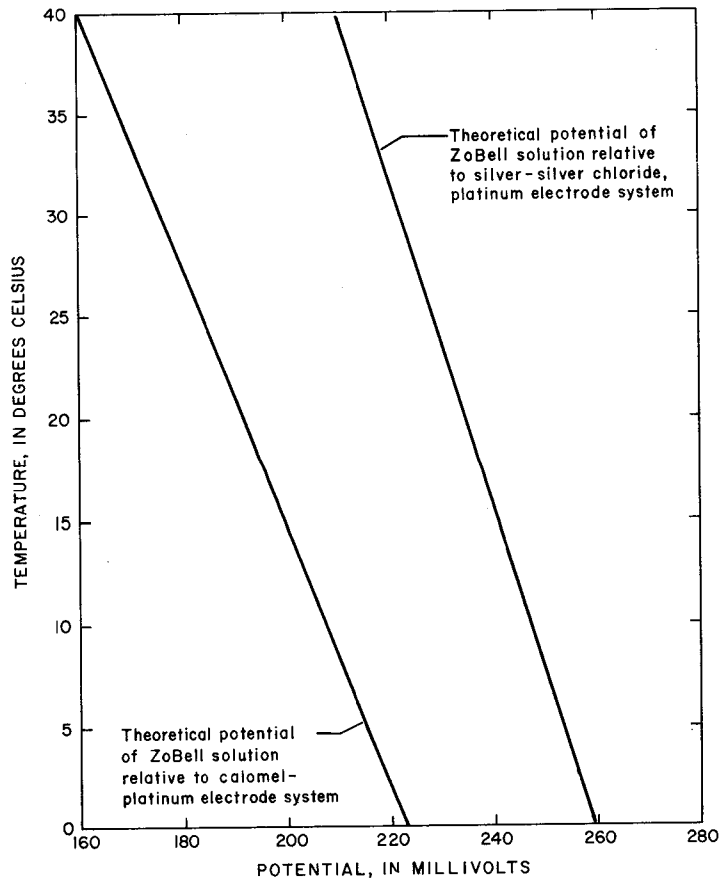

Figure 2-39.—The potential of ZoBell solution, relative to reference-electrode systems, at various temperatures.

In equation form,

$$Eh_{sys} = E_{obs} + Eh_{ZoBell+ref} - E_{ZoBell\,(obs)}\,, \tag{2-21}$$

where

Eh_{sys} = The true Eh of the environment relative to the standard hydrogen electrode,
E_{obs} = the observed potential of the environment relative to the reference electrode,
$Eh_{ZoBell+ref}$ = the theoretical Eh of the reference electrode and ZoBell solution relative to the standard hydrogen electrode, and
$E_{ZoBell\,(obs)}$ = the observed potential of ZoBell solution relative to the reference electrode.

2.G.2.e.2. APPLICATION AND INTERFERENCE

Redox potential measurements in laboratory solutions where activities of oxidized and reduced species may approach unity can be expected to match theoretically calculated potentials reasonably well. Experience has shown that many natural water systems do not give measured Eh values that can be quantitatively interpreted. Measurements made in water containing dissolved oxygen, for ex-

ample, give values lower than might theoretically be expected. Garrels and Christ (1965) attribute this to a slow, rate-determining step in the reaction of aqueous oxygen with other ions. If dissolved oxygen (DO) is above 0.01 mg/L, the DO determination may be more useful than attempting to determine Eh. It is also generally useless to try to measure Eh in systems containing hydrogen sulfide.

Back and Barnes (1965) were able to correlate measured redox potentials with dissolved ferrous iron contents of ground water in moderately reducing systems. Most other experiences with Eh measurements that are described in the literature lead one to conclude that the measurement is primarily a qualitative tool. The measurement may give useful information about systems whose solid and solute components are reasonably well known from other kinds of measurements. Stumm (1966) and Doyle (1968) discuss limitations and uncertainties inherent in Eh measurements. Charged colloidal material and differences in composition and concentration of the unknown and reference solutions may create errors. Oil and grease may coat the noble-metal electrode, preventing contact with the sample.

2.G.2.e.2.a. Apparatus, reagents

1. Orion 401 specific-ion meter or equivalent.
2. Orion combination electrode 96-78-00 or equivalent and Orion electrode filling solution 90-00-01 or equivalent. (Thimble platinum and separate reference electrodes are also suitable.)
3. ZoBell reference solution:
   Dissolve 1.4080 g of potassium ferrocyanide $K_4Fe(CN)_6 \cdot 3H_2O$ (0.00333M), 1.0975 g of potassium ferricyanide $K_3Fe(CN)_6$ (0.00333M), and 7.455 g of potassium chloride KCl (0.10M) in distilled water to make 1 liter. This solution is stable for several months but should be kept in a black plastic bottle and out of sunlight as much as possible. It has a standard potential of +428 millivolts at 25°C. **This solution is poisonous and should be handled with care.**
4. Ring stand, clamp holder, and universal V-jawed clamp.
5. Eh cell (fig. 2-40).
6. Plastic 100-mL beaker.
7. Water bath for ZoBell solution (plastic pail or bottom half of a 1-gallon plastic bottle).
8. Thermometer.
9. Equipment for measuring dissolved oxygen.
10. Small strips of crocus cloth for polishing platinum electrode.

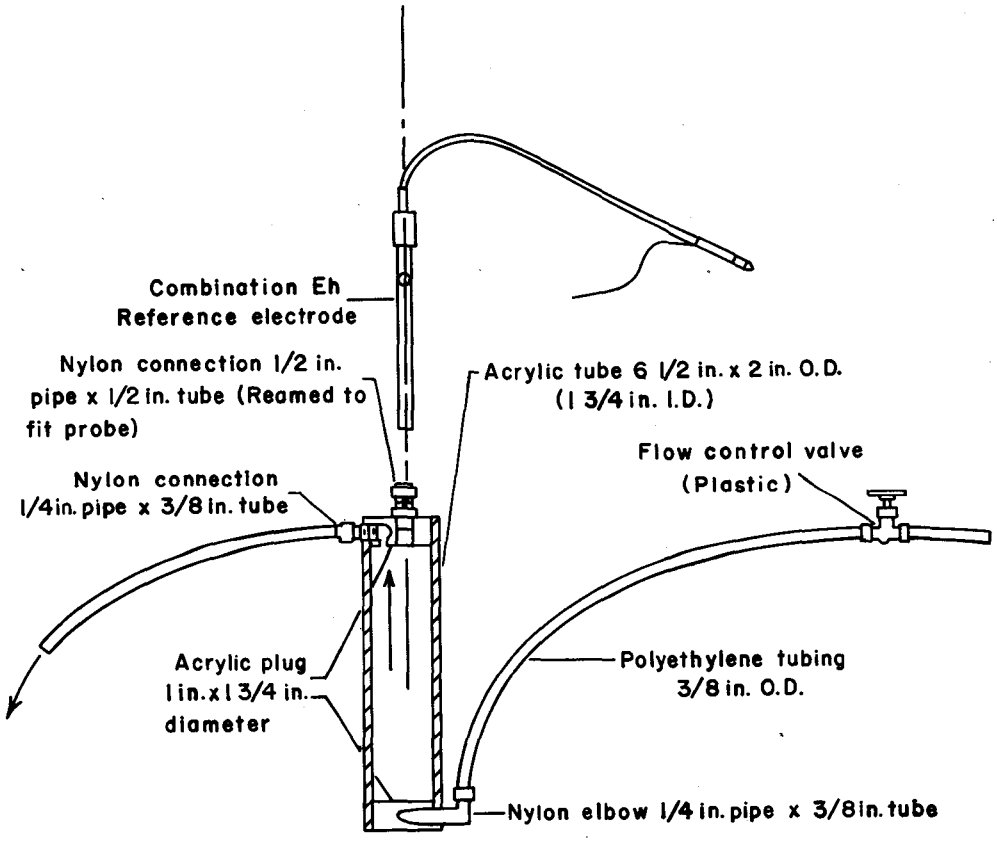

Figure 2-40.—Eh measuring cell.

2.G.2.e.2.b. Procedure

1. Fill combination electrode with proper filling solution (Orion 90-00-01 or equivalent). Depress body and let some of the fluid drain to waste. Bring ZoBell solution to the temperature of sample by allowing sample to flow over closed bottle. Record temperature. While the ZoBell solution is equilibrating to the sample temperature, determine the presence of dissolved oxygen in the water sample. If dissolved oxygen is greater than 0.05 mg/L, do not proceed with the Eh measurement. If dissolved oxygen is absent, proceed with step 2.

2. Place combination electrode in the ZoBell solution that has been equilibrated to the sample temperature. Plug electrode leads into meter and turn function switch on meter to millivolt mode. Allow several minutes for electrode to equilibrate while maintaining the bottle of ZoBell solution in the water bath. Record reading. If reading differs by more than 10 millivolts from the theoretical value at that temperature (fig. 2-39), replace reference electrode fluid and repeat measurement. If that procedure will not bring the reading within 10 millivolts of the theoretical value, polish the platinum end of the electrode with a piece of crocus cloth and recheck reading. If this procedure fails, the electrode should be replaced. If reading is within ±10 millivolts of the theoretical value, rinse electrode with sample water and proceed with step 3.

3. Place electrode in the plastic Eh cell pointing up (fig. 2-40) and let the water flow through the cell. Filler hole in side of electrode should be above the top of Eh cell. Make sure all air bubbles are removed from the system. Use control valve on inlet to insure that the head of sample is below level of reference solution of the electrode or some of the sample will be forced into the reference electrode and change the potential of the system. Clamp Eh cell onto the ring stand.

4. Turn function switch on meter to millivolt mode and allow the water to flow through the cell until the readings stabilize. Stabilization usually occurs within 20 minutes, but may require as much as an hour or more. Turn off sample flow to prevent any streaming potential and immediately record meter reading. This is the observed Eh of the sample, or more specifically, the observed full-cell emf relative to the reference electrode.

5. Record the data and calculate the Eh relative to the standard hydrogen electrode as follows:

Data Record

A. Temperature of sample ..... _____

B. Observed potential, in millivolts, of ZoBell solution, relative to reference electrode, at sample temperature ... _____

C. Theoretical potential, in millivolts, of ZoBell solution, relative to reference electrode, of sample temperature (fig. 2–39) ..... _____

D. Theoretical potential, in millivolts, of reference electrode system and ZoBell solution, relative to the standard hydrogen electrode, at sample temperature (fig. 2–41) ..... _____

E. Observed potential of sample in millivolts ..... _____

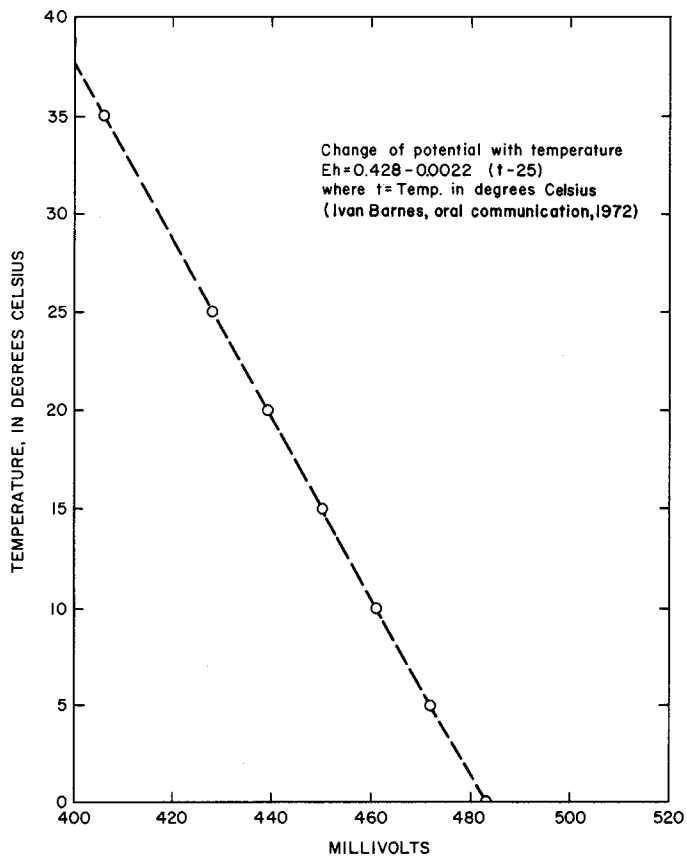

Figure 2–41.—The potential of ZoBell solution, relative to the standard hydrogen electrode, at various temperatures.

Calculations

I. Checking the Electrode

Calculate difference between observed potential and theoretical potential of ZoBell solution, relative to reference electrode,

$$B - C = \text{difference.}$$

If this difference is less than ±10 millivolts, proceed with next step. If difference is greater than ±10 millivolts, see step 2 procedure for remedial measures.

II. Calculate the Eh of the System

E − B + D = Eh value of the system. Report Eh value [either positive (+) or negative (−)] to nearest 10 millivolts.

A field example may help to clarify the procedure:

October 6, 1971 at 0930, St. Paul, Minnesota; G. Ehrlich, H. Reeder, W. Wood.

Well 2-N, artificial-recharge site 539 feet deep, 6-inch diameter, finished in the Prairie duChein.

Pumping 10 gal/min for 22 hours.

Temperature of water from well is 10.0°C.

The observed potential of ZoBell solution, relative to the combination reference-platinum electrode, at 10°C was +215 millivolts. (Theoretical potential for ZoBell solution, relative to this electrode system, at 10°C is +207 millivolts; see fig. 2-39. The 8-millivolt difference was considered small, and the decision was made to proceed with the measurements.) The observed potential of the water sample after system stabilized in 30 minutes was −120 millivolts.

Data record

A. Temperature of sample ..... 10°C

B. Observed potential, in millivolts, of ZoBell solution, relative to reference electrode, at sample temperature .... +215

C. Theoretical potential, in millivolts, of ZoBell solution relative to reference electrode, at sample temperature (from fig. 2-39) ..... +207

D. Theoretical potential, in millivolts, of reference electrode system and ZoBell

solution, relative to standard hydrogen electrode, at sample temperature (fig. 2–41) ..... +461

E. Observed potential of sample, in millivolts ..... −120

Calculations

I. B − C = (+215) − (207) = +8 millivolts

II. Eh_{sys} = E − B + D = (−120) − (215) + (461) = +126 millivolts

Report at +130 millivolts.

2.G.2.f. DISSOLVED OXYGEN

Oxygen dissolved in ground water is usually derived from contact with the atmosphere before recharge to the aquifer. The solubility of oxygen in water depends on the partial pressure of oxygen in the atmosphere, the dissolved solids, and the temperature. Experience indicates that the presence of dissolved oxygen in ground water is a more common occurrence than is generally believed. This is particularly true in hydrologically stressed systems. Dissolved oxygen can exist at great depths in aquifers that have little or no oxidizable material in the water-flow path and can also be present in any aquifer where the water's residence time is short compared to the rate of oxygen consumption.

2.G.2.f.1. METHOD SUMMARY

The "National Handbook of Recommended Methods for Water-Data Acquisition" (1977), Chapter 5, describes methods used commonly for determining dissolved oxygen. Some of these methods are subject to rather serious interferences. Regardless of the method used, great care must be taken to prevent atmospheric aeration of the sample during collection and analysis. Using a flow chamber to prevent contact of the sample with the atmosphere and a portable dissolved-oxygen meter for analysis eliminates or minimizes the effects of most interferences and yields a continuous record of dissolved oxygen during the pumping of a well.

The sensing element of the dissolved-oxygen meter is basically a polarographic system in which two solid metal electrodes in contact with an electrolyte are separated from the test solution by an oxygen-permeable membrane. The membrane serves as a diffusion barrier against impurities. The rate oxygen diffuses through the membrane is proportional to the pressure differential across the membrane. When oxygen diffuses through the membrane, it is rapidly consumed at the cathode. Thus, the rate of diffusion is proportional to the absolute pressure of oxygen outside the membrane. When a suitable polarizing voltage is applied across the cell, the consumption of oxygen at the cathode causes a current to flow through the cell. This current is directly proportional to the quantity of oxygen consumed in the cell.

For precise dissolved-oxygen determinations, the meter should be calibrated before each use. Preferably, the calibration should be accomplished on the water under test. One sample of the water should be deoxygenated by adding an excess of sodium sulfite; a second sample should be aerated to saturation. This dissolved-oxygen concentration of the air-saturated sample can be determined from figures 2–42 and 2–43, provided the water temperature, barometric pressure, and altitude of the sampling site are known. In the absence of interferences, a more precise dissolved-oxygen value for the aerated sample can be determined by use of the Alsterberg azide modification of the Winkler method (Brown and others, 1970, p. 126) or any approved modification of this technique. Where interfering substances are suspected, calibration should be accomplished on distilled water aerated to saturation.

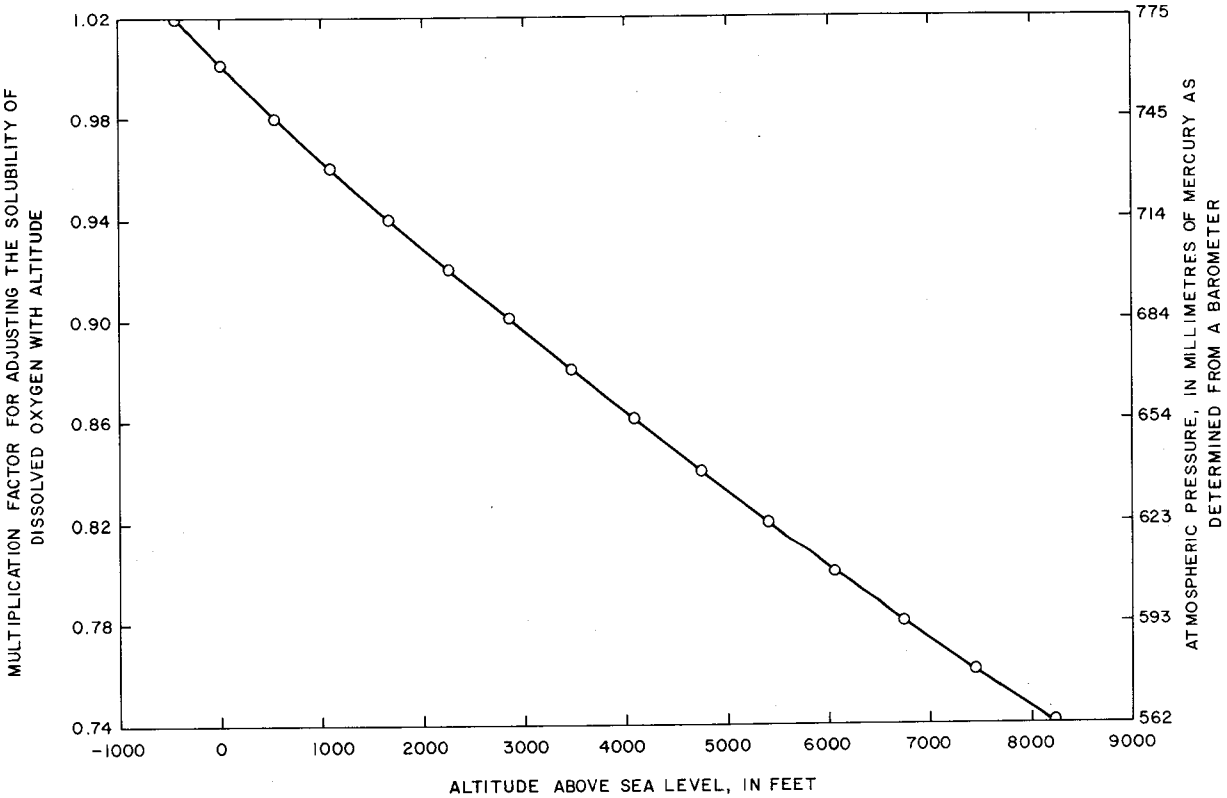

Figure 2-42.—Solubility of oxygen in water at sea level as a function of temperature.

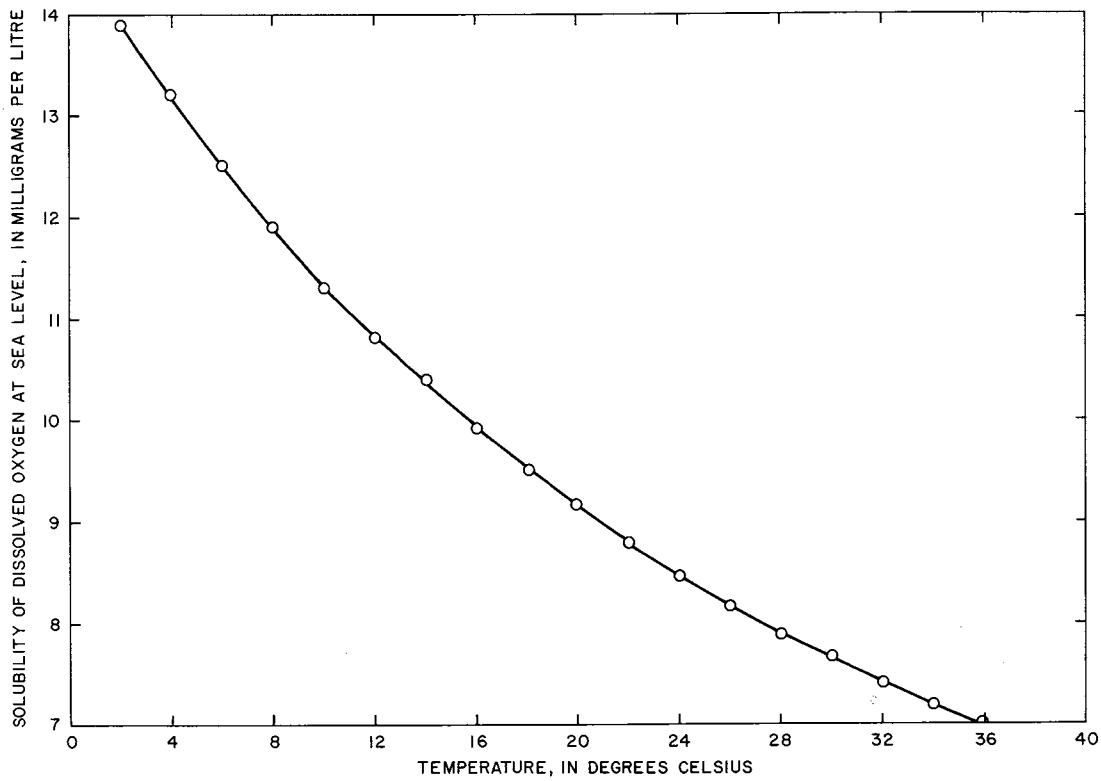

Figure 2-43.—Correction factor for the solubility of oxygen at different atmospheric pressures and altitudes.

The meter must be precisely calibrated according to the manufacturer's instructions before each use. In general, satisfactory calibration can be accomplished by using air-saturated water. In this procedure, the water sample is aerated by being shaken in the presence of air for 15–20 minutes (a one-litre uncapped narrow-mouthed bottle (half full works well) or by using a battery-powered aerator for 5–10 minutes. Temperature of the water is then measured. Figure 2–42 shows the dissolved-oxygen concentration of air-saturated water at sea level as a function of temperature. Figure 2–43 shows correction factors that must be applied to the apparent oxygen concentration when the atmospheric pressure varies from 760 mm of mercury. By use of the figures, the correct value of oxygen dissolved in the air-saturated sample can be obtained and the meter calibrated.

2.G.2.f.2. APPLICATION AND INTERFERENCE

The membrane-electrode method is applicable for measuring dissolved oxygen in any well or spring from which a sample can be collected without aeration.

Oxygen-permeable membranes used for the electrode system are permeable to a variety of other gases, none of which is easily depolarized at the indicator electrode. In addition, the concentrations of most of these gases in ground water are probably too small to cause significant interference with dissolved-oxygen determinations. However, using the membrane electrode in water containing such gases as hydrogen sulfide without loss of sensitivity requires frequent membrane changing, electrolyte replacement, and electrode recalibration.

2.G.2.f.2.a. Apparatus, reagents

1. Yellow Springs model 54 ARC oxygen meter with sensor, or equivalent.
2. Flow chamber with flow control valve (fig. 2–44).
3. Ring stand, clampholder and universal V-jawed clamp.
4. Bottle of electrolyte for the sensor.
5. Extra membranes for the sensor.
6. Thermometer.
7. Two 8-ounce plastic bottles.
8. 1-liter plastic bottle for aeration of the reference sample.
9. Battery-operated aerator.
10. Battery-operated magnetic stirrer and stirring bars.
11. Saturated solution of sodium sulfite.
12. Cobaltous chloride solution.
13. Reagents and plasticware for Alsterberg azide modification of Winkler method for dissolved-oxygen determination (Brown and others, 1970, p. 126).

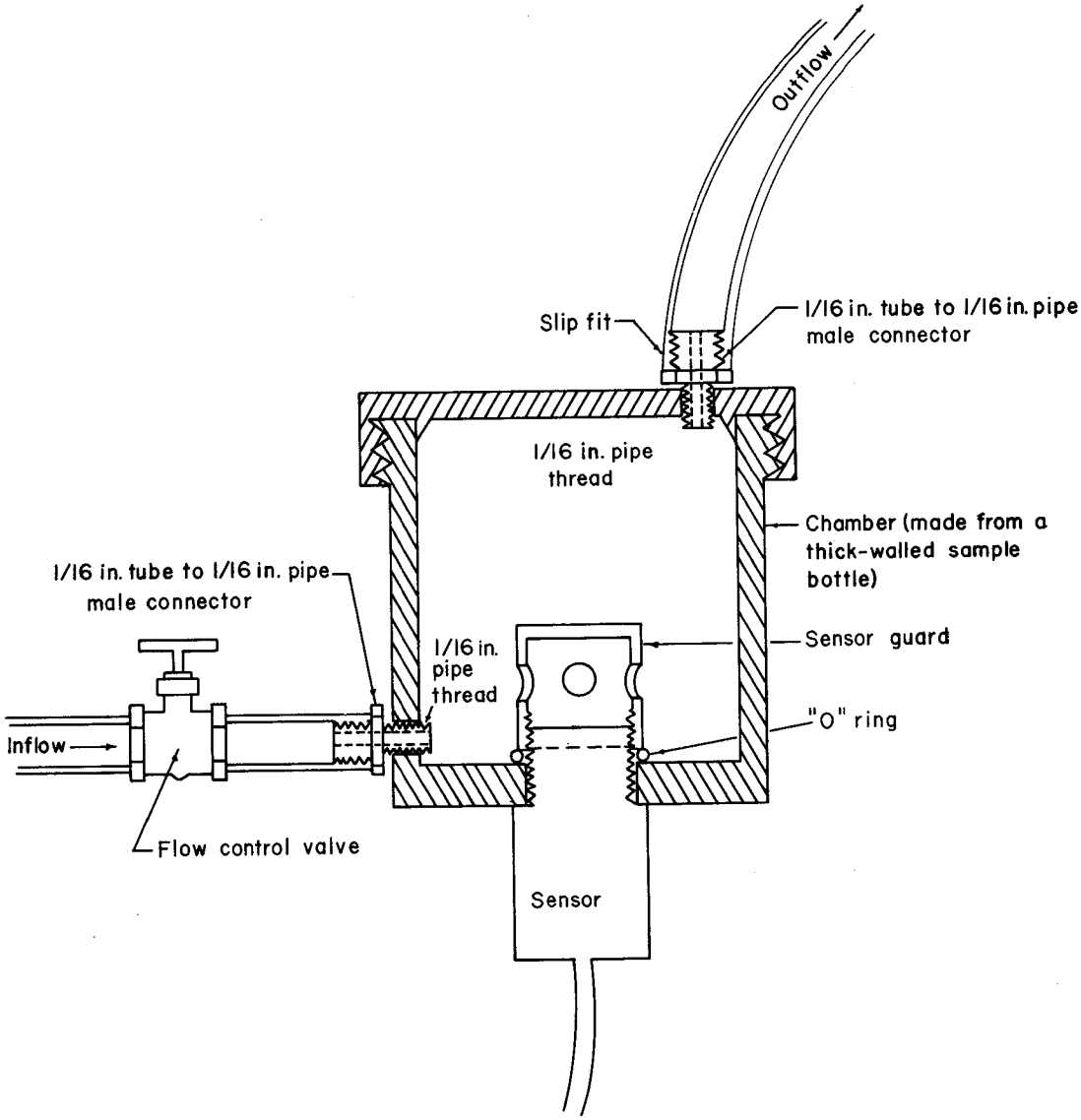

Figure 2-44.—Flow chamber for determination of dissolved oxygen from a pumped well.

2.G.2.f.2.b. Procedure

1. Pour sample into an 8-ounce plastic bottle containing several milliliters of saturated solution of sodium sulfite and a trace of cobaltous chloride. Replace cap and stir on magnetic stirrer for several minutes.

2. Prepare oxygen meter for calibration according to manufacturer's instructions.

3. Switch meter to the 0–10 position. Remove sensor guard and insert the sensor in de-aerated sample. If dissolved oxygen in sample is greater than 0.0 mg/L, add saturated sodium sulfite in small increments until a reading of 0.0 mg/L is obtained. Add an excess of several milliliters after a reading of 0.0 mg/L is obtained.

4. Pour a second sample into a 1-litre plastic bottle and aerate for 5–10 minutes with battery-operated aerator.

5. Determine the dissolved-oxygen concentration on a aliquot of the aerated sample by the Alsterberg azide method (Brown and others, 1970, p. 126). If the barometric pressure is known, determine the dissolved-oxygen concentration of the air-saturated sample from figures 2–42 and 2–43.

6. Pour an aliquot of the aerated sample into a clean 8-ounce plastic bottle. Switch meter to the 0–10 position and insert the sensor in aerated sample. Adjust speed of magnetic stirrer until maximum reading is obtained.

7. With the calibration control, adjust the dissolved-oxygen reading to the value obtained by step 5.

8. Place sensor in the flow chamber (fig. 2–44). Place the "O" ring over the sensor, being careful not to disturb the membrane. Replace sensor guard and tighten until the "O" ring is depressed very slightly. Place the top on the flow chamber and gently open the flow control valve. Measure the dissolved-oxygen concentration at about 5–10 minute intervals until a stable reading is obtained. Record the value to the nearest 0.1 mg/L.

2.G.3. IN SITU (DOWN-HOLE) MEASUREMENTS OF WATER QUALITY

2.G.3.a. TEMPERATURE

Useful information in interpreting aquifer water quality can be obtained by measurements within boreholes filled with static water or with drilling mud. A thermocouple or resistance temperature sensor accurate to 0.01°C should be used to measure water temperature under static conditions. Temperatures measured in boreholes may indicate the source of water at various depths and may also indicate the source of water under production conditions.

2.G.3.b. SPECIFIC CONDUCTANCE OF BOREHOLE FLUIDS

Measurements of the specific conductance of the fluid in a borehole filled with static water may indicate the conductivity of the water in the surrounding aquifer. Make measurements with a battery-operated specific-conductance meter which is temperature compensated. Calibrate the meter with a standard solution daily during use. Like temperature, interpretation of specific conductance from down-hole measurements is only interpreted qualitatively. Simultaneous measurements of temperature and specific conductance are recommended because this produces the minimum disturbance of the fluid column (Keys and MacCary, 1971).

2.G.3.c. RESISTIVITY

Down-hole measurements of resistivity have been interpreted for ionic concentrations of the interstitial fluids. Patten and Bennett (1963) described the methods of resistivity measurement and approaches to qualitative interpretation. In water-filled holes, interpretation is based on the assumption that the water in the borehole is identical to that in the formation at each depth. Spontaneous potentials measured between the surface and varying points in a mud- or water-filled borehole have been used to infer the ionic activity in surrounding strata. Keys and MacCary (1971) and Section 2.D.2. "Borehole Methods" in this chapter describe the methods and limitations of spontaneous potential logs.

2.G.4. LOCATION AND INSTALLATION OF WELLS FOR DETERMINING CHANGES IN GROUND-WATER QUALITY

Investigations of naturally occurring variations in physical, chemical, or biological characteristics of ground water may require installation of new wells for sample collection and in-hole

measurements. Evaluating the impact of manmade and natural changes in ground water quality usually requires a complex sampling pattern. In both instances, the hydrologist should use all knowledge about the ground-water reservoir and the location, type, and rate of outside influences.

Pollution of ground water by industrial, agricultural, and municipal sewage wastes may pose a local or regional problem. Monitoring wells are often required to assess the distribution and intensity of these effects. Construction of test wells should be governed by the type of water-chemistry data sought. For example, wells used for evaluating metals should be constructed of nonmetallic materials. All wells should be developed thoroughly before sample collection begins.

Determine the location of sample collection wells by the expected distribution of the water-quality pattern. Pollutants which are introduced from the soil's surface or within the unsaturated zone are usually in the highest concentrations near the top of the saturated zone. The movement of pollutants within the saturated zone is usually dominated by lateral hydraulic flow within the ground-water system as dictated by the hydraulic gradient. Often, plumes of pollution from point sources extend down gradient within the aquifer. The concentration of pollutants dissipates gradually along flow lines because of absorption, filtration, dilution, decay of radioactive materials, dispersion, and death of microorganisms.

In evaluating the ground-water quality changes caused by infiltrating water from irrigation or seepage from lagoons and drainage fields, the hydrologist must consider the changes in hydraulic gradient produced by the recharge mound. Injection wells for waste-water disposal also create alterations in the hydraulic gradient, but the introduction of foreign water is governed by the permeability of the various aquifer layers, the location of the screened portion of the injection well, and the clogging effects of the waste water on the well aquifer system during operation.

Examples of monitoring well installation have been given by Hughes and others (1964) and Le Grand (1964), for landfill evaluation; by Childs and others, (1974) for ground-water pollution by septic tanks; by Le Grand (1970) for agricultural pollutants; and by Warner (1975) and Yare (1975) for industrial pollutants. Karabian (1974) has used estimates of pollutant infiltration rates and concentration of polluting chemicals to predict ground-water quality effects.

No recommended methods for determining sample well location can be given that are applicable to all conditions. Each specific situation requires preliminary investigation, interpretation of early results, adjustments in frequency and source of samples, and adjustments in location of collection points to meet the unique requirements of each study.

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2.H. AQUIFER TESTS[1]

An aquifer test is a controlled field experiment to determine the hydraulic properties of water-bearing and associated rocks. The test is made by observing ground-water flow produced by known hydraulic boundary conditions, such as variations of head along a connected stream, pumping wells, changes in weight imposed on the land surface, or changes in recharge. The hydraulic boundary conditions may be imposed as part of the natural hydrologic system or by man. Ground-water flow varies in space and time and depends on the hydraulic properties of the rocks and the boundary conditions imposed on the ground-water system.

The most common procedure for determining the hydraulic properties of aquifers is to (1) identify the hydraulic and physical boundary conditions affecting flow in the aquifer, (2) calculate the expected response in the aquifer by letting the hydraulic properties be variable and taking into account the hydraulic and physical boundaries, (3) compare the observed response with the computed response, and (4) adopt those hydraulic properties that were assumed in the computed response that matched the observed response.

Response can be computed in a variety of ways. Most commonly, the following methods are used:

Analytical solutions. — These are algebraic or integral equations that relate flow at boundaries, hydraulic properties, space, and time. Each solution applies generally to one set of assumed conditions only.

Flow nets. — Flow nets apply only to steady flow. Flow paths and head contours, at right angles to each other everywhere in the flow field of an isotropic aquifer, are drawn by trial and error. The resulting net may be used for estimating transmissivity.

Electric analogs. — Electric analogs can be used for generating response predictions effectively by simulating the aquifer and its boundary conditions that are highly variable in time and space.

Digital computers. — Where analytical solutions are expressed in integral form, the digital computer is effective for evaluating the integral numerically, thereby providing useful response information. Also, the digital computer can be used for simulating the flow system in much the same way as the electric analog.

Much has been written describing the development of response curves and their use for determining the hydraulic properties of aquifers. However, little attention has been given the mechanical aspects of test organization and data collection. Furthermore, the basic framework common to all aquifer tests is not apparent in the available literature. The purposes of this Section of Chapter 2 are to (1) describe the common framework on which all test analysis is based, (2) detail the procedures for designing a test, (3) emphasize the importance of criteria to be met in the design and field execution of aquifer tests, and (4) call attention to required data.

In performing a test it makes no difference whether response curves are obtained as analytical solutions or by other methods, such as flow nets, electric analogs, or digital computers. Data requirements and methods of analyses are almost independent of the methods used for computing response curves. In most situations, aquifer response has the same magnitude regardless of whether boundary controls are positive or negative. The only difference between response in a drawdown test and in a recovery test is the direction of change in head. In this discussion, most illustrative material is therefore selected from analytical solutions for those situations in which drawdowns are imposed on the aquifer. Furthermore, this section limits discussion to aquifer tests involving pumping wells. The general techniques described are equally effective for analyzing flows regulated by changing stream stages, for example, except that time and space scales need to be modified. Reader familiarity with the general concept of aquifer testing is presumed.

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[1] This section is an update of Stallman's 1971 report prepared by E. P. Weeks.

2.H.1. NOMENCLATURE

Symbol	*Definition*	*Units*
$\propto$	A constant, or a delay index.	Dimensionless, or inverse time.
b	Thickness of saturated part of aquifer.	Length.
b'', b'''	Thickness of confining beds.	Length.
B	$(T/\propto S)^{1/2}$, a constant.	Dimensionless.
B	A constant.	Dimensionless.
O	A constant.	Dimensionless.
K'', K'''	Hydraulic conductivity of confining beds.	Length per unit time.
$K_z K_r$	Hydraulic conductivity of aquifer to vertical (z) and horizontal (r) flow, respectively.	Length per unit time.
Q	Discharge from a well.	Volume per unit time.
r	Distance from control well to observation point.	Length.
s	Change in head, or drawdown.	Length.
S	Storage coefficient of the aquifer.	Dimensionless.
S'	Apparent storage coefficient, observed in aquifers dewatered significantly in proportion to saturated thickness.	Dimensionless.
S'', S'''	Storage coefficient of confining beds.	Dimensionless.
S_y	Specific yield of aquifer.	Dimensionless.
t	Time.	Time.
T	Transmissivity of aquifer.	Area per unit time.
u	$r^2S/4Tt$.	Dimensionless.

2.H.2. GENERAL PROCEDURES

Aquifer tests require three phases: design, field observation, and data analysis.

2.H.2.a. DESIGN

This phase is probably the most important but least recognized aspect of aquifer tests. The cost of an aquifer test ranges from a few hundred dollars for the least complicated test to several thousand dollars for the most sophisticated test, depending on the manpower and equipment allocated to the experiment. To improve the probability that a given test will be successful and therefore avoid unnecessary spending, it is important to design the experiment carefully, followed by careful and complete data collection. Information required in the design phase is as follows:

A. The geologic and hydraulic setting of the flow system is known in sufficient detail so that the conditions controlling flow are known explicitly. Examples: aquifer thickness and extent, variations in transmissivity, approximate values of transmissivity and storage coefficient, and magnitude of control to be imposed, such as change in discharge or head.

B. Response curves, based upon the control and boundary conditions to be imposed by the test, are available or can be developed at acceptable cost.

C. Equipment required for observing aquifer response is available or can be installed at acceptable cost. Examples: devices for measuring well discharge or stream stage, observation wells, and packers for isolating flow to a particular zone in a pumping well that is screened in several intervals of depth.

D. Available and/or installed observation equipment will produce a definitive set of measurements, a set that will probably provide an accurate measure of the hydraulic properties of the aquifer.

Item D above is a summary of the design phase—through careful examination of available information, decide whether a proposed test site and associated equipment are capable of determining the hydraulic properties of the aquifer accurately and whether the expected results are worth the effort.

2.H.2.b. FIELD OBSERVATION

The observations needed to measure boundary conditions and aquifer response adequately are decided largely in the design phase of the test. For example, by predicting response of the aquifer, the timing of measurements in the field is predetermined. If drawdown at a given observation well is expected to be measurable only after 4 days of pumping, there would be little use for water-level measurements taken at the observation well at half-minute intervals after a nearby well starts pumping. Adequate attention to design, wherein response is predicted, aids the efficient allocation of the observers' time.

2.H.2.C. DATA ANALYSIS

If the design and field-observation phases of the aquifer test are conducted successfully, data analysis is automatically routine and successful. Test-site and control conditions have been identified explicitly, the requirements for analytical methods have been specified, data collection has been completed, and there remains simply the chore of transforming field observations into estimates of the hydraulic properties.

At every test site the boundary conditions and hydraulic properties are unknown prior to testing; therefore, the analysis of the problem in the design phase contains uncertainties. The designer of the test must take these uncertainties into account to allow for latitude in so-called known conditions. For example, if the transmissivity can be estimated from other data within ± 25 percent, the value of another field test is relatively small. If transmissivity is predictable within plus or minus an order of magnitude or more, placement of observation wells and timing of required measurements in the field will be affected strongly.

2.H.3. WORKING HYPOTHESIS

Field and laboratory studies have indicated that Darcy's law gives a satisfactory approximation of ground-water flow and that for many field situations water storage in the aquifer is proportional only to head. For these reasons and for a specific set of boundary conditions, it is feasible to predict the head distribution in an aquifer with respect to space and time.

To summarize, head distribution in the vicinity of a controlled well can be predicted if we know (1) the type (flow or head) and magnitude of control applied at the well, (2) the well radius, the depths at which the well bore is open to the aquifer, and the hydraulic conditions along the bore, (3) the three-dimensional distribution of hydraulic conductivity in the region affected by the well, and (4) the storage characteristics of the aquifer.

If any one of these four elements is unknown, accurate predictions of head distribution, or changes of head, are generally impossible.

Theis (1935) was the first to present a formula showing the nonsteady hydraulic response in an aquifer resulting from constant discharge from a well. Paralleling the requirements given in the preceding paragraph, Theis' assumptions may be stated as follows:

1. Discharge of the well is changed by the amount Q at an arbitrary reference time $t=0$.
2. The well is open to the aquifer throughout the aquifer thickness, the well radius is infinitesimal, and flow to the well per unit length open to the aquifer is uniform.

3. The aquifer is homogeneous and isotropic, is of uniform thickness, and remains filled with water. It extends to infinite radius from the pumped well and is bounded above and below by impermeable rocks.
4. Storage in the aquifer is proportional to head.

Assumption 3 is the basis for the concept of transmissivity—the capacity of the aquifer to transmit water along the principal plane of the aquifer. Transmissivity, T, is assumed to equal the average hydraulic conductivity times aquifer thickness. Assumption 4 is the basis for the concept of the storage coefficient S, — the quantity of water released from or taken into storage, per unit area of aquifer, when the head in the aquifer is changed by a unit length.

Theis' (1935) equation showing the change in head or drawdown s expected for the conditions assumed, may be written as follows:

$$s=\frac{Q}{4\pi T}\int_{u}^{\infty}\frac{e^{-u}}{u}du=\frac{Q}{4\pi T}W(u), \tag{2-22}$$

where $u=r^2S/4Tt$ (2-23)

and r is the distance from the center of the discharging well to the point at which s is observed. $W(u)$ is commonly called the "well function of u."

If we know from geologic and other information that the hydraulic conductivity, discharging well, and storage characteristics meet assumptions 1-4 at a particular site and if we observe s versus r^2/t *for a known* Q, only the values of T and S are unkown. T and S can be calculated by graphical manipulation of the data and equations (2-22) and (2-23) as described by Brown (1953).

Graphical analysis of drawdown is centered around a type curve—here a curve of u versus $W(u)$—plotted on log paper. The following is a brief description of the graphical method from Ferris, Knowles, Brown, and Stallman (1962, p. 94-98); only the equation and figure numbers and the constants have been changed to fit this text:

Rearranging equations 2–22 and 2–23 there follows:

$$s=\left[\frac{Q}{4\pi T}\right]W(u) \tag{2-24}$$

or

$$\log s=\left[\log\frac{Q}{4\pi T}\right]+\log W(u) \tag{2-24a}$$

and

$$\frac{r^2}{t}=\left[\frac{4T}{S}\right]u \tag{2-25}$$

or

$$\log\frac{r^2}{t}=\left[\log\frac{4T}{S}\right]+\log u \tag{2-25a}$$

If the discharge, Q, is held constant, the bracketed parts of equations 2-24a and 2-25a are constant for a given pumping test, and $W(u)$ is related to u in the manner that s is related to r^2/t. This is shown graphically in figure 2-45. Therefore, if values of the drawdown s are plotted against r^2/t, or $1/t$ if only one observation well is ued, on logarithmic tracing paper to the same scale as the type curve, the curve of observed data will be similar to the type curve. The data curve may then be superposed on the type curve, the coordinate axes of the two curves being held parallel, and translated to a position which represents the best fit of the field data to the type

curve. An arbitrary point is selected anywhere on the overlapping (part) of the sheets and the coordinates of this common point * * * are recorded. It is often convenient to select a point whose coordinates (on the type curve graph) are both (either) 1 (or multiples of 10). These data are then used with equations 2-24 and 2-25 to solve for T and S.

A type curve on logarithmic coordinate paper of $W(u)$ versus $1/u$, the reciprocal of the argument, could have been plotted. Values of the drawdown (or recovery) s would then have been plotted versus t, or t/r^2, and superposed on the type curve in the manner outlined above. This method eliminates the necessity for computing $1/t$ values for the values of s.

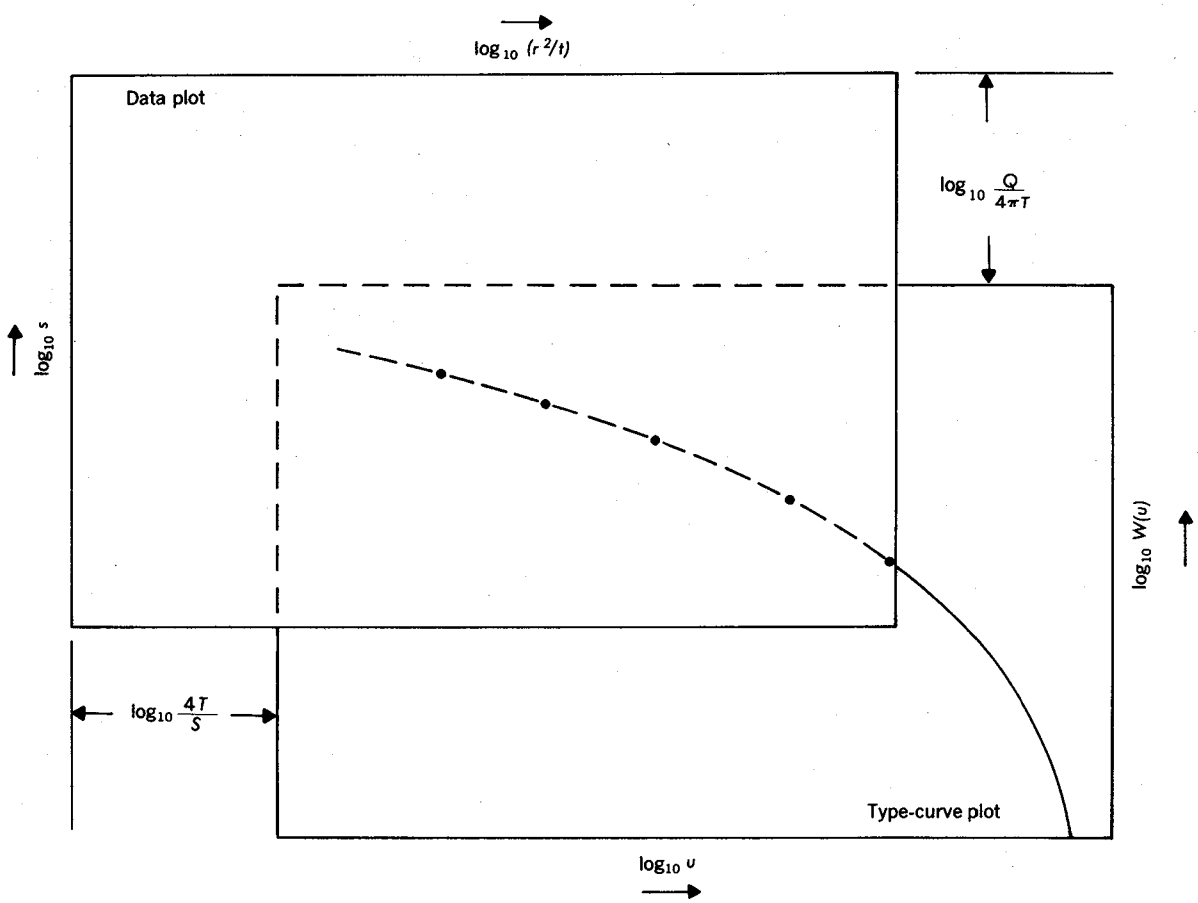

Figure 2-45.—Relation of $W(u)$ and u to s and r^2/t and displacements of graph scales by amounts of constants shown. After Ferris, Knowles, Brown, and Stallman (1962, p. 98, fig. 24).

Theis' type curve—u versus $W(u)$—is unique only because it pertains to a particular set of conditions at the pumped well and in the aquifer. The dimensionless group u is fundamental to all aquifer systems. Thus, a general form of equation 2-22 may be written as follows:

$$s=\frac{Q}{CT}f\left(\frac{r^2S}{Tt},\ \alpha,\ \beta,\ \ldots\right) \tag{2-26}$$

where the constant C and the function f are dependent on the shape of the aquifer and on the distribution and nature of hydraulic coefficients of the rocks. α and β refer to other dimensionless groups required to define a particular aquifer, such as the ratio K_r/K_z indicating a form of

anisotropy where K_r is hydraulic conductivity to radial flow and K_z is hydraulic conductivity to flow paralleling the axis of the well. Equation 2-26 may be written in terms of either s or Q, depending on which is controlled for testing purposes. Data analysis for all aquifer tests, using the appropriate type curve u versus $f(r^2S/Tt, \alpha, \beta \ldots)$ can be accomplished by the graphical method illustrated in figure 2-46. If s is controlled at the pumped well and Q is allowed to vary with time, the data curve of figure 2-46 will be S/Q versus $1/t$ at the pumped well, and at distance r from the pumped well, the data curve s/Q versus t or s/Q versus t/r^2 may be used for analysis.

Many descriptions of data analysis have stressed using special types of graph paper, intercepts, and asymptotic forms of each type curve. In general, these methods do not enhance the hydraulic data obtained, and the type-curve analysis procedure is preferred in most cases. However, the asymptotic semilogarithmic plot solution described by Cooper and Jacob (1946) is sometimes preferred to determine transmissivity using data from a production well affected by well losses, or from a piezometer near a partially penetrating production well. This is true because the well losses or effects of partial penetration become constant fairly early during the test. Thus, the arithmetic plot of drawdown versus the logarithm of time for the later data is shifted on the time scale, but retains the proper slope. Consequently, transmissivity, but not the storage coefficient, can be determined from such an analysis. The curvature of the log-log plot would be affected, however, because addition or subtraction of the constant drawdown caused by well-loss or partial penetration effects from that caused by transient radial flow would result in a decreasing graphical displacement as time and drawdown increase, resulting in erroneous values for both T and S.

Accordingly, it probably is advisable to prepare both log-log and semilog arithmetic plots of test data to take advantage of the best detection features of both types of plots.

2.H.4. TYPE CURVES IN THE HYDROLOGIC LITERATURE

Early development of algebraic equations that describe aquifer response to discharge centered on simplified models of the well and aquifer. As with all products, once the worth of aquifer tests became recognized by successful use in the field (through the efforts of pioneers such as C. V. Theis), the demand increased, the market enlarged, and the product improved by continuing refinement. It is interesting to chart the progress made with artesian situations, where the discharging well fully penetrates a homogeneous isotropic aquifer of infinite areal extent and the discharge is changed in amount, Q, at time $t=0$. Gunther Thiem is credited with first developing, in 1906, the response equation for steady radial flow (Ferris and others, 1962). The Thiem formula endured as the analytical equation for aquifer test analysis for about 30 years. The Theis (1935) equation represents a highly significant improvement in the technology of ground-water flow accounting for storage was introduced. The Theis equation permitted tests to be made in much less time than required by the Thiem steady state analysis. Prior to 1946, equations were based on the assumption that confining beds above and below the aquifer had zero hydraulic conductivity. Jacob (1946) changed that by introducing the steady-flow equation for a "leaky" aquifer, an aquifer in which one or both of the confining beds are significantly permeable. Hantush and Jacob (1955) advanced a solution for nonsteady flow in the leaky aquifer, assuming continuous steady flow through one of the contiguous confining beds. Hantush (1960) presented equations for nonsteady contributions from both the upper and lower confining beds of an artesian aquifer. However, the equations obtained fit only parts of the drawdown, and their applicability to a particular test must be investigated by comparing them to time criteria.

Hantush (1967) and Witherspoon and others (1971) advanced the leaky-aquifer test theory by including the effects of limited storage in confining beds on drawdowns in the pumped aquifer, the source bed, and the confining bed. In fact, Witherspoon and others (1971) present equations for drawdowns in any of three aquifers separated by semipermeable confining beds containing storage due to pumping any one of the aquifers. Much of the theory regarding leakage in multiaquifer systems is too complicated to use in aquifer test analysis, however.

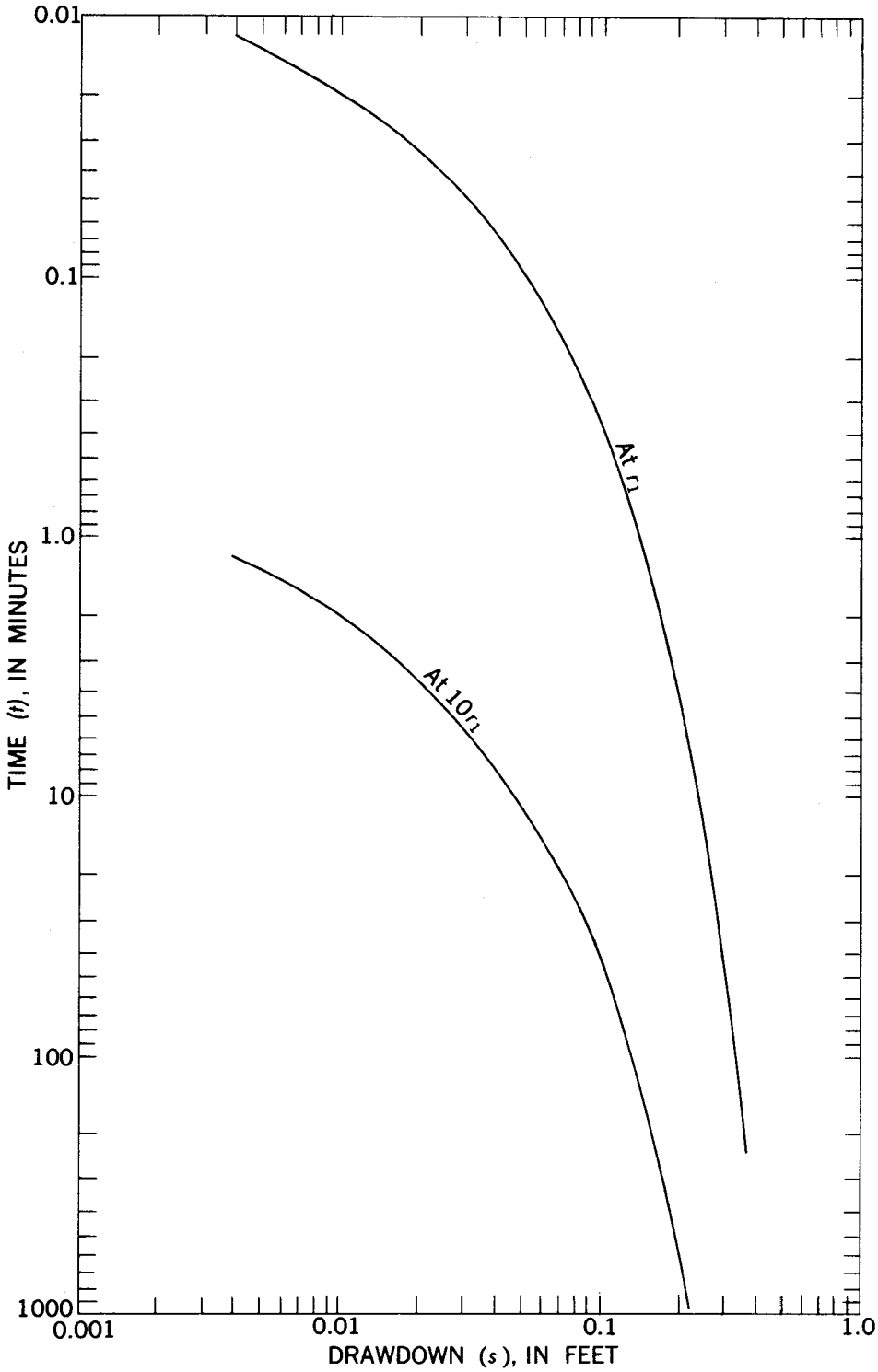

Figure 2-46. – Predicted response to pumping in observation wells.

Other work following Theis (1935) has involved more realistic treatment of boundary conditions at the control well. Hantush (1961a, 1961b) described time-drawdown response due to pumping a partially penetrating well. Papadopulos and Cooper (1967) and Papadopulos (1967a, 1967b) describe the effects of storage in the production-well bore on drawdowns in the well and in nearby observation wells, respectively.

Recent work has emphasized unconfined flow including, but not limited to, the work of Boulton (1954a, 1954b, and 1963), Streltsova (1972), Boulton and Streltsova (1975), Dagan (1968), and Neuman (1972, 1974, and 1975). More general solutions, each applicable to a wide range of test conditions, are needed and will probably be developed as theoretical studies gain scope.

The numerous conditions at the control well and in the aquifer which are commonly treated in analytical solutions are listed in table 2-3, which is indexed to examples of a few selected theoretical studies. The list serves to emphasize that many physical conditions at test sites are important to aquifer response and that there is no single response equation capable of handling all test configurations. Categories A to D in table 2-3 parallel the requirements for fully specifying the test-site conditions as noted earlier in this chapter. Category E has been added to show the availability of type curves in the literature and emphasis in each article. Adequate numerical values of type curves were not published in many of the original theoretical derivations. Useful sources of type-curve values are given in footnotes.

Study of table 2-3 reveals by induction that there is no justification, nor any need, for one to show favoritism toward a single type-curve formulation in aquifer-test analysis. Yet, such favoritism is frequent among hydrologists. A hidebound attitude toward selection and use of one type curve to the exclusion of all others may result in erroneous values of the hydraulic coefficients. Selection of the proper curve, or sets of curves, for data analysis can be made only if the characteristics of the control well and aquifer are known and are analogous to those assumed in derivation of an analytical equation. Should the literature fail to contain a type curve that fits site conditions, one may resort to modeling techniques as an alternate to mathematical analysis for finding the form of C and $f\,(r^2s/Tt,\ \alpha,\ \beta\ .\ .\ .)$ in equation 2-26 (Stallman, 1965).

2.H.5. TEST DESIGN

The purpose of design is to improve the probability that a test will yield acceptably accurate values of the hydraulic coefficients.

2.H.5.a. SITE EVALUATION

The cost of testing is frequently reduced by using combinations of production and abandoned wells rather than installing new wells. Few existing well configurations are suitable for test purposes, and most wells are ill equipped for observation. Evaluation of existing facilities in the area where tests are proposed to find those which are potentially usable is the first step in design. By recalling that an aquifer test involves applying a known stress to a know aquifer and observing the response, one may easily establish criteria for site evaluation, as follows:

2.H.5.a.1. CONTROL WELL

1. If it is to be pumped, the control well must be equipped with reliable power, pump, and discharge-control equipment.
2. The water discharged must be conducted away from the control well so it cannot return to the aquifer during the test. This point is of special importance in testing shallow unconfined aquifers.
3. The wellhead and discharge lines should be accessible for installing discharge-regulating and discharge-monitoring equipment.

4. It should be possible to measure depth to water in the control well before, during, and after pumping.
5. The diameter, depth, and position of all intervals open to the aquifer in the control well should be known, as should total depth.

2.H.5.a.2. OBSERVATION WELL

1. Response of all wells to changing water stages should be tested by injecting a known volume of water into each well and measuring the subsequent decline of water level. The initial rise of water should be dissipated within a few minutes (to within about 0.01 of the initial rise) if the observation well is to reflect changes of head in the aquifer during the test. Long abandoned wells tend to become clogged, and consequently the response test is one of the most important prepumping examinations to be made if such wells are to be used for observation.
2. Total depth, diameter, and screened interval should be known for each observation well.
3. Radial distance from the control well to each of the observation wells must be determined.

2.H.5.a.3. AQUIFER

1. Depth to, thickness of, and areal limits of the aquifer to be tested should be known.
2. Nearby aquifer discontinuities caused by changes in lithology or by incised streams and lakes should be mapped.
3. Estimates of all pertinent hydraulic properties of the aquifer and adjacent rocks must be made by means feasible. Also, if leaky confining beds are suspected, leakage coefficients should be estimated. For unconfined aquifers, conductivity to vertical flow is important. In some case, aquifer transmissivity may be estimated from the specific capacity of the well, based on equations and charts presented by Theis (1963), Brown (1963), or Meyer (1963). The effect of well loss on specific capacity is not included in these charts. However, such losses may be accounted for if step drawdown test data are available, based on equations presented by Jacob (1947) or Rorabaugh (1953). Alternatively, transmissivity may be estimated from sample logs of wells or test holes, based on the equation:

$$T=\sum_{1}^{n} K_m b_m; \tag{2-27}$$

where n = number of layers comprising the aquifer;
K_m = estimated hydraulic conductivity of mth layer, LT^{-1}; and
b_m = thickness of mth layer, L.

The hydraulic conductivity can be estimated from a graph or table of such values versus particle size or lithology, such as that used by Johnson (1966, 1967) or R. T. Hurr (Lohman, 1972, p. 53). Johnson's and Hurr's relationships were developed for specific aquifers, but similar charts might be prepared for other aquifers.

A value for the storage coefficient of an artesian aquifer may be estimated from the porosity and the barometric efficiency of the well, if known, by the equation (Jacob, 1940, p. 583):

$$S=(\gamma/E_w)nb\left(\frac{1}{BE}\right) \tag{2-28}$$

where γ = *specific weight of water per unit area,* $MT^{-2}L^{-2}$;
E_w = bulk modulus of elasticity of water, $MT^{-2}L^{-1}$;
n = porosity, dimensionless;
b = aquifer thickness, L; and
BE = barometric efficiency, dimensionless.

Table 2-3.—*Selected literature on aquifer tests showing site conditions treated and subject emphasis.*

ARTESIAN

UNCONFINED FLOW

Category	Nonleaky							Leaky			Multiple			
	Theim (1904)	Theis (1935)	Jacob and Lohman (1952)	Stallman (1963)	Hantush (1964)	Hantush (1965)	Hantush (1962b)	Hantush and Jacob (1955)	Hantush (1959)	Hantush (1960)	Papadopulos (1966)	Hantush (1967)	Neuman and Witherspoon (1969)	Witherspoon and others (1971)
A. Type of control imposed:														
Step change Q	x	x		x		x	x	x		x	x	x	x	x
Step change s			x		x		x		x		x			
Pulsed Q														
Pulsed s														
Variable Q														
Variable s														
B. Control-well Characteristics:														
Full penetration	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Partial penetration														
Diameter infinitesimal	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Diameter finite														
Seepage face														
Well loss														
Radial screens														
C. Conductivity and flow conditions:														
Homogeneous, isotropic	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Homogeneous, anisotropic														
Heterogeneous, isotropic														
Impermeable confining beds	x	x	x	x	x	x	x				x			
Permeable confining beds (steady)								x	x			x		
Permeable confining beds (nonsteady)										x			x	x
Sloping beds							x							
Areally infinite	x	x	x		x		x	x	x	x	x	x	x	x
Areally semi-infinite				x		x								
Areally discontinuous						x								
Dewatering negligible	x	x	x	x	x	x		x	x	x	x	x	x	x
Dewatering significant						x	x							
Flow radial	x	x	x	x	x	x		x	x	x	x			
Flow radial and vertical							x					x	x	x
Nonsteady flow		x	x	x	x	x	x	x	x	x	x	x	x	x
Steady flow	x					x		x		x				
D. Storage relation:														
Linear to head		x	x	x	x	x	x	x	x	x	x	x	x	x
Head and time														
Artesian		x	x	x	x	x		x	x	x	x	x	x	x
Unconfined							x							

Category	Horizontal plane anisotropy				Partial penetration				Well Characteristics								
	Hantush (1966a)	Hantush (1966b)	Hantush and Thomas (1966)	Papadopulos (1967)	Hantush (1961a)	Hantush (1961d)	Hantush (1964)	Weeks (1969)	Jacob (1947)	Rorabaugh (1953)	Lennox (1961)	Cooper and others (1965)	Bredehoeft and others (1966)	Cooper and others (1967)	Papadopulos and Cooper (1967)	Papadopulos (1967)	van der Kamp (1976)
A. Type of control imposed:																	
Step change Q	x	x	x	x	x	x	x	x	x	x	x				x	x	x
Step change s													x				
Pulsed Q														x			
Pulsed s														x			
Variable Q		x															
Variable s												x					
B. Control-well Characteristics:																	
Full penetration	x	x	x	x					x	x	x	x	x	x	x	x	x
Partial penetration		x			x	x	x	x									
Diameter infinitesimal	x	x	x	x	x	x	x	x	x	x	x						
Diameter finite												x	x	x	x	x	x
Seepage face																	
Well loss									x	x	x						
Radial screens																	
C. Conductivity and flow conditions:																	
Homogeneous, isotropic					x	x			x	x	x	x	x	x	x	x	x
Homogeneous, anisotropic							x	x									
Heterogeneous, isotropic																	
Impermeable confining beds	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Permeable confining beds (steady)	x	x					x										
Permeable confining beds (nonsteady)																	
Sloping beds																	
Areally infinite	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Areally semi-infinite																	
Areally discontinuous																	
Dewatering negligible	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Dewatering significant																	
Flow radial	x	x	x	x					x	x	x	x	x	x	x	x	x
Flow radial and vertical		x			x	x	x	x									
Nonsteady flow									x	x	x	x	x	x	x	x	x
Steady flow																	
D. Storage relation:																	
Linear to head	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Head and time																	
Artesian	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Unconfined																	

Category	Variable lischarge		Miscellaneous			
	Ferris and others (1962)	Hantush (1964)	Hantush (1962)	Hantush and Papadopulos (1962)	Bixel and others (1963)	Moench and Prickett (1972)
A. Type of control imposed:						
Step change Q			x	x	x	x
Step change s						
Pulsed Q						
Pulsed s						
Variable Q	x	x				
Variable s						
B. Control-well Characteristics:						
Full penetration	x	x	x		x	x
Partial penetration				x		
Diameter infinitesimal	x	x	x		x	x
Diameter finite			x			
Seepage face						
Well loss						
Radial screens				x		
C. Conductivity and flow conditions:						
Homogeneous, isotropic	x	x		x	x	x
Homogeneous, anisotropic						
Heterogeneous, isotropic		x	x			
Impermeable confining beds	x	x	x	x	x	x
Permeable confining beds (steady)		x				
Permeable confining beds (nonsteady)						
Sloping beds		x				
Areally infinite	x	x	x	x		x
Areally semi-infinite						
Areally discontinuous					x	
Dewatering negligible	x	x	x	x	x	x
Dewatering significant						
Flow radial	x	x	x		x	x
Flow radial and vertical						
Nonsteady flow	x	x		x		x
Steady flow						
D. Storage relation:						
Linear to head	x	x	x	x	x	x
Head and time						
Artesian	x	x	x	x	x	x
Unconfined						x

Category	Water table in aquifer														Water table in overlying aquitard	
	Boulton (1954a)	Boulton (1954b)	Boulton (1963)	Boulton (1964)	Boulton (1965)	Prickett (1965)	Stallman (1965)	Norris and Fidler (1966)	Dagan (1967)	Neuman (1974)	Streltsova (1972)	Neuman (1974)	Boulton and Streltsova (1975)	Neuman (1975)	Cooley (1972)	Cooley and Case (1973)
A. Type of control imposed:																
Step change Q	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
Step change s					x											
Pulsed Q																
Pulsed s																
Variable Q																
Variable s																
B. Control-well Characteristics:																
Full penetration	x	x	x	x	x	x				x	x		x	x	x	x
Partial penetration							x	x	x			x		x		
Diameter infinitesimal	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
Diameter finite					x											
Seepage face					x											
Well loss																
Radial screens																
C. Conductivity and flow conditions:																
Homogeneous, isotropic	x	x	x	x	x	x				x	x		x			
Homogeneous, anisotropic							x	x	x			x		x		
Heterogeneous, isotropic															x	x
Impermeable confining beds																
Permeable confining beds (steady)																
Permeable confining beds (nonsteady)																
Sloping beds																
Areally infinite	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x
Areally semi-infinite								x								
Areally discontinuous																
Dewatering negligible	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
Dewatering significant					x											
Flow radial		x	x	x		x									x	x
Flow radial and vertical	x				x		x	x	x	x	x	x	x	x		
Nonsteady flow	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Steady flow																
D. Storage relation:																
Linear to head	x						x	x	x	x	x	x	x	x	x	x
Head and time		x	x	x		x										x
Artesian	0	x	x	x	0	x	0	0	0	x	x	x	x	x		
Unconfined	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

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E. Emphasis on paper:										
Q versus time	x x	x	x				x x		x	
s versus time and space	x x x x x	x x	x x x x	x x x x	x x x x	x x x x x x x x x	x x	x x x x	x x x x x x x x x x x x x	x x
Analytical equation	x x x x x x x	x x x	x x x x	x x x x	x x	x x x x x x x x	x	x x x x	x x x x x x x x x x x	x x
Graphical type curve	1 x[1] x[1]	1 1						x	x[5] 1 x x x x[1] x x x x x	
Tables, type-curve	1 1 x x	x[2] x[3] x			4 x	x x x[1] x x	x	x	x x x x x x x x x	
Numerical or analog techniques			x x			x x		x	x x x	x x
Theory development	x x x x x x	x x x	x x x x	x x x x	x x	x x x x x x x x	x x	x x x x	x x x x x x x x x	x x
Application of data				x x x	x x	x x x x x	x	x	x x x x x x x x	

[e] Dupuit-Forchheimer assumptions made
[1] Lohman (1972)
[2] Hantush (1961c)
[3] Hantush (1961b)
[4] Hantush (1961e)
[5] Stallman (1962)

Alternatively, if no data are available, S may be estimated by assuming a specific storage, S_s, of about $3 \times 10^{-6} m^{-1}$ and using the equation:

$$S = S_s b$$

where b = aquifer thickness in meters.

For unconfined aquifers, specific yield may be estimated from the nature of the material drained during the test. Rough estimates of specific yield range from 0.01 for clay to 0.1 for silt and 0.2 or greater for sand and gravel (Johnson, 1967).

The ratio of horizontal to vertical hydraulic conductivity is important in the analysis of tests using partially penetrating production wells and of tests on unconfined aquifers. This ratio is dependent upon the degree of stratification of the aquifer, and can vary from 1:1 or 2:1 to more than 100:1. Data presented by Mansur and Dietrich (1965) and by Weeks (1969) indicate that the ratio might be estimated as being about 5:1 or 10:1 in a relatively homogeneous aquifer exhibiting only slight stratification. However, in strongly stratified aquifers, the ratio would be much higher (Johnson, Moston, and Morris, 1968, p. 24-27).

Two important factors in the successful design of an aquifer test are the vertical hydraulic conductivity and the specific storage of the overlying and underlying semiconfining beds. Both these factors show an extreme range. For example, a Cretaceous semiconfining clay bed in the Annapolis, Maryland area has a vertical hydraulic conductivity of about 5×10^{-5}m/day (Mack, 1974), whereas several Pleistocene glacial till semiconfining beds in Ohio and Illinois have a vertical hydraulic conductivity of .001-.02 m/day (Norris, 1962). The specific storage coefficient of semiconfining-bed materials also shows a wide range, depending upon the nature of the materials; their degree of consolidation and cementation; and the preconsolidation load stress, or maximum overburden load stress to which the beds have been subjected subsequent to their deposition. For example, Riley (1969) estimates the specific storage of clay beds in the valley fill deposits at a site in the San Joaquin valley to be about $1 \times 10^{-5} m^{-1}$, in the range of preconsolidation load stress, as compared to a value of about $1 \times 10^{-3} m^{-1}$ in the range of virgin load stress. (Virgin load stress represents stress greater than that to which the bed had previously been exposed.) As another example, Wolff (1970a) found that the specific storage of an unconsolidated bed of fine sand, silt, and clay near Salisbury, Maryland, was about $3 \times 10^{-5} m^{-1}$. In general, in areas for which land subsidence and semiconfining-bed compaction is not evident, an investigator might use, for his pretest design estimate, a value of $3 \times 10^{-6} m^{-1}$ for the specific storage of a consolidated confining bed, and a value of $3 \times 10^{-5} m^{-1}$ for an unconsolidated bed. On the other hand, if compaction has occurred, and it is anticipated that the test will be run under conditions that result in virgin load stress, the subsidence and water-level decline data themselves should be used to estimate specific storage.

The uncertainty involved in using the above examples and suggestions for estimating vertical hydraulic conductivity and specific storage of the semiconfining beds should be fully recognized. The investigator should use all available information on the geology and hydrology of the semiconfining beds to estimate their hydraulic properties.

The importance of making the pretest site evaluation cannot be overstressed. To ignore such an evaluation is to invite failure of the test. Although in this report application of site evaluation to existing well configuration is emphasized, all elements apply equally if wells are to be specially installed for testing the aquifer.

2.H.5.b. RESPONSE PREDICTION

The pretest evaluation serves two general purposes. It describes the aquifer and control well in sufficient detail so the appropriate type curve to be used for data analysis is evident (provided of

course that one analogous to the site conditions exist). Also, it provides the basis for predicting the outcome of the test with available facilities and pinpoints deficiencies in observation-well locations. If site conditions deviate markedly from all known type-curve formulations, the site should be abandoned for testing purposes unless the cost of a special-purpose type-curve development is considered acceptable.

If a suitable type curve is available, estimates of the hydraulic properties are entered into the response equation, together with the magnitude and type of control, to find the expected head or drawdown distribution at the available observation wells. Test data, to be most effective, must sample a variety of positions on the type curve(s). If the observation wells are not located to accomplish such a sampling, calculated results will be in doubt. As an example, consider the nonleaky-artesian model of Theis. Figure 2-46 shows schematically the drawdown versus time expected in a particular observation well located at distance r_1 from a control well. It is practically impossible to obtain meaningful measurements of drawdown during the first minute of the test. Thus, only the flat part of the right-hand curve can be defined by measurements in the available observation well. Study of the matching process in figure 2-45 shows that such data will produce accurate measurement of transmissivity because the data curve can be located relatively accurately with respect to $W(u)$, the ordinate, disregarding the misfit along the abscissa. Finding the match point for t and u is another matter, however. For the estimates shown in figure 2-46, it is unlikely the storage coefficient could be obtained within an order of magnitude. If the pumping test is to provide accurate values of both T and S, drawdowns must be observed over both the steep and flat part of the type curve.

If only one observation well is to be drilled for testing, where should it be located? From the Theis type curve, we find the time scale is proportional to r^2. To produce a detectable drawdown of 0.01 foot 2 minutes after pumping starts, the time scale should be shifted about two orders of magnitude to the right in figure 2-46. Thus, an observation well at a distance of about $10r_1$ from the control well would provide definitive data for both T and S, assuming that our evaluation of the test site is correct. Furthermore, test observations made over a 24-hour period will obviously afford all the curve definition needed to determine T and S accurately.

Where several wells are available, predicted response should be plotted as t/r^2 or r^2/t for all wells on one sheet of graph paper. The total of all information from the test site should afford complete definition of curve shape. It is not required that each well provide data that fits both the steep and flat parts of the type curve. Data from one or more of the wells having small r may plot only in the flat, while others may plot only in the steep part. The objective of design is to assure adequate response measurements over the whole of the test facility—not piecemeal.

Pretest predictions are particularly important in the design of aquifer tests where leakage from or across the confining beds is anticipated. Such predictions will aid in selecting the proper set of response curves and in circumventing problems of their nonuniqueness, as described below. If the confining layer is thin and relatively permeable and incompressible, the response curves of Hantush and Jacob (1955) will apply, whereas those of Hantush (1960) will apply if the confining layer is thick, of low permeability, and highly compressible. Quantitatively, selection of the proper set of response curves depends on one of two inequalities given by Hantush (1960, p. 3716). For example, the Hantush-Jacob (1955) response curves will apply if

$$t > \frac{5b'^2 S_s}{K'} \tag{2-30}$$

for the more permeable-coning layer,
where b' = confining layer thickness, L;
S_s = specific storage of the confining layer, L^{-1}; and
K' = hydraulic conductivity of the confining layer, LT^{-1}.

Thus, if $b' = 10$ feet, $K' = .05$ ft/day, and $S'_s = 10^{-6}$/ft, and the confining layer is overlain or underlain by a source bed, the curves of Hantush and Jacob (1955) would apply after the test had been in progress about .01 day, or 15 minutes. On the other hand, if $K' = 10^{-4}$ ft/day, $b' = 100$ ft, and $S'_s = 10^{-4}$ ft^{-1}, the Hantush (1960) response curves would apply for the first 1000 days, based on Hantush's (1960, p. 3716) inequality

$$t < \frac{b'^2 S'_s}{10\,K'}, \tag{2-31}$$

and the Hantush and Jacob (1955) curves would not apply for 50,000 days.

Additional aquifer-test design problems arise if the response curves of Hantush (1960) apply, because the curves are nonunique for a significant range of confining bed properties. In fact, there is virtually no difference in the shape of the response curves for values of Hantush's (1960) β ranging from zero (the Theis curve) to about 0.7. The parameter

$$\beta = \frac{r}{4}\left(\frac{K'S'}{Tb'S} + \frac{K''S''}{Tb''S}\right)^{1/2}, \tag{2-32}$$

where r = distance from production well to observation well, L;

K', K'' = vertical hydraulic conductivity of upper and lower semiconfining layers, respectively, (L/T);

S, S', S'' = storage coefficient of the aquifer and upper and lower semiconfining beds, respectively (dimensionless);

T = transmissivity of the aquifer, L^2/T; and

b', b'' = thickness of the upper and lower semiconfining beds, respectively (L).

If β falls within this range for a given observation well, it is not possible to determine unique values of T, S, and β using data from that well alone. On the other hand, if data for more than one observation well are available, a composite t/r^2 data plot may be prepared and matched to the type-curve family. A unique match may then be obtained in invoking the added constraint that r values for the observations wells must fall on curves having proportional β values. For example, if data are available for wells at 100 and 200 feet from the production well, the data for the two wells must match curves having β values of the ratio 1:2. If only one observation well is available, and the pretest prediction is that the β value lies between zero and 0.7, consideration should be given to installing an additional observation well at some distance to obtain separate response curves. Moreover, if knowledge of the confining bed properties is important, the investigator should consider emplacing a piezometer in the confining bed itself, with the plan that the data be analyzed by the ratio method of Neuman and Witherspoon (1972). Leahy (1976) has recently made use of the ratio method in conjunction with the modified leaky aquifer method (Hantush, 1960) to estimate vertical conductivity and specific storage of a confining bed in Delaware.

One caveat is in order on use of the Neuman-Witherspoon method. In practice, it has sometimes been found (Wolff, 1970b, for example) that piezometers completed in the semiconfining bed exhibit reverse water-level fluctuations, in that water levels in the semiconfining bed rise for some period of time after the start of pumpage from the aquifer. These changes apparently are related to radial and vertical deformation of the aquifer and semiconfining beds resulting from their compressibility (Wolff, 1970b). Such phenomena were not considered in the development of the ratio method, and their effects on the accuracy of the method are not known. Additional work is needed in this area.

Where site conditions are more complicated, such as those including partial penetration or unconfined flow, the prediction of observation-well response is of course less certain. However, for all

proposed tests, such a prediction should be made without fail; by using the theoretical response curves that are based on conditions comparable to those at the test site, one can guard against major deficiencies in the configuration of observation wells. Many test configurations could be rescued from failure by the simple expedient of drilling only one observation well at a key point in the system.

Artesian or confined systems are generally more amenable to testing than unconfined systems. Artesian flow to wells is described by the simpler set of boundary conditions. In unconfined systems, mobility of the upper boundary, vertical flow components, and nonlinear release of water from storage are difficult to treat but have been successfully attacked recently. However, all these complicating features of unconfined flow affect the early response simultaneously. Present state of the art does not provide a means for quantitatively recognizing the magnitude of response due to each factor individually.

Much recent work has been concentrated on the development of response curves for unconfined aquifers. Early important contributions on the topic were made by Boulton (1954a, 1954b). In one analysis (1954a), he assumed negligible dewatering, linear release from storage, and termination of flow lines on the water table. In the other analysis (1954b), he investigated the effects of delayed yield from storage, expressed as an exponential function of time. Boulton's delayed yield model has enjoyed considerable acceptance, in large part because of the applications described by Prickett. (1965).

Recent work (Neuman, 1972, 1974, 1975; Streltsova, 1972; Streltsova and Rushton, 1973; Boulton and Streltsova, 1975), has centered on analyzing the aquifer as being compressible (containing internal storage), but with the flow lines terminating at the water table, as in Boulton's (1954a) analysis. These analyses yield type curves very similar to Boulton's (1954b) delayed yield curves, and have resulted in Boulton's arbitrary "delay index" being described in terms of S_y, b, the ratio of horizontal to vertical hydraulic conductivity, and the ratio of well radius to aquifer thickness. There is considerable dispute on the exact nature of this relationship, however (Neuman, 1975; Streltsova, 1976; Neuman, 1976; Gambolatti, 1976). On the other hand, Cooley (1972) and Cooley and Case (1973) have shown that the delay index is exactly related to the hydraulic conductivity, thickness, and specific yield of the aquitard in a system in which the aquifer is overlain by a semiconfining bed containing a watertable.

Historically, when testing unconfined aquifers, it has been common practice to pump long enough that the effects of vertical flow components and delayed yield from storage become negligible. Under these conditions, the response curves for artesian conditions may be used to analyze the test, if a correction is made for the effects of dewatering. However, no firm criteria have existed for judging how long is "long enough". With the analytical solutions now available, some criteria exist for judging the length of time required for effectively attaining an artesian response in an unconfined system. According to Boulton (1954a) and Hantush (1964a, p. 366), vertical flow components is unconfined aquifers significantly affect response when

$$t < 5bS/K_z, \text{ in the region } 0 < r/b < 0.2, \tag{2-33}$$

where b is aquifer thickness and S is specific yeild. Equation 2-33 is derived analytically, and it is assumed that nonsteady radial and vertical flow components exist in the vicinity of a fully penetrating well, specific yield is constant in time and space, and drawdown in negligible compared with aquifer thickness. Equation 2-33 produces a rather startling revelation of the pumping time required for approaching artesian-type flow. For $b = 100$ feet, $S = 0.2$, and $K_z = 10$ feet per day, we find response is affected by vertical flow for as long as $t = 5 \times 100 \times 0.2/10 = 10$ days near the pumped well.

Electric-analog studies (Stallman, 1965) showed vertical flow components to be significant for

$$t < r^2S/T, \text{ or } t < 9bS/K_z, \text{ in the region } (r/b)\,(K_z/K_r)^{1/2} < 3 \tag{2-34}$$

where K_r and K_z are hydraulic conductivity to radial and vertical flow, respectively.

Weeks (1969, p. 209–210), however, concluded that, data from piezometers open near the water table match the artesian curves at

$$t > bS_y/K_z \text{ for } r/b(K_z/K_r)^{1/2} < 0.4 \tag{2-35}$$

$$\text{and } t > bS_y/K_z\,(.5 + 1.25\, r/b\,(K_z/K_r)^{1/2}) \text{ for greater values of } r/b\,(K_z/K_r)^{1/2}. \tag{2-36}$$

(Week's second equation is incorrectly given in the original paper.) This conclusion was based on the comparison of field data from several tests on unconfined aquifers to the appropriate artesian response curves. Visual examination of plots constructed from Neuman's (1975) type-curve data basically support the time-criterion equation given by Weeks for observation wells located at small radii from the production well. However, for

$$r/b\,(K_z/K_r)^{1/2} > 1.5 \tag{2-37}$$

or so, Neuman's data suggest that Weeks' equation substantially underpredicts the time requirement after which the artesian-response equations can be used. Hence, the equations should be used with care in evaluating the data for more distant observation wells.

If the pumping time in a test of an unconfined aquifer can be extended long enough to surpass the time requirements evident from equations 2-33 to 2-37, equations of radial artesian flow can be employed for data analysis, provided the control well fully penetrates the aquifer. If the control well partially penetrates the aquifer, equations accounting for partial penetration (Hantush, 1961a, 1961d; 1964a, p. 355; Stallman, 1965) must be employed, or one is restricted further to using data in the region

$$r > 1.5b\,(K_r/K_z)^{1/2}. \tag{2-38}$$

Use of type curves for predicting response at a test site and the liberal use of criteria like equations 2-33 to 2-38 for design purposes are necessary to reduce the prospect of failure to achieve the test objective, which is the accurate measurement of the hydraulic properties of the aquifer.

2.H.6 FIELD OBSERVATION

The records required for analysis and the tolerance in measurement generally considered acceptable are as follows:

1. Control-well discharge (±10 percent).
2. Depth to water in wells below measuring point (±0.01 ft).
3. Distance from control well to each observation well (±0.5 percent).
4. Synchronous time (±1 percent of time since control effected).
5. Description of measuring points.
6. Elevations of measuring points (±0.01 ft).

7. Vertical distance between measuring point and land surface (±0.1 ft).
8. Total depths of all wells (±1 percent).
9. Depth and length of screened intervals of all wells (±1 percent).
10. Diameter, casing type, screen type, and method of construction of all wells (nominal).
11. Location of all wells in plan, relative to land-survey net or by latitude and longitude (accuracy dependent on individual need).

Items 1-4 are data collected specifically as part of the testing process. Many items are recorded on well-schedule and water-level forms by personnel taking part in the tests, and these forms should become part of the permanent records. Examples of two of the various types of forms in use by the U.S. Geological Survey are shown in figures 2-47 and 2-48. The well schedule (fig. 2-48) is designed to make use of automatic data-storage and retrieval techniques. For recording water-level data from aquifer tests, the form shown in figure 2-48 is used. Mud, rain, bitter cold, intense heat, insects, barbed wire, balky engines, and a host of other environmental distractions associated with aquifer tests compete for the observer's attention against the mundane measurements. Simple but complete forms for all data recording, prepared in a noncompetitive environment, serve as convenient reminders to the observer so he will not inadvertently omit a key measurement while in the field, provided, of course, the observer takes the forms with him.

Lithology and construction features of the control and observation wells are generally determined by interviewing the well owners and (or) the well drillers. Field measurements of well depths and casing diameters afford a rough check on the accuracy of information obtained by interview. Detailed lithologic logs and construction features should be noted during drilling of all wells installed expressly for testing purposes. It is commonly advisable to make geophysical logs in the test wells, such as resistivity, self-potential, gamma, and neutron logs, to provide some understanding of subsurface conditions. Accurate location in plan of observation wells, referenced to the position of the control well, is especially important in a test of a heterogeneous or anisotropic aquifer. Position of the test site with respect to a regional land-survey net or by latitude and longitude is also required so that the data obtained can be effectively used to portray the regional characteristics of the aquifer.

FORM NO. 9—1904—A
Revised September 1980

SITE NO.

U.S. DEPT. OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Recorded by _____ Date _____

SITE SCHEDULE

Check One ____ English ____ Metric Units

GENERAL SITE DATA (0)

Site Ident No (5–19) | RG Number R=0 * | Transaction T= A D M V * (add, delete, modify, verified)

Site-Type 2= C D E H I M Ø P S T W * (collector, drain, excavation, sink hole, connect well, multi-ple, out crop, pond, spring, tunnel or shaft, well,) | Data Reliability 3= C U L M * (field checked, unchecked, location accurate, not, minimal data) | Reporting Agency 4= *

Project No. 5= * | District 6= * | State 7= * | County (or town) _____ | 8= *

Latitude 9= * (deg min sec) | Longitude 10= * (deg min sec) | Lat-Long Accuracy 11= S F T M * (sec, 5 sec, 10 sec, Min)

Local Number 12= * | Land Net Loc. 13= (1/4 1/4 1/4) S (section,) T (township,) R (range, merid) *

Location Map 14= * | Scale 15= *

Altitude 16= * | Method of Measurement 17= A L M * (altimeter, level, map) | Accuracy 18= *

Topo Setting 19= A B C D E F G H K L M Ø P S T U V W * (alluvial fan, playa, stream channel, depression, dunes, flat, flood plain, hill top, sink, swamp, mangrove swamp, offshore, pedi-ment, hill side, terrace, undulating, valley flat, upland draw) | Hydrologic Unit (OWDC) 20= *

Use of Site 23= A C D E G H Ø M P R S T U W X Z * (anode, standby, emer. supply, drain, geothermal, geo-, seismic, heat, observa-tion, reserv., mine, oil or gas, recharge, repress, test, unused, with-drawal, waste, destroyed) | Secondary Site Use 301= * | Tertiary Site Use 302= *

Use of Water 24= A B C D E F H I J K M N P Q R S T U Y Z * (air-cond., bot-tling, com-mercial, de-water, power, fire, do-mestic, irri-gation, industrial (cooling), mining, medi-cinal, indus-trial, public supply, aqua-culture, recreation, stock, institution, unused, desal, other)

Secondary Water Use 25= * | Tertiary Use of Water 26= * | Depth of Hole 27= * | Depth of Well 28= * | Source of Depth Data ① 29= *

Water Level 30= * | Data Measured 31= / / (month day year) * | Source ① 33= *

Method of Measurement 34= A B C E G H L M N R S T V Z * (airline, analog, calibrated airline, estimated, pressure gage, calibrated pressure gage, geophysical logs, manometer, non-rec. gage, reported, steel tape, electric tape, calibrated electric tape, other)

Site Status 37= D E F G H I J N Ø P R S T V W X Z * (dry, recently flowing, flowing, nearby flowing, nearby recently flowing, injector site, inj-site monitor, meas. discon., obstruction, pumping, recently pumped, nearby pumping, nearby recently pumped, foreign substance, well destroyed, surface water effects, other)

Source of Geohydrologic Data ① 36= * | Pump Used 35= * (no) | Date of First Construction/Completion 21= / / (month day year) *

OWNER IDENTIFICATION (1)

R=158 * | T= A D M * (add, delete, modify) | Date of Ownership 159 # / / (month day year) *

Name: Last 161 # * | First 162= * | Middle Initial 163= *

OTHER SITE IDENTIFICATION NUMBERS (1)

R=189 * | T= A D M * (add, delete, modify) | Ident 190 # * | Assigner 191= *

New Card Same R & T | Ident 190 # * | Assigner 191= *

SITE VISIT DATA (1)

R=186 * | T= A D M * (add, delete, modify) | Date of Visit 187# / / (month day year) * | Name of Person 188= *

FIELD WATER QUALITY MEASUREMENTS (1)

R=192 * | T= A D M * (add, delete, modify) | Date 193 # / / (month day year) * | Geohydrologic Unit 195 # *

New Card Same R thru 195 | Temperature 196# 0 0 0 1 0 * | Degrees C 197= *

Conductance 196# 0 0 0 9 5 * | µ Mhos 197= *

Other (STORET) Parameter 196# * | Value 197= *

Other (STORET) Parameter 196# * | Value 197= *

FOOT NOTES:

① Source of Data Codes:

A D G L M O R S Z
(other, driller, geologist, logs, memory, owner, other gov't, other reported, reporting agency, other)

Figure 2-47.—Example of a well-schedule form.

WELL CONSTRUCTION DATA (1)

R = 58 * | T = A D M * (add, delete, modify) | Entry No 59 # * | Date of Construction Completion 60 = / / * (month day year) | Source of ① Const. Data 64 = *

Name of Contractor/Driller 63 = *

Method of Construction 65 = A B C D H J P R T V W Z *
air-rotary, bored or augered, cable-tool, dug, hydraulic rotary, jetted, air-percussion, reverse rotary, trenching, driven, drive wash, other

Finish 66 = C F G H Ø P S T W X Z *
porous concrete, gravel w/ perf, gravel screen, horizontal gallery, open end, perforated or slotted, screen, sand point, walled, open hole, other

Type of Seal 67 = B C G Z *
bentonite, clay, cement grout, other

Bottom of Seal 68 = *

Method of Development 69 = A B C J N P S Z *
air-lift pump, bailed, compressed air, jetted, none, other pump, surged, other

Number of Hours in Development 70 = *

Special Treatment During Development 71 = C D E F H M Z *
chemicals, dry ice, explosives, deflocculant, hydrofracturing, mechanical, other

DIMENSIONS OF THE HOLE CONSTRUCTED (2)

R = 72 * | T = A D M * (add, delete, modify) | Construction Entry No 59 # *

New Card for Each Hole Segment Same R, T & Field 59

Top of Hole Segment Below LSD	Bottom of Hole Segment below LSD	Diameter of Hole Segment
73 # *	74 = *	75 = *
73 # *	74 = *	75 = *
73 # *	74 = *	75 = *
73 # *	74 = *	75 = *
73 # *	74 = *	75 = *

CASING SCHEDULE (2)

R = 76 * | T = A D M * (add, delete, modify) | Construction Entry No 59 # *

New Card for Each Casing With Same R, T & Field 59

Top of Casing Segment Below LSD	Bottom of Casing Segment Below LSD	Diameter of Casing Segment	Casing Material ⑤	Thickness of Casing
77 # *	78 = *	79 # *	80 = *	81 = *
77 # *	78 = *	79 # *	80 = *	81 = *
77 # *	78 = *	79 # *	80 = *	81 = *
77 # *	78 = *	79 # *	80 = *	81 = *
77 # *	78 = *	79 # *	80 = *	81 = *

OPENINGS SCHEDULE (2)

R = 82 * | T = A D M * (add, delete, modify) | Construction Entry No 59 # *

New Card for Each Open Section With Same R, T and Field 59

	(Openings Data)	(Openings Data)	(Openings Data)
Top of Section Below LSD	83 # *	83 # *	83 # *
Bottom of Section Below LSD	84 = *	84 = *	84 = *
Type of Openings ⑥	85 = *	85 = *	85 = *
Type of Material ⑦	86 = *	86 = *	86 = *
Diameter of Open Section	87 = *	87 = *	87 = *
Width of Opening	88 = *	88 = *	88 = *
Length of Opening	89 = *	89 = *	89 = *

FOOT NOTES:

① Source of Data Codes:
A D G L M O R S Z
other, driller, geologist, logs, memory, owner, other gov't, reported, reporting agency, other

⑤ Casing Material Codes
B C D G I M P R S T U W Z
brick, concrete, copper, galv iron, wrought iron, other metal, PVC or plastic, rock or stone, steel, tile, coated steel, wood, other

⑥ Type of Openings Codes
F L M P R S T W X Z
fracture, louvered shuttered, mesh, perforated or slotted, wire-wound, screen (unknown), sand point, walled, open hole, other

⑦ Type of Material Codes for Open Sections
B C G I M P R S T Z
brass or bronze, concrete, galv iron, wrought iron, other metal, PVC or plastic, stainless steel, steel, tile, other

Figure 2-47.—Example of a well-schedule form—Continued.

PRODUCTION DATA (1)

R = 134 146 * (flowing, pumped) | T = A D M * (add, delete, modify) | Entry No 147 # * | Date 148 = / / * (month day year)

Discharge: 150 = * | Source of Data ① 151 = * | Draw-down 309 = *

Method of Measurement 152 = B C E F M O P R T U V W Z * (bailer, current, meter, estimated, flume, totaling, meter, orifice, pitot-tube, meter, reported, trajectory, venturi, volumetric, weir, other)

Production Level 153 = * | Static Level 154 = * | Source of Data ① 155 = * | Specific Capacity 272 = *

Method of Measurement 156 = A B C E G H L M N R S T V Z * (airline, analog, airline, calibrated, gage, estimated, pressure gage, pressure, calibrated, geophysical, logs, manometer, non-rec., gage, reported, steel tape, electric tape, calibrated, electric tape, other) | Pumping Period 157 = *

LIFT DATA (1)

R = 42 * | T = A D M * (add, delete, modify) | Type of Lift 43 # A B C J P R S T U Z * (air, bucket, centrifugal, jet, piston, rotary, submergible, turbine, unknown, other) | Entry No 254 # *

Pump Intake Setting 44 = * | Type of Power 45 = D E G H L N W Z * (diesel, electric, gasoline, hand, LP gas, natural gas, windmill, other)

Date 38 = / / * (month day year) | Horsepower 46 = *

MAJOR PUMP DATA (2)

R = 47 * | T = A D M * (add, delete, modify) | Type of Lift 43 # * | Lift Entry No 254 # * | Manufacturer of Pump 48 = *

Serial No of Pump 49 = * | Name of Power Company 50 = *

Power Company Account No 51 = * | Power Meter No 52 = * | Pump Rating 53 = *

Person or Company Who Maintains the Pump 54 = * | Additional Lift 255 = * | Rated Pump Capacity 268 = *

STANDBY POWER DATA (2) (See LIFT DATA for codes of fields 43 and 56 below)

R = 55 * | T = A D M * (add, delete, modify) | Type of Lift 43 # * | Type of Power 56 = * | Horsepower 57 = * | Lift Entry No 254 # *

AVAILABLE LOG DATA (1)

R = 198 * | T = A D M * (add, delete, modify) | New Card for Each Log Type Same R & T

Type of Log ②	Begin Depth	End Depth	Source of Data ①
199 # *	200 = *	201 = *	202 = *
199 # *	200 = *	201 = *	202 = *
199 # *	200 = *	201 = *	202 = *
199 # *	200 = *	201 = *	202 = *

WATER QUALITY DATA COLLECTION (1)

R = 114 * | T = A D M * (add, delete, modify) | Begin Year 115 # * | End Year 116 = * | Source Agency 117 # *

Frequency of Collection ③ 118 = * | Network Site ⑤ 257 # * | Type of Analyses ④ 120 = * | Analyzing Agency 307 = *

WATER LEVEL DATA COLLECTION (1)

R = 121 * | T = A D M * (add, delete, modify) | Begin Year 122 # * | End Year 123 = * | Source Agency 124 # *

Frequency of Collection ③ 125 = * | Network Site ⑤ 258 # *

WATER PUMPAGE/WITHDRAWAL DATA COLLECTION (1)

R = 127 * | T = A D M * (add, delete, modify) | Begin Year 128 # * | End Year 129 = * | Source Agency 130 # *

Frequency of Collection ③ 131 = * | Network Site ⑤ 259 # * | Method of Collection 133 = C E M Z * (calculated, estimated, metered, other)

OTHER DATA AVAILABLE (1)

		Entry Number	Type of Data	Loc	Format
R = 180 *	T = A D M * (add, delete, modify)	312 # *	181 = *	182 = C D R Z * (cooperator, district, reporting agency, other)	261 = F M P Z * (files, machine readable, published, other)
New Card Same R & T		312 # *	181 = *	182 = C D R Z *	261 = F M P Z *

FOOT NOTES:

① Source of Data Codes: A D G L M O R S Z (other, driller, geologist, logs, memory, owner, other gov't, other reported, reporting agency, other)

② Type of Log Codes: A B C D E F G H I J K L M N Ø P Q (time, collar, caliper, driller's, electric, fluid conduct, geologist, magnetic, induction, gamma ray, dipmeter, laterlog, microlog, neutron, μ later, photo, radio-active)

③ Frequency of Collection Codes: A B C D F I M Ø Q S W Z (annual, bi-monthly, continuous, daily, semi monthly, intermittent, monthly, one time only, quarter annual, semi-annual, weekly, other)

④ Type of Quality Analyses Codes: A B C D E F G H I J K L M N Z (physical, common chemical, trace elements, pesticides, nutrients, sanitary, codes B&D, codes B&E, codes B&C, codes B&F, codes D&E, codes C.D&E, all or most, codes B&C & radioactive, other)

⑤ Network Codes: S T U V X Z (sonic, temp, gamma-gamma, fluid velocity, core, other); 1 2 3 4 (national district project cooperator)

Figure 2-47.—Example of a well-schedule form—Continued.

GEOHYDROLOGIC UNIT DESCRIPTIONS (1)

R = 90 * | T = A D M * (add, delete, modify) | Entry No 256 # * | Depth to Top 91 = * | Depth to Bottom 92 = *

93 = * (Unit Identifier) | 304 = * (Contributing Unit) | 96 = * (Lithology) | 97 = * (Lithologic Modifier)

AQUIFER DATA (2)

R = 94 * | T = A D M * (add, delete, modify) | Geohydrologic Unit Entry No 256 # *

Date 95 # / / * (month day year) | Water Level 126 = * | % Water Contributed 132 = *

GEOHYDROLOGIC UNIT DESCRIPTIONS (1)

R = 90 * | T = A D M * (add, delete, modify) | Entry No 256 # * | Depth to Top 91 = * | Depth to Bottom 92 = *

93 = * (Unit Identifier) | 304 = * (Contributing Unit) | 96 = * (Lithology) | 97 = * (Lithologic Modifier)

AQUIFER DATA (2)

R = 94 * | T = A D M * (add, delete, modify) | Geohydrologic Unit Entry No 256 # *

Date 95 # / / * (month day year) | Water Level 126 = * | % Water Contributed 132 = *

PERTINENT REMARKS

R = 183 * | T = A D M * (add, delete, modify) | New Card Same R&T

Remark No. 311 # * | 185 = *

311 # * | 185 = *

① Contributing Unit Codes

P	S	N	U
primary contributing	secondary contributing	non-contributing	unknown

Figure 2-47.—Example of a well-schedule form—Continued.

County :_____ Observation well no._____

Location:_____ Pumped well no. _____

Average Q_____ gpm r =_____ft. r^2 =_____

Date	Hour	t (min)	t′ (min)	t/t′	Depth to water	s (unadjusted)	Adjustment Δs	s′ (adjusted)	Q (gpm)	Remarks

Figure 2-48.—Example of an aquifer test form.

2.H.6.a. WATER LEVELS

Section 2.A. describes the commonly used methods for measuring water levels.

Most type curves relate control to change in head, or drawdown. The changes in depth to water observed during the test may include components due to other variables such as recharge or barometric response. Flow in most aquifers is not steady. It is therefore necessary to observe depths to water for a time before testing to determine the trend of the water level for use in determining drawdowns. A graphical definition of drawdown is illustrated in figure 2–49. Accurate drawdowns can be observed only if water-level trends are accurately forecast, or the response due to testing is large compared to other effects. As a general rule, the period of observation before $t=0$ should be at least twice the length of the pumping test.

In many artesian wells, water levels fluctuate in response to changes of barometric pressure. Such fluctuations may be as large as a foot or more in a few days (Boettcher, 1964, p. N15). If response to pumping is relatively small, test observations should be corrected to remove the barometric effects before comparison with type curves. At all test sites for artesian aquifers, continuous recordings of barometric pressure (to a sensitivity of ± 0.01 inch of mercury) should be made throughout the trend-identification and testing periods. Graphs showing the correlation between the magnitudes of short-term fluctuations in barometric pressure and depth to water observed before the test can be used to correct the water depths measured during the test. Such fluctuations may be seen in the depths to water used for constructing the trend line shown in figure 2–49. Conditions at very few test sites are so stable that the hydrologist need not be concerned about antecedent trends. Therefore, he must always have sufficient background information on water-level fluctuations at the test site to evaluate accuracy of the drawdowns inferred from measurements of depth to water.

Water levels in wells are also affected by other "noise," such as the operation of nearby wells, recharge, earth and ocean tides, and loading of the aquifer by trains and earthquakes. Measurements made before the test will identify the extent to which such effects control the depth to water at the test site. Significant effects due to nearby wells can ordinarily be removed from the data with accuracy if the on-off times of the wells are monitored before and during the test.

Depth to water in all wells should be measured with sufficient frequency that each logarithmic cycle in time on the data plots contains at least 10 data points spread through the cycle. Thus, after $t=0$, depth to water should be measured in each well, at $t=1$, 1.2, 1.5, 2, 2.5, 3, 4, 5, 6, 7, and 8 minutes, approximately, and at all succeeding decimal multiples of these numbers to the end of the test. If the test design indicates that measurable drawdown is not expected at a given observation well for several hours after the test starts, the early measurements may, of course, not be necessary.

During the first 2–3 hours after control is initiated, ideally an observer should be stationed at the control well and each nearby observation well. After $t=300$ minutes, measurements are nearly 2 hours apart, and it becomes a relatively simple task for one observer to "make the rounds." It is not necessary to measure all wells simultaneously, but it is highly desirable to achieve nearly uniform separation of the plotted drawdowns on a logarithmic scale. All watches used should be synchronized before the test is started, and provision should be made to notify all observers at the instant control is initiated.

2.H.6.b. DISCHARGE

For those tests in which discharge is to be held constant throughout the test, it is important to observe the discharge periodically and adjust as needed. Pumps powered by electric motors produce the most constant discharge. Engines, even though equipped with automatic speed control, produce discharge varying as much as 25–50 percent. A continuous vigil on most engine-powered pumps must be maintained if reasonably constant discharge is to be realized, unless automatic control of

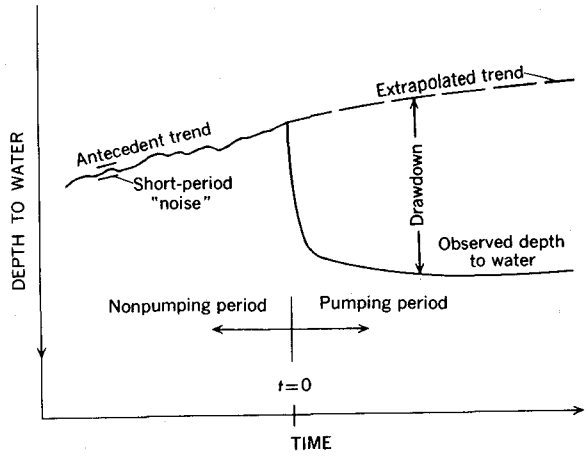

Figure 2-49.—Hydrograph for hypothetical observation well showing definition of drawdown.

discharge is effected by a costly electronic discharge monitor coupled with an electrically driven valve near the wellhead.

If the test requires a step change in discharge, a valve in the discharge line is partly closed before starting the pump. Ideally, discharge (pretest $Q=0$) is measured for the first time within a minute or two after the pump is started. As the water level in the pumped well declines, discharge tends to decrease. Discharge is maintained constant by progressively opening the valve, a procedure tending to keep the total head against the pump constant.

How frequently the discharge needs to be measured and adjusted for a test depends on the pump, well, aquifer, and power characteristics. Output from electrically driven equipment nominally requires measurement, and possibly adjustment, at 5, 10, 20, 30, 60, 120, 240, 480, 720, and 1,440 minutes after the pump is started and daily thereafter. All other pumping equipment requires more frequent attention. No rules can be set because there is a wide variation in equipment response. When there is doubt about control of discharge, the observer should continuously monitor the test until experience indicates drift rates; then measurement frequency can be established accordingly. The discharge rate should never be allowed to vary more than ± 10 percent, if practicable, because such variations produce aberrations in drawdowns that are difficult to treat in data analysis.

Tests can be made on shut-in artesian wells by suddenly opening the well to flow and thereby creating a nearly constant drawdown. Such tests require measurements of discharge at about the same frequency as indicated for drawdown, about 10 measurements per logarithmic cycle in time. The variations in discharge with time can be analyzed by using the type curve of Jacob and Lohman (1952).

2.H.7. DATA ANALYSIS

2.H.7.a. DRAWDOWN CORRECTIONS

Data analysis involves chiefly the transformation of raw field data into calculated values of hydraulic coefficients. The first step is to plot observed depths to water and discharge as a function of time for each observation point. Notes are made on the resulting hydrographs to indicate sources of aberrations in depth to water, and those which might be adjusted are identified. Pretest observations are compared with records of barometric pressure to find whether corrections are needed. The

observations are also examined to determine whether tide-induced or other interference is likely to inject components that affect depths to water, have relatively short duration, and are not related to the test control. The effects of all extraneous factors should be removed from all the data by applicable correlation techniques. Hydrographs are then prepared showing corrected depth to water versus time. Extrapolation of the corrected pretest trend line is then used to determine to what depth water would have occurred at the observation well if there had been no test control (fig. 2–49). For each time of measurement after control is initiated, drawdown is obtained by subtracting the trend value of depth to water from the corrected observed depth to water.

Few type curves account for dewatering of unconfined aquifers. Jacob (1963) showed that if drawdowns observed in thin unconfined aquifers are adjusted by subtracting $s^2/2b$, equations based on assumed negligible dewatering and radial flow can be used for analysis. Where the dewatering adjustment is significant, the data plot used is $s-(s^2/2b)$ and type curves of artesian flow. The value of S is determined by adjusting S' as follows:

$$S=(b-s)\,S'/b, \tag{2–39}$$

where s is the approximate drawdown at the geometric mean radius of all observation wells at the end of pumping. Jacob's correction is based on the Dupurt-Forchheimer assumptions, and thus is most applicable to data from observation wells fully penetrating the aquifer, although the corrections are not inappropriate for piezometers open at a point within the bottom two-thirds of the aquifer. Moreover, the correction is only applicable after the data begin to follow the artesian response curve (Neuman, 1975, p. 334), and would not apply if significant effects of partial penetration exist.

2.H.7.b. TYPE CURVE APPLICATION

After correction of the raw data to eliminate or reduce the amount of extraneous interference, and to adjust for dewatering, the resulting drawdowns are plotted on log paper versus t or t/r^2. If the design and observation phases of the test have been conducted successfully, the adjusted data curve(s) is fitted to the type curve already selected and the hydraulic coefficients are calculated by the matching process shown in figure 2–45.

One of the minor benefits the hydrologist derives from the design and observation phases of aquifer tests is a strong sense of complacency. After all that care, how is it possible the results might be in error? Large errors in interpretation are commonplace where there is uncertainty about the characteristics of the aquifer. Note the type curve (Hantush, 1960) for early times (toward right side of graph) in figure 2–50. The curve $\beta=0$ is for nonleaky artesian aquifers and is identical with the Theis-type curve.

Increasing β is associated with increasing contribution to flow from permeable confining beds. It is easily seen that if the Theis-type curve is applied to data without discrimination, errors in T may easily be as much as an order of magnitude, while the computed value of S can be in greater error if the confining beds are permeable.

An example of a match of multiple observation-well data to the Hantush (1960) type curves is shown in figure 2–51. This test, performed on a well near Houston, Texas, is an area where significant subsidence has been induced by ground-water withdrawal, and thus almost undoubtedly should fit the Hantush (1960) curves. Note that differences in positions of the data curves are in the right direction to indicate the effects of confining-bed storage, but their departures from the Theis curve are too small to be totally convincing. Nonetheless, selection of the best-matching β curve values,

the appropriate r values for the observation wells, and an estimates of S'_s results in a hydraulic conductivity of the confining layer comparable to that used in modeling the Houston aquifer (Jorgenson, 1975). Nonetheless, the lack of clear definition of the effects of confining-bed leakage in the data response curves suggests that an observation piezometer in the confining layer would have been desirable in order to apply the Neuman-Witherspoon (1972) ratio method.

2.H.7.c. UNCONFINED AQUIFERS

Tests of unconfined aquifers, involving a more complex set of boundary conditions, offer greater prospect for complacency than do tests on artesian systems. To illustrate, we will consider a set of data from a pumping test made on an unconfined aquifer near Lamar, Colo. This test was analyzed using response curves developed from an electric analog model by Stallman (1965). The response curves are based on the assumptions that internal storage within the aquifer is negligible. Although recent work (Neuman, 1972, 1974) has shown that internal storage generally is significant, the curves for which internal storage is ignored approach those for which it is considered, as well as the "late time" curves for Boulton's (1954) delayed yield equation, as time becomes large. Thus, use of Stallman's curves with the late time data should be appropriate.

The control well fully penetrated a thin alluvial fill and had a total depth of 49 feet below the land surface; the casing diameter was 16 inches. Observation wells of 1¼ inch steel pipe were driven to selected depths at selected radii (fig. 2–52). The water table was about 11 feet below the land surface at the test site.

Depths to water were measured by tape, and discharge was disposed of in a ditch, where it was observed by stream-gaging methods. The control well was pumped at the rate of 2,000 gpm for about 3 days beginning at 0900 hours, April 14, 1964. The pump was powered by an electric motor, and discharge was constant within ±5 percent throughout the test.

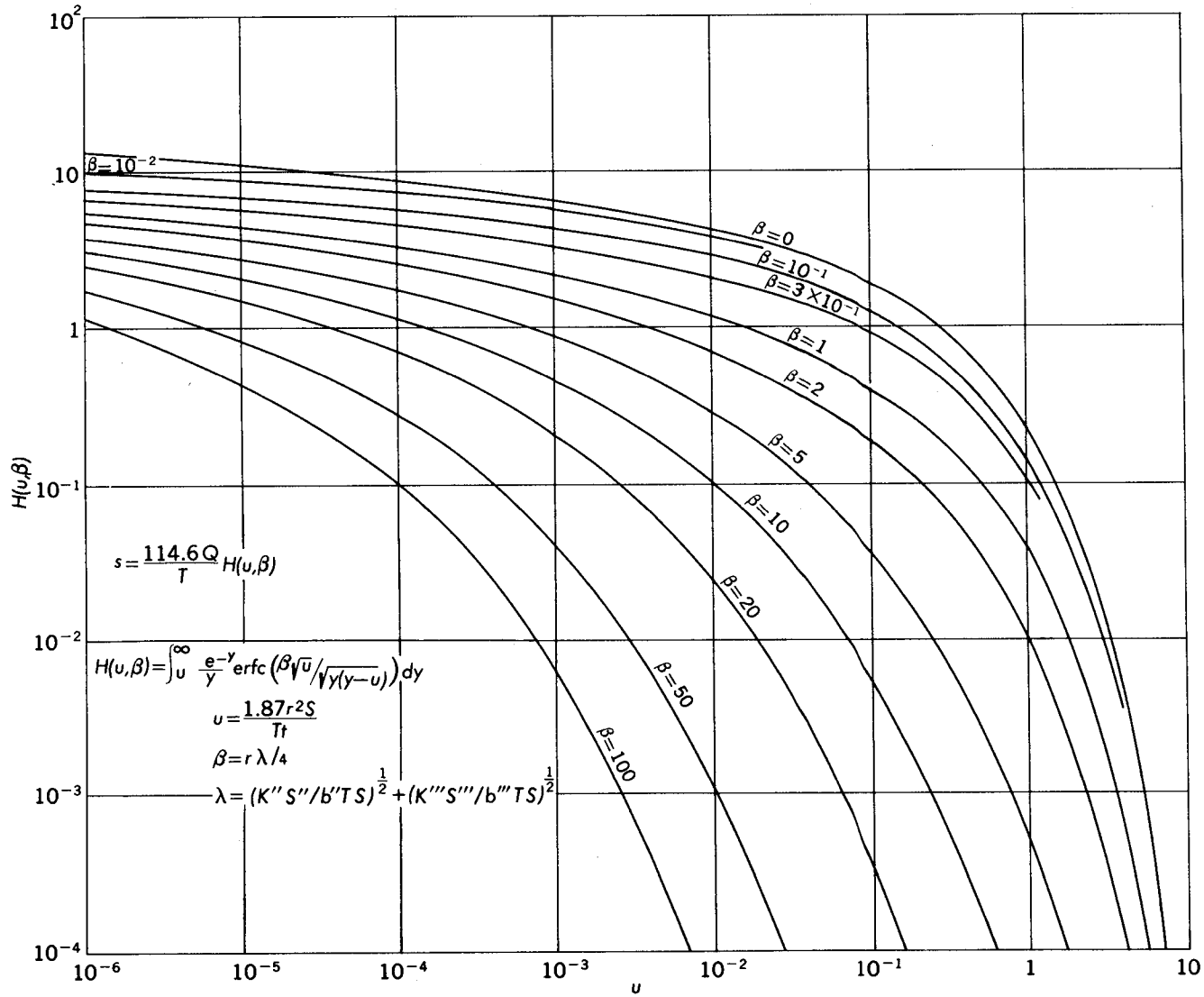

Figure 2-50.—Logarithmic graph of the function H (u, β).

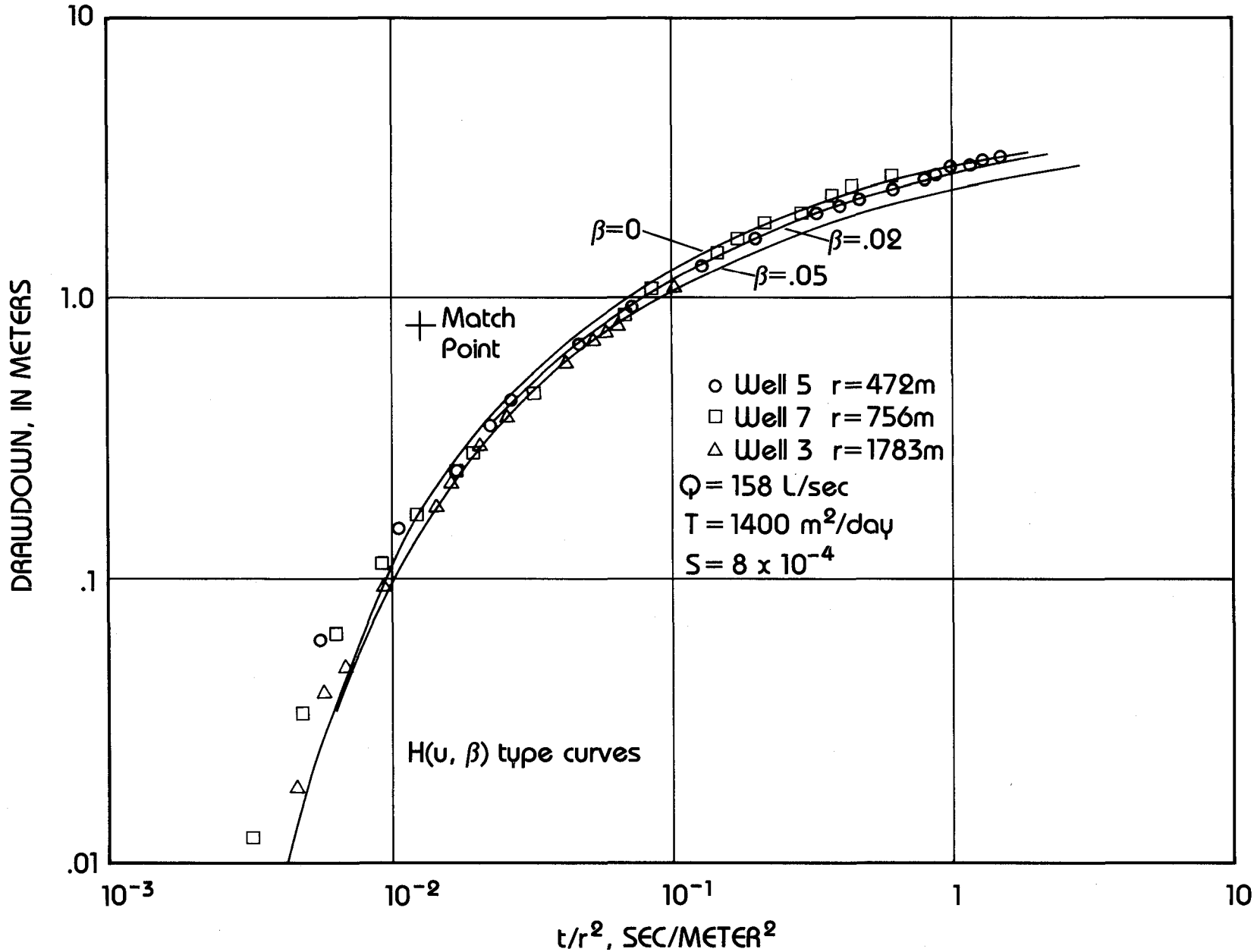

Figure 2-51.—Graph showing match of drawdown data for three observation wells.

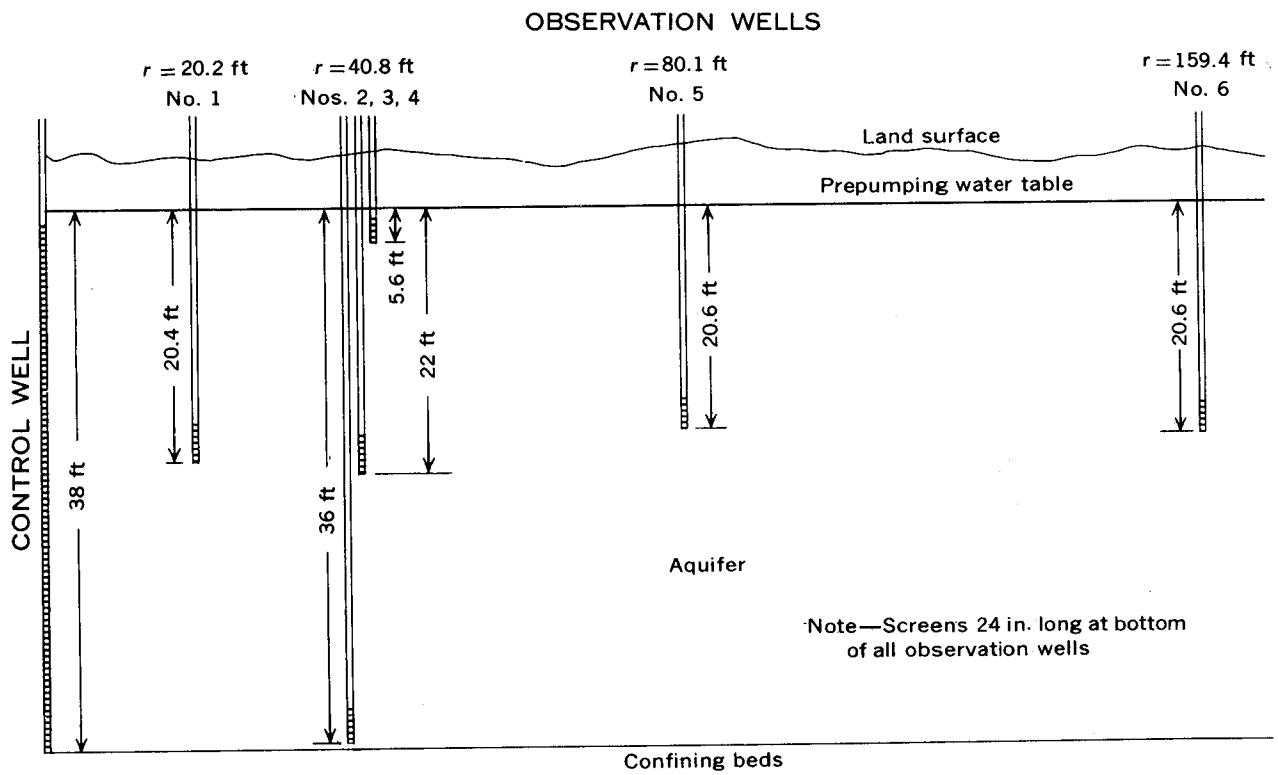

Figure 2-52.—Section through Nevius test site, near Lamar, Colo., showing radii to and depths of observation wells (not to scale).

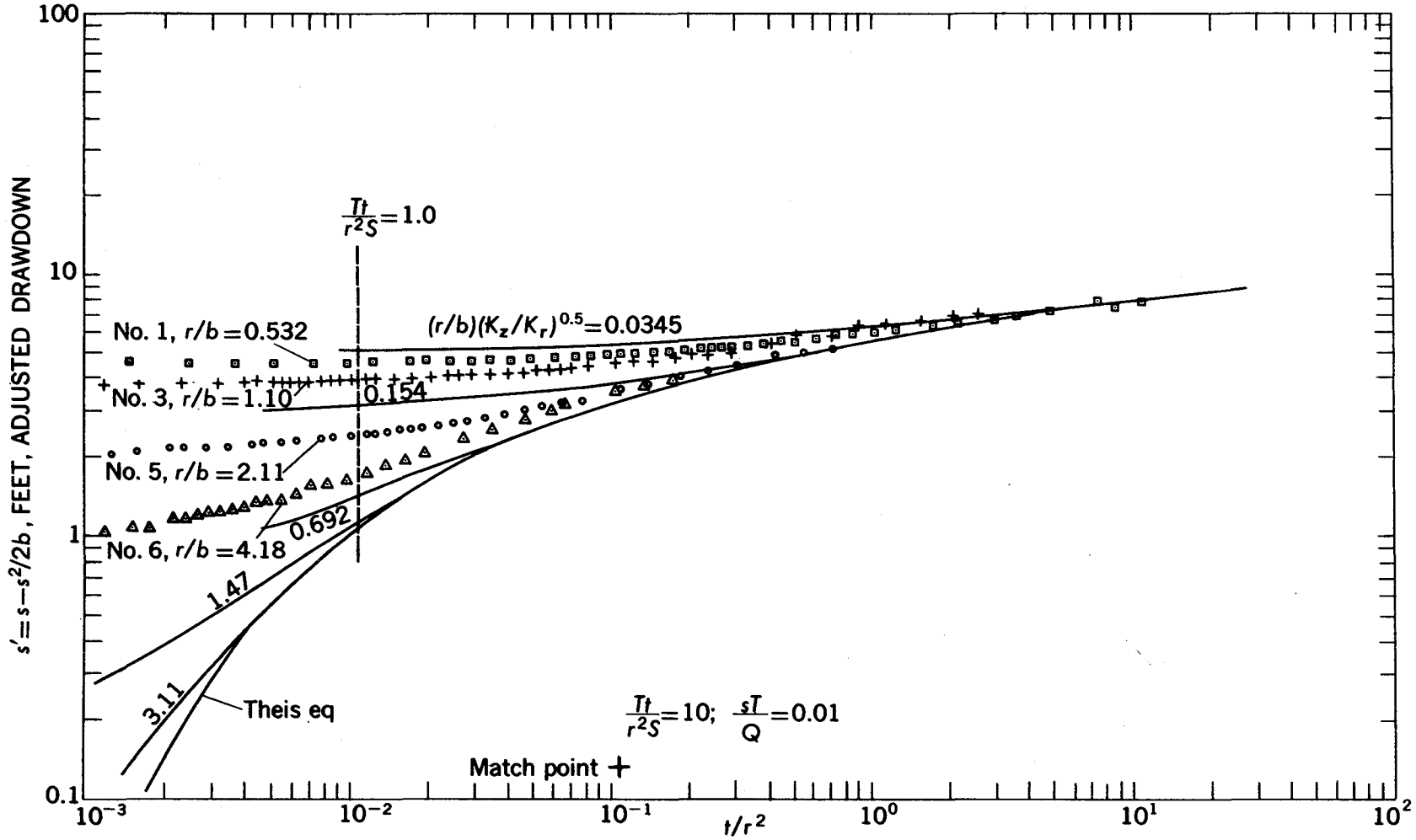

Figure 2-53.—Data from wells screened in middepths of aquifer at Nevius test site, showing-type curve match. Type curves from Stallmaan (1965, p. 305, fig. 100).

Graphs of s versus t/r^2 from wells, 1, 3, 5, and 6 are shown in figure 2-53. Because observed drawdowns (9 ft) were large compared with saturated thickness (38 ft), field data were corrected for dewatering (Jacob, 1963). The data were matched to type curves (solid lines) for the middepth of the aquifer (Stallman, 1965, p. 305, fig. 10D). Note that data to the right in figure 2-53 form a flat slope, difficult to match with the Theis-type curve for an accurate indication of S. Visual fitting of the type curves produces values of S lying between 0.15 and 0.25. Nuclear-meter measurements of specific yield (Stallman, 1967, fig. 11) show that $S=0.184$ at a nearby location. The match point in figure 2-53 was selected by trial and error so that S' would equal 0.22. This value of S' was determined by using equation 2-39 to adjust for dewatering, as follows:

$$S' = 0.184 \times 38/(38-6) = 0.22$$

At the final match point, $Tt/r^2S=10$, $t/r^2=1.07\times10^{-1}$ min/ft², $sT/Q=0.01$, and $s=0.13$ ft, from which $T=3\times10^4$ ft²/d, $S'=0.22$, and $S=0.185$.

Rather than attempt to determine K_z/K_r directly from figure 2-53, it is convenient to draw an auxiliary type curve and a recast data curve showing the relations sT/Q versus r/b from the data and sT/Q versus $(r/b)\ (K_z/K_r)^{1/2}$ on log scales. The matching process using the auxiliary type curve should provide an estimate of K_z/K_r. Values of sT/Q taken from the type curves (Stallman, 1965, p. 305, fig. 10D) where $Tt/r^2S=1.0$ are shown versus r/b in figure 2-54. Values of sT/Q at $Tt/r^2S=1.0$ are shown as a function of $(r/b)\ (K_z/K_r)^{1/2}$ in figure 2-55. Match point A, where $r/b=1.0$ and $(r/b)\ (K_z/K_r)^{1/2}=0.08$, in figure 2-55 was obtained with the data of figure 2-54. This indicates

$$(r/b)\ (K_z/K_r)^{1/2} = 0.08 = 1.0\ (K_z/K_r)^{1/2},$$

and therefore

$$(K_z/K_r) = 0.0064.$$

If $T=3\times10^4$ ft²/d, then $K_r=790$ ft/d and $K_z=5.2$ ft/d. This value is somewhat smaller than that of 15 to 40 ft/day derived by analysis of data from the unsaturated zone at the site (Stallman and Reed, 1968). Possibly one or more relatively thin low-permeability layers exist between the water table and the screened interval, accounting for this apparent discrepancy.

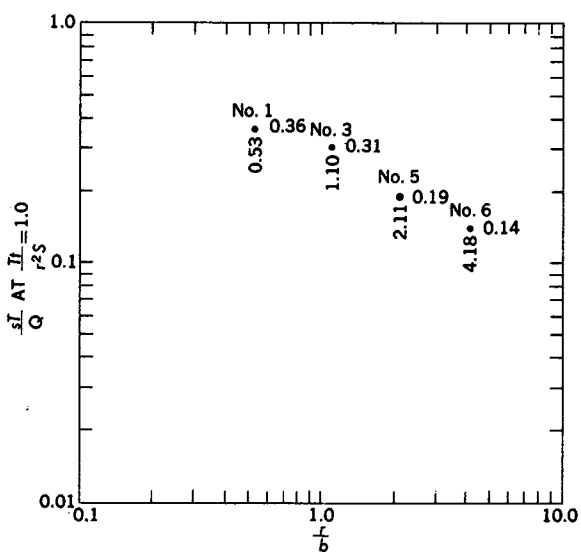

Figure 2-54.—Dimensionless drawdowns from Nevius test data at $Tt/r^2S=1.0$ as a function of r/b.

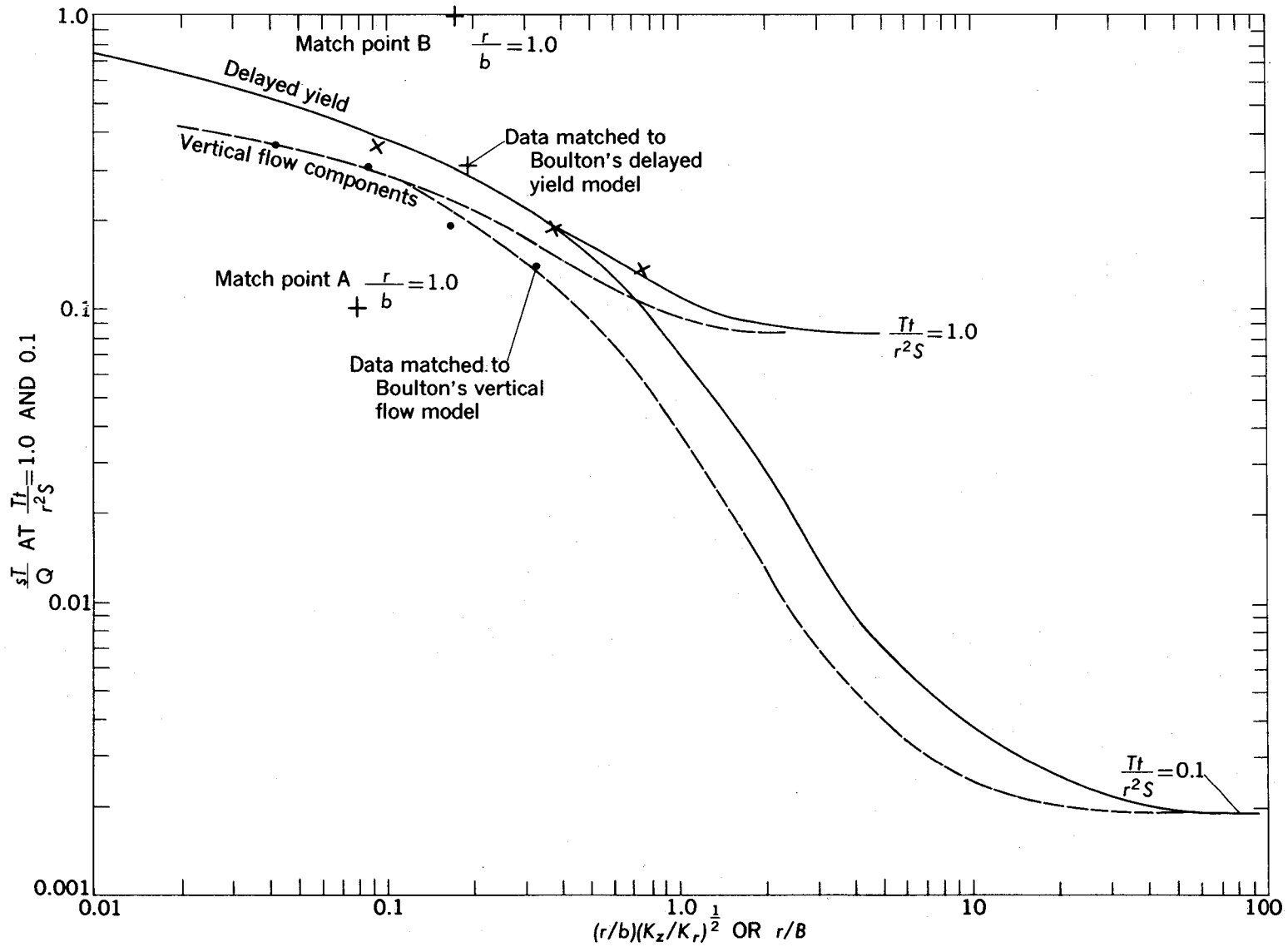

Figure 2-55.—Auxiliary type curves from Boulton's (1963) models, showing fit to Nevius data.

The match of the data for the Nevius test to the analog-generated response curves is good. However, part of the ability to obtain such a match results from the fact that the test had been run long enough that the data began to follow the Theis curve. Had the test been shorter, it would have been difficult to obtain a convincing match. Hence, although a great deal of recent theoretical work is available on unconfined aquifer response to pumping, it is still desirable to conduct the test long enough that the artesian response functions apply, if possible.

2.H.8. CONCLUDING REMARKS

A great many analytical equations have been derived to describe drawdown response due to pumpage from aquifers under a variety of geohydrologic, well construction, and production conditions. It is important to be aware of the scope of available solutions in order to plan and design aquifer tests to be able to get full and accurate information on hydraulic properties at the test site. In addition, the use of digital radial flow models to develop response curves for those geohydrologic conditions for which analytical equations are not available or have not been evaluated should be considered.

Careful planning and design, based upon site investigation and pretest prediction, are essential in performing successful aquifer tests. The importance of identifying the geohydrologic situation during the site investigation cannot be overemphasized, because the theoretical response curves for different conditions tend to be similar in shape. Thus, use of the shape of the data response curve to identify the geohydrologic model applicable to the test site could be very misleading and result in erroneous conclusions. Pretest prediction, based on estimates of the hydraulic properties of the aquifer and the adjacent confining beds, is also important for successful aquifer-test design. Such predictions can indicate the need for additional observation wells, their location, and the duration necessary for a successful test.

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Chapter 3

Sediment

CHAPTER 3 — SEDIMENT

Prepared by
Work Group 3 on Sediment

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CHAPTER 3—SEDIMENT

3.A. INTRODUCTION

This chapter deals with both moving sediment and deposited sediment. The methods recommended cover samplers and sampling procedures, handling and preserving samples, analyzing samples in the laboratory, measuring turbidity[1], surveying reservoirs, measuring channel morphology, and controlling the quality of these measurements. The recommended methods are based on considerations of the effects of sediment characteristics and temporal variations and their relations to different environments, including land surface; streams; lakes, reservoirs, and ponds; estuaries; and conduits and outfalls. Methods for use in the ocean environment are not included.

Many activities related to the conservation, development, and utilization of land, mineral, and water resources either increase or decrease the rate of sediment movement, thereby causing a variety of sediment-related problems. For example, a change in the runoff regime from a drainage basin may concentrate or disperse sediment in the stream channel, and in turn, affect the flow capacity of the stream. Because of the complex interrelationships that affect sediment erosion, transport, and deposition, a knowledge of climate, physical attributes of drainage basins, hydraulic and hydrologic characteristics of streamflow, and quantitative and qualitative aspects of sediment are all required to solve sediment problems.

Some people might think that the solution to most sediment problems is to stop landscape and channel erosion. This is not only impossible, but also would destroy the natural balance and allow new problems to emerge. Erosion and sediment deposition should be controlled to fit the situation. For example, intensive sediment movement (perhaps 100 t/ha/yr) from a small construction site may be tolerated for a few weeks, especially if the sediment is deposited before it reaches a stream; but a small amount of topsoil (perhaps 1 t/ha/yr) from cropland with adsorbed herbicides may be intolerable if it reaches a stream.

Experience gained over the years has led to greater understanding and appreciation of sediment problems; however, recent lawsuits (Busby, 1961, 1967; ASCE, 1975, p. 629–674) attest to the fact that man's activity still causes detrimental environmental changes resulting from fluvial

[1] Turbidity is generally accepted as a nontechnical qualitative descriptor.

sediment transport. Life scientists are becoming more aware of the effect that sediment has on algal growth and higher forms of marine life.

Numerous direct and indirect effects of sedimentation have been recorded (Livesey, 1970). For example, bottom sediments contaminated by industrial or municipal wastes may be dispersed by dredging operations (U.S. Federal Water Pollution Control Administration, 1969, p. 56) and enter the food chain through fish and other aquatic life. Many references show that pesticides and radionuclides can be absorbed on bottom sediments in rivers. Toffaleti (1969) has demonstrated the need for including bottom sediments in mathematical models of waste transport.

Water-related sediment problems vary widely. For example, problems range from relatively minor overnight erosion of a garden plot to long-term deposition at the delta of a major river. Most problems range from short-term impacts on small streams where sediments are eroded from cropland or construction sites during rainstorms, to long-term impacts on large streams where sediments degrade aesthetics, interfere with stream-channel capacity or reservoir capacity, and cause unwanted deposition of sorbed pollutants. Although visual inspections may help, solving a sediment problem usually requires measuring the quantitative and qualitative character of sediments suspended in, transported by, and deposited from natural and manmade streams and water bodies.

Glymph (1975) states that we have recently realized that sediment can be as much a pollutant as are industrial wastes and effluents from sewage treatment plants. Rutherford (1976) has posed the question: How much longer can the strained soil colloids near commercial, industrial, and other waste-producing areas continue to extract and store pollutants through ionic exchange before they become totally clogged, and how fast are these soils becoming unwanted sediments in nearby water bodies? More sophistication is required to determine sediment yields and sediment properties in small basins to be used as a basis for cost-effective sediment and pollution management programs.

Modeling experts have made progress (*see* table 3-1), although sometimes producing conflicting results, in outlining predictive equations in sedimentation (Fleming, 1975; Negev, 1967; Meyer and Wischmeier, 1969; Bennett, 1974). However, the development of a complete set of equations appears to be only remotely possible. Therefore, numerical simulation techniques using current and pertinent basic data offer the most practical way to predict specific fluvial-sediment phenomena. Fleming and Leytham (1976, p. 1–244) conclude that, "The widespread practical applications of conceptual sediment models would appear to be limited by serious shortages of basic data".

Because sediment movement is affected by the ever-changing environment, measurements for sediment quantity and characteristics which can be correlated with the environmental changes will be increasingly important. Sediment data are also needed to verify the effectiveness of sediment control measures. Most sediment measurements are made to satisfy one of three general program objectives:

1. To obtain general information from a network of sediment-measuring stations which provide unbiased, comprehensive information about sediment movement in streams.
2. To obtain special information relative to specific problems so water managers can better choose among alternative actions.
3. To disclose and describe process relationships between water, sediment, and environment.

Table 3-1.—*Examples of models for sediment processes (after Fleming, 1975)*

Process	Empirical/component method	Conceptual simulation	Statistical		
			Regression/correlation	Probabilistic	Stochastic
Erosion	Horton, sheet-erosion equation. ARS, universal soil-loss equation. Musgrave, soil-loss equation. Ellison, soil-splash equation. Dragoun, sheet-erosion equation.	Negev, sediment-erosion-transport model. ARS upland erosion model. Hydrocomp, simulation programing.	Anderson, sediment-yield equation. Fleming, suspended-load design curves. SCS, gully erosion equation. Beer and Johnson, gully growth equation. Thompson, gully advance equation.	Frequency analysis of sediment-yield transport and deposition.	
Transport	Schulits, computer programs for bedload formulas. Du Boys, transport formula. Einstein, bedload function. Colby, modified Einstein method. Blench, regime equation. Laursen, transport theory. Inglis-Lacey, transport formula. Toffaleti, transport formula.		Sediment-rating curves.		Random generation of sediment data. Sakhan, Riley, and Renard, simulation of sediment transport with stochastic transfer at the streambed.
Deposition	Fall velocity theory. Sediment suspension/deposition theory. Density current theory. Ackerman and Corinth, reservoir sedimentation equation.	Thomas, U.S. Army Corps of Engineers reservoir sedimentation model. (Also simulates transport.)	Farnham, Beer, and Heinemann, regression analysis of reservoir sedimentation. Stall and Bartelli, correlation of reservoir sedimentation and watershed factors.	Einstein, bedload function.	

When sediment data are suitable for multiple use, they should be cataloged and made available to potential users. In the past most data findings were published in reports, but today most data are stored in computers which users can access to select the specific data they need. In addition to computer storage, data summaries should be published every 3 to 5 years to facilitate program review and to provide a library for users who do not have access to computers.

Because of the variety of groups and disciplines involved in sediment sampling and the different purposes for sampling, equipment and techniques of measurement have proliferated. These recommendations are intended to provide a better understanding of the essential requisites for valid sampling and data-collection programs in which sediment is one of the constitutents. They are also intended to promote the use of suitable standardized equipment to improve sediment data accuracy and to provide data that are comparable from one source to another.

3.B. GLOSSARY

The following definitions are given to help achieve a uniform understanding of the methods recommended for sediment data acquisition. The definitions have been adapted from recommendations being prepared for the American Society of Testing and Materials, and they agree closely with similar definitions presented in publications such as the American Geological Institute (1972), the Soil Conservation Society of America (1976), and the U.S. Inter-Agency Reports (1957A), (1963).

Accelerated erosion. Erosion at a rate greater than normal, usually associated with activities of man which reduce plant cover and increase runoff. (*See* geologic erosion.)

Aggradation. The geologic process by which stream beds, flood plains, and the bottoms of other water bodies are raised in elevation by the deposition of material eroded and transported from other areas. It is the opposite of degradation.

Aliquot. A fractional part representative of the whole.

Alluvial. Pertains to alluvium deposited by a stream or flowing water.

Alluvial channel. See alluvial stream.

Alluvial deposit. Clay, silt, sand, gravel, or other sediment deposited by the action of running or receding water.

Alluvial stream. A stream whose channel boundary is composed of appreciable quantities of the sediments transported by the flow, and which generally changes its bed forms as the rate of flow changes.

Alluvium. A general term for all detrital deposits resulting directly or indirectly from the sediment transport of (modern) streams, thus including the sediments laid down in riverbeds, flood plains, lakes, fans, and estuaries.

Antidunes. A series of generally sinusoidal-shaped bed forms that commonly move upstream accompanied by in-phase waves on the water surface. Antidunes develop in a sand-bed stream when the Froude number is close to or greater than one.

Armoring. The formation of a resistant layer of relatively large particles resulting from removal of finer particles by erosion.

Bedload. Material moving on or near the stream bed by rolling, sliding, and sometimes making brief excursions into the flow a few diameters above the bed.

Bedload discharge. The quantity of bedload passing a transect in a unit of time.

Bedload sampler. A device for sampling the bedload.

Bed material. The sediment mixture of which the bed is composed. In alluvial streams bed-material particles are likely to be moved at any moment or during some future flow condition.

Bed-material sampler. A device for sampling bed material.

Bottomset bed. Fine-grained material (usually silts and clays) slowly deposited on the bed of a quiescent body of water and which may in time be buried by foreset beds and topset beds.

Boulder. See table 3-2, p. 3-9.

Channel. A natural or artificial waterway which periodically or continuously contains moving water.

Clay. See table 3-2, p. 3-9.

Coagulation. The agglomeration of colloidal or finely divided suspended matter, generally caused by the addition of a chemical coagulent.

Cobbles. See table 3-2, p. 3-9.

Cohesive sediments. Sediments whose resistance to initial movement or erosion is affected mostly by cohesive bonds between particles.

Colloids. Finely divided solids which do not settle in a liquid but which may be coagulated chemically or biochemically. (*See* table 3-2, p. 3-9.)

Composite sample. A sample formed by combining two or more individual samples, or representative portions thereof.

Concentration of sediment (by mass). The ratio of the mass of dry sediment in a water-sediment mixture to the mass of the mixture. This concentration when determined on a mass basis as parts per million may be converted to grams per cubic meter on the basis of table 3-7, page 3-89.

Degradation. The geologic process by which stream beds, flood plains, and the bottoms of other water bodies are lowered in elevation by the removal of material from the boundary. It is the opposite of aggradation.

Delta. A deposit of sediment formed where moving water (as from a stream at its mouth) is slowed by a body of standing water.

Density. The mass of a substance per unit volume, ρ in kg/L or Mg/m^3. Use ρ_s for density of solid particles, ρ_w for water, ρ_d for dry sediment with voids, ρ_{sat} for saturated sediment, ρ_{wet} for wet sediment, and ρ_b for submerged sediment (bouyant weight).

Density current. A highly turbid and relatively dense current which usually moves along the bottom of a body of standing water.

Deposition. The mechanical or chemical processes through which sediments accumulate in a resting place.

Depth-integrated sample. A discharge-weighted (velocity-weighted) sample of water-sediment mixture collected at one or more verticals in accordance with the technique of depth integration. The discharge of any property of the sample expressible as a concentration can be obtained as the product of the concentration and the water discharge represented by the sample.

Depth integrating, suspended-sediment sampler. An instrument capable of collecting a water-sediment mixture isokinetically as its intake is traversed across the flow: hence, a sampler suitable for performing depth integration.

Depth-integration. A method of sampling at every point throughout the sampled depth whereby a water-sediment mixture is collected so that the contribution to the sample from each point is proportional to the stream velocity at the point. This yields a discharge-weighted sample. Ordinarily, depth integration is performed by traversing either a depth- or point-integrating sampler vertically at an acceptably slow constant rate; however, depth integration can also be accomplished with vertical-slot samplers.

Diameter, standard fall. See standard fall diameter.

Diameter, standard sediment. See standard sedimentation diameter.

Discharge-weighted concentration. The dry mass (weight) of sediment in a unit volume of stream discharge, or the ratio of the mass discharge (dry) of sediment to the mass discharge of water-sediment mixture.

Disperse. To deflocculate or disaggregate compound particles, such as aggregates, into individual component particles (ultimate particles).

Dispersed system. A condition in particle-size analyses whereby particles begin to settle from an initial uniform dispersion, such that particles of equivalent fall diameters settle at the same rate.

Dissolved load. The part of the stream load that is carried in solution, such as chemical ions yielded by weathering and erosion of the land mass.

Dissolved solids. The mass of dissolved constituents in water determined by evaporating a sample to dryness, heating to 103–105°C for two hours, desiccating, and weighing.

Drainage basin. The area tributary to or draining to a lake, stream, or measuring site. (*See* watershed.)

Dunes. Bed forms with a triangular profile that advance downstream due to net deposition of particles on the steep downstream slope. Dunes move downstream at velocities that are small relative to the streamflow velocity.

Equal-discharge-increment (EDI) method. A procedure for obtaining the discharge-weighted suspended-sediment concentration of flow at a transect by: (1) performing depth integration at

the centers of equal-flow segments across the transect, and by (2) using a vertical transit rate at each sampling vertical that provides equal sample volumes from all flow segments.

Equal transit rate. Obsolete, replaced by the term "equal-width increment."

Equal-width-increment (EWI) method. A procedure for obtaining the discharge-weighted suspended-sediment concentration of flow at a transect by: (1) performing depth integration at a series of verticals equally spaced across the transect, and by (2) using the same vertical transit rate at all sampling verticals.

Erosion. The wearing away of the land surface by detachment and movement of soil and rock fragments through the action of moving water and other geological agents.

Fall velocity. The falling or settling rate of a particle in a given medium.

Filtrate. The fluid that has passed through a filter.

Filtration. The process of passing a liquid through a filter to remove suspended matter that usually cannot be removed by settling. The filter may consist of granular material such as sand, magnetite, or diatomaceous earth; finely woven cloth, unglazed procelain, or specially prepared paper.

Fine material. Particles of a size finer than the particles present in appreciable quantities in the bed material; normally silt and clay particles (particles finer than 0.062 mm).

Fine-material load. That part of the total sediment load that is composed of particles fo a finer size than the particles present in appreciable quantities in the bed material. Normally, the fine-material load consists of material finer than 0.062 mm.

Flocculant. An agent that produces flocs or aggregates from small suspended particles.

Flocculation agent. A coagulating substance which, when added to water, forms a flocculant precipitate that will entrain suspended matter and expedite settling; for example, alum, ferrous sulphate, or lime.

Fluvial. (1) Pertaining to streams. (2) Growing or living in streams or ponds. (3) Produced by river action, as a fluvial plain.

Fluvial sediment. Particles derived from rocks or biological materials which are transported by, suspended in, or deposited by streams.

Foreset bed. Inclined layers of sandy material deposited upon or along an advancing and relatively steep frontal slope. A foreset bed progressively covers a bottomset bed, and in turn is covered by a topset bed.

Froude number. A dimensionless number expressing the ratio between influence of inertia and gravity in a fluid. It is the velocity squared divided by length times the acceleration due to gravity.

Gaging station. A selected cross section of a stream channel where one or more variables are measured continuously or periodically to index discharge and other parameters.

Geologic erosion. The erosion process on a given land form that is not associated with the activities of man.

Grading. Degree of mixing of size classes in sedimentary material: Well graded implies a more or less uniform distribution from coarse to fine; poorly graded implies uniformity in size of lack of continuous distribution.

Gravel. See table 3-2, p. 3-9.

Gross erosion. The total of all sheet, gully, and channel erosion in a drainage basin, usually expressed in units of mass.

Instantaneous sampler. A suspended-sediment sampler that instantaneously traps a sample of the water-sediment mixture in a stream at a desired depth.

Isokinetic sampling. To sample in such a way that the water-sediment mixture moves with no acceleration as it leaves the ambient flow and enters the sampler intake.

Measured sediment discharge. The quantity of sediment passing a stream transect in a unit of time that is computed with information derived from sampling. Sampling with suspended-sediment samplers makes the measured sediment discharge the same as the *measured suspended-sediment*

discharge. This is computed as the product of: (1) the discharge-weighted concentration from the suspended-sediment samples, (2) the total water discharge through the transect, and (3) an appropriate units-conversion constant. Thus, measured suspended-sediment discharge for the transect includes all of the suspended sediment moving in the sampled zone, but only part of the suspended sediment moving in the unsampled zone whenever spatial concentrations in the sampled and unsampled zones are different (a concentration gradient exists).

Median diameter. The size of sediment such that one half of the mass of the material is composed of particles larger than the median diameter, and the other half is composed of particles smaller than the median diameter.

Nephelometer. An instrument that measures the amount of light scattered in a suspension.

Native water. Water from a water body that has been unaffected by sampling, handling, and preservation.

Noncohesive sediments. Sediments consisting of discrete particles. For given erosive forces, the movement of such particles depends only on the properties of shape, size, and density, and on the position of the particle with respect to surrounding particles.

Optical opacity. An expression for the amount of light absorbed and scattered by a suspension reported as: (1) extinction coefficient, (2) percent of incident light scattered in 90°, and/or (3) percent of incident light transmitted at 180° over a standard distance.

Particle size. A linear dimension, usually designated as "diameter," used to characterize the size of a particle. The dimension may be determined by any of several different techniques, including sedimentation, sieving, micrometric measurement, or direct measurement. (*See* table 3-2, p. 3-9).

Particle-size distribution. The frequency distribution of the relative amounts of particles in a sample that are within specified size ranges, or a cumulative frequency distribution of the relative amounts of particles coarser or finer than specified sizes. Relative amounts are usually expressed as percentages by mass.

Particle-size, intermediate axis. The size of a rock or sediment particle determined by direct measurement of the axis normal to a plane representing the longest and shortest axes.

Plane bed. A sedimentary bed without elevations or depressions larger than the maximum size of the bed material.

Point-integrating sediment sampler. An instrument capable of collecting a water-sediment mixture isokinetically for a specified period of time by opening and closing while under water. An instrument suitable for performing point integration.

Point-integrated sample (point sample). A sample of water-sediment mixture collected at a relatively fixed point in accordance with the technique of point integration. A point-integrated sample is discharge weighted. However, because the sample is obtained from a single point, the concentration of any component of the mixture that is transported exactly at stream velocity can be considered as either a spatial or a discharge-weighted concentration. Samples collected with instruments that instantaneously capture a quantity of water-sediment mixture are not true point-integrated samples.

Point integration. A method of sampling at a relatively fixed point whereby the water-sediment mixture is withdrawn isokinetically for a specified period of time.

Pollution. The condition caused by the presence of substances of such character and in such quantities that the quality of the environment is impaired. (*See* water pollution.)

Pumping sampler. A sampler with which the water-sediment mixture is withdrawn through a pipe or hose, the intake of which is placed at the desired sampling point.

Reservoir. An impounded body of water or controlled lake where water is collected and stored.

Residue. Material that remains after gases, liquids, or solids have been removed.

Rill erosion. Land erosion forming small, well-defined incisions in the land surface less than 30 cm in depth.

Ripple. Small triangular-shaped bed forms that are similar to dunes but have much smaller heights and lengths of 0.3 m or less. They develop when the Froude number is less than approximately 0.3.

Runoff. Flow that is discharged from the area by stream channels—sometimes subdivided into surface runoff, ground-water runoff, and seepage.

Sampled zone. That part of a transect presumed to be wholly represented by sediment samples.

Sampling vertical. An approximately vertical path from the water surface to the bottom along which one or more samples are collected to define various properties of the flow, such as sediment concentration.

Sand. See table 3-2.

Scale of particle sizes. The scale recommended is essentially that prepared by Lane (1947), for the Sub-Committee on Sediment Terminology, AGU. (*See* table 3-2.)

Scour. The enlargement of a flow section by the removal of boundary material through the action of the fluid in motion.

Sediment. (1) Particles derived from rocks or biological materials that have been transported by a fluid. (2) Solid material (sludges) suspended in or settled from water.

Sedimentation. A broad term that pertains to the five fundamental processes responsible for the formation of sedimentary rocks: (1) weathering, (2) detachment, (3) transportation, (4) deposition (sedimentation), and (5) diagenesis; and to the gravitational setting of suspended particles that are heavier than water.

Sediment delivery ratio. The ratio of sediment yield to gross erosion expressed in percent.

Table 3-2.—*Scale of particle sizes for sediment*

Class name	*Millimeters*	*Micrometers*	*Phi value*
Boulders	>256	.....	<-8
Cobbles	256 – 64	.....	-8 to -6
Gravel	64 – 2	.....	-6 to -1
Very coarse sand	2.0 – 1.0	2,000 – 1,000	-1 to 0
Coarse sand	1.0 – 0.50	1,000 – 500	0 to +1
Medium sand	0.50 – 0.25	500 – 250	+1 to +2
Fine sand	0.25 – 0.125	250 – 125	+2 to +3
Very fine sand	0.125 – 0.062	125 – 62	+3 to +4
Coarse silt	0.062 – 0.031	62 – 31	+4 to +5
Medium silt	0.031 – 0.016	31 – 16	+5 to +6
Fine silt	0.016 – 0.008	16 – 8	+6 to +7
Very fine silt	0.008 – 0.004	8 – 4	+7 to +8
Coarse clay	0.004 – 0.0020	4 – 2	+8 to +9
Medium clay	0.0020 – 0.0010	2 – 1	+9 to +10
Fine clay	0.0010 – 0.0005	1 – 0.5	+10 to +11
Very fine clay	0.0005 – 0.00024	0.5 – 0.24	+11 to +12
Colloids	<0.00024	<0.24	>+12

Sediment discharge. The mass or volume of sediment (usually mass) passing a stream transect in a unit of time. The term may be qualified, for example, as suspended-sediment discharge, bedload discharge, or total-sediment discharge.

Sediment load. A general term that refers to material in suspension and/or in transport. It is not synonymous with either discharge or concentration. (*See* bedload and suspended load.)

Sedimentology. The scientific study of sediment, sedimentary rocks, and the processes by which they are formed—more specifically for this report, it is a study of detachment, transport, and deposition of sediment particles in streams and other water bodies.

Sediment particle. Fragments of mineral or organic material in either a singular or aggregate state.

Sediment production. An unacceptable term. Use erosion. (*See* sediment yield.)

Sediment sample. A quantity of water-sediment mixture or deposited sediment that is collected to characterize some property or properties of the sampled medium.

Sediment transport (rate). See sediment discharge.

Sediment yield. The total sediment outflow from a drainage basin in a specific period of time. It includes bedload as well as suspended load, and usually is expressed in terms of mass, or volume per unit of time.

Settling. The downward movement of suspended-sediment particles.

Sheet erosion. The more or less uniform removal of soil from an area by raindrop splash and overland flow without the development of water channels. Included with sheet erosion, however, are the numerous, conspicuous small rills that are caused by minor concentrations of runoff.

Sieve diameter. The smallest standard sieve opening size through which a given particle of sediment will pass.

Silt. See table 3-2, p. 3-9.

Siltation. An unacceptable term. Use sediment deposition, sediment discharge, or sediment yield as appropriate.

Soil. Unconsolidated mineral and organic surface material that has been sufficiently modified and acted upon by physical, chemical, and biological agents so that it will support plant growth.

Spatial concentration. The dry mass of sediment in a unit volume of water-sediment mixture in place.

Specific gravity. Ratio of the mass of any volume of a substance to the mass of an equal volume of water at 4°C.

Split sample. A single sample separated into two or more individual parts in a manner that each part is representative of the original sample.

Standard fall diameter. Sometimes simply fall diameter. The diameter of a sphere that has a specific gravity of 2.65 and has the same standard fall velocity as the particle.

Standard fall velocity. The average rate of fall that a particle would finally attain if falling alone in quiescent distilled water of infinite extent at a temperature of 24°C.

Standard sedimentation diameter. The diameter of a sphere that has the same specific gravity and the same standard fall velocity as the given particle.

Streambank erosion. The removal of bank material by the force of flowing water and the caving of streambanks.

Stream discharge. The quantity of flow passing a stream transect in a unit of time. (The flow contains both dissolved solids and sediment.)

Supernate or supernatant. The liquid (e.g. water) above the surface of settled sediment.

Suspended load. That part of the sediment load which is suspended sediment. (*See* sediment load.)

Suspended sediment. Sediment that is carried in suspension by the turbulent components of the fluid or by Brownian movement.

Suspended-sediment concentration. See concentration of sediment.

Suspended-sediment discharge. The quantity of suspended sediment passing a transect in a unit of time.

Suspended-sediment sample. See sediment sample.

Suspended-sediment sampler. Device to sample flow and its suspended-sediment load.

Thalweg. The line connecting the lowest or deepest points along a stream bed, valley or reservoir, whether under water or not.

Topset bed. A layer of sediments deposited on the top surface of an advancing delta which is continuous with the landward alluvial plain.

Total-sediment discharge. The total quantity of sediment passing a section in a unit of time.

Total-sediment load (total load). All of the sediment in transport; that part moving as suspended load plus that moving as bedload.

Transect. A sample area, cross section, or line chosen as the basis for studying one or more characteristic of a particular assemblage.

Transmissometer. An instrument that measures the energy of a light ray that has passed through a suspension.

Transportation (sediment). The complex processes of moving sediment particles from place to place. The principal transporting agents are flowing water and wind.

Turbidity. Only a general definition is possible because of the wide variety of methods in use. This term has been used as an expression of the optical properties of a sample which causes light rays to be scattered and absorbed rather than transmitted through the sample. (*See* optical opacity.)

Turbidity current. See density current.

Turbulence. In general terms, the irregular motion of a flowing fluid.

Unmeasured sediment discharge. The difference between total sediment discharge and measured suspended-sediment discharge.

Unsampled depth. The unsampled part of the sampling vertical; usually within 8–15 cm of the stream bed depending on the kind of sampler used.

Unsampled zone. A part of a transect that is not wholly represented by sediment samples. (*See* sampled zone.)

Volume weight. Use density.

Washload. See fine-material load.

Water discharge. See stream discharge.

Watershed. All lands enclosed by a continuous hydrologic-surface drainage divide and lying upslope from a specified point on a stream. (*See* drainage basin.)

Water pollution. The addition of harmful or objectionable material to water in sufficient quantities to adversely affect its usefulness.

3.C. CHARACTERISTICS OF SEDIMENT ENVIRONMENTS

3.C.1. LAND SURFACE

The sediment environment at the land surface includes all areas not in stream channels or inundated by water, and represents immensely diverse conditions. The immediate source area for much of the sediment in stream channels and other water bodies is from the land surface. Sedimentation, or more specifically the transport and deposition of sediment, is a staged process. Particles detached and entrained in a given event may move downslope but remain on the land surface, or they may become part of the stream load.

The land surface varies from rock outcrops to well-developed soils. For areas of rocky parent material or bedrock at the land surface, the sediment environment is strongly affected by the physical factors of slope steepness, climate, and the geologic material, and is weakly affected by plant cover and other biological variables. In undisturbed areas, sediment particle size depends on the parent rock; rates of erosion and movement are controlled by precipitation, weathering rates, detachability, slope, and plant cover. In disturbed areas the particle size of the sediment moved may not differ greatly from that moved from undisturbed areas, but the rates of erosion can be expected to increase because plant cover or natural armoring may be lost and weathering rates may be increased.

A mature soil indicates that the long-term erosion phase of the sedimentation process has been slower than the soil-forming processes. This condition requires the presence of good vegetative cover on the land surface. Generally, a mature soil is one having a profile in equilibrium with its environment, developed under good drainage from parent material of mixed mineralogical, physical, and chemical composition, and expressing the full effects of the forces of climate and living matter.

Disturbances of soils cause a variety of complex changes in the sediment environment. Disturbances of the surface environment which do not result in increased runoff or in significant concentration of flow, may only minutely increase sediment yield. Because disturbance mixes the soils, the water-sediment mixture in runoff will be more varied in particle size and chemical composition than would be expected for undisturbed soils.

Disturbances that increase runoff or channel water generally cause the sediment yield to increase dramatically. The range of particle sizes in transport broadens with an attendant change in the chemical composition of the soil being eroded. New channels and/or gullies form which may permanently alter the yield and character of sediment from the particular landscape.

Sediment environments range from thin rocky soils to thick mature soils. Time and changes in climate, stream downcutting, geologic uplift, or man's activities cause changes in the sediment environments of all land surfaces, so that an area at one place on the continuum may shift toward either the bedrock or the mature-soil end of the scale.

The sediment-contributing area on any drainage basin is usually less than 100 percent of the drainage basin. The sediment sources and the rate of yield change with the amount of disturbance and tend to increase with an increase in the intensity of storm events.

Regardless of conditions on an existing land surface, erosion and entrainment occur mainly in response to rainfall events (Wolman and Miller, 1960). Rainfall events vary in magnitude—the

larger events occur less frequently. There may be no sediment-producing rainfall events in any given year or there may be tens or hundreds of such events. Typically, one would expect anywhere from a few events to 30 to 40 annually. They may occur for only a few hours or a few days in a year, but collectively they make up the annual sediment yield from a land surface. For example, in Scott Run Basin, (1961–64), the average annual rainfall was 1,030 mm. From a total of 88 storm events (Vice, Guy, and Ferguson, 1969, p. 31), the average annual duration of storm runoff was 5.6 days in the January–March quarter, 3.1 days in April–June, 0.8 days in July–August, and 2.9 days in September–December. Neff (1967) found that more than 60 percent of the long-term sediment yield in arid regions was associated with runoff events having a return interval of 10 years or more, whereas in humid regions only 10 percent of the yield occurred during these larger storms.

Several years of record are needed if reliable information concerning average annual sediment conditions are to be developed. For a given degree of reliability, the length of record needed would generally depend on the number of rainfall events each year and on the range in sediment conditions encountered among the different events. For channel design and sediment-control management, measurement of the sediment transport characteristics and chemistry of the sediment during sediment producing storm events may be necessary. Chemical characterization may be used to indicate sediment sources in the drainage basin.

3.C.2. STREAMS

The previous section discussed the land-surface environments that are the basic sources of stream sediment. In addition, the stream channel itself may be a sediment source. As previously mentioned, the processes of erosion and deposition on the landscape cause a highly variable quantity of sediment to be available for movement by streams. Available sediment or sediment in streams may be classified as fine or coarse.

3.C.2.a. FINE SEDIMENT

Fine sediment (<0.062 mm) is easily suspended by natural stream turbulence, and hence travels through a stream system with about the same velocity as the water (Guy, 1966). The quantity of fine sediment in a stream cross section depends on the amount of erosion in the drainage basin and the routing of the particles by the flow to the cross section in question; it depends only indirectly on the flow rate of the stream in a particular reach. The exact concentration of fine sediment in transport during stormflow is unpredictable with respect to time, and frequently increases by a factor of 100 to 1,000 times that of normal flow. Heidel (1956) has noted the progressive lag of sediment concentration with flood waves. Thus, much of the error in sediment data obtained by present measurement techniques results from the lack of enough observations to define the large temporal variations in concentrations.

3.C.2.b. COARSE SEDIMENT

Coarse sediment (>0.062 mm) is usually found in appreciable quantities in the bed of a stream and is transported both as suspended load and bedload. The mode and rates of transport depend on the properties of the fluid, the sediment, the flow, and the channel geometry (Colby, 1961;

Colby, 1964; Leopold and Maddock, 1953). Colby (1961) has related the discharge of bed material (coarse sediment) to depth and velocity of flow; thus, coarse-sediment discharge often can be related to water discharge at a given stream transect (cross section).

The movement of coarse particles consists of a series of steps interrupted by periods of no motion when the particle is a part of the bed material. A particle moves and becomes a part of either the suspended load or the bedload whenever lift and drag forces and/or impact from another moving particle overcome the resisting forces and dislodge the particle from its resting place. The magnitude of the force on a particle varies according to the fluid properties, the velocity and turbulence of the flow, the physical character of the particle, the location of the particle relative to bed relief, and the degree of exposure of the particle. The degree of exposure depends largely on the size and shape of the particle relative to other particles in the bed mixture. Because of these factors, even in steady flow the discharge of coarse sediment can be expected to fluctuate significantly with time at a point, and to vary substantially from one point to another over the stream bed.

In order to define the coarse-sediment discharge at a transect, measurements must be made over time at a number of different locations. Also, because of the close relationship between coarse-sediment discharge and the flow forces, at any given time particles that move as bedload at one transect may or may not move as suspended load at another transect. As a result, the bedload portion of the total-sediment discharge observed at one transect is not necessarily representative of that at some other transect.

3.C.2.c. SUSPENDED-SEDIMENT DISCHARGE

All particles in suspension that have a density greater than water tend to settle. Since the concentration at any depth in a stream vertical is more or less constant, the settling of particles at every level must be opposed by an upward counteracting flux of particles. The upward flux occurs as the result of the natural establishment of a vertical concentration gradient. The steepness of the gradient at every point is such that the concentrations of parcels of water-sediment mixture moving upward (due to turbulence) through a horizontal plane at that point are just sufficiently higher than the concentrations of parcels moving downward (due to turbulence) to produce a net upward flux that balances the downward flux due to settling. The coarser the particles the steeper the gradient. Particles finer than about 0.062 mm will be essentially uniform throughout the entire depth in most streams.

Due to the spatial variations in the coarse and fine suspended-sediment concentrations and in flow velocities, the discharge of suspended sediment at any given instant must be determined from

$$Q_s = \int_A C\,U\,dA, \tag{3-1}$$

where Q_s is the "instantaneous" suspended-sediment discharge through a section of area A,
U is the velocity of sediment particles through an elemental area dA, and
C is the suspended-sediment concentration in the elemental spatial volume.

In the practical application of equation (3-1), U is considered to be equal to the flow velocity and C is considered to be constant during any given sampling period associated with it's determination.

Integrating the above equation over time yields the quantity of suspended-sediment discharge during any specified duration, T. That is,

$$S = \int_T Q_s \, dT = \int_T \int_A C \, U \, dA \, dT, \tag{3-2}$$

where S is the quantity of suspended-sediment discharged through area, A, during the elapsed time, T. Techniques commonly used to evaluate equation (3-1) are given in section D.

3.C.3. LAKES, RESERVOIRS, AND PONDS

Lakes, reservoirs, and ponds are relatively still bodies of water which serve as sinks for sediments (Flint, 1972). Those with outlets will usually trap much but not all of the sediment carried to them (Brune, 1953). Factors affecting the sediment environment include the trap efficiency, the presence of suspended material, and the character of the bottom sediments. The major variables which determine the character of the sediment in this type of environment are the source and character of the inflow, the size and morphometry of the water body, the volume of the water body relative to the rate of outflow, the age of the water body, and the time of year.

Lakes or reservoirs with one or more major inlet stream develop deltas composed of coarse materials deposited as foreset beds and topset beds, and fine materials deposited far into the impoundment as bottomset beds. As a delta develops, the extension of the river channel tends to form topset beds on the delta. Wide fluctuations in water levels, such as those occurring in flood-control and irrigation reservoirs, significantly affect the deposition patterns in many reservoirs. Most natural lake bottoms show the results of hundreds or thousands of years of the sedimentation processes. Lake currents and the character and the timing of the sediment-laden inflows will be reflected in the particle size and deposition patterns of bottom sediments.

To provide reliable infomation, sampling programs must have well-defined goals and take into account the factors controlling the distribution of sediment in the lake, reservoir, or pond.

3.C.4. ESTUARIES

Significant differences in the sediment environment are found in different types of estuaries. In estuaries where tidal fluctuations cause the volume of sea water flowing into and out of the estuary to be very large relative to the volume of river flow, sufficient mixing usually occurs so that the vertical distribution of salinity is uniform with depth, and only longitudinal salinity gradients exist. Under these circumstances, even though the flow reverses, sedimentation processes are roughly similar to those that occur under unsteady flow conditions in rivers.

The most prevalent type of estuary along the Atlantic and Pacific coasts of North America is the partially mixed estuary. In this type the volume of fresh-water inflow is sufficiently large relative to the volume of sea-water flow to create a complex pattern of salinity gradients. This in turn produces a net vertical circulation in which, seaward from a point of zero net flow on the channel bottom, there is a predominance of landward flow of relatively dense saline water along the bottom and a predominance of seaward flow of less dense, relatively fresh water near the surface, even though the body of the flow alternates direction with the tide. This generally produces a

characteristic feature termed a "turbidity maximum." The turbidity maximum is a bell-shaped, longitudinal, suspended-sediment concentration distribution that progressively develops in magnitude and then abates and translates landward and seaward with the tide.

In addition to suspended-sediment distributions engendered by vertical circulation patterns, larger estuaries typically develop horizontal circulation patterns because of the Coriolis effect, major ocean circulation patterns, and sometimes prevailing wind patterns. These horizontal circulation patterns frequently cause a predominance of flow in certain channels during the flood period and in other channels during the ebb period. These patterns may produce extreme lateral variations in suspended-sediment concentration and disposition of bottom sediments.

As a result of the different hydraulic and sediment characteristics in estuaries, sampling techniques and requirements necessarily vary from one estuary to another. The common characteristic of all estuaries is that at any given time the concentration, composition, and transport direction of the suspended sediment is different in some degree from every other point in the estuary, and that at every point in the estuary these quantities vary continuously throughout time. As a result, a measurement at a single point or cross section cannot be used to represent the transport of suspended sediment in the entire estuary nor the transport through any other point or cross section in the estuary. These conditions dictate the necessity of defining precise sampling goals and most likely limit the usability of a given set of samples to the specific purpose for which it was collected.

3.C.5. CONDUITS AND OUTFALLS

The physical and chemical composition of the sediment entering a stream from conduits or outfalls could include a wide variety of fluvial sediments, metals, other inorganic materials, or organic materials. In contrast to more natural streams, the distinquishing characteristic of flow in conduits and outfalls is that it consists of wastes or effluents of industrial or municipal processing, or outflows of artificial watersheds, such as storm-sewer systems. In either case the conditions which determine the flow and the type of sediments and their concentrations are controlled mostly by man's activities. Sampling programs and sampling methods will be effective only if the components of sediment inputs and hydraulic conditions are considered.

3.D. SAMPLERS AND SAMPLING PROCEDURES

A wide variety of samplers and procedures have been developed and are commonly used for sampling sediment. In general, the requisites for sampling moving sediment are different from those for sampling sediment deposits. In this section, equipment and procedures for sampling both sediment in motion and deposited sediment in various environments are discussed. Additional information on sampling reservoir deposits is covered in a separate section on reservoir surveys.

3.D.1. SEDIMENT IN MOTION

3.D.1.a. LAND SURFACE

Quantitative analysis and understanding of the character of sediment in motion in streams and in other water bodies usually require a knowledge of the sources of such sediment. The basic source of sediment is erosion of the land surface, the magnitude of which is directly related to ground cover, which in turn is related to land use. The amount of fine sediment moving in streams is related to land use; hence, measurements of the land-surface erosion are usually made by using small plots where land use can be controlled.

Methods of data collection and the results from some of the runoff and sediment-yield measurements made on small plots have been described (ASCE, 1975; Mutchler, 1963). A wheel-type sampler (Parsons, 1954) is recommended to trap an aliquot of the runoff from the plot where a time distribution is not considered essential. All or a slot-divided part of the runoff may be stored in a tank for sampling after runoff ceases.

3.D.1.b. STREAMS

3.D.1.b.1. SUSPENDED SEDIMENT

3.D.1.b.1.a. Criteria

Suspended sediment in streams is sampled for a variety of purposes. In general, the intent is to supply samples for analyzing to provide information on the quantity (concentration) and on the physical and chemical characteristics of the sediment in suspension. Samplers and sampling procedures must be designed to yield samples that accurately represent the characteristics under study. Suspended-sediment samples are mixtures of solids and liquid, and the solid and liquid phases have quite different densities. Most fluvial sediment has a specific gravity of approximately 2.65 as compared with 1.0 for water. In the sampling process, this difference can create serious discrepancies between the concentrations of samples and the flow from which they are withdrawn.

Some operators or designers of sampling equipment have failed to recognize this fundamental fact and have erroneously believed that a water sample collected by any method is representative of the water-sediment mixture. Improperly collected samples often appear to be satisfactory because of the overriding visual effect of the fine sediment. Particles larger than about 0.062 mm separate quite rapidly from a stream tube; the process usually is not obvious except for particles larger than about 0.2 mm.

Because of the significant effect of flow acceleration on sample accuracy, it is imperative that the sampling operation keep the disturbance of the flow to an absolute minimum. With this in mind together with other considerations, a list of general requirements for an "ideal" sampler was published in the first of the U.S. Inter-Agency Reports (1940A) and is still valid today. The list of general requirements, together with recommended requirements for various samples are given in appendix 3.L.1.

The basic requirement of any sampler is that the sample collected must be representative of the water-sediment mixture in the immediate vicinity of the sampling point or sampling zone at the time of sampling.

3.D.1.b.1.b. Types of samplers

Although no single sampler has been built that satisfies all the requirements of the ideal sampler, a number of different samplers have been developed that satisfy the essential requirements for obtaining satisfactory samples. These samplers can be classified into three general types—integrating samplers, instantaneous samplers, and pumping samplers. Integrating samplers accumulate a water-sediment mixture over a period of time by withdrawing it from the ambient flow through a relatively small nozzle. Instantaneous or grab samplers essentially trap a volume of the suspension by instantaneously closing off the ends of a flow-through chamber. Pumping samplers withdraw a mixture of the suspension through an intake by a pumping action. Where their application is appropriate, integrating samplers are preferred because they obtain a water-sediment mixture from a long filament of flow, can be traversed through the flow and thereby sample at more than one point, and require no energy input or complicated velocity sensing and adjusting apparatus.

Suspended-sediment samplers, regardless of type, can be categorized by the orientation of their intakes as follows:

1. Samplers with intakes oriented into the streamflow and parallel to the flow.
   (a) Sample container and intake nozzle mounted as one integrated unit with short conduit connecting the two.
   (b) Sample container and intake as one integral unit.
   (c) Sample container separated from intake by several feet of conduit.
2. Samplers with intakes oriented at right angles to streamflow.
   (a) Sample container and intake nozzle mounted as one integrated unit with short conduit connecting the two.
   (b) Sample container separated from intake by several feet of conduit.
   (c) Sample container without nozzle or conduit.

Based on laboratory and field tests, the categories have been listed above in descending order of sampling precision (U.S. Inter-Agency Report, 1941A). For example, samplers in category 1 are the most precise. Category 1a pertains mainly to US-series samplers; category 1b refers to horizontally oriented grab samplers; category 1c includes pumping samplers used in the field from a boat, or siphon samplers used for laboratory studies. Those in category 1c generally have been used where samples are to be collected very close to the bottom of a stream or laboratory flume, where unusually large sample volumes have been required, or where samples are required from depths beyond the capacity of the US series.

Samplers in categories 2a and 2b include most pumping samplers designed for unattended operation. The right-angle orientation of the intake for these samplers is a compromise between sampling precision and the ability of the nozzle to shed debris.

Category 2c includes vertically oriented grab samplers and several early samplers consisting of open-top containers to be lowered into the stream and allowed to fill by gravity. Samples collected by this procedure are usually referred to as dip samples. A few of the early samplers consisted of a container covered with a cap that could be pulled free or pierced at the desired sampling depth.

3.D.1.b.1.c. ***US-series samplers***

The US-series of suspended-sediment samplers, developed by the Federal Inter-Agency Sedimentation Project sponsored by the U.S. Water Resources Council, is generally considered to embody an optimum number of the required and desirable features of the ideal sampler. The US-series integrating samplers are designed to sample isokinetically (to sample in such a way that the water-sediment mixture moves with no acceleration as it leaves the ambient flow and enters into the sampler intake). For this reason, it is recommended that they be used for suspended-sediment sampling wherever possible. Most pumping and other types of special samplers are not designed to sample isokinetically. Inquiries regarding detailed specifications for these samplers and their purchase should be addressed to Engineer-in-Charge, Federal Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Hennepin Island and Third Avenue, SE., Minneapolis, Minn. 55414.

3.D.1.b.1.c.1. Integrating samplers—Within the group of integrating samplers are both depth-integrating and point-integrating samplers (U.S. Inter-Agency Report, 1952). Depth-integrating samplers are designed to be used in a sampling procedure called depth integration. In this procedure, the sampler is lowered and raised at a uniform rate throughout the depth or a portion of the depth. The water-sediment mixture accumulates from all points in the sampled depth in such a way that at every point an incremental volume of mixture is collected that is proportional to the flow velocity at that point. The samplers are designed with an air exhaust port; however, there are no valves of any sort so that the water-sediment mixture continuously enters the nozzle and displaces the air within the sample container.

The U.S. Inter-Agency Committee on Water Resources Report 14 (1963) states that, "Point-integrating samplers are more versatile than the simpler depth-integrating types. They can be used to collect a sample . . . at any selected point beneath the surface of a stream except within a few inches of the bed, and also to sample continuously over a range in depth. They are used for depth-integration in streams too deep [or too swift] to sample in a round-trip integration . . . [and] can start [sampling] at any depth and continue in either an upward or downward direction . . . ." Point-integrating samplers have an intake nozzle and an air exhaust that permits air to leave the container as the sample enters like the depth-integrating samplers; however, the intake and exhaust passages are controlled by a valve. When the valve is in the open position, the sampling action is the same as in the depth-integrating sampler. Also, a chamber that is open to the outside at the bottom is formed within the sampler body. When the valve is closed, air initially in the chamber is progressively compressed and forced into the sample container via an interconnecting passage as the sampler is lowered through the depth. This action equalizes the pressure in the sample container with that of the hydrostatic pressure. Pressure equalization eliminates any initial inrush of fluid when the intake-exhaust valve is opened for sampling. Whenever the hydrostatic pressure is so great that the air initially within the sampler is compressed to a volume less than that of the sample container, water will spill into the container and contaminate the sample. Hence, for every size of sampler there is a limiting depth below which the sampler should not be used.

Because of the wide range of conditions encountered in nature and the variety of installations at measurement sites, a number of different depth-integrating and point-integrating samplers have been designed for the US-series. Table 3-3 lists physical characteristics of integrating samplers that are available. Photographs of some of these are shown in figure 3-1. Samplers suspended by cable are

Table 3-3.—*Physical characteristics of US-series depth-integrating and point-integrating samplers for collecting samples of water-suspended sediment mixtures*

[Type: DI, depth-integrating; PI, point-integrating. Available nozzle size: A, 6.4 mm; B, 4.8 mm; C, 3.2 mm. Body material: AL, aluminum; BR, bronze; PS, plated steel]

Name	Type of sampler	Method of suspension	Mass (kg)	Overall length (m)	Available nozzle size	Sample container size (mL)	Maximum allowable depth (m)	Maximum calibrated velocity (m/s)	Distance between nozzle and sampler bottom (mm)	Body material	Remarks
US DH-48	DI	Rod	2.0	0.33	[1] A, B	473	(2)	2.7	90	[3] AL	For wading.
US DH-59	DI	Cable	10.2	.42	A, B, C	473	(2)	1.5	114	[3] BR	For hand-line operation.
US DH-75P	DI	Rod	.4	.26	B	500	(2)	2.0	83	[3] PS	For sampling only in subfreezing temperatures.
US DH-75Q	DI	Rod	.4	.29	B	1,000	(2)	2.0	114	[3] PS	Similar to US DH-75P.
US DH-76	DI	Cable	10.9	.47	A, B, C	946	(2)	2.0	80	[3] BR	Similar to US DH-59.
US D-43	DI	Cable	22.6	.52	A, B, C	473	(2)	2.1	105	BR	No longer available.
US D-49	DI	Cable	28.0	.61	A, B, C	473	(2)	2.1	103	[3] BR	
US D-49AL	DI	Cable	18.0	.61	A, B, C	473	(2)	2.0	103	[3] AL	Similar to US D-49.
US D-74	DI	Cable	28.2	.66	A, B, C	473 or 946	(2)	2.0	103	[3] BR	Similar to US D-49.
US D-74AL	DI	Cable	11.4	.66	A, B, C	473 or 946	(2)	1.8	111	(3, 4)	Similar to US D-74.
US P-46	PI	Cable	45.2	.66	B	473	42.7	3.0	122	BR	No longer available.
US P-50	PI	Cable	135.6	1.12	B	473 or 946	[5] 61.0 [6] 41.0	3.0	140	BR	
US P-61-A1	PI	Cable	47.5	.71	B	473 or 946	[5] 54.9 [6] 36.6	2.0	109	[3] BR	
US P-63	PI	Cable	90.4	.86	B	473 or 946	[5] 54.9 [6] 36.6	2.0	150	[3] BR	
US P-72	PI	Cable	17.7	.71	B	473 or 946	[5] 22.0 [6] 15.5	1.6	109	[3] AL	Similar to P-61-A1 but for hand-line operation.

[1] 4.8-mm nozzle available by special order.

[2] Varies with nozzle and container sizes as follows:

Nozzle size	Container size 473 mL	Container size 946 mL
C	5.8 m	4.9 m
B	4.9 m	4.9 m
A	2.7 m	4.9 m

[3] Available with epoxy-painted body, nylon nozzles, and silicone-rubber gaskets for trace metals.

[4] Aluminum body, bronze head.

[5] With 473-mL container.

[6] With 946-mL container.

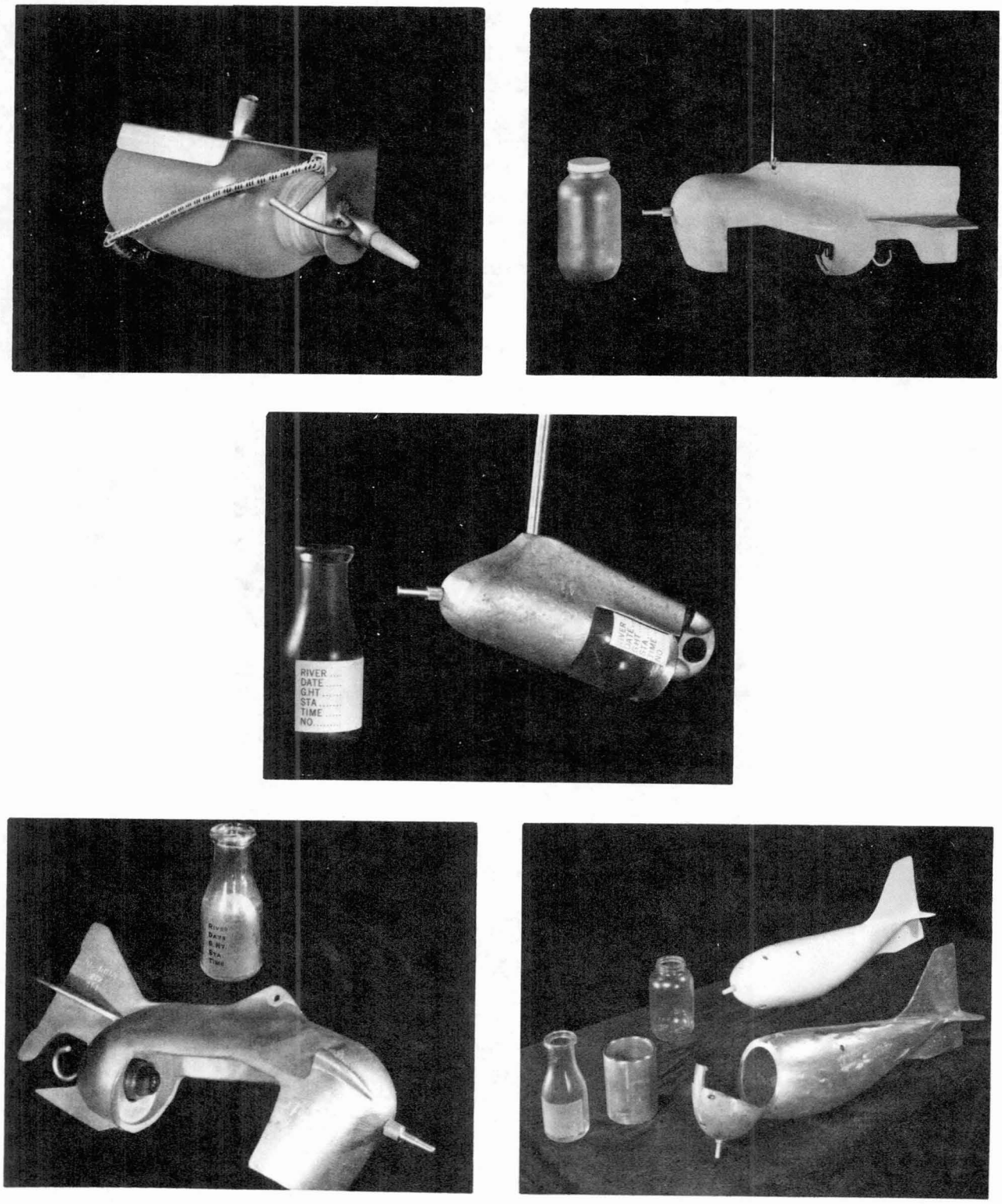

Figure 3-1.—Photographs of some US-series depth-integrating samplers.

suitable for operating from bridges, cableways, and boats. The valving systems of all point-integrating samplers are actuated electrically with DC power supplies of moderate voltage.

3.D.1.b.1.c.2. Pumping samplers—US-series pumping samplers are intended for permanent installations where the intake can be fixed at a given point in the stream. Normally, the intake is oriented at 90° to the flow; hence, the samplers are not designed to sample isokinetically, but rather to pump at rates such that the velocity in the intake exceeds the stream velocity at the sampling point by several times. This procedure yields accurate sample concentrations for clay and silt particles, but tends to yield less than normal concentration for coarser particles (U.S. Inter-Agency Report, 1966). As a result, this type sampler should be used only in streams where the suspended sediment is predominately clay or silt or where special provisions are made to analyze the clay-silt and coarse-particle fractions separately.

Three types of pumping samplers are presently available—the US PS-69, a US PSTM (for trace metals), and the smaller US PS-73. A photograph of a US PS-69 sampler is shown in figure 3-2.

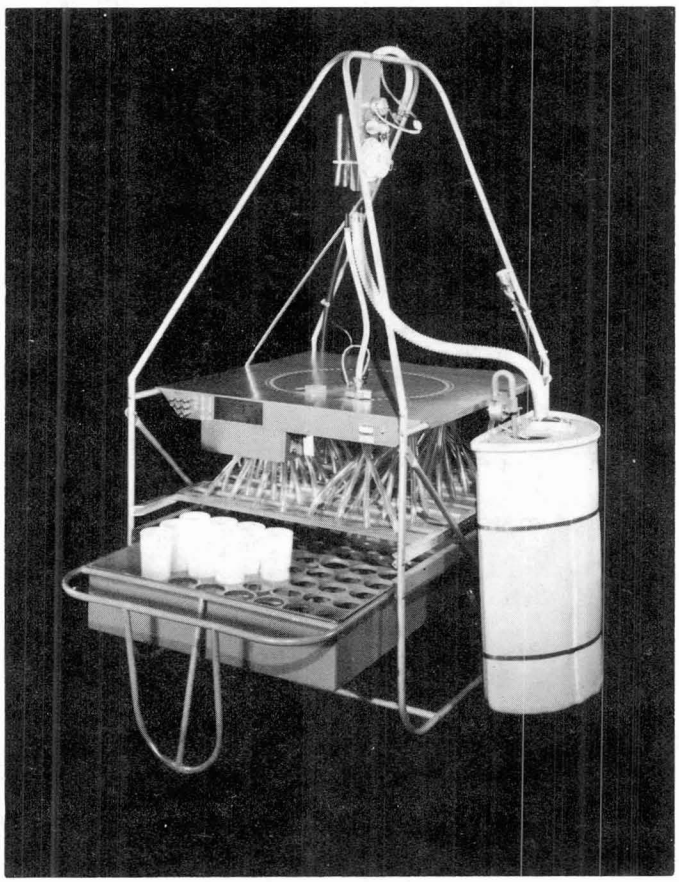

Figure 3-2.—Photograph of a US PS-69 sampler for obtaining nonisokinetic suspended-sediment samples.

Operation of the US PS-69 requires three 12-volt batteries (36-volt primary). It pumps a water-sediment mixture from a fixed point in the stream according to a predetermined scheme. For each pumping event the sampler automatically clears the intake pipe of residual sediment and fills a separate sampler container. The sampling procedure can be initiated with a manual switch, a constant interval timer, or a switch that activates a timer whenever a preselected stage is exceeded.

The unit has a capacity for seventy-two 1-L sample containers. The first step in the sampling cycle is to flush the system to clear the lines of trash and to prime the pump. At the end of the sequence, the sample distributor nozzle positions itself over the appropriate sample container and the pump cycle begins. Initially, the pumped water-sediment mixture refills the flush tank for the next sample, then the sample is extracted and dispensed to the sample container. The stage record is marked simultaneously to indicate the time and stage that the sample was collected. Various modifications are being added to this system to permit adjustment of the sampling frequency and the stage at which a sample is collected. The US PS-69 normally is housed together with standard gaging-station equipment.

The US PS-73 is a self-contained, weatherproof pumping sampler that weighs 93 kg and has a capacity for either twenty-four 1-L or thirty-six 500-mL containers. It functions in the same way and has much of the same hardware, the same control unit, and the same power requirements as the US PS-69.

3.D.1.b.1.c.3. Special samplers—Included in the US series are several samplers that are intended for use on flashy, intermittent streams which are not easily accessed. These samplers are designed to obtain a single sample automatically, whenever the water-surface elevation reaches a preselected level.

The most widely used of these samplers is the single-stage US U-59 (U.S. Inter-Agency Report, 1963, p. 118–121), which consists of a sample bottle fitted with a rubber stopper and two inverted U-shaped tubes that serve as the intake and the exhaust. One leg of each tube passes through the stopper and the other leg terminates in the streamflow. The exhaust tube extends deeper into the bottle and terminates at a higher point outside the bottle than the intake tube. The unit is mounted at a fixed elevation in an upright position with respect to the bottle. After the sampler becomes submerged during a rising stage, the water-sediment mixture flows through the intake, fills the bottle to the end of the exhaust tube, and then rises up the exhaust until a pressure balance is achieved. As the stage continues to rise, the exhaust becomes submerged and a back pressure is created which blocks further inflow.

The US U-59 is inexpensive, and normally several units are mounted at different levels along a vertical member to obtain samples at increasing gage height. However, because it samples only near the surface of the flow, and does not sample at stream velocity, the U-59 is capable of providing accurate concentrations of only the fine (<0.062 mm) material in suspension. Also, proper operation is not always assured because the tubes may become plugged by trash, windblown material, and insects.

A newer unit, the US U-73, uses a flow-through sample chamber that is closed off by a float-spring mechanism whenever the stage reaches a preselected level. This sampler can be programed to sample on either a rising or falling stage.

The Tait-Binckley sampler is a horizontal, flow-through grab sampler that is sometimes used to obtain spatial concentrations. It consists of three metal tubes of equal diameter that are mounted coaxially in a horizontal frame. The middle tube, which is supported in bearings for free rotation about its axis, is connected to the rigidly mounted end tubes by thin rubber cylinders. The sample is trapped by rotating the middle section by a pull on a line that is wound around the section; the rotation twists the rubber sections and seals off the ends of the sample chamber. This sampler is not part of the US series and is not recommended for use except for very special purposes.

Point-integrating samplers that provide a time-integrated sample are preferred over grab samplers of this type.

3.D.1.b.1.d. Sampling procedures

Suspended-sediment samples are ordinarily collected from streams to define: (1) the concentration of suspended sediment at a given location and instant in time, (2) the quantities of suspended sediment transported per unit time past given locations, and/or (3) the disposition of substances associated with the suspended sediment. If the purpose of sampling is to provide information on the spatial distribution of some property of the water-sediment mixture or of the temporal distribution of the property at specific points in the flow section (a transect), then point samples should be collected, preferably by using point-integrating samplers. However, if, as is common in river studies, the purpose of sampling is to provide information on the discharge of suspended sediment or some property associated with the suspended sediment, then depth integration should be considered. Depth integration is also an efficient method for obtaining the discharge-weighted concentration of sediment and its adsorbed constituents for specific time units.

Although measured point concentrations and velocities are often combined and integrated in accordance with equation (3-1) to determine the suspended-sediment discharge through a transect (ASCE, 1975), the process can be performed mechanically by sampling according to a technique called "depth integration." A depth-integrating sampler (a sampler that samples continuously and isokinetically) is lowered and/or raised at a constant speed throughout the depth at a vertical. This provides a volume of water-sediment mixture in the sample from every element of sampled depth that is proportional to the water discharge at the corresponding elements of depth. The concentration collected from every sampled increment of depth is therefore "discharge weighted," and the concentration of the sample from the vertical, $\overline{C}_v$, is the mean discharge-weighted concentration in the sampled depth[2] at the vertical (U.S. Inter-Agency Report, 1963; ASCE, 1975.). The mean discharge-weighted concentration can be multiplied by the water discharge through the area traversed by the nozzle to give the suspended-sediment discharge through that area. By sampling by depth integration at verticals spaced across a transect in such a way that concentrations also are discharge-weighted laterally, a mean discharge-weighted concentration in the sampled zone at the transect, $\overline{C}_v$, is obtained and can be combined in accordance with equation (3-3) to yield, Q'_s, the suspended-sediment discharge through the sampled zone.

$$Q'_s = \overline{C}_v Q', \tag{3-3}$$

where Q' is the water discharge through the sampled zone.

In practice, $\overline{C}_v$ is commonly multiplied by the total-water discharge through the transect to obtain a "measured" suspended-sediment discharge, which is an estimate of the suspended-sediment discharge through the entire transect. If spatial concentrations do not vary with depth, that is if no vertical concentration gradients exist, the computed value is the total suspended-sediment discharge through the transect. However, if spatial concentrations, c, are greater at the bottom than at the top (as is the usual case) so that gradients exist, the computed value will be less than the total suspended-sediment discharge, and there will be an unaccounted part in the unsampled zone called the "unmeasured suspended-sediment discharge" (Hubbell and Matejka, 1960).

[2] US-series samplers are capable of sampling only to within 80–150 mm of the stream bottom. Sediment moving below this limit represents transport in the unsampled zone. Although the stream velocity may be considerably less than in the sampled zone, the concentration of sand-sized particles in the unsampled zone may be considerably more.

It is important to recognize that the mean spatial concentration for the transect, $\bar{C}$, which is defined by

$$\bar{C} = \frac{1}{A}\int_A c\,dA, \tag{3-4}$$

is a different quantity than the discharge-weighted concentration for the transect as given in equation (3-3).

Regardless of the purpose for sampling, in order to define spatial variations in sediment properties, samples should be collected from throughout the depth at a series of verticals spaced laterally across the channel width. As indicated earlier, material finer than about 0.062 mm is usually distributed fairly uniformly in the flow section, but the distribution of coarser material varies significantly both laterally and vertically (ASCE, 1975). Since most streams carry a mixture of both fine and coarse sediments, variability of concentration within the section is to be expected. A convenient method for evaluating the extent of variability is given by Guy and Norman (1970). It should be recognized also that in addition to spatial variations within the section, suspended-sediment concentrations vary in both the short and long term. The character of long-term variations affects the required sampling frequency, and short-term variations caused by turbulent fluctuations must be considered in collecting a sample.

3.D.1.b.1.d.1. Point integration—To sample by point integration, divide the flow area laterally into increments and collect samples at various elevations along a vertical in each increment (U.S. Inter-Agency Report, 1940A; ASCE, 1975). Select increment widths and vertical sampling intervals so that concentration and velocity differences between adjacent points are small enough to conform to desired accuracy. Use a US P-61-A1 or any other point-integrating sampler that samples isokinetically. (Point-integrating samplers are recommended in preference to grab samplers because they provide a time-integrated sample.) If the samples are to be used to determine transport rate, flow velocities must be measured at each sampling point. With US-series samplers, a moderately accurate velocity can be determined by dividing the sample volume collected at a point by the product of the sampling time and the cross-sectional area of the nozzle.

3.D.1.b.1.d.2. Depth integration—Depth integration should be performed using a US D- or P-series sampler. While a sample is being collected, the sampler must be moved vertically at a uniform velocity (transit rate). Sampling can be continuous over the entire depth, or interrupted in a series of segments over the depth. The only basic requirements are that at each sampling vertical: (1) the entire depth is sampled isokinetically, (sample container cannot be completely filled), (2) the vertical transit rate in any given direction is the same over all parts of the depth and never exceeds the product of K times the mean stream velocity at the vertical,[3] and (3) sampling does not extend in one-way integration over a distance greater than $K_e V_i/A_n$, or half this distance in two-way integration (K_e must be ≤ 0.4 and is the largest K value possible for a given nozzle area, A_n, and sample volume, V_i) (U.S. Inter-Agency Report, 1952)[4]. These procedures insure that the volume of sample collected from every element of depth at a vertical is represented in the total sample volume for the vertical in the same proportion as the water discharge through each corresponding element is to the total discharge through the width represented by the vertical.

[3] K is a factor determinable for different intake-nozzle sizes and sample container capacities from Eq. 6 given in U.S. Inter-Agency Report (1952, p. 28). Graphs of K versus depth are presented for standard nozzle sizes and 473 mL containers in U.S. Inter-Agency Report (1963, p. 45). The factor should never exceed 0.4.

[4] If a US-series sampler having a 3.2-mm nozzle is used with a uniform transit rate such that a sample of 350–400 mL is obtained by one-way integration in depths less than 9.1 m or by two-way integration in depths less than 4.6 m, all sampling requirements are automatically satisfied (ASCE, 1975).

Two different depth-integrating methods are commonly used to obtain a mean discharge-weighted concentration for a cross section (U.S. Inter-Agency Report, 1963). Both methods weight the concentration with discharge laterally as well as vertically. They are termed the equal-discharge-increment (EDI) method and the equal-width increment (EWI) method[5].

3.D.1.b.1.d.2.a. EDI method—In the EDI method, the cross-sectional area is divided laterally into a series of subsections, each of which conveys the same water discharge (U.S. Inter-Agency Report, 1963). Depth integration is then carried out at the vertical in each subsection where half of the subsection discharge is on one side and half is on the other side. In each individual subsection, a vertical transit rate is used that will provide a sample volume for the vertical which is equal to the sample volumes for every other vertical. Thus, the procedures provides a group of subsamples that are the same size and that represent the same proportion of the total water discharge through the sampled zone. Such subsamples can be combined to provide a single composite sample. Alternatively, if the subsample volumes are different, the concentrations of all subsamples can be averaged to give the sample concentration. In either case, the concentration is discharge-weighted both vertically and laterally. Generally, if more than five verticals (more than five subsections) are sampled, an accurate mean discharge-weighted concentration will be obtained (Guy and Norman, 1970; Hubbell and others, 1956). The primary disadvantage of the EDI method is that the lateral distribution of water discharge must be known or measured each time prior to sampling.

3.D.1.b.1.d.2.b. EWI method—In the EWI method (ETR method), depth integration is performed at a series of verticals in the flow section that are equally spaced across the transect to obtain a series of subsamples (ASCE, 1975, p. 335). Unlike the EDI method, however, the vertical transit rate used at each vertical is exactly the same as that used at every other vertical, and the subsamples are composited even though they are of different volumes. This procedure provides a transect sample whose concentration is discharge weighted both vertically and laterally and whose volume is proportional to the water discharge in the sampled zone. Because the transect sample is a composite, more than one vertical can be collected in a single sample container. An advantage of the EWI method is that a knowledge of the lateral distribution of discharge is not required. On the other hand, (1) it is sometimes difficult to maintain the same vertical transit rate at all verticals, (2) more verticals must be sampled for a given accuracy than with the EDI method, and (3) wherever the flow is not essentially perpendicular to the transect, the width increment between sampling verticals must be adjusted by dividing it by the sine of the angle between the flow lines and the transect. Generally, 10 to 20 verticals will provide an accurate mean discharge-weighted concentration by the EWI method (Guy and Norman, 1970).

3.D.1.b.1.e. Station operation

In many instances, there is an interest in obtaining continuous and relatively long-term records for the suspended-sediment discharge in a stream. For this kind of an operation, consideration must be given to the site where the sediment-discharge measurements will be made, how the transport will be monitored routinely, and how frequently comprehensive measurements must be made to provide continuity to the record.

3.D.1.b.1.e.1. Site selection—In most cases, and especially where the sediment transport is of interest, the sampling transect (site) must be located at or near a gaging station so that accurate

[5] Previously, the EDI and EWI methods were known as the centroids-of-equal-discharge increments method and the equal-transit rate (ETR) method, respectively.

information on the stream discharge will be available at all times. However, consideration should also be given to the suitability of the site for providing consistent and easily interpretable sediment data. Transects immediately upstream from a confluence may be subjected to backwater and normally should be avoided. As the backwater condition changes, the relationship between sediment-transport rate and pertinent hydraulic variables change. Hence, more sampling and interpretation is required, which in turn increases the effort to define the sediment characteristics of interest. Flow sections immediately downstream from a confluence often have strong and highly variable lateral concentration gradients and therefore must be sampled more frequently than would more "normal sections". The variations occur because the rate of lateral mixing in streams usually is slow, so the different concentrations contributed by each branch at different times retain their identity and position in the cross section for some distance below the junction (Guy and Norman, 1970).

Though the sampling site is at a "normal" section in a relatively straight reach, there will be an unmeasured load in the zone 80–150 mm above the stream bed due to bedload transport at the bed surface and suspended-sediment transport below the lowest position occupied by the sampler nozzle (*see* p. 3-24 and 3-25). In streams where the unmeasured load is relatively high, it is often advantageous to select a site where the turbulence is exceptionally high so that most of the total sediment load is in suspension and can be sampled with conventional suspended-sediment samplers and techniques (ASCE, 1975).

Most streams at times are too deep to wade, hence, sampling sites usually are located at bridges or cableways. The upstream side of bridges is normally the best section; however, the accumulation of debris or trash on the piers (particularly midstream piers), can seriously distort flow and sediment distribution patterns and thereby necessitate additional sampling. At the downstream side, visibility upstream is limited, and care must be taken to avoid sampling in areas of high turbulence near the piers. Sediment samples collected in the vicinity of piers may likely be unrepresentative of the general sediment transport.

Because the highest sediment-transport rates usually occur during high flows, it is imperative to obtain data during flood periods. Thus, the sampling site, whether it be at a bridge or a cableway, must be accessible during the flood. Also, many floods occur at night, so potential lighting should be taken into account in making a site selection. Once the sampling site has been selected, it is important to use the same transect throughout the period of sampling so that the variability of all factors affecting sediment movement is minimized.

3.D.1.b.1.e.2. Monitoring suspended-sediment transport—Ordinarily, records of suspended-sediment discharge are determined on the basis of sample information obtained on a nonuniform frequency; more samples are collected when the sediment discharge is changing than when it is constant. Because of the required effort, sampling by the EDI or EWI methods is rarely done daily or more frequently. Rather, routine sampling is carried out by a local observer at a single vertical or at a few verticals. Information from these samplings, in turn, is adjusted to represent the entire flow section continuously on the basis of periodic comparisons between samples from the routine locations and samples from comprehensive transect-wide sampling by the EDI or EWI method. In small- and moderate-size streams, routine sampling is commonly performed at one fixed vertical in the transect; in large streams where the lateral variation in sediment movement is substantial, routine sampling is more likely carried out at three or more verticals.

Where access to the stations is difficult, or where variations in the suspended-sediment discharge occur very rapidly, pumping samplers are sometimes installed. US U-59 single-stage samplers are also

used under these conditions. Pumping samplers are also used extensively where only fine (<0.062 mm) material is in suspension. Slot samplers (described by Skinner, written communications, ASTM) are sometimes used on small streams, particularly for research applications in mountainous areas.

Most often, discharge-weighted concentrations for single-vertical or limited-vertical sampling are adjusted to represent the transect by multiplying by a simple coefficient determined from the temporal variation in periodically defined values of $\overline{C}_v/C_v$, in which $\overline{C}_v$ and C_v are mean discharge-weighted concentrations for the transect and the routine sampling verticals, respectively (Guy and Norman, 1970; Porterfield, 1972). However, at some locations more elaborate correlations must be developed.

When pumping samplers are used, the location of the intake is an important consideration. It should be located at a position where sample concentrations can be expected to be related to the mean discharge-weighted concentration for the transect in a consistent and predictable manner. The intensity of turbulence, size of material in transport, and local flow patterns all significantly affect concentration distributions within a transect; hence, preliminary measurements should be made before fixing the sampling point. At some stations, multiple intakes may provide more consistent adjustment coefficients. Intakes also have been mounted on floating supports so that samples are always obtained at a fixed distance from the water surface and coefficients are more consistent. Adjustment coefficients are usually close to 1.0 where the sediment is predominately finer than 0.062 mm; however, for the fraction coarser than about 0.2 mm, coefficients usually vary excessively. For this reason, it is advantageous to determine the concentration of both the fine (<0.062 mm) and coarse (>0.062 mm) material in all samples and determine adjustment coefficients for each fraction.

A logical step to improve a sediment record is to employ a monitoring device to sense the fine sediment concentration continuously or at least every few minutes. Although a number of different monitoring devices have been developed, none is acceptable for all conditions. To date, instruments have been based on the effects of fine sediment on the attenuation and/or scattering of light, nuclear radiation, or sound (Guy, 1966). Because fine sediment is usually uniformly distributed in the stream cross section, representative samples often can be pumped from a single point in the section to sensing devices and/or sample bottles. See section 3.G. on turbidity (optical opacity). Inasmuch as the kind of fine sediment will vary somewhat from basin to basin and within a given basin, direct sensing devices must be calibrated by means of conventional samples. With proper and adequate calibration, continuous monitoring ordinarily will result in a greatly improved record of fine-sediment discharge over that presently obtained with daily or hourly depth-integrated samples.

For many streams, the relationship (rating) of velocity and depth to stage will be reasonably stable. On these streams a relatively stable relation of coarse-sediment discharge to stage is likely, and this can be the basis, given a few rating samples, for determining a continuous record of coarse-sediment discharge. Such an indirect method of obtaining coarse-sediment discharge probably would be superior to a record computed entirely from single-vertical samples, especially if the results of periodic measurements of the coarse sediments moving in the entire flow section were used to adjust the computational ratings. The adjustment of coarse-sediment transport with time would be similar to adjustments currently applied to single-vertical sampling techniques and to water-discharge ratings. The periodic conventional sediment-discharge measurements also can be used to define the size gradation of the coarse-sediment discharge.

Bedload particles move as a series of steps interrupted by periods of no motion when the particles are a part of the bed material. A particle moves whenever the lift and drag forces or the impact of another moving particle overcome the resisting forces and dislodge the particle from its resting place. The movement of bedload particles invariably deforms the bed and produces bed forms (i.e., ripples, dunes, plane bed, bars, etc.) which, in turn, affect the flow and the bedload transport. Because of the effects of bed forms and the other factors that influence bedload transport even in steady flow, the bedload discharge fluctuates with time at a point and varies substantially from one point to another over the bed surface.

In order to measure the bedload discharge at a transect by sampling, repetitive measurements must be made at a number of different lateral locations (Einstein, 1948). Because the bedload discharge varies over the length of the bed forms, measurements at each lateral location should be made at random longitudinal positions on several different bed forms (de Vries, 1973) or repetitively at each location for a long enough time for several bed forms to pass by. Also, because of the close relation between bedload discharge and flow forces at any given time, particles that move as bedload in one reach may not move or may move as suspended load at another. As a result, the proportion of bedload discharge to total sediment discharge may vary longitudinally, and discharges observed in a given reach are not necessarily representative of the bedload discharge in other reaches.

In the past, measurements of bedload movement have been made both to document the existence and character of bedload discharge, without regard to its quantity, and to define, as accurately as possible, actual transport rates. Usually, the measurements have been made with samplers; however, other techniques are sometimes employed. For instance, bedload discharges have been determined from measurements of the migration of bed forms (Simons and others, 1965), the movement of tracer particles (Sayre and Hubbell, 1963), the erosion or deposition (scour and fill) in a given area, and the difference in the concentrations of some nonconservative property associated with the bedload particles between different locations along the path of particle movement (Hubbell and Glenn, 1973). Whereas reasonably accurate results have been obtained with these latter methods, they all depend on information collected over relatively long periods of time. Of the available methods, only sampling can provide short-term rates. At present, no single sampler or type of sampler is recommended. The following discussion is offered because some knowledge of the bedload transport is mandatory.

3.D.1.b.2.a. Types of samplers

Many different kinds of samplers have been developed to measure bedload transport (Hubbell, 1964; U.S. Inter-Agency Report, 1940B). In general, each kind of sampler was designed to sample a particular range of sizes and transport rates. Two broad classifications of bedload samplers exist. Direct-measuring apparatus collect and accumulate bedload particles; indirect-measuring apparatus monitor some property of the bedload or the characteristics of some phenomena that occur as a result of bedload movement.

Direct-measuring apparatus, the most prevalent, can be classified into box or basket samplers, pan or tray samplers, pressure-difference samplers, and slot or pit samplers. Indirect-measuring apparatus are largely limited to acoustical devices that measure the attenuation of acoustic energy or the magnitude and frequency of particle-sampler and/or particle-particle collisions (Hubbell, 1964).

Every direct-measuring sampler such as the Helly-Smith sampler must be calibrated to determine its sampling efficiency. The efficiency is the ratio of the weight of bedload collected during any single sampling time to weight of bedload that would have passed through the width occupied by the sampler entrance. In general, the overall sampling efficiency of a specific sampler is not constant but varies with the size distribution of the bedload particles, the flow conditions, the rate of bedload transport, and the degree of filling of the sampler.

3.D.1.b.2.b. Sampling procedures

With direct-measuring bedload samplers, information on the bedload discharge is obtained by accumulating particles for a given period of time. In order to minimize errors introduced because of spatial and temporal variations in the transport rate, a number of individual samples must be collected at each of several different lateral positions across the width of the flow section. The number of replicate samples required from each position depends on the magnitude of the temporal variations. Whenever it is possible, many samples should be collected and then analyzed statistically to determine the optimum number necessary for a given accuracy. When this is not possible, sufficient samples should be collected until the running average of the wet weights of consecutive samples, or an estimate of the average, achieves a desired stability. Because the rate of bedload transport may vary over the length of the individual bed forms, a moderately stable average rate for any given lateral position can be obtained only if samples are collected periodically during the time required for several bed-form wave lengths to pass by the sampling point; this procedure provides samples from a number of random positions along the lengths of several bed forms. Conversely, if it is possible, sampling at a given lateral position can be performed at various points along a line parallel to the direction of bed form movement; this procedure similarly provides samples from a number of random positions along the lengths of several bed forms.

The number of lateral sampling positions required to represent the discharge adequately, depends on the character of the lateral variations in transport and whether or not longitudinal sampling is undertaken. Initially, no fewer than about 20 sampling positions should be used unless the discharge is very uniform laterally. If both the transport rate and the bed-form configuration is fairly uniform laterally, sampling sequentially at numerous points across a section essentially provides samples from a number of random positions along the length of the bed forms. Hence, if traverses are made repetitively over a long enough time for several bed-form wave lengths to pass by the measuring section, the necessity to sample both randomly along the length of the bed forms and at different lateral positions is satisfied.

When sampling in high velocities with a sampler supported on a suspension line, care must be taken to avoid inadvertently collecting stationary bed material. As the sampler is lowered into layers of progressively lower velocity, the drag force on the sampler continually decreases and the unit achieves an upstream motion which must be arrested before it strikes the bed and scoops up bed material. This upstream motion can be reduced by using a front stay line to limit the downstream displacement. The stay line may cause some samplers to oscillate on the bed and thus pick up stationary particles. Without a stay line, however, whenever the sampler is retrieved it has a tendency to slide upstream prior to lifting off the bed; during this process scooping is possible.

Ordinarily, the "instantaneous" bedload discharge at a point is computed by dividing the dry weight of a sample by the duration of the collection time. This discharge is adjusted by the sampling efficiency to give the true transport rate, and if necessary the true transport rate is corrected by an appropriate amount to eliminate any discharge that is inherently

accounted for by suspended-sediment discharge measurements. Final corrected rates for the point are combined, usually as a simple average, to represent the bedload discharge at the point. The bedload discharge at each point is then multiplied by the width it is assumed to represent and the reciprocal of the proportion that the sampler entrance width is of a unit width to obtain a subsection discharge. Discharges of each subsection for the entire width are summed, in turn, to yield the bedload discharge for the entire transect.

3.D.1.b.3. TOTAL LOAD

At many normal river sections the total load consists of suspended load, which is composed of particles that move within the body of the flow essentially at stream velocity, and bedload, which is composed of particles that move in an interrupted fashion in frequent contact with the bed. Because of the different modes of movement, no sampler is available for sampling total load at normal river sections. However, the total load is usually determined by combining separate measurements of the suspended load and the bedload. At some kinds of "unusual" transects, such as at outfalls, sills, weirs, and highly turbulent flow sections where all of the sediment particles in transport are entrained by the flow, conventional equipment can be used to measure the total sediment discharge by sampling through the nappe or throughout the entire depth (ASCE, 1975). Such flow sections are often called total-load transects.

Suspended-sediment sampling equipment and techniques can be applied at total-load transects to determine the transport rates of particles finer than 2 mm. For particles coarser than 2 mm, equipment capable of collecting and retaining coarser particles, but based on the principles of suspended-sediment sampling equipment should be used. Such equipment includes basket and slot samplers.

Variations in the total-sediment discharge across the flow section result from lateral variations in flow properties, suspended-sediment concentration, and bedload discharge (ASCE, 1975). Thus, sampling must be carried out in accordance with the principles of suspended-sediment sampling and replicate samples must be collected at sufficient lateral locations to account for variations in the entrained bedload particles.

3.D.1.c. LAKES, RESERVOIRS, AND PONDS

Sediment is transported into lakes, reservoirs, and ponds either as suspended sediment or as bedload. In the upstream portion of a reservoir, data to be collected on sediment movement are similar to those collected in a river where there is appreciable flow velocity. Progressing into the reservoir, the flow velocity approaches zero, and movement, if any, results from complex circulation patterns similar to those described under the section on sampling in estuaries. Because of these complex circulation patterns and the complexity of the suspended and bedload sediment movement, the sampling techniques need to be evaluated for accuracy and pertinence to the objectives of a sampling program. Numerous samples of both suspended and bedload sediment may be required to define sediment movement adequately in a reservoir delta. In the delta or upstream reaches of reservoirs, sampling either the suspended sediment or bedload can be accomplished by using the samplers described in the sections on sampling in streams or in estuaries.

Standard suspended-sediment samplers, similar to those used in streams, should not be used in areas of lakes, reservoirs, or ponds where there is little or no velocity. Under these conditions,

samplers that operate on principles similar to grab-type samplers are recommended. These samplers, generally of the Kemmerer type, are essentially open tubes with actuated stoppers (Rand, 1976, p. 1013) and are usually suspended from a boat or barge by cable. The modified Foerst sampler is recommended; however, if the modified Foerst sampler is not available, the heavier and somewhat similar van Dorn sampler may be used. The Neyrpic sediment sampler having a fish-like shape and an intake nozzle may also be used.

The above samplers are cumbersome and inadequate where the data-collection needs are extensive, especially where the sediment concentration is very low. In the absence of the coarser sediment particles, a single or multiple intake system for pumping samples is recommended. The accuracy of the analyses of the pumped sample may be improved because a larger sample is obtained.

3.D.1.d. ESTUARIES

3.D.1.d.1. SUSPENDED SEDIMENT

Suspended sediment is sampled in estuaries for many of the same reasons that it is sampled in streams. However, in estuaries, sediment-transport phenomena are somewhat different than in streams because of the occurrence of density gradients and tidal flow; cross-sectional areas usually are very large; instantaneous water discharges are rarely known; and the primary concerns are usually associated with dredging and polluting of the marine environment. As a result, most estuarine suspended-sediment sampling is designed to define spatial concentrations and the amounts of contaminants associated with unit quantities of sediment, rather than to yield discharge-weighted concentrations.

3.D.1.d.1.a. Types of samplers

Because of the need for spatial concentrations, point or trap samplers have been used extensively in the past for sampling estuarine water for other than sediment. Most such samplers are oriented vertically during sampling, and thus do not sample isokinetically. Therefore, they are not recommended for use in collecting suspended-sediment samples. Unfortunately, several characteristics of standard US-series, suspended-sediment samplers limit their applicability in estuaries: first, because they have a maximum usable depth (*see* table 3-3); and second, because the electrical valving systems tend to short out in salt water. Except in relatively shallow estuaries of low salinity, this type of sampler cannot be used for either point-integrated or depth-integrated sampling. In addition, suspended-sediment concentrations at times are extremely low (2 to 10 g/m^3); hence, volumes of water-sediment mixture substantially larger than those provided by standard samples are required to obtain the desired accuracy for suspended-sediment concentrations and size distributions.

To overcome these difficulties, a collapsible-bag sampler capable of collecting up to an 8-L sample is recommended (Stevens and Lutz, 1969). This sampler avoids all of the pressure-related problems and limitations inherent in US-series samplers by using a plastic bag that is collapsed and devoid of air as a sample container. The water-sediment mixture enters the bag through a horizontal calibrated nozzle at stream velocity and causes the bag to expand as it fills. By providing the sampler with an appropriate valving system, it can be used for either point-integrated or depth-integrated sampling.

Pumping samplers that withdraw large quantities of water-sediment mixture from a point are also used in estuaries to obtain water samples. If samples are collected for biological or water-quality analysis, sampling at stream velocity (isokinetically) generally is unnecessary. However, if sampling

is for suspended-sediment analysis, the water-sediment mixture should be withdrawn through a nozzle that is oriented directly into the flow at such a rate that the mean velocity in the nozzle is the same as the flow velocity at the sampling point (Prych and others, 1967).

3.D.1.d.1.b. Sampling procedures

Depending on the purpose of the samples, either point-integrated or depth-integrated samples might be the most appropriate. Where the intent is to define the spatial distribution of some property of the suspended sediment in the estuary, such as concentration, samples should be collected by the point-integration method at various depths in each of a number of verticals across a transect or across several transects. For transport studies, where the purpose of the sample is to provide information for determining sediment discharges, the depth-integration sampling technique should be used provided instantaneous water discharges are available and the flow is essentially unidirectional at the time of sampling. In both kinds of sampling, each sample represents conditions only during the time of collection, and sampling must be carried out repetitively at each point in order to define the temporal variation throughout an entire tidal cycle.

Sampling at a specific location and time in the tidal cycle cannot be used to completely characterize variations in the suspended-sediment properties in the estuary from one tidal cycle to another, or from one season to another. However, appropriate sampling programs for a given location in the estuary can be devised by analyzing comprehensive sample data collected at that location throughout a number of tidal cycles selected to represent typical variations throughout the period of interest. In general, this necessitates developing models to provide a framework for the sampling results. Where a sediment concentration maximum is present, the model must account for the change in the position of the maximum.

Because of the continual change in the properties of the water-sediment mixture at every point in the estuary, neither the EWI nor the EDI methods of sampling are appropriate. Concentrations can easily vary tenfold during the time required to obtain a set of samples at several locations across all but very small estuaries. To overcome this difficulty, it is necessary to sample continuously through a tidal cycle at a number of locations to define temporal distributions at each location.

3.D.1.d.2. BEDLOAD

Due to complicated flow circulation, periodic reversal of flow direction, and complex vertical distributions of velocity and density, bedload transport (transport of sediment along the bottom) in estuaries is considerably more difficult to measure than it is in rivers. Net transport rates over periods of time (several tidal cycles or more) can be estimated by several of the indirect means used in rivers (*see* section 3.D.1.b.2.); however, the measurements usually are difficult to make. Direct-measuring bedload samplers used in rivers can also be employed in estuaries; however, such samplers have variable sampling efficiencies (*see* section 3.D.1.b.2.a.).

While making bedload measurements, regardless of method, it is necessary to document the transport direction. A synoptic view of dominant transport direction can be obtained by analyzing fathometer records throughout the estuary. Fathometer traces show the shapes of the bed forms from which the direction of bedload movement can be inferred—particles move up the relatively flat "windward" slope and cascade down the steep "leeward" slope. This kind of analysis is facilitated by obtaining records of bottom configuration with sidescan sonar equipment rather than

ordinary fathometers. Sidescan sonar provides a three-dimensional view of bed configurations rather than showing simply the variation of depth along a line (Klein, 1967; Hubbell and others, 1971).

3.D.1.e. CONDUITS AND OUTFALLS

As mentioned in section C.5, sediment movement in conduits and outfalls is likely to be different in character and quantity than it is in streams. Velocities in conduits and at outfalls are usually sufficiently high so that nearly all particles are suspended. Many conduits do not ordinarily carry sand or coarser materials. Some may carry toxic materials in solution or adsorbed on the sediment particles. Regardless of these conditions, samplers, and sampling procedures for suspended sediments should generally be similar to those given for streams (sec. 3.D.1.b.).

The small size of the conduit or outfall in relation to the size of streams makes it more likely that manually collected grab samples can be obtained without a notable decrease in sample quality, especially where the flow contains little or no sand-size material. When practical, the sample container itself should be used to collect the sample to avoid problems of transfer and possible contamination. However, if it is impossible to reach the flow with the sample container, a small submersible pump or a suction line from a nonsubmersible pump may be used to bring the required volume to an accessible location. Harris and Keffer (1974), describe the sizing and methodology for using pumping samplers in conduits in order to obtain representative samples. They also discuss the limitations of pumping samplers in general, and the advantages and disadvantages of many commercially available samplers.

3.D.2. DEPOSITED SEDIMENT

Deposited sediment is sampled to provide information on such things as the size, specific gravity, and mineralogy of particles that make up sediment deposits, particularly particles at and near the water-sediment interface (usually the stream-bed surface); stratigraphy and bedding patterns of deposits; density and compaction of deposits; amounts and distribution of contaminants associated with deposited sediments; character and distribution of benthic organisms; and geochemical character of deposited material. For some of these purposes, samples can be disturbed. That is, the individual particles can be rearranged relative to each other and the volume and shape of the sample can be altered from the original condition of the deposit without affecting the analysis. For most purposes, undisturbed samples are required. Different samplers and sampling procedures are available for various environments.

With respect to streams, bed-material samplers collect samples of the stationary material that makes up the stream bed and is available for transport. Such samplers should not sample the bedload (except incidentally) because the particle-size distribution of bed-material samples and bedload samples collected at the same point in the channel bed are rarely, if ever, identical.

3.D.2.a. LAND SURFACE

Quantitative analysis and understanding the character of deposited sediment on flood plains, alluvial fans, deltas, and other locations requires that representative deposited-sediment samples be

obtained for study. Equipment and procedures needed to obtain these samples can usually be adapted from those used to obtain samples of bed material in streams (sec. 3.D.2.b.) and in lakes, reservoirs, and ponds (sec. 3.D.2.c.). Some of the methods outlined by ASTM (1978), such as "Soil and Rock for Engineering Purposes" (D-420), "Soil Investigation and Sampling by Auger Borings" (D-1452), and "Thin-Walled Tube Sampling of Soils" (D-1587), may be suitable or can be adapted for conditions and objectives at some locations.

3.D.2.b. STREAMS

3.D.2.b.1. TYPES OF SAMPLERS

The most common purpose for sampling sediment deposits in streams is to obtain information on the character of sediment particles that are subject to movement. In streams, this material is commonly called the bed material. Ordinarily, bed-material samples are collected at or near the bed surface to define the particle-size distribution and density of the sediment available for transport. For such purposes, disturbed samples may be used provided that the proportions of the various components of the sample are similar to those in the deposits.

Another basic reason for sampling deposits of sediment in streams is to determine whether sediment laden with pesticides, trace metals, or other contaminants is depositing in specific locations. These "hot spots," including sludge deposits downstream from waste-water treatment plants, could have major biological impact on the stream.

In order to obtain satisfactory samples, the bed-material sampler should enclose a volume of the bed material and then isolate the sample from water currents while the sampler is being lifted to the surface of the stream. The ease by which the sample can be transferred to a suitable container is important. Many bed-material samplers do not embody these features; hence, they may provide altered, unrepresentative samples. Photographs and descriptive material for a number of early bed-material samplers are given in U.S. Inter-Agency Report 2 (1940B).

3.D.2.b.1.a. Shallow samples

Samplers for obtaining material moderately close to the bed surface generally fall into one of the following types:

1. Drag bucket or scoop.
2. Grab bucket or clamshell.
3. Vertical pipe or core.
4. Piston core.
5. Rotating bucket.

For one or more of the reasons mentioned above, the drag bucket or scoop, and the grab bucket or clamshell types are not usually recommended for sampling the bed of flowing streams. The characteristics of the drag bucket are such that some of the sample material may wash away, and the clamshell does not always close properly if the bed contains gravel. However, in situations where these samplers must be used, a special effort must be made to determine the representativeness of the samples.

The vertical-pipe or core samplers are essentially tubes which are forced into the streambed. Penetration in fine-grained sediment is easy; however, penetration in sand usually is limited to about

0.5 m or less. During retrieval, the sample is retained inside the cylinder by a partial vacuum formed above the sample and/or by a core retainer at the lower end. These samplers generally yield good quality samples and are inexpensive and simple to maintain.

Three models of bed-material samplers have been developed by the Federal Inter-Agency Sedimentation Project. These samplers, denoted BMH-53, BM-54, and BMH-60, are shown in figure 3-3 and are available as stock items from the project (address on page 3–19).

The recommended bed-material sampler, BMH-53 (U.S. Inter-Agency Report, 1963), is a piston-type, manually-operated core sampler designed for use in shallow streams that can be waded. The sampler consists of a 51-mm-diameter by 203-mm-long cylinder fitted with a rod-mounted piston. As the cylinder is pressed into the stream bed, the piston retracts and holds the sample in the cylinder by means of a partial vacuum. The piston is also used to eject the sample.

For deeper streams that have a sand bed, both the BM-54 and the BMH-60 samplers are recommended (U.S. Inter-Agency Report, 1963). These samplers have a spring-loaded rotating bucket. The bucket is initially rotated back into the body of the sampler and latched in place. The sampler is then lowered by means of a cable. When the sampler contacts the bed and the cable tension is released, the latch trips and the spring causes the scoop to rotate into the bed in an arc of 180° which drives the cutting edge upward against a seal. The sample is sealed, thus insuring that material will not be lost when the sampler is raised (a particle of gravel may prevent the sampler from sealing). The bucket samples to a maximum depth of about 51 mm and will hold about 160 mL. The BM-54 weighs 45 kg, and the BMH-60 weighs 14 kg. Instructions for operating the BM-54 are given in U.S. Inter-Agency Report (1958A).

3.D.2.b.1.b. Deep-core samples

When the purpose of sampling is to obtain information on the vertical composition of the deposits or on the distribution of contaminants, moderately deep "undisturbed" samples are required. These samples are usually collected with core samplers or piston-core samplers that have removable sample-container liners. In fine-grained sediments, penetration into the bed is fairly easy, but material adjacent to the tube or liner wall may be displaced from its original position, and some of the layers may tend to compact while others do not. Various schemes have been employed to minimize these effects. The Swedish foil sampler (Pickering, 1966), for example, uses thin axial metal strips (foils) that are drawn out continuously from a foil magazine in the cutter head to enclose the sample as the tube is driven downward. In this process, the foils remain stationary relative to the sediment core, and particle displacement and friction between the sediment and the tube wall are eliminated.

Fine sediments are usually easily cored, but sand and gravel are difficult to core moderately deep because they are resistant. Cores up to about 1 m in length are collected with piston-core samplers that are similar to but longer than the BMH-53, or they may be collected manually by driving a core tube into the bed. Longer cores require more specialized samplers. Prych and Hubbell (1966) developed a portable sampler that readily cores sands to a depth of 1.8 m through the combined action of axial force, vibration, and suction. The sampler is usable in water depths up to 50 m and in flow velocities up to about 2 m/s. The axial force is achieved with a suspension system that is arranged so that when the sampler is resting on the bed, applying tension to the suspension cable produces a downward force on the core tube; this same system supports the sampler against overturning due to flowing water. The core tube is vibrated by means of an electrical-mechanical vibrator mounted at the top of the core tube. An internal piston provides suction.

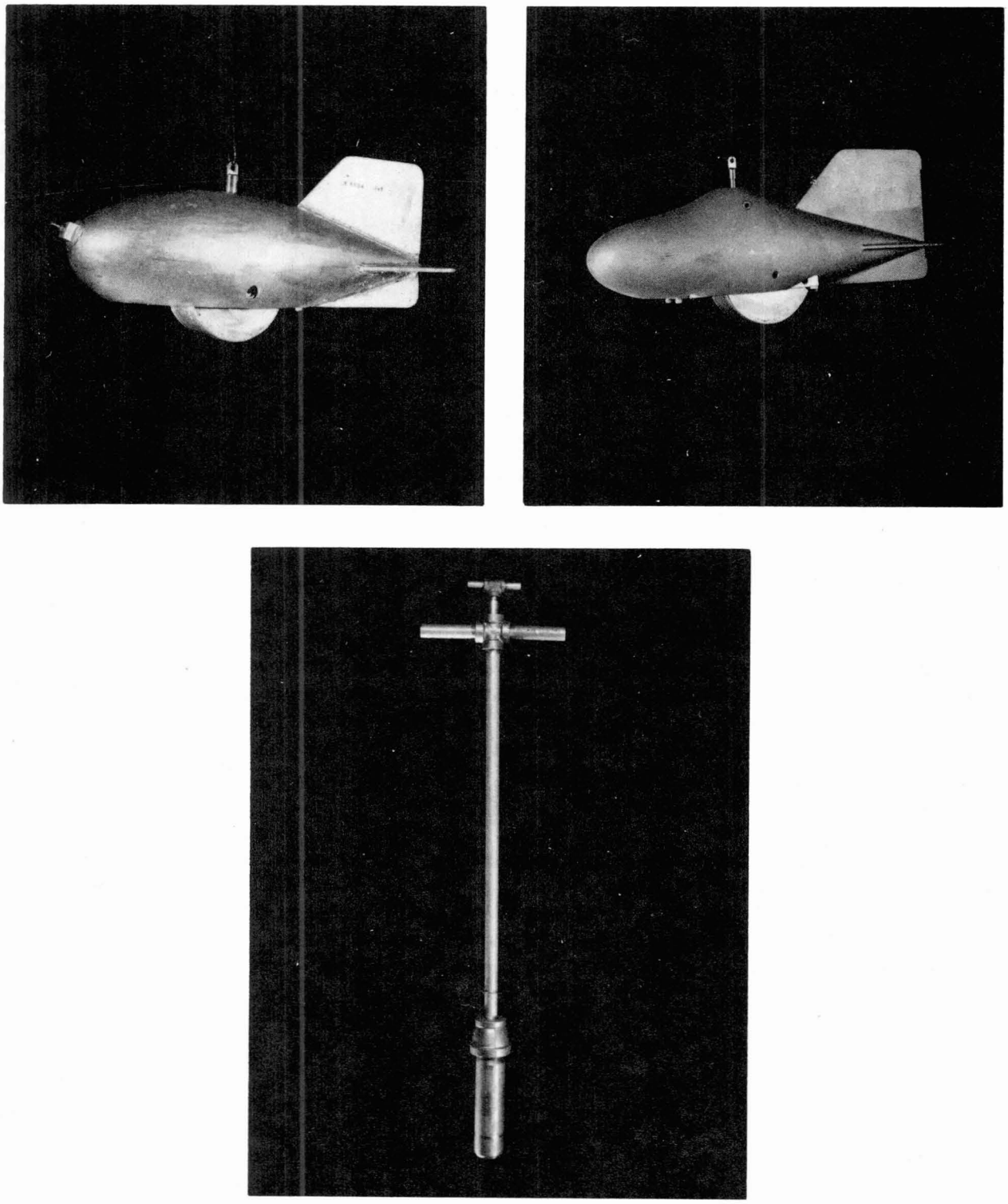

Figure 3-3.—Photographs of three US-series bed-material samplers.

Samples deep in the sediment generally require drilling equipment or special pile-driving equipment, which often produces samples that are highly disturbed or compacted.

3.D.2.b.1.c. Coarse-particle samples

Bed material in stream channels may vary from silt and clay to cobbles and boulders. The standard bed-material samplers described above are designed to collect samples of material in the clay to coarse-sand range. Materials in the gravel, cobble, and coarser ranges are extremely difficult to sample effectively because penetration is difficult and large quantities of material must be collected.

Because coarse sediment is both difficult to collect and to analyze, manual collection and measurement is necessary to determine a representative sample of this material. The stream must be either dry or easily wadable because there is no practical method to determine the size of coarse particles for a nonwadable stream. The recommended method for wadable streams (Wolman, 1954, 1955) is to use a grid pattern to locate the sampling points. The grid may be defined by pacing uniformly spaced points along a series of roughly parallel lines or by using uniformly spaced points along several taped lines. The number of defined points must be at least 200 if the relative quantity of some of the coarser sizes is to be reliably determined. The particle underlying each grid point should be retrieved, and its intermediate diameter measured and recorded. If more detail is desired concerning particle shape, the long and short diameters are also measured. Where the grid point is over sand or finer material, a small volume (perhaps 15 mL) must be collected and combined with samples from other such points for sieve analysis. Equal volumes of such fine material must be collected at each point.

Kellerhals, Rolf, and Bray (1971) show that if particles of various sizes are randomly dispersed throughout a deposit, the number percentages for surface grains are equal to the weight percentages of a three-dimensional sample of the deposit, assuming that all particles have the same specific gravity. Therefore, sizes determined by hand measurement can be combined with sizes determined by sieving into a continuous frequency distribution. Table 3-4 demonstrates the method using data obtained by Williams and Guy (1973). In this example, the above specifications were not met because only 59 grid points were sampled (14 points had stones and 45 points had fine material)—the sizes in the stone range are poorly represented.

Where the surface can be photographed, the gradation of coarse sizes can be determined by using the Zeiss Particle Size Analyzer (Ritter and Helley, 1968). The photographs can be obtained with a 35-mm camera, generally about 2 m above the stream bed. (The height that is needed to obtain a good sample depends on the focal length of the lens and on the size of the bed material.) A reference scale, such as a steel tape or meter stick, must appear in the center of the photograph.

3.D.2.b.2. SAMPLING PROCEDURES

Surface bed material is the sediment in the topmost layers of the stream bed. The procedures for sampling this material depend on the depth of flow, the size of the particles, and how the sample-analysis results are to be used. For instance, if the stream bed consists of sand overlain with a thin veneer of gravel, and the purpose for sampling is to provide size information for computing the bedload discharge, then the most appropriate procedure would be to collect a number of samples exclusively from the gravel veneer itself. On the other hand, if sampling is to provide data for

Table 3-4.—*Computational procedure for combining a sieve analysis with a pebble count*

[Location of sample: Bryant fan, station 1,800. Adjustment factors: 14/59 = 0.237 for large (pebble-counted) stones, 45/59 = 0.763 for fine (sieved) particles]

(1)	(2)	(3)	(4)	(5)	(6)
Size class (mm)	Number of stones	Percentages within subgroups		Percent by weight, entire range of sizes	Cumulative percent finer than upper size limit
		larger stones	sieve-pipet analysis		
4,096-2,048	.....	.....	.....	.....	.....
2,048-1,024	.....	.....	.....	.....	.....
1,024-512	.....	.....	.....	.....	.....
512-256	1	7.1	.....	1.7	100.0
256-128	1	7.1	.....	1.7	98.3
128-64	2	14.3	.....	3.4	96.6
64-32	6	42.9	.....	10.2	93.2
32-16	4	28.6	.....	6.8	83.0
	14	100.0			
16-8	.....	.....	14.2	10.8	76.2
8-4	.....	.....	11.4	8.7	65.4
4-2	.....	.....	14.3	10.9	56.7
2-1	.....	.....	19.0	14.5	45.8
1-0.5	.....	.....	15.8	12.1	31.3
0.5-0.25	.....	.....	12.2	9.3	19.2
0.25-0.125	.....	.....	7.1	5.4	9.9
0.125-0.062	.....	.....	3.2	2.4	4.5
0.062-0.031	.....	.....	2.8	2.1	2.1
				100.0	100.0

estimating bedload discharges throughout a range of flows, then separate sets of samples from both the sand and gravel layers might be appropriate. These could be obtained by segmenting cores collected with the US BMH-53 piston-core sampler. If the sampling is in a sand- or gravel-bedded stream in which the bed material is formed into ripples, dunes, or moving bars, particles are continually being buried and subsequently re-exposed and transported. As a result, the character of the material is fairly homogeneous vertically, and either the BM-54 or the BMH-53 provides acceptable samples. The selection of the best procedure for any given situation is one of the most difficult decisions to make in sediment work. Besides deciding on the proper sampler and sampling depth, judgments must be made on the number and pattern of sample collecting and on how to composite the samples.

In most circumstances, a number of samples should be collected at or near a cross section to characterize the bed material. The samples can be combined into a single composite sample to provide a mean value(s) for the variable(s) under study, provided that the material is fairly uniform. However, samples of dissimilar character should not be combined for a single analysis. A knowledge of the dissimilar characteristics of the bed material in different parts of the sampling area is often important. Also, because the results from individual analyses can be combined mathematically to yield average values, it is better not to combine samples if the merit of compositing is in doubt.

The optimum number of samples depends on the nature and heterogeneity of the material and the variable(s) under study. For particle-size distribution, the number of samples required to provide mean values of a preselected level of accuracy can be determined by the procedures given by Guy and Norman (1970, p. 53) or Hubbell and others (1956). In coarse materials where the particles are so large that an easily collected sample contains only a few particles within each size range, a technique such as that described by Wolman (1954) must be employed (sec. 3.D.2.b.1.c.). One study on a sand-bedded stream (Hubbell and others, 1956) showed that even though the bed material appeared to be reasonably uniform, 15 samples had to be collected in order to achieve a 70-percent chance that the mean percent-finer value for a given size did not deviate from the true mean value for that size by more than 5 percent. Generally, as the range of sizes in the bed material increases, more samples are required to provide accurate mean values. Whenever possible, a statistical study should be made at sites of repetitive sampling to determine how accuracy varies with the number of samples.

When information is required on the vertical distribution of deposited stream sediment or of some quantity associated with the sediment, sampling must be performed by coring. These in turn can be divided into specific segments for analysis. Because one core may constitute many samples, the number of cores must be limited to provide the optimum amount of information.

3.D.2.c. LAKES, RESERVOIRS, AND PONDS

Special equipment is required to sample reservoir bottom sediments in order to determine their density, grain-size distribution, and perhaps chemical characteristics. A variety of samplers have been used to obtain these data. The type to use depends on such factors as sediment grain size, depth of water, degree of consolidation, and sediment depth. Underwater sediments vary in texture. Generally the coarser grained sediments are deposited before they reach the end of the water body. Therefore, the density of reservoir sediment deposits tends to decrease with distance from the head of the reservoir.

3.D.2.c.1. TYPES OF SAMPLERS

3.D.2.c.1.a. Gravity and piston-core samplers (deep water)

The gravity and piston-core samplers are used to obtain undisturbed samples of lake, reservoir, and pond deposits.

The gravity-type sampler (U.S. Bureau of Reclamation, 1958) consists of a top section made of pipe weighted with lead. An encapsulated ball valve in the base of the top section creates the vacuum needed to retain the sample as the instrument is being raised. Coring tubes made of 50-mm inside-diameter galvanized pipe of different lengths are connected to the base of the top section. The length of tube depends on the type of sediments. The steel cutting head at the bottom of the sampler holds the plastic tube liners in place. From a water craft, lower the sampler to the water surface by cable off a power-operated reel. Then allow the sampler to accelerate to achieve the desired penetration. When penetration is complete, raise the sampler to the surface, remove the cutting head, place a cap over the exposed end of the plastic liner, and withdraw the plastic liner containing the sample from the coring tube. Cut off the liner at the other end of the sample and cap and label the sample. The sampler can be operated with a minimum of difficulty in reservoir depths up to 30 m and can penetrate deposits up to 3-m thick.

The U.S. Bureau of Reclamation (1970) uses a heavier and larger piston-type core sampler for obtaining a penetration of 6 m. Because of its bulk, lower the sampler from a large raft or a barge. When the trigger weight touches the sediment surface, the sampler's trigger arm releases the coring head, which allows the sampler to free fall and the cutting shoe to penetrate the sediment. The falling weight drives the tube to the point of maximum penetration. A partial vacuum holds the sample in place as the sampler is raised to the surface.

3.D.2.c.1.b. Piston-core sampler (shallow water)

A sampler made of 0.9-m, 1.8-m, or 2.7-m long stainless-steel tubes (Heinemann, 1962) is commonly used for taking underwater samples in relatively shallow depths. A piston and rod fit inside the tubes. Snap the sampler to tie ropes or cables and suspend it from a reel mounted on an A-frame to assist removing the sampler from the reservoir deposits. To achieve the desired penetration, hold the sampler vertically with the piston at the sediment surface while the barrel is driven into the deposits by repeated drops of the driving weight. The relatively undisturbed sample is forced from the barrel by pushing the piston rod. If necessary, examine the core in the field for texture, stratification, and organic matter. Take a 0.1-m sample from the core about every 0.3 m. Measure the sample length and its depth in the deposit on the piston rods. Place the samples directly into plastic cartons, cap and number them, and record their description and location.

3.D.2.c.1.c. Coring, double-tube, and fixed-piston samplers (above water)

Sediments deposited above the water level, such as in the reservoir headwaters area, are often composed of coarse-grained material in the sand range (0.062-2.0 mm). These can be sampled with a coring-type sampler such as the US BMH-53 (U.S. Inter-Agency Report, 1963). See figure 3-3.

Examples of other types of samplers for sampling exposed sediments include double-tube types and fixed-piston types (U.S. Bureau of Reclamation, 1963). The Denison and Denver samplers are examples of the double-tube type, are similar in design, and have disposable liners for handling and shipping the soil cores. The sample lengths are 0.5 m for the Denison and 0.6 m for the Denver sampler. These are well suited for sampling fine-grained, uncemented, or lightly cemented sediments. These samplers will recover reasonably undisturbed samples if the sediment is slightly cohesive and if the boring is done carefully. The Hrorsler and Osterberg samplers are two of the fixed-piston types. They are available in 76-mm or 127-mm outside-diameter sizes. They are particularly well adapted to sampling cohensionless sands and soft, wet soils.

3.D.2.c.2. RADIOACTIVE PROBES

To determine the density of reservoir sediment deposits *in situ,* use radioactive probes. The probes can determine the unit mass without removing the sample. When the probe is placed in a sediment deposit, its radioactive source emits photons, some of which are absorbed by the sediment. The denser the material, the more energy is absorbed. An instrument, such as a Geiger tube, records the energy from unabsorbed photons, thus indicating a correlation with the unit mass of the deposited sediment.

One such instrument, called a gamma probe (Murphy, 1964), is about 3-m long and weighs 45.4 kg. It consists of three basic components—the probe, ratemeter, and retriever. The upper section of the probe is equipped with a cable connector and a lead-filled cavity that provides suitable mass for the driving force in a free-fall state. The middle section of the probe contains detectors,

preamplifiers, a vertical sensor, and shock absorbers. The lower section of the probe contains a radioisotope source and lead shielding. A counting scaler records the total count of the return radiation while the probe is submerged vertically in the sediment deposits. The count rate is related exponentially to the density of the material.

Another type of probe (U.S. Corps of Engineers, 1965) uses a less-dangerous, radium-226 energy source that has a longer half-life. This light-weight probe (5.4 kg) without attached weights is 0.63-m long and can be operated from either cable suspension or hand-held pipe sections.

A dual probe is available (McHenry, 1971) for measuring in shallow reservoir deposits. The operational functions of this probe are similar to the light-weight probe, except that the measurement is on the horizontal plane; the radiation source and the detector are separate probe units spaced 0.3 m apart. A pipe column, formed by pipe sections fastened to the probe as necessary to increase its length, lowers the probe to the measurement position.

3.D.2.d. ESTUARIES

3.D.2.d.1. TYPES OF SAMPLERS

Sampling deposited sediment in estuaries is essentially the same as sampling sediment in streams and reservoirs, except that more information may be required on the vertical distribution of deposited sediment. Although surface sampling is common, the primary emphasis is on core sampling to obtain reasonably undisturbed samples from various depths below the bed surface. Gravity-type core samplers are most often used. This type sampler consists of a core tube with a core-retaining device and cutter head at the bottom and a surcharge and guide vanes at the top. Many such samplers are designed with a removable sample-container liner inside the core tube and a core-tube piston. To penetrate the sediment, drop the sampler in free fall. In areas where the bottom material is uncompacted silt or clay, samples up to about 2.4 m in length can be obtained. Where penetration is somewhat difficult, use core samplers similar to the gravity samplers but with various driving-force systems such as rockets and explosive charges.

As in other environments, coring in estuary sand is difficult. Gravity corers are relatively ineffective and are capable of securing samples only to about 1 m in length at most. Special drilling or pile-driving equipment will core to greater depths. Applying low-to-moderate frequency vibrations to the core tube and suction pistons inside the core liner greatly facilitate penetration. The core sampler developed by Prych and Hubbell (1966) incorporates these features and has been used extensively in the Columbia River estuary to sample sand deposits to 1.8 m.

Surface samples can be collected with the same types of samplers used in streams. Many estuarine samplers are designed for use in the ocean as well, and their capacities are larger than stream samplers. The US BM-54 is an effective estuarine sampler and is recommended for general use. All of these types of samplers yield disturbed samples.

Obtaining representative samples of fresh, unconsolidated bottom deposits of fine sediment and organic detritus in estuaries and reservoirs is most difficult. Samples of this material are necessary to determine the pollution of sedimentation because high concentrations of organic pesticides and heavy metals are sorbed on and transported by sediment. Specific methods cannot be recommended at this time (1978).

3.D.2.d.2. SAMPLING PROCEDURES

Sampling in estuaries is much the same as sampling in streams. However, because of the large areas involved, the complex circulation patterns, and the influence of large populations of benthic organisms, the composition of the bottom material varies from place to place. Thus, samples should be collected in specific areas that are representative of particular conditions rather than in indiscriminate transects. For surface sampling, many replicate samples should be collected at each location to provide data for statistically evaluating the sample variations. Bathymetric information of the sampling site helps because the samples can then be studied within the context of their surroundings. This is particularly true for core samples.

3.D.2.e. CONDUITS AND OUTFALLS

3.D.2.e.1. CONDUITS

Most conduits are designed to flow without depositing sediment. However, if deposition occurs, the sediment may be sampled through an opening in the roof in larger conduits, if the hydraulic grade line is lower than the opening. Equipment and procedures can be adapted from those presented for streams and estuaries. Sampling deposited sediment in smaller conduits is more difficult.

3.D.2.e.2. OUTFALLS

Samples of deposited sediment from outfalls in streams, lakes, reservoirs, and estuaries can be obtained with equipment and procedures recommended in section 3.D.2.

3.D.3. DENSITY OF DEPOSITS

Reservoirs lose storage capacity because of the accumulation of incoming sediment. Incoming sediment is measured on the basis of the mass of suspended sediment, bedload, and water discharge moved by the stream.

The conversion of total sediment inflow to a reservoir from a mass to a volume requires an estimate of the density of the deposits (sometimes termed unit weight or specific weight) (Lara and Pemberton, 1963). As described in section 3.F.2.a., the suspended samples are analyzed in terms of dry mass of sediment. Therefore, the factor for converting the mass of the sediment to the storage volume is normally defined as the density in terms of the dry mass per unit volume.

When the sediments are saturated, the voids are filled with water and the measurement can be made in terms of the saturated density, ρ_{sat}.

The density of sediments deposited in a reservoir depends on three major factors: (1) the manner in which the reservoir is operated, (2) the texture and size of the deposited sediment particles, and (3) the compaction or consolidation rate of the deposited sediments. Two procedures for determining the density of sediment deposits are available. The first procedure uses *in-situ* sampling of the deposits in existing reservoirs. Data collected as a part of past reservoir surveys on

sediment deposits have aided considerably in determining the density; however, for large reservoirs it is difficult to determine an average unit mass. Numerous samples are necessary to define average density because of irregular sediment deposition patterns and changes in types of material deposited throughout the reservoir. The second procedure for determining the density of sediments uses mathematical equations. Since their establishment (Lara and Pemberton, 1963; Lane and Koelzer, 1943), additional data have been collected on density of deposited materials which provide credence to the equations. Density computations from these equations take into consideration three variables—reservoir operations, sediment size, and compaction. See equation (3-5) and table 3-5.

$$W_t = W_i + 0.43\,K\left[\frac{T}{T-1}\,(\log_e T) - 1\right] \tag{3-5}$$

where W_t = Density for given average deposit in T years, Mg/m^3,
W_i = Initial unit mass from table 3-5 weighted on the basis of particle-size gradation, Mg/m^3,
K = Lane and Koelzer factors from table 3-5 weighted on the basis of particle-size gradation, Mg/m^3, and
T = Time after deposition, years.

Table 3-5.—*Initial-mass (W_i) and K factors for computation of density of sediment deposits, in Mg/m^3*

Type of reservoir operation	[1] Initial masses, W_i			[2] K factors		
	Clay	Silt	Sand	Clay	Silt	Sand
1. Sediment submerged	0.42	1.12	1.55	0.26	0.091	0
2. Moderate to considerable annual drawdown	0.56	1.14	1.55	0.135	0.029	0
3. Normally empty	0.64	1.15	1.55	0	0	0
4. Riverbed sediments	0.96	1.17	1.55	0	0	0

[1] Lara and Pemberton (1963).
[2] Lane and Koelzer (1953).

3.E. SAMPLE HANDLING AND PRESERVATION

Procedures for handling and preserving sediment samples depend on the specific analyses needed, that is, analyses for mass concentration, particle size, or adsorbed trace metals and/or other toxic materials. As noted by Feltz and Culbertson (1972), deteriorated samples negate all the cost and effort expended in obtaining good samples. The procedures for handling and preserving samples usually depend on whether the sample is from the suspended or the bottom environment. When the sample is from the suspended environment, the most difficult problem is obtaining sufficient sediment for the many subsamples required for the different analyses. A composite of a large number of representative samples may be necessary to provide enough sediment. The quantity of sediment available in samples of deposited sediment is usually sufficient for a large number of analyses.

3.E.1. SUSPENDED SEDIMENT

Requirements for handling and preserving suspended-sediment samples that are needed only to determine mass and/or particle size are given by Guy and Norman (1070, p. 45–47) and Guy (1969, p. 18, 26). Generally, breakage can be avoided by using multibottle containers and by protecting the bottles from freezing. Excessive organic growth and/or evaporation loss can be minimized by logging and obtaining gross weight prior to storage and by storing the samples in a cool, dark area. Preservatives are not recommended.

3.E.1.a. SAMPLE SPLITTING

When several subsamples may be needed to determine adsorbed trace metals and/or other toxic materials, in addition to analysis to determine mass and/or particle size, it is recommended that a sample splitter and the procedure described by Pickering (1976A) be used. (*See* appendix 3.L.2.) U.S. Environmental Protection Agency (1974) recommendations for preserving water samples are given in table 3-6. These recommendations should generally be adaptable to analysis for the same constituents on sediment.

3.E.1.b. TRACE METALS

Handling and preserving samples for determining trace metals require special precautions to prevent contaminating the samples:

1. The collection bottles should be precleaned by thoroughly washing with detergent and tap water; rinsing with 1:1 nitric acid, tap water, 1:1 hydrochloric acid, tap water, and deionized distilled water in that order.
2. In the field, as soon as possible after collection, the sample should be filtered, and the filtrate should be acidified immediately to a pH of 2 or less. The filtrate may be held for a period not to exceed 6 months before metals analysis.
3. If total metals concentrations are of interest as opposed to the separate suspended and dissolved fractions, the sample should be acidified in the field with nitric acid to a pH of 2, or less. Holding time to analysis should not exceed 6 months.

3.E.1.c. EXAMPLE OF A NATIONAL SAMPLING PROGRAM

The National Stream-Quality Accounting Network is designed to provide a wide range of water-quality data on streams throughout the Nation. Sample handling and preserving methods,

Table 3-6.—*U.S. Environmental Protection Agency (1974) recommendations for preservation of water samples according to measurement*

Measurement	Volume required (mL)	Container	Preservative	Holding time[1]
Acidity	100	[2] P, G	Cool, 4°C	24 hours
Alkalinity	100	P, G	Cool, 4°C	24 hours
Arsenic	100	P, G	HNO_3 to pH <2	6 months
BOD	1,000	P, G	Cool, 4°C	[3] 6 hours
Bromide	100	P,G	Cool, 4°C	24 hours
COD	50	P, G	H_2SO_4 to pH <2	7 days
Chloride	50	P, G	None required	7 days
Chlorine requirement	50	P, G	Cool, 4°C	24 hours
Color	50	P, G	Cool, 4°C	24 hours
Cyanides	500	P, G	Cool, 4°C NaOH to pH 12	24 hours
Dissolved oxygen				
Probe	300	G only	Determined on site	No holding
Winkler	300	G only	Fix on site	No holding
Fluoride	300	P, G	Cool, 4°C	7 days
Hardness	100	P, G	Cool, 4°C	7 days
Iodide	100	P, G	Cool, 4°C	24 hours
MBAS	250	P, G	Cool, 4°C	24 hours
Metals				
Dissolved	200	P, G	Filter on site HNO_3 to pH <2	6 months
Suspended			Filter on site	6 months
Total	100		HNO_3 to pH <2	6 months

Measurement	Volume required (mL)	Container	Preservative	Holding time[1]
Mercury				
Dissolved	100	P, G	Filter HNO_3 to pH <2	38 days (Glass) 13 days (Hard plastic)
Total	100	P, G	HNO_3 to pH <2	38 days (Glass) 13 days (Hard plastic)
Nitrogen				
Ammonia	400	P, G	Cool, 4°C H_2SO_4 to pH <2	[4] 24 hours
Kjeldahl	500	P, G	Cool, 4°C H_2SO_4 to pH <2	[4] 24 hours
Nitrate	100	P, G	Cool, 4°C H_2SO_4 to pH <2	[4] 24 hours
Nitrite	50	P, G	Cool, 4°C	[4] 24 hours
NTA	50	P, G	Cool, 4°C	24 hours
Oil and grease	1,000	G only	Cool, 4°C H_2SO_4 to pH <2	24 hours
Organic carbon	25	P, G	Cool, 4°C H_2SO_4 to pH <2	24 hours
pH	25	P, G	Cool, 4°C Determined on site	[3] 6 hours
Phenolics	500	G only	Cool, 4°C H_3PO_4 to pH <4 1.0 g/L $CuSO_4$	24 hours

Phosphorus				
Orthophosphate, dissolved	50	P, G	Filter on site Cool, 4°C	[4] 24 hours
Hydrolyzable	50	P, G	Cool, 4°C H_2SO_4 to pH <2	[4] 24 hours
Total	50	P, G	Cool, 4°C	[4] 24 hours
Total dissolved	50	P, G	Filter on site Cool, 4°C	[4] 24 hours
Residue				
Filterable	100	P, G	Cool, 4°C	7 days
Nonfilterable	100	P, G	Cool, 4°C	7 days
Total	100	P, G	Cool, 4°C	7 days
Volatile	100	P, G	Cool, 4°C	7 days

Settleable matter	1,000	P, G	None required	24 hours
Selenium	50	P, G	HNO_3 to pH <2	6 months
Silica	50	P only	Cool, 4°C	7 days
Specific conductance	100	P, G	Cool, 4°C	[5] 24 hours
Sulfate	50	P, G	Cool, 4°C	7 days
Sulfide	50	P, G	2 mL zinc acetate	24 hours
Sulfite	50	P, G	Cool, 4°C	24 hours
Temperature	1,000	P, G	Determined on site	No holding
Threshold Odor	200	G only	Cool, 4°C	24 hours
Turbidity	100	P, G	Cool, 4°C	7 days

[1] It has been shown that samples properly preserved may be held for extended periods beyond the recommended holding time.
[2] Plastic or glass.
[3] If samples cannot be returned to the laboratory in less than 6 hours and holding time exceeds this limit, the final reported data should indicate the actual holding time.
[4] Mercuric chloride may be used as an alternate preservative at a concentration of 40 mg/L, especially if a longer holding time is required. However, the use of mercuric chloride is discouraged whenever possible.
[5] If the sample is stabilized by cooling, it should be warmed to 25°C for reading, or temperature correction made and results reported at 25°C.

together with constituents to be monitored, sampling frequency, sampling techniques, and data handling for this program are given by Pickering (1974).

3.E.2. BOTTOM SEDIMENT

Samples of sediment for routine particle-size analysis can be transported and stored without refrigeration. Bottom sediment samples, including soils, collected for determination of arsenic, phosphorus, and selenium, must be refrigerated or frozen while being transported and while awaiting analysis. For most analyses, do not keep refrigerated samples longer than 4 days. Well-frozen samples can be held for long periods. As in the case of water samples, nutrients and oil and grease analysis should be initiated within 24 hours of sample collection. Glass containers should be filled only three-fourths full to prevent them from breaking when they freeze. Plastic bottles can be used to store samples except those for pesticide analysis. Only wet ice storage can be used for bioassay. Nearly all analyses, including some for particle size, require that the sample not be allowed to dehydrate.

Additional recommendations for handling and preserving samples for moisture and volatile solids and samples for Kjeldahl nitrogen, nitrogen, COD, oil and grease, and trace metal determinations are as follows:

1. Place frozen samples in large beakers and thaw at room temperature overnight. This step is essential to prevent the sample container breaking because of thermal shock.
2. Remove excess water by decanting or suction. Be careful not to lose the organic fluff material in the sample.
3. If large pieces of foreign material, such as twigs, stones, and shells, were not removed at the stream site, pass the sample through a number 10 (2-mm) mesh screen and remove the foreign material. The advantage of removing this material at the stream site is that stream water and the wet sieving process can be used.
4. Samples that have a substantial shell content should be set aside for special handling and analysis and brought to the attention of the chemist.
5. Combine the required samples in a large enamel or Teflon-coated container. Mix thoroughly and split the sample. (*See* appendix 3.L.2.)
6. Homogenize two subsamples:

   One subsample is used for moisture and volatile solids determination. Label the container "HOMOGENIZED DO NOT ACIDIFY."

   Acidify the second subsample with concentrated sulfuric acid to about pH 2 to 3. Use Hydrion paper. Label the container "HOMOGENIZED AND ACIDIFIED". This section subsample is for total Kjeldahl nigrogen, nitrogen, COD, oil and grease, and trace metal determinations.

7. Place the two homogenized sediment samples in a refrigerator at the end of the working day whether the analyses have been completed or not. This step is necessary to prevent or at least minimize chemical changes in the sample.
8. Sediment samples that cannot be homogenized should be labeled "NOT HOMOGENIZED."

3.F. LABORATORY ANALYSIS

3.F.1. CHEMICAL ANALYSIS

The chemical analysis of sediment samples often requires special sampling, storage, and preservation procedures. These procedures are described in section E. For details on the individual methods of chemical and radiological analysis the reader is directed to Chapter 5.

3.F.2. PHYSICAL ANALYSIS

Accepted laboratory methods and procedures for determining the sediment concentration of the water-sediment mixture, the particle-size distribution, the specific gravity, and the unit mass of deposited sediments are given in the following paragraphs[6]. Only those physical properties necessary for the computation of sediment-discharge and sediment-accumulation rates and amounts are considered. The reader is directed to the following literature for additional information (ASCE, 1975; Day, 1965; Guy, 1969; U.S. Inter-Agency Report, 1941B and 1957A).

3.F.2.a. SUSPENDED-SEDIMENT CONCENTRATION

Though the quantity and character of sediment in a sample may vary over a range of concentrations and particle sizes, suspended-sediment samples seldom exceed 50,000 g/m^3 or contain particles coarser than fine gravel (4.0 mm); they usually contain considerable silt and clay. It is easier and more convenient to work with the mass of samples rather than their volumes; therefore, the concentration is normally determined as a ratio of the dry sediment mass to the mass of the water-sediment mixture and stated in the laboratory as parts per million. Sediment concentration should generally be expressed in grams per cubic meter, although sometimes milligrams per liter is used. Conversion from parts per million to grams per cubic meter or milligrams per liter is easily accomplished (*see* table 3-7, p. 3–89). It is recommended that data be reported to the nearest 1 g/m^3 for concentrations to 1,000 g/m^3 and to 3 significant figures for higher concentrations. Special procedures would need to be adopted where it is desirable to determine concentrations to the nearest 0.1 g/m^3.

Evaporation and filtration are the two most frequently used methods for determining sediment concentration. Many laboratories need the capability of using both methods. The filtration method is faster if the quantity of sediment in the sample is small and/or relatively coarse grained. When the Gooch crucible is used with a suitable filter, a dissolved-solids correction is not needed. Laboratory procedures for both methods are well documented (ASCE, 1975; Guy, 1969; U.S. Inter-Agency Report, 1941B).

3.F.2.a.1. EVAPORATION METHOD

The evaporation method is usually best for high concentrations of sediment, such as those frequently encountered in erosion research or in many arid-region streams. The method may be used for low concentrations, but a correction for dissolved solids may be required. Detailed laboratory procedures for this method are given in appendix 3.L.3.

[6] Some of the material contained in this section was contributed by Ferris E. Dendy, of the USDA Sedimentation Laboratory, from an unpublished report prepared for a proposed field manual for research in agricultural hydrology.

3.F.2.a.2. FILTRATION METHOD

The filtration method works well for low concentrations and eliminates the need for separate determination of dissolved-solids concentration. The procedures outlined in appendix 3.L.4. utilize a Gooch crucible with a suitable filter material, such as glass microfiber filter papers. The Gooch crucible is only one of the many filtration methods used in making a sediment-concentration analysis. Other types of filtration crucibles are available commercially and may be used if desired. One of the simplest methods is to place a filter paper in a glass funnel and allow gravity to force filtration. To obtain a satisfactory filtration, all fine particles should be retained as well as coarse particles so that the filtrate is not cloudy.

In the foregoing procedures for determining the concentration of the water-sediment mixture, no provisions were given for removing organic matter from the sample. Normally, this is not done in a concentration analysis. However, removing organic matter may be necessary where its content is high and/or where concentrations must be reported on an organic matter-free basis. A procedure for removing organic matter from the sample is given in the procedures for particle-size analyses.

3.F.2.a.3. SEPARATION OF FINES AND SANDS

Separation of the fine material from the sands at 0.062 mm is frequently required in order to define the concentration of the separate parts or to assist in the particle-size analysis of the sediment. If the visual-accumulation tube is to be used for subsequent particle-size analyses of the sands, the separation should be made with a 0.053-mm sieve. Laboratory procedures for separating fines and sands are given in appendix 3.L.5.

3.F.2.b. PARTICLE-SIZE ANALYSIS

A given sediment sample will usually require more than one method of analysis because of the broad range of particle sizes. Even if more than one method of particle-size analysis is used on a given sample, the gradation for the entire range of sizes in the sample can be given provided that the proportion of the sample used for the different methods is noted.

In addition to the size determinations, the total concentrations can be obtained by adding the concentrations of the different size fractions found by the various methods used. Since, however, a method for total concentration determinations has already been presented, the following methods will be discussed only as they relate to particle-size determinations.

The selection of particle-size classes or grades to be determined depends on the objectives of the analysis. Size classes recommended by the Subcommittee on Sediment Terminology of the American Geophysical Union given by Lane (1947) are recommended. See table 3-2.

Recommended quantities of sediment in the sample, desirable range in concentration, and recommended particle-size range for the most frequently used methods of particle-size analysis are as follows:

Method	*Size range (mm)*	*Analysis concentration (g/m^3)*	*Quantity of sediment (g)*
Sieves . . .	0.062–32	. . . . .	. . . . .
VA tube. .	0.062– 2.0	. . . . .	0.05–15.0
Pipet	0.002– 0.062	2,000–5,000	1.0 – 5.0
BW tube. .	0.002– 0.062	1,000–3,000	0.5 – 1.8

Many suspended-sediment samples will not contain sufficient sediment for any of these methods, in which case, the analysis may be limited to simply determining the percentage of fines and sands. In other cases, samples from the same location for the same runoff event may be combined to achieve the desired quantity of sediment. On the other hand, bed and bank material samples, and sometimes suspended-sediment samples, will require splitting to obtain the desired quantity of sediment for analysis. Dry samples of noncohesive sediments may be reduced by using a commercially available sample splitter or by quartering. Moist samples may also be reduced by quartering or by simply inserting a thin-walled tube to the bottom of the sample container at two or three locations and withdrawing a portion of the sample.

The above recommended quantities can be modified for some studies by using special procedures and by perhaps accepting lower data standards. For example, regarding the BW-tube (bottom-withdrawal tube) method, the U.S. Bureau of Reclamation, Denver, Colorado, has successfully used a 100 g/m^3 minimum analysis concentration of silt-clay by adopting some special analysis and weighing procedures and by operating in a more carefully controlled environment.

3.F.2.b.1. FINE-SEDIMENT METHODS

The hydrometer, the bottom withdrawal tube, and the pipet are the most commonly used methods for determining the particle-size distribution of fine sediments less than 0.062 mm (ASCE, 1975; Guy, 1969; U.S. Inter-Agency Report, 1941B).

3.F.2.b.1.a. Limitations of various methods

Laboratory procedures for the hydrometer method, which have been used extensively in the study of soils, are well documented (ASTM, 1965; Day, 1965). Although the method is relatively simple and inexpensive, its use in sediment work has been limited to fine-grained bottom material because of the need for a relatively large quantity of sediment.

The BW-tube method requires specially constructed and calibrated tubes (U.S. Inter-Agency Report, 1953). It is not used extensively. Even though it is more accurate for very low concentrations of fine materials than the pipet method, it is more time consuming. If it is necessary to use the BW-tube method instead of the pipet method, the methods outlined by American Society Civil Engineers (ASCE, 1975, p. 418–424) are recommended.

3.F.2.b.1.b. Pipet method

The pipet method is probably the most accurate and routinely used method in fluvial sediment analysis. It was easily adapted for fluvial sediment analyses from its use in analyzing soils (Olmstead, Alexander, and Middleton, 1930). Detailed laboratory procedures for the pipet method are given in appendex 3.L.6.

3.F.2.b.2. SAND SIZING METHODS

Two generally accepted methods for determining the size distribution of sand-size (0.062–2.0 mm) particles are the sieving and visual-accumulation tube methods. Larger size particles require direct measurement, volume-displacement measurement, or some other means (ASCE, 1975, p. 410). See sections 3.D.2.b.1.c. and 3.F.2.b.3.

3.F.2.b.2.a. Sieving: wet and dry methods

Both wet and dry sieving methods are used to separate sand particles. In wet sieving, material finer than the sieve opening is washed through, preferably while the sample and sieve screen are submerged in water. Dry sieving requires a sample that is completely dry.

In seiving, the size of the sample is important. Be careful not to overload individual sieves. When using the 76-mm diameter sieves, the minimum recommended sample size is 0.05 g (ASCE, 1975) for medium-size sand (0.5 mm or less). Recommendations for maximum sample size are: (1) For medium or fine sands, use less than 20 to 50 g for 203-mm diameter sieves and less than 3 to 7 g for 76-mm sieves, and (2) for fine sands, use 10 to 20 g for 203-mm sieves and less than 1.5 to 3.0 g for 76-mm sieves (Vanoni, Brooks, and Kennedy, 1961).

The procedures described in appendix 3.L.7. for sieving may be used for sand sizes ranging from 0.062 to 2.0 mm. Coarser and finer grained particles should be removed from the sample by hand sieving and analyzed separately.

3.F.2.b.2.b. Visual-accumulation tube method

The visual-accumulation tube method, often referred to as the VA-tube method, is intended primarily for particle-size analyses of sand-size material (U.S. Inter-Agency Report, 1957B). The suggested size range is from 0.053 to 2.0 mm. Particle sizes outside this range should be removed by sieving and analyzed by other methods.

The VA-tube method is a simple, fast, and relatively inexpensive method to obtain size information based on fall velocity that accounts for the hydraulic properties of the particles. Stratification of the settled particles is, however, not a definite indication of physical sizes, especially if the sample contains considerable amounts of organic matter and heavier- or lighter-than-normal minerals. The results, expressed by calibration as the sedimentation diameters of the particles, are usually better suited for studies of sediment transport and deposition than are the results obtained by sieving.

Samples must be prepared so that when the particles are released, each particle will fall individually. To fall individually, particles must be free of clay, organic matter, and air bubbles. Dry samples must be dispersed in water and allowed to soak for several hours before analyzing. Samples that have been stored may require a dispersing agent to completely separate particles, and hydrogen peroxide may be required to remove algae.

Detailed instructions on operating the visual-accumulation tube have been prepared by the U.S. Inter-Agency Project (1958B)[7]. A condensed version of these instructions and a photograph of the equipment is given in appendix 3.L.7. It is recommended, however, that the laboratory technician study a copy of the VA-tube operator's manual before analyzing the samplers.

3.F.2.b.3. LARGE PARTICLES

Normally samples brought to the laboratory will not contain particles larger than very coarse gravel. The size of larger particles is usually determined in the field by direct measurement. For relatively spherical particles the diameter or circumference may be measured directly with calipers or tape. For irregularly shaped particles, the nominal diameter may be obtained by averaging three

[7] Communications regarding drawings, specifications, and availability of the visual-accumulation tube may be addressed to: Federal Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Hennepin Island and Third Avenue, SE., Minneapolis, Minn. 55414.

mutually perpendicular diameters determined by direct measurements (ASCE, 1975) or by measuring only the intermediate diameter if less percision is needed.

The nominal diameter of some large particles may be determined in the laboratory by volume displacement. Measurements are made by immersing a particle in a graduated cylinder filled with liquid and determining the volume of liquid displaced (ASCE, 1975). The displaced volume, V, is converted to the nominal diameter, d_n, of an equivalent sphere by the equation:

$$d_n = 1.24\ V^{1/3}. \tag{3-6}$$

Cylinders of various sizes are required to assure reasonable accuracy. The diameter of the cylinder should not be more than about two times the nominal diameter of the particle to be measured.

3.F.2.C. SPECIFIC GRAVITY

The specific gravity of dry soil solids, G_s, is defined as the ratio of the mass of a given volume of soil solids at a stated temperature to the mass of an equal volume of distilled water at a stated temperature. Because the mass of 1 cm^3 of distilled water is 1 g, specific gravity is equivalent to grams of dry solids per cubic centimeter (Day, 1965).

Equipment and Supplies. A constant volume pycnometer, drying oven, thermometer, balance, and distilled water are required.

Analytical Procedure:

1. Weigh pycnometer filled with distilled water, preferably at 15°C, to the nearest 0.1 mg.
2. Remove a small amount of water and add a known mass of oven-dryed sediment.
3. Apply suction or boil the mixture to remove air bubbles. Finish filling pycnometer with distilled water at the same temperature.
4. Weigh pycnometer filled with water and sediment to the nearest 0.1 mg.
5. Compute specific gravity as follows:

$$G_s = \frac{W_s}{W_w - W_{ws} + W_s}, \tag{3-7}$$

where G_s = Specific gravity,
W_s = mass of sediment, g,
W_w = mass of water in the water-filled pycnometer, g, and
W_{ws} = mass of water-sediment mixture, g.

If a liquid other than water is used, the computations must take into account the specific gravity of liquid used, and the results should be converted to terms of water.

3.F.2.d. DENSITY: DRY, WET, AND SATURATED

The determination of density requires knowing the mass (weight) of a sample of known volume, usually in reference to sediment in place. Although various sampling methods have been developed for soils, undisturbed samples for sediment, particularly submerged

sediments, are difficult to obtain (Day, 1965; Gottschalk, 1951; Heinemann and Dvorak, 1965).

The density of sediment (or soil) is sometimes expressed in grams per cubic centimeter but kilograms per liter or megagrams per cubic meter are recommended. The measurement includes all the material in the volume, the solid particles plus all voids which may or may not contain moisture. If the void or pore space is completely filled by a liquid (usually water), the sediment is saturated. If part of the void space is occupied by liquid and part by gas (usually air), the sediment is partly saturated. Therefore, the density, ρ, is expressed as the ratio of the mass, W (both solids and water), for a unit volume, V, of sediment:

$$\rho = \frac{W_s + W_w}{V}, \tag{3-8}$$

where ρ = density,
W_s = mass of dried soil or sediment, g or Mg,
W_w = mass of water, g or Mg, and
V = total volume, cm^3 or m^3.

Thus, if all the void space is occupied by air, the soil or sediment is dry and the dry density, ρ_d, is simply the ratio W_s/V.

The following analytical procedure is recommended for determining dry density:

1. Determine the volume of the sample. This is usually determined from the size of the sampler and will be included in the field record.
2. Place sample in a tared drying pan and dry to a constant weight at 105°–110°C; determine and record net dry weight to nearest one part per thousand.
3. Compute unit mass as described above.

The procedure described above for density of sediment is also used for tank- or vat-accumulated samples obtained from erosion studies. Most tank- or vat-accumulated samples should be collected in metal or glass containers of known volume. These containers are usually tared and suitable for oven drying so no sample transfer is required. Remove all sediment from the outside of the container before drying and weighing.

3.F.2.e. MOISTURE CONTENT

The moisture content of deposited sediments is frequently required in computations of dry-sediment mass.

Equipment and supplies.—A balance, drying oven, and drying pans or cans are required.

Analytical procedure.—Since most samples are collected and stored in small metal cans, the usual procedure is to dry the sample in the sample can.

1. Weigh the wet sample as soon as possible after the sample is received in the laboratory and before evaporation occurs, and record W_{sw} to the nearest one part per thousand. Be sure all soil and debris are removed from the outside of the can before weighing.

2. Dry the sample at 105°–110° C to a constant mass and record W_{sd} to the nearest one part per thousand. Percent moisture on a dry basis is

$$M_d = \frac{W_{ws} - W_{ds}}{W_{ds}} \times 100, \tag{3-9}$$

where W_{ws} = mass of wet sediment, and
W_{ds} = mass of dry sediment.

The above determinations can be used in erosion studies where it is often more advantageous to determine the percent dry matter based on the total mass of the wet sediment. Percent dry matter is

$$C_p = \frac{W_{ds}}{W_{ws}} \times 100. \tag{3-10}$$

3.G. TURBIDITY (OPTICAL OPACITY)

Turbidity, an imprecise term which is used to describe the cloudy or murky appearance of water, has different meanings for different users. Technically, turbidity is an optical property of a fluid that causes light to be scattered and absorbed rather than to be transmitted. The amount of scattering and absorption is determined by the concentration of particles, their shape, size distribution, reflective index, color, and absorption spectra. The quantitative measurement of turbidity is affected by several instrument characteristics, such as the angle of measurement, the size and shape of the optical beam, the volume of the sample, and the spectral distribution of the light source. The many different ways now used to define or measure this property make turbidity standards ambiguous.

McCluney (1975) summarizes the proliferation of methods, instruments, standards, and units for turbidity measurements. The original instrument designed to measure turbidity was the Jackson Candle Turbidimeter, a laboratory device that measured a combination of optical variables, such as light scattering, adsorption, and reflectance, using the human eye as the detector. Efforts to automate turbidity measurements have resulted in a variety of instruments, including nephelometers and transmissometers, to measure various optical characteristics, such as percent scattering at a specified angle, percent transmission, and extinction length. Each type of instrument is calibrated with one of several standards. Some of these instruments have been successfully used on small streams to record an indication of the temporal changes of suspended-sediment concentration between times of conventional sampling (Reed, 1976; Walling, 1977).

In May 1974, a turbidity workshop (Austin and others 1974) elicited participation from nearly 100 representatives of private industry, universities, and State, Federal, and foreign governments. Conclusions and recommendations from this workshop favored abandonment of quantitative measurements of turbidity of natural waters in favor of precise optical measurements to be reported in scientific terminology. It is expected that these recommendations will be adopted by the Sedimentation Committee for the Water Resources Council, the American Society for Testing and Materials, and the Coordinating Council for Water-Data Acquisition Methods. Adoption of these recommendations need not negate the value of historic turbidity data if the new optical measurements and the previous measurements can be correlated.

Pickering (1976B) states that measurements of light transmittance and light scattering made by the U.S. Geological Survey should be standardized by adopting specific types of instruments and reporting in appropriate optical units, such as extinction coefficient, percent of incident light scattered at 90°, and percent of indicent light transmitted at 180° over a standard distance. The word "turbidity" should not be used in reporting these measurements for natural waters.

In view of the ambiguity in the many methods to measure turbidity of natural waters, no specific method is recommended herein. This should not detract from the fact that, with rapid changes in technology, there should be an effort toward developing automatic sensors for detecting and recording the quantity and character of sediment in streams. Past work with these sensors has ranged in complexity from relatively simple to highly complex (U.S. Inter-Agency Report, 1964; Flammer, 1962). The sensors have received limited acceptability because of cost, spatial errors, lack of sensitivity, or reliability.

3.H. RESERVOIR SURVEYS

3.H.1. GENERAL

Many procedures for measuring the accumulated volume of sediment deposits in relatively small reservoirs were established during a nationwide study of reservoir sedimentation in 1935 (Eakin, 1939). Some of these procedures, with various modifications, are still used by Federal and State agencies in the United States. In larger reservoirs, procedures have evolved through practice by the agencies operating these large reservoirs and through association with interagency developments (Lane and Koelzer, 1943).

Although reservoirs differ widely in size, most fall within two categories: retention reservoirs for the control of floods, sediment, or debris; and single or multiple-purpose reservoirs designed for flood control, irrigation, water supply, power production, recreation, navigation, conservation, and water-quality control. Because of the unique physical and operating characteristics of each reservoir, methods and techniques used for measuring reservoir sediment deposits are quite diverse. Many represent a state of the art that developed from necessity, some are based on the availability of equipment or of previous operator experience, and some have definite application limits. The terms reservoir survey or sedimentation survey imply a variety of field observations and measurements, laboratory analyses, data processing, and report preparation. Report preparation includes not only the required analysis of data needed for the operating program, but also other aspects of the study results, such as methods used and unusual problems encountered. Necessary conclusions can be reached without preparing a final report, but without a written report others cannot benefit from all the time, effort, and expense expended in the measurement program.

This section describes the art of current reservoir surveys. The description of methods may emphasize operations needed for the more complex problems associated with larger reservoirs. Methods for small surveys are described by Gottschalk (1952) and U.S. Soil Conservation Service (1968), or can be improvised based on this description.

3.H.2. SCOPE

The number of reservoirs surveyed, the intensity of coverage in these reservoirs, and the timing of sediment deposit measurements, depend on knowledge needed for one or more of several reservoir uses. The size of the impoundment will affect the location and nature of the sediment deposits, and will therefore likely affect the scope of the measurement program on a given reservoir. For example, as deposition depletes the storage volume of a large multipurpose reservoir, a periodic reallocation of available storage must be made to satisfy the operational requirements of the various water users. Since such deposition is both continuing and variable with respect to time and distribution within the reservoir, survey measurements are necessary to document the physical changes occurring in water storage capability. From these measurements, computations establish the water volumes remaining in each incremental storage zone and the rate of depletion. This information provides the basis for storage reallocations and adjustment of operational area-capacity tables and serves as a basis for planning future project operations. For smaller reservoirs designed only for retaining sediment or debris, measuring sediment deposits is necessary to establish the remaining capacity and security of the system storage-depletion trends, to establish sediment-yield rates for the contributing catchment, and to evaluate project effectiveness and the need for replacing storage by removing the deposits.

Developing a reservoir sediment-measuring program, investing in efficient and effective facilities and equipment, conducting field surveys, and preparing the resulting report are expensive. In order to assure optimum returns from this investment, plan carefully and systematically. Preparations should include not only the administrative details, such as schedules, costs, and personnel assignments, but also technical details, such as mapping, range layout and monumentation, procuring equipment and supplies, and training personnel.

Plans should reflect the nature and magnitude of existing or anticipated project problems and the correlation of measurement data to other reservoir projects for verification. Classifying objectives by functional or operational types is desirable. In addition to the primary functional objectives, secondary objectives may include the need to provide information for planning and designing future projects. Examples of functional objectives would include such determinations as changes in reservoir storage volumes, redistribution of deposits due to reservoir drawdown, amount of tailwater lowering due to downstream degradation, and sediment yield from contributing watersheds. Operational objectives may include providing bench marks for forecasting future depletion rates, establishing limitations on flowage easements, revising intake or outlet design, orienting recreation facilities or structures, and assessing water-quality control methods.

In general the scope of the sediment-deposition measurement program will depend on the study objectives and may be one of the following types:

Scope	*Coverage*	*Scope of observations*	*Time required*
Reconnaissance	Usually entire reservoir with observations only at selected locations.	Identification of major changes with a minimum of detailed observations.	A few days or less depending on impoundment size and access.
Partial	Extensive over a limited reach of the impoundment.	Sufficient detailed measurements to establish magnitude and cause of local change.	A few days to several weeks depending on objectives.
Complete	Extensive over entire reservoir including inflow and outflow channels.	Normally detailed and precise measurements. Depends on study objectives.	Depends on impoundment size and access. Can vary from a week to several months.

3.H.3. SURVEY METHODS

The size of the reservoir, the scope of the program, and perhaps the availability of equipment and operating experience usually dictate the type of survey to be made. The survey for relatively small reservoirs can usually be accomplished using basic methods and procedures, whereas the survey for relatively large reservoirs usually requires some complex and specialized techniques. Thus the survey techniques and practices needed require the specification of the type of survey; the operation schedule and personnel needs; the degree of preparatory work; and the land survey, the hydrographic survey, and sediment sampling methods.

3.H.3.a. TYPES OF SURVEYS

Two general methods of determining the sediment volume and water capacity of a reservoir are by the contour survey and the range-line survey. Selecting a method depends on the availability and character of previous mapping or survey records, the purpose and scope of study objectives, the size of the reservoir, and the degree of accuracy desired. The range-line method usually requires less field work and less expense than does the contour method.

3.H.3.a.1. CONTOUR SURVEY

The contour-survey method involves determining sediment or water volumes through changes in the reservoir topographic contours (U.S. Bureau of Reclamation, 1975; U.S. Soil Conservation Service, 1968). Therefore, relatively close-interval contour maps are required for comparison. For all except the larger reservoirs, the interval generally should not exceed 0.5 m. This method has a distinct computational advantage over the range-line method when deposition or scour covers relatively large, irregular areas; however, it is usually expensive because of the time required for any field surveys or special photogrammetric requirements (Wolf, 1974). Photogrammetric methods become increasingly more efficient for larger reservoirs, especially where the reservoir is dry or at a very low stage. Detailed hydrographic coverage is needed for the part covered with water.

Where a contour map of the reservoir prior to inundation is not available, it is possible to develop such a map by systematically spudding or by otherwise determining the depth of the deposits. Surface contour changes produced by shoreline erosion or offshore deposition must be evaluated also.

3.H.3.a.2. RANGE-LINE SURVEY

Range-line surveys involve determining cross-sectional changes along range lines. Water volumes or deposition volumes can be computed from the distance between range lines. The method does not measure all volume changes occurring over irregularly shaped surface areas unless the range lines are closely spaced. For larger reservoirs, a computation technique proposed by Burrell (1951) has been developed to use contour data along with range data to circumvent this problem (ASCE, 1975; U.S. Soil Conservation Service, 1968).

The range-line method consists of laying out a system of representative ranges (*see* fig. 3-4 and 3-5) and determining the present water depths at intervals along the ranges; sediment depths are also needed if an accurate prior survey is not available. The number and location of ranges depend on the shape and size of the reservoir being surveyed. The main body of the reservoir and its principal tributary arms are subdivided by ranges so that sediment deposits in each subdivision or segment is represented, insofar as possible, by the average of conditions bordering the ranges.

For each major tributary or arm of the reservoir, a new series of ranges is started without regard to the direction of the ranges on the main body of the reservoir. The first range should be laid out across the mouth of the tributary or arm and perpendicular to its general direction as nearly as practical.

If it is anticipated that periodic resurveys will be made, the end of each range should be marked above the normal shoreline with a permanent marker, such as a precast, $0.1 \times 0.1 \times 1$ m reinforced

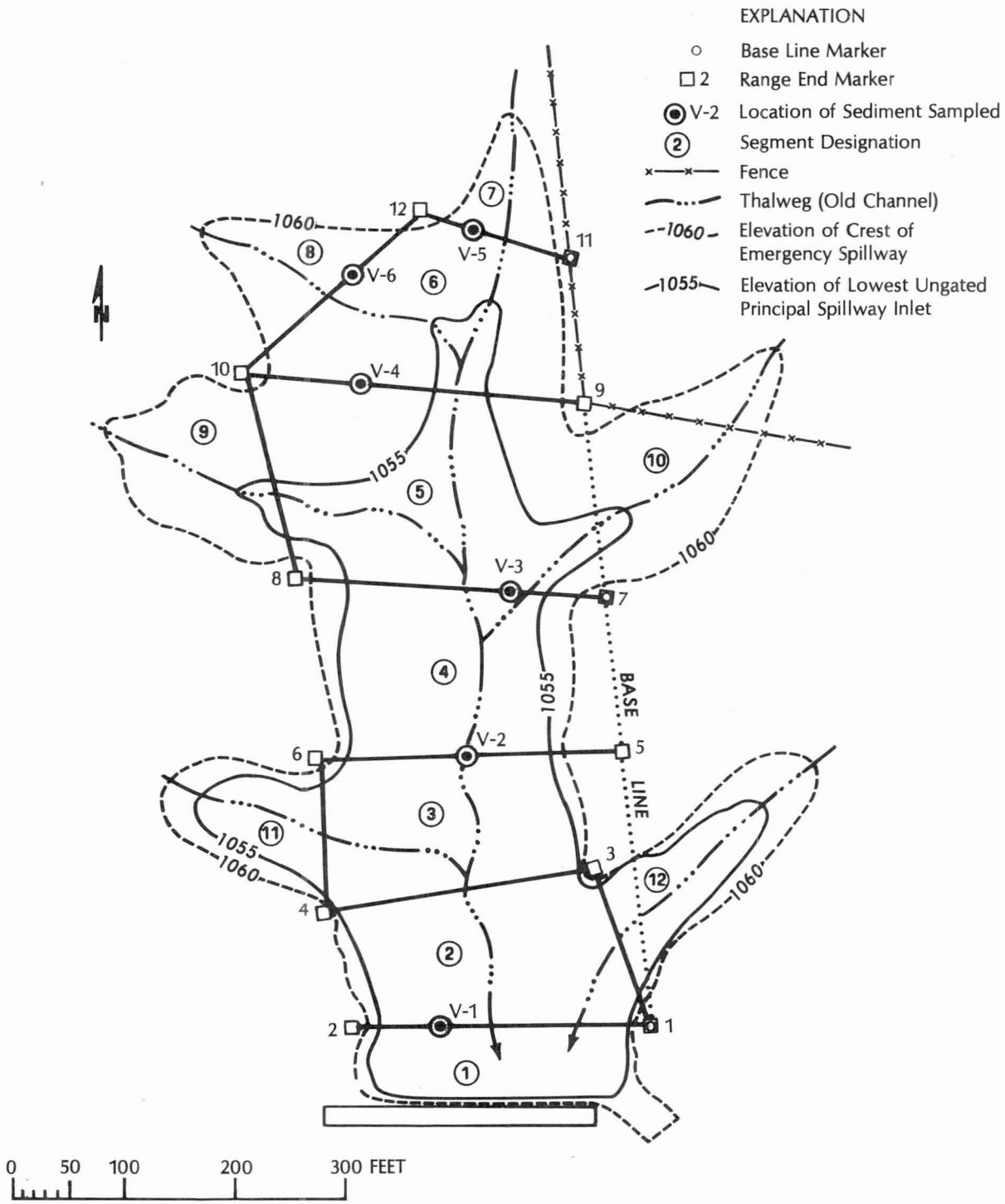

Figure 3-4.—Example of range layout for a small reservoir.

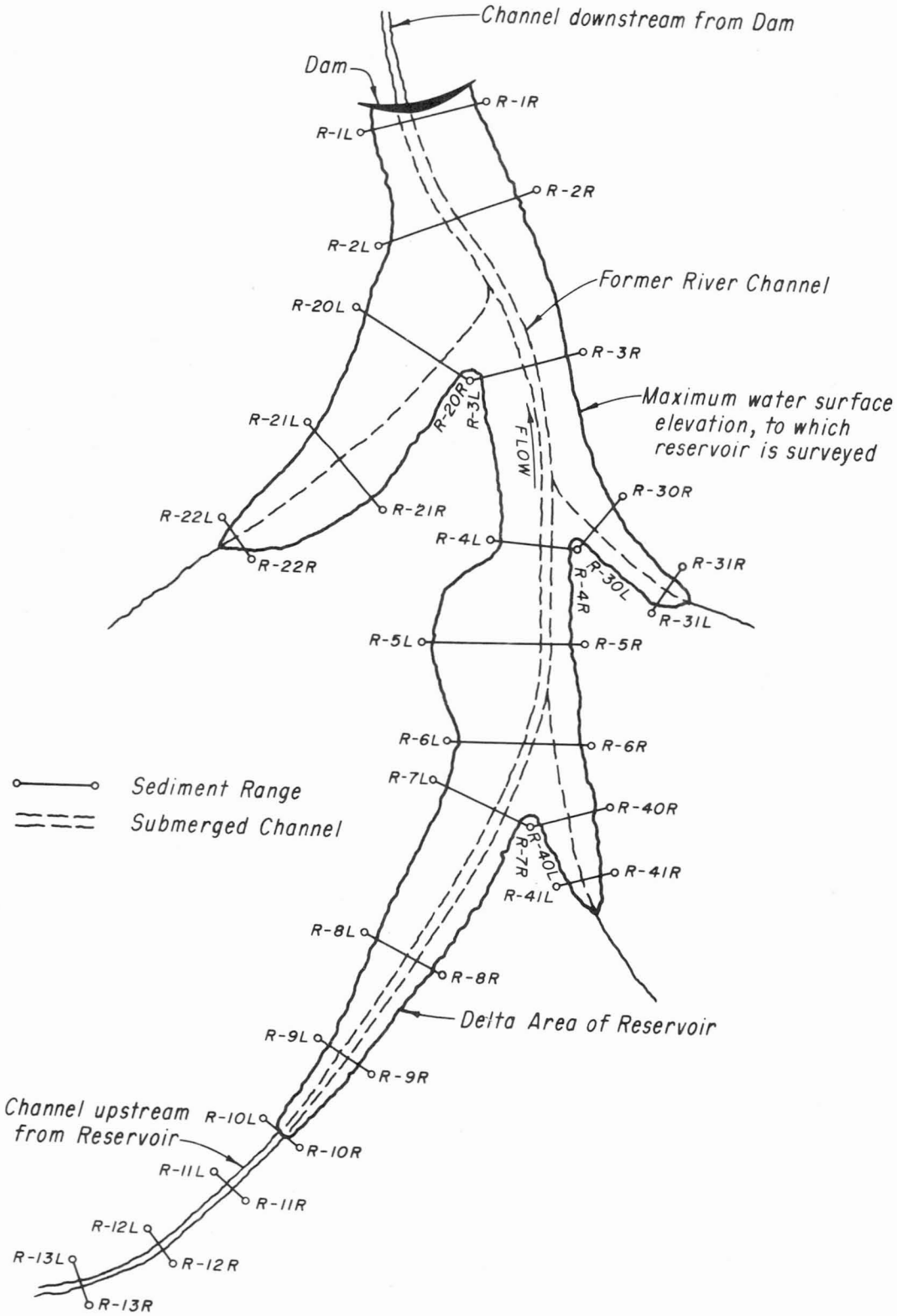

Figure 3-5.—Example of range layout for a large reservoir.

concrete post. The markers should be set into the ground deep enough so that they are not affected by frost action. Whenever sediment surveys are to be made after a new dam is closed, monumentation and subsequent survey control work should be accomplished prior to flooding the reservoir. In mountainous areas where large-size material is likely to be deposited in the reservoir, an original survey of the pool area is particularly important. For sediments larger than sand, determining the original bottom of the reservoir by probing or sounding will be impossible or extremely difficult at best. Mapping or observing the reservoir contours prior to inundation is useful in determining range locations because breaks in slopes can be readily observed and measured.

3.H.3.b. OPERATIONAL SCHEDULES

A schedule is necessary to integrate the planned operations. The size of the impoundment, elapsed time since previous survey, status of ground control, availability of personnel and equipment, scope of study objectives, and sometimes agency practice will determine the detail required for such a scheduling effort. Functional and operational objectives may require different procedures in using available resources. Thus, methods or techniques to be used in satisfying study objectives should be identified early in the planning stage. The field work is the most expensive part of the operation; the laboratory work is the second most expensive. Time spent in planning and incorporating these operations into an efficient operational schedule is very important to a successful program. Presurvey orientation of personnel is also desirable, particularly when new or unfamiliar requirements and procedures are involved. Possible alternatives in the schedule should be provided in case of adverse weather conditions or equipment breakdown. In addition, each aspect of the operation requires extensive safety precautions.

3.H.3.c. PERSONNEL NEEDS

Personnel requirements vary depending on policy and the scope of the survey, but accepted practice usually calls for an engineer-in-charge to direct and coordinate the activities of the field parties. For surveying small reservoirs, the engineer may also serve as party chief over a crew consisting of an instrument man, one or two rodmen, and perhaps a boat operator. Since a bearing-and-distance survey is generally used for the horizontal control, the rodmen also serve as leadsmen or sounder operators when the traverse crosses inundated areas.

For surveying large reservoirs, a more specialized and experienced crew, perhaps divided into several parties, is needed. For example, one party might concentrate on all land survey work. Their responsibility would be to locate and flag the range monuments, survey the ground contours to a point near the water's edge, and establish temporary bench marks for later use by the hydrographic crew. When using electronic sounding and distance-measuring instruments, the hydrographic crew is divided into at least two parties. The sounding party consists of the crew chief, the sonic-sounder operator, the operator of the distance-measuring instrument, and the boat operator. The shore party includes an instrument man, rodman, and at times a small-boat operator. They are responsible for completing the range-line survey from the temporary bench marks established by the land-survey party to some underwater point that can be duplicated by the sounding party, plus directing the movement of the sounding boat along the range line. When using less modern hydrographic survey techniques, the number of personnel required varys considerably depending on the method of operation.

A nucleus of qualified and experienced personnel is essential for an efficient and productive field operation. Key personnel include: (1) a hydrographic crew chief experienced in all phases of the field operations plus knowledgeable about computation and report needs; (2) a crew member capable of maintaining and repairing all field and electronic instruments; and (3) an experienced boat operator to assure the safety of personnel and equipment. Training field personnel should not be limited to individual assignments but should also include some training in the work of other crews and individuals to improve communication and job satisfaction. An effective means of developing competent personnel is by using the crew members for both field and office work. This gives a greater insight of study needs to the personnel and promotes their enthusiasm by giving the recognition of sharing authorship of the complete work.

3.H.3.d. PREPARATORY WORK

Most of the preparatory work involves establishing the range-line control network and assembling proper hydrographic survey instruments and equipment. In order to document the amount and location of sediment deposits and changes in impoundment volume, sufficient transect (range-line) measurements to determine the cross-sectional areas or topographic contours must be made. Such measurements require base maps, or perhaps detailed contour mapping if making topographic comparisons, for orientation and location of a sediment-range network. Examples of range networks are given in figures 3-4 and 3-5. The number and spacing of the ranges is a judgment decision where the desired precision of the volume measurements must be balanced against the time and cost of the survey operations, i.e., more ranges produce greater precision, but they also produce higher cost. Details on standard practices for range identification, spacing, network control, and associated requirements can be found in ASCE (1975), U.S. Corps of Engineers (1961), Heinemann and Dvorak (1965), and U.S. Soil Conservation Service (1968).

Measuring elevation points or contour intervals along the range line is normally accomplished using hydrographic survey techniques. (If the reservoir is dry, land survey methods combined with measurements of deposition thickness and unit mass may be adequate). Equipment requirements revolve around the need for a stable but movable floating platform or boat, a means of determining the position of the boat as it traverses the range line, a method for continuously measuring the water depth, and devices for probing and sampling the sediment deposits. For small reservoirs, the requirements are satisfied by slight modifications to land-survey and soil-sampling techniques. However, the requirements quickly multiply whenever the water surface exceeds about 100 ha. For a given situation a variety of acceptable equipment may be available covering a range of capabilities, complexities, and prices. Matching suitable equipment with data requirements and personnel training is an important part of planning. Further details and references on hydrographic survey equipment and sampling instruments are given in sections 3.H.3.f and 3.H.3.g.

3.H.3.e. LAND SURVEY METHODS

Land surveying that is needed for reservoir surveys involves establishing a traverse that locates and identifies all reservoir ranges, or control points in the case of a contour survey. Included would be the definition of range stationing and (usually) mean-sea-level elevations at individual permanent and temporary bench marks, as well as the measurement of changes in the land contours along the range line and above the reservoir water surface level. Generally third-order accuracy for the basic

horizontal and vertical control to permanent bench marks is adequate. Fourth-order accuracy will ordinarily suffice for range-line work.

Transit leveling combined with stadia distances are common practice for range-line work (or planetable alidade levels with stadia distances for topographic work). The scope of work can be a major factor in determining the need for complete traverse control for large reservoirs. When the reservoirs are located in remote and inaccessible country, a complete traverse network tie between range monuments may not be feasible because of cost. In such instances, monuments can be marked in the field and their relative position identified by aerial photography. By using the measured distances between monuments on a given range, the photo scale can be established. This permits missing portions of a traverse to be incorporated into the overall network.

Instruments that are needed for the traverse include a transit, a level, rods and stadia boards, chain and pins, and range poles. The equipment is common, and methods are standard (Abbett, 1956; Davis, Foote, and Kelly, 1966; U.S. Soil Conservation Service, 1968). Distance-measuring devices, operating by the principles of high-frequency radio waves or modulated and reflected light beams, now provide an economical means for establishing horizontal control for both large and small range network. These instruments are expensive but their accuracy and ease of operation permits a more efficient survey routine (U.S. Corps of Engineers, 1964).

3.H.3.f. HYDROGRAPHIC SURVEY METHODS

Hydrographic survey methods are used to determine the underwater reservoir bottom, usually at specific transects, or to determine contours of the bottom. Normally the water surface serves as an elevation reference point, and depths are measured along established range lines or at identified locations to define the bottom configuration.

3.H.3.f.1. DATUM CONTROL

Taking hydrographic soundings requires determining the position of a sounding point and simultaneously measuring the water depth. Such distance measurements are made from fixed land monuments or known control points. The water surface serves as the horizontal reference plane. For surveying smaller reservoirs by either the contour or range method, positions are usually determined from stadia and/or angle measurements and the depths, by pole or weight-sounding from a small boat. In some instances, measurements from the ice cover are made during the winter. This is not a preferred method, but it might be adequate for a reconnaissance survey. For larger reservoirs, the sounding points are usually located along an established range line by measuring the distance from the range monuments. Brief descriptions of the constant-speed, stadia, bearings or angles, current-meter, wire, and electronic methods of maintaining horizontal control during a range-line survey follows.

3.H.3.f.1.a. Constant speed

The constant-speed method of measuring distance requires the boat to traverse a range line at a constant speed to take soundings at known time intervals. Several buoys or markers at known locations along the range line can serve as checkpoints. Special sounding locations are determined by either time or distance interpolation. Since it is impractical to maintain a constant boat speed for

any appreciable distance, this method is used primarily for reconnaissance sounding operations where such accuracy limitations are acceptable.

3.H.3.f.1.b. Stadia

The stadia method uses common transit or alidade techniques, whereby measurements are made to a stadia board mounted in the sounding boat while it slowly traverses the range line. Soundings and stadia measurements are usually made simultaneously, but in some instances several soundings may be taken at equal intervals between stadia measurements and their position fixed by interpolation. The limit for measuring distance depends on the length of the stadia board, and as expected, the accuracy decreases with increased distance. Thus, the method is commonly used when distances are less than approximately 500 m. By stationing an instrument man at each end of the range and overlapping several stadia readings at midpoint, the total sounding distance can be almost doubled. The use of half-interval stadia readings will permit still greater coverage but decreased accuracy. Combining the stadia and constant-speed methods permits better definition of sounding points very near the shore where the boat speed is not constant. Additional detail can be found in Abbett (1956), Davis, Foote, and Kelly (1966), and McCain (1957).

3.H.3.f.1.c. Bearings or angles

The bearing or angle method involves locating the sounding position by the intersection of two or more distances or angles. Measurements can be made from either the shore or the sounding boat. The planetable technique is very common where the sounding boat traverses a given line and its position fixed at intervals by intersection of that line. Single transit or sextant angles from a base line will produce similar results. Another alternative uses the intersection angles from two transits located on a base line or sextant angles between markers at known intervals along a base line.

The angle or bearing technique permits the simple computation of the distance along the range line, but requires considerable preparatory work in establishing and measuring base lines, plus additional personnel to man the instruments and record data. Another technique involves distance measurements between the boat and known shore points. One or more "simultaneous" distances are measured and the boat position is determined by intersection of the distance arc with the range line or with other measured arcs. The accuracy defining "fix points" depends on the precision of angle measurements and base line control. Further explanation of these techniques can be found in ASCE (1975), Davis, Foote, and Kelly (1966), Fry (1948), and U.S. Corps of Engineers (1964).

3.H.3.f.1.d. Towing current meter

The towing current-meter method has application for both reconnaissance and general hydrographic surveys. A standard Price current meter is suspended from the sounding craft to a sufficient depth from the hull to avoid influence of the bow wave. The optimum suspension point is normally not critical since the sounding speed is usually slow enough to avoid a major bow-wave disturbance. However, the boat speed is restricted to a rate less than the critical limit where the cable-suspended current meter and weight tend to yaw from a stable, near-vertical position. The distance traveled along the range line becomes a function of the accumulative revolutions of the meter times the calibration constant for that meter. Electronic counters, coupled with the sonic-sound "fix" switch, permit a semiautomatic operation of recording and documenting positions along the range line. McCain (1957) and Fowler and Livesey (1957) describe this method in more detail.

3.H.3.f.1.e. Wire

Several variations for determining horizontal positions by wire distance measurement are available. Automating the mechanical counter for distance and sonic-fix recording is also possible. Mechanical counters have a thin wire or cable that passes continuously around the circumference of a calibrated wheel or between a calibrated wheel and tension device to measure the distance traveled. In some applications the wire is stored on a reel and played out as the sounding boat traverses the range line. In another adaptation the wire is first stretched along the range line and the boat counter simply measures the distance along the wire from some known starting point. For short ranges an alternative wire method uses a marked cable or tag line stretched taut across the range. Standard techniques for this method are further discussed by ASCE (1975), McCain (1957), Rausch and Heinemann (1968), and U.S. Soil Conservation Service (1968).

3.H.3.f.1.f. Electronic or optical

The techniques and instrumentation used for electronic or optical distance measurement are technically complicated, usually highly accurate, and relatively expensive. However, they possess the capability of being used independently in a horizontal positioning scheme or being integrated into a totally automated and continuously recording positioning-depth measurement system. Generally the practice at this time integrates an electronic or optical-distance measurement with the sonic-depth sounding only at random fix-point intervals with appropriate notes recorded on the sounder chart. This scheme is essentially a one-dimension, line-of-sight distance measurement where the sounding craft maintains position on the range line by online markers or shoreline transit control. The factors of initial high cost and sophisticated maintenance prevent the various automated systems now on the market from qualifying as the standard method for all hydrographic survey operations. These sophisticated methods use three basic position techniques—the range-azimuth method, the range-range method, and the automatic dead-reckoning method. Any of these systems provide the capability of automatically recording continuous position-depth measurements on magnetic tape for later processing or for instantaneous output of cross sections or "track maps" as the survey progresses. Operational methods and procedures, which can vary with the specific scheme or system employed, are usually well documented in the manufacturer's operational and maintenance manuals. The reader should also refer to U.S. Corps of Engineers (1972, 1973, and 1974).

3.H.3.f.2 SOUNDING TECHNIQUES

Techniques for obtaining depth soundings include using sounding poles, lead-lines or wire-sounding cables, and electronic sonic-echo equipment. The sonic method is preferred for obtaining soundings because it can continuously record, it is accurate, and to some degree it is versatile for special-purpose measurements. However, the other methods are more advantageous in cost, operation, and simplicity in some circumstances.

3.H.3.f.2.a. Sounding pole

The sounding-pole method for obtaining soundings is generally limited to water depths less than the standard pole length of 6.7 m. Modern poles are made of light-weight metals for strength, neutral buoyancy, and sound-transmitting capability. An experienced soundsman can measure the water depth as well as distinguish the relative characteristic of the bottom material by the feel of the pole and the tone produced by the metal pole as it contacts the bottom. This "sound"

technique has been used successfully for defining the extent of gravel bars or rock outcroppings. The sounding-pole method has been further described by Davis, Foote, and Kelly (1966), U.S. Soil Conservation Service (1968), and U.S. Corps of Engineers (1964).

3.H.3.f.2.b. Lead-line or sounding cable

The lead-line or sounding-cable method of sounding is relatively simple and inexpensive in terms of equipment cost, but it is physically exhausting in deep-water operations. The availability of inexpensive sonic sounders has virtually superseded the use of this method for general hydrographic survey work. However, like the sounding-pole method, there are some situations where the sounding cable has advantages. Standard practices for using the sounding cable are given in Davis, Foote, and Kelly (1966), U.S. Soil Conservation Service (1968), and U.S. Corps of Engineers (1964).

3.H.3.f.2.c. Sonic-echo soundings

The sonic-echo sounding method is recommended for most sounding work because of the variety of instruments available. Cost is usually the major factor that prevents wider application. As noted in section 3.H.3.f.1.f., the sonic sounder can become an integral part of an automated system to produce almost instantaneous cross-section plots as the hydrographic survey progresses. Simultaneously, it will store all horizontal-control and water-depth data on cassette cartridges for further data processing. Highly trained personnel are needed to calibrate, operate, and maintain the more complex, versatile, and expensive equipment.

Most current hydrographic sounding operations use the sonic-sounder recorder chart for recording calibration checks, range stationing or distance measurements, water stage or elevation, and other pertinent information. For this reason, the instrument is the focal point of the survey operation. In depths of less than approximately 1.2 m, supplemental pole soundings are necessary to assure depth coverage when background noise obliterates the true sounding trace. These depths, as well as water's-edge stationing and sandbar-elevation data, can be conveniently transcribed on the sounder chart to provide a continuing record of the survey as it progresses along the range line. For reconnaissance or exploratory soundings, the sounder chart is generally used for all record notations. Additional detail on method of operation for this equipment is given by the manufacturer and by ASCE (1975) and U.S. Corps of Engineers (1972, 1973, and 1974).

3.H.3.g. RESERVOIR SAMPLING

The scope of sampling observations depends on the sedimentation survey objectives. As a minimum, measurements of the density and particle-size distribution at representative locations throughout the reservoir should be made for each survey. A radioactive sediment probe provides the best method for *in situ* measurement of density; however, some operational limitations exist regarding overall sample depths and penetration of deposits, and radiologic safety, but the method provides accurate measurements and avoids costly laboratory handling and analysis of core samples. The sediment density probe has been discussed by ASCE (1975), U.S. Corps of Engineers (1965), McHenry and Hawks, (1963).

In relatively cohesive sediments, core sampling is the best way to measure the total deposit depths because it provides samples for determining particle-size distribution and chemical quality of the sediments. However, for noncohesive material, such as sand, core sampling may not be accurate

because penetration may cause compaction or retrieval problems. For sampling procedures see section 3.D.2.c.

3.H.4. LABORATORY ANALYSES

The overall reservoir survey must include laboratory analysis to characterize bottom sediments and sometimes suspended sediments. Common analyses include the density and/or particle-size distribution of bottom-sediment samples. Standard methods for sample handling and laboratory analysis are defined in sections 3.E. and 3.F., respectively.

3.H.5. DATA EVALUATION AND REPORTING

The scope of data evaluation from reservoir surveys depends on the purposes outlined in the survey plan. The reporting format varies with the publication criteria of individual agencies, but in general, the report outlines follow an informally accepted standard. However, for certain cases in both data evaluation and reporting there are specific standards covering all reservoir-sedimentation surveys that have been prepared by the U.S. Water Resources Council's Committee on Sedimentation. (*See* section 3.H.5.d.) The following discussion concerning reservoir storage volumes, sediment depletion rates, area capacity tables, and reservoir-sediment data summaries should help in preparing technical reports. References on data evaluation techniques and procedures include Bondurant (1955), Borland and Miller (1958), Burrell (1951), Gottschalk (1948), Heinemann and Dvorak (1965), Lazenby and Nelson (1976), Smith, Vetter, and Cummings (1960), Dendy and Champion (1973), and U.S. Tennessee Valley Authority (1968).

3.H.5.a. RESERVOIR STORAGE VOLUMES

The basic computation of reservoir storage volumes concerns determining both water and sediment volumes. This may include defining the longitudinal and vertical distribution of sediment deposits by range increments in addition to defining the representative density of both aerated and submerged deposits.

3.H.5.b. SEDIMENT DEPLETION RATES

Sediment depletion rates are derived from changes in the storage volumes between surveys. Further computations can establish total or incremental drainage-area delivery rates and reservoir trap efficiency factors. If the suspended-sediment inflow is measured, computations can establish approximately the unmeasured sediment load and particle-size distribution, which in turn are usually correlated with the density of the sediment deposit.

3.H.5.c. AREA–CAPACITY TABLES

Another major product of any reservoir sedimentation survey is updated area-capacity tables or curves. These tables, which define the total reservoir storage volumes and pool surface area by elevation increments, provide the basis for both daily and long-term reservoir operations.

3.H.5.d. RESERVOIR SEDIMENT–DATA SUMMARY

The reservoir-sediment data summary (fig. 3-6) is prepared in accordance with specific instructions developed by the U.S. Water Resources Council's Committee on Sedimentation. This summary should be prepared as completely as possible and promptly forwarded to the committee for inclusion in periodic bulletins summarizing reservoir sedimentation surveys. Standard forms and instructions are available from the committee for this summary report.

RESERVOIR SEDIMENT
DATA SUMMARY
SCS-34 Rev. 6-66

CANTON LAKE
NAME OF RESERVOIR

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

46-13b
DATA SHEET NO.

DAM

1. OWNER Corps of Engineers	2. STREAM North Canadian	3. STATE Oklahoma
4. SEC. 27,28,33 TWP. 19N RANGE 13W	5. NEAREST P.O. Canton 2 N	6. COUNTY Blaine
7. LAT. 36 °05 ′ ″ LONG. 98 °36 ′ ″	8. TOP OF DAM ELEVATION 1648.0	9. SPILLWAY CREST ELEV. 1/1638.0

RESERVOIR

10. STORAGE ALLOCATION	11. ELEVATION TOP OF POOL	12. ORIGINAL SURFACE AREA, ACRES	13. ORIGINAL CAPACITY, ACRE-FEET	14. GROSS STORAGE, ACRE-FEET	15. DATE STORAGE BEGAN
a. FLOOD CONTROL	1638.0	15,750	272,300	401,500	2/ 25 Jul 47
b. MULTIPLE USE					
c. POWER					
d. WATER SUPPLY	3/1615.2	8,360	106,450	129,200	16. DATE NORMAL OPER. BEGAN
e. IRRIGATION					
f. CONSERVATION	3/1596.5	3,340	22,750	22,750	4 Jul 48
g. INACTIVE					

17. LENGTH OF RESERVOIR 13.1 MILES | AV. WIDTH OF RESERVOIR 1.8 MILES

WATERSHED

18. TOTAL DRAINAGE AREA 4/ 12,483 SQ. MI.		22. MEAN ANNUAL PRECIPITATION 19.30 INCHES
19. NET SEDIMENT CONTRIBUTING AREA 5/ 6,081 SQ. MI.		23. MEAN ANNUAL RUNOFF 0.28 (28.58 yrs) INCHES
20. LENGTH 300 MILES	AV. WIDTH 40 MILES	24. MEAN ANNUAL RUNOFF 186,400 AC.-FT.
21. MAX. ELEV. 6500	MIN. ELEV. 1575	25. ANNUAL TEMP.: MEAN 58.5 RANGE 106 to -2.5

SURVEY DATA

26. DATE OF SURVEY	27. PERIOD YEARS	28. ACCL. YEARS	29. TYPE OF SURVEY	30. NO. OF RANGES OR CONTOUR INT.	31. SURFACE AREA, ACRES	32. CAPACITY, ACRE-FEET	33. C/I. RATIO, AC.-FT. PER AC.-FT.
July 1947	-	-	Range (D)	44	15,750	401,500	2.15
6/May 1953	5.83	5.83	Range (D)	22	15,750	390,800	2.10
6/Oct 1959	6.42	12.25	Range (D)	22	15,750	385,900	2.07
Sept 1966	6.92	19.17	Range (D)	25	15,700	383,300	2.06

26. DATE OF SURVEY	34. PERIOD ANNUAL PRECIPITATION	35. PERIOD WATER INFLOW, ACRE-FEET			36. WATER INFL. TO DATE, AC.-FT.	
		a. MEAN ANNUAL	b. MAX. ANNUAL	c. PERIOD TOTAL	a. MEAN ANNUAL	b. TOTAL TO DATE
May 1953	20.05	288,890	540,420	1,684,200	288,890	1,684,200
Oct 1959	19.51	162,760	422,930	1,044,900	222,780	2,729,100
Sept 1966	18.69	99,170	159,390	686,260	178,160	3,415,360

26. DATE OF SURVEY	37. PERIOD CAPACITY LOSS, ACRE-FEET			38. TOTAL SED. DEPOSITS TO DATE, ACRE-FEET		
	a. PERIOD TOTAL	b. AV. ANNUAL	c. PER SQ. MI.-YEAR	a. TOTAL TO DATE	b. AV. ANNUAL	c. PER SQ. MI.-YEAR
May 1953	10,690	1,834	0.302	10,690	1,834	0.302
Oct 1959	4,880	760	0.125	15,570	1,271	0.209
Sept 1966	2,660	384	0.063	18,230	951	0.156
				7/18,500	7/ 965	7/0.159

26. DATE OF SURVEY	39. AV. DRY WGT., LBS. PER CU. FT.	40. SED. DEP., TONS PER SQ. MI.-YR.		41. STORAGE LOSS, PCT.		42. SED. INFLOW, PPM	
		a. PERIOD	b. TOTAL TO DATE	a. AV. ANN.	b. TOT. TO DATE	a. PERIOD	b. TOT. TO DATE
May 1953	70.9	466.4	466.4	0.457	2.66	7,224	7,212
Oct 1959	56.2	65.3	255.8	0.317	3.88	1,795	5,138
Sept 1966	56.1	76.4	190.6	0.237	4.54	3,447	4.799

Figure 3-6.—Reservoir sediment-data summary

26. DATE OF SURVEY	43. DEPTH DESIGNATION RANGE IN FEET BELOW, AND ABOVE, CREST ELEVATION											
	63-55	55-45	46-40	40-35	35-30	30-25	25-20	20-15	15-8	8-cr	cr +5	+5-+10
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN DEPTH DESIGNATION											
May 1953	4.3	12.1	11.9	15.7	17.1	15.2	12.0	7.4	4.3	0.0	0.0	0.0
Oct 1959	3.2	7.7	5.6	12.0	16.4	22.2	14.7	9.9	6.7	1.6	0.0	0.0
Sept 1966	3.5	13.2	9.1	13.1	16.3	15.4	11.5	7.4	6.2	2.8	1.4	0.1

26. DATE OF SURVEY	44. REACH DESIGNATION PERCENT OF TOTAL ORIGINAL LENGTH OF RESERVOIR														
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	-105	-110	-115	-120	-125
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN REACH DESIGNATION														
May 1953	2.5	6.4	10.7	19.3	21.3	17.9	15.6	4.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Oct 1959	2.3	2.2	4.7	17.0	27.2	19.1	17.1	6.1	3.1	1.2	0.0	0.0	0.0	0.0	0.0
Sept 1966	4.3	5.7	7.7	18.0	22.3	16.2	14.1	5.3	3.3	1.8	1.3	0.0	0.0	0.0	0.0

45. RANGE IN RESERVOIR OPERATION

WATER YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AC.-FT.	WATER YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AC.-FT.
1947 (2 mo)	-	-	248	1957	1625.51	1596.32	422,930
1948	1599.80	-	90,800	1958	1616.12	1613.68	185,310
1949	1614.27	1595.91	437,640	1959	1615.40	1613.12	104,130
1950	1623.84	1602.85	532,180	1960	1615.56	1613.79	145,230
1951	1628.05	1602.36	540,420	1961	1614.65	1613.79	135,330
1952	1605.30	1598.65	81,170	1962	1615.16	1613.12	106,920
1953	1598.75	1588.66	29,530	1963	1614.21	1610.21	61,326
1954	1596.75	1588.30	52,846	1964	1611.93	1600.86	20,513
1955	1615.50	1585.66	223,790	1965	1616.18	1600.41	159,390
1956	1613.27	1604.33	10,953	1966	1615.52	1609.82	74,720

46. ELEVATION-AREA-CAPACITY DATA

ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY
1580	0	0	1610	6,323	79,150			
1585	242	256	1614	7,535	106,700			
1590	1,489	3,987	1615	7,879	114,400			
1595	2,678	14,160	1620	9,497	157,800			
1596.5	3,018	18,430	1625	11,258	209,800			
1600	3,652	29,950	1630	12,756	269,800			
1603	4,411	42,100	1635	14,510	338,100			
1605	4,873	51,390	1638	15,700	383,300			

47. REMARKS AND REFERENCES

1/ Top of spillway gates closed. Spillway crest is at elevation 1613.0.
2/ Date of diversion.
3/ Reservoir is being operated at "designated" pool elevation 1615.2 which temporarily provides municipal water supply for Oklahoma City.
4/ Area as determined by AWR committee for April 1954 drainage area data publication.
5/ Excludes 4,642 sq. mi. of watershed not contributing to sediment; 1735 sq. mi. above Fort Supply Dam and 25 sq. mi. surface area of Canton Lake.
6/ To provide a uniform presentation of data from all sedimentation resurveys of Canton Lake, data summaries for the 1953 and 1959 resurveys have been revised to conform with present instructions.
7/ Includes above crest deposits.

48. AGENCY MAKING SURVEY U.S. Army Engineer District, Tulsa
49. AGENCY SUPPLYING DATA U.S. Army Engineer District, Tulsa 50. DATE October 1970

for Canton Lake, Oklahoma, 1947–1966.

3.I. CHANNEL CHANGES

3.I.1. APPLICATION AND SCOPE

Stream channels will aggrade, degrade, or move laterally as a result of natural or manmade environmental changes that affect the water or sediment movement form the catchment, or as a result of changes that affect the stream channel directly. These may include significant changes in land use, such as urbanization, dams, channel controls, channel straightening, diversion, added flow, subsidence, uplift, mining, and landslides. Some channel changes, which may be attributed to general morphological changes, are accelerated when the seasonal water discharge pattern is altered or when there are upstream changes in the sediment load or size of sediment.

It is important to note the qualitative stream-channel equilibrium relationship described by Lane (1955):

$$Q_w S \approx Q_s D, \tag{3-11}$$

where Q_w = water discharge,
S = river slope,
Q_s = sediment load, and
D = effective diameter of the sediment transported.

Degradation or aggradation of the stream channel will likely occur if any of the factors in the equilibrium relationship change.

A stream-channel monitoring program should provide quantitative data about the characteristics of a stream channel at a given time as well as over a period of time. At a given point in time, the monitoring program can provide the channel length, mean cross-sectional area, total channel volume, channel slope, channel elevation, channel shape, channel boundary materials, and the location of the channel. If the same parameters are measured another time, they can be compared with the first set. If they are plotted to the same scale using the same horizontal and vertical control, changes in channel parameters can be visually compared. Thus, whether the channel is aggrading, degrading, or migrating can be determined, as well as the magnitude of these changes (Herb, 1976).

The following factors should be considered before beginning a channel monitoring program:

1. Is the proposed study reach representative of the stream, or part of the stream, under consideration?
2. Is the channel reach relatively free, within the limits of normal vegetative constraints, to adjust its width, depth, slope, and length of meander in response to changes in the flow regime?
3. Is the study reach free of the effects from physical controls imposed by man's activities, such as buildings, bridges, and training structures, or of natural controls, such as rock outcrops and ledges?
4. If the purpose of the study is to monitor channel response to changes in the flow and/or sediment regime, is the study reach free of upstream constraints, such as dams or construction activity which would modify the parameters under investigation?
5. Is it desirable and feasible to establish a comparative reach on a nearby stream?

3.I.2. PROCEDURE

The basic procedure for monitoring channel changes consists of a series of comparative surveys of selected channel reaches. These surveys will establish a series of cross sections which can be used to

determine the length, volume, and location of a reach of the stream channel, together with the composition of the channel boundary. When initially establishing a channel-monitoring system, the investigator must provide adequate horizontal and vertical control for the surveys. Aerial photographs, including enlarged portions, are useful for planning and conducting the field operation and for the file as a record.

The procedures described above are applicable to surveys on streams which are dry or easily waded. Otherwise, underwater methods described for hydrographic surveys under section 3.H.3.f. are applicable.

3.I.2.a. CONTROLS

Vertical and horizontal controls can be tied to a series of bench marks that must be relocatable. The controls can be permanent structures such as building foundations or wingwalls on bridges, or they can be temporary references installed for the duration of the study. Because temporary and even permanent references may be lost, it is necessary to have several reference points near a given study reach.

From these horizontal and vertical reference points, lay out enough cross sections or ranges to adequately define the physical attributes of the stream as well as the sediment and plant cover variations in the reach. Lay out enough cross sections to define the channel when plotted in plan view. One or two extra points should be plotted to define the thalweg between the cross sections. The ranges should be generally normal to the channel; or more specifically, they should be perpendicular to a line tangent to the thalweg. The ranges may also be located as the bisector of the angle between straight-line segments defined by azimuth stadia points that locate the thalweg. The end points of the ranges should be tied into the survey net and bracket the area where the channel is likely to migrate during the study.

3.I.2.b. THE SURVEY

Once the end points are located, survey the reach photogrammetically or by field measurements. Photogrammetric methods require stereoplotting equipment that uses automatic-recording cross-section or coordinate reading equipment. For most river work photogrammetry provides an accuracy of 0.1 m vertically and 0.5 m horizontally. However, field measurements are more precise. Horizontal stationing may be established along the range line by tape or stadia.

Determine the elevation and location of the following points along the range line:

1. Points at regular intervals, such as every 10 m (to be determined by the width of the cross section) in areas of constant slope.*
2. Points at prominent features in the cross section, such as edge of water, edge of banks, thalweg, large stones, and plant-cover boundaries.
3. Points necessary to define the shape of undercut banks.
4. Points at other breaks in slope.

*For the study at Reston, Virginia, on streams draining 20 to 200 ha, maximum spacing of the points was set at 1.5 m horizontal and 0.1 m vertical.

The elevation of these points, with the exception of work accomplished by photogrammetric methods, is generally determined to the nearest 0.01 m. Station numbers on the range line should increase from left to right facing downstream, and range-line numbers should increase upstream.

Field notes in addition to the above survey notes should contain adequate narrative descriptions to permit complete reconstruction of the survey in the office. To describe the surveys totally, both regular photographs and stereophotographs of the cross sections should be available. This allows a more qualitative as well as quantitative analysis of the survey at a later date. Photographs and slides should be filed with the survey notes. Detailed description is necessary because related computations and comparisons may be made by different individuals many years after the initial survey.

3.I.2.c. SAMPLING OF FLOW BOUNDARY

3.I.2.c.1. SEDIMENTS

Sample the boundary under study to define, as needed, specific properties of the boundary materials. Sediment properties should include particle-size gradation and density, and may include shape, specific gravity, and fall velocity of representative particles as well as sorting, cohesiveness, stability, plasticity, porosity, unconfined compressive strength, and permeability of representative bulk samples. These properties may be correlated with erosion, transport, and deposition along the channel.

Obtain a representative sample for each important segment or deposit where sediment characteristics differ; samples on the surface of the flood plain may be spaced less than 100 m apart, and bank samples may be spaced less than 1 m apart. The property or properties to be measured and the nature and character of the deposit dictate the size of the sample, the equipment needed, and the method to be used. (*See* section 3.D.2.a.)

3.I.2.c.2. PLANT COVER

A description of the plant cover along the range lines usually indicates the general character of the plant cover along the reach under study. Plant cover may affect erosion, deposition, evapotranspiration, and perhaps some of the bulk sediment characteristics. Isolated large trees on the flood plain should also be noted if they are near a stream bank that may be eroded. The survey notes should correlate plant cover with changes in sediment characteristics, overland flow, and the water table along the range line and between the range lines.

3.I.2.d. DRAFTING

The next step is to transform the raw data from the field measurements into a form that will be useful for future analysis. Two important products of the field survey are a map of the stream showing the location of the range lines, thalweg, channel banks, and other data (such as flood-plain delineation) and a cross-section plot for each range.

The map will provide a measure of channel length between consecutive ranges, which is useful in examining changes in sinuousity and in making computations to determine changes in channel volume. All reference points should be indicated on the map.

3.I.2.e. CHANNEL CROSS-SECTIONAL AREA AND VOLUME

The channel cross-section area is defined by the wet perimeter below a horizontal line across the channel to the lowest of the two banks (a designation for bank-full capacity). Therefore, during the field survey when all features of the reach can be observed, identify the general bank-full level, translate this to the cross-section ranges, and indicate the location in the survey notes.

The channel volume is determined by multiplying the channel length (represented by each channel cross section) by the area of this cross section and summing the totals for the whole reach. The channel length is usually defined by the sum of straight-line lengths connecting the thalwegs of stadia or succeeding cross-section ranges on the thalweg. If succeeding range locations are designated, $A, B, C \ldots N$, the area at each range is designated $A', B', C' \ldots N'$, and the stream length between thalweg location A and thalweg location B is designated as $\overline{AB}$, etc. The total channel volume is:

$$\left(\frac{\overline{AB}}{2}\right)(A') + \left(\frac{\overline{AB} + \overline{BC}}{2}\right)(B') + \left(\frac{\overline{BC} + \overline{CD}}{2}\right)(C') + \ldots + \left(\frac{\overline{MN}}{2}\right)(N') \qquad (3\text{-}12)$$

If similar surveys and computations are made at another time, it is possible to compare the measurements for channel length, mean cross-sectional area, total channel volume, channel slope, channel elevation, channel shape, and location of the channel in space. By plotting the data to the same scale using consistent horizontal and vertical control, it is possible to compare channel changes for the different surveys and to determine the magnitude of aggradation, degradation, or migration.

3.J. QUALITY CONTROL

Wening (1976) has stated that quality is the sum of features and characteristics of a product or service that bear on its ability to satisfy a given need. He also states that quality control is the overall system of activities that provides quality that is adequate, dependable, and economic. The quality of a sediment record incorporates the quality of the many individual samples or data elements obtained to represent the record and the quality or representativeness of these samples with respect to the long-term climatic and environmental factors affecting sediment movement.

It is not possible in this chapter to indicate how to evaluate precision for the many methods presented. Therefore, this discussion presents quality-control concepts which affect the general worth of the record, which in turn affects the planning and management of operations for sediment-data acquisition. Additional detail on the subject may be found in ASTM (1974 and 1976).

3.J.1. DATA ELEMENTS

The general quality of a specific element of sediment data obtained to represent a given point in space at a given time is affected by methodology, equipment, and the operator through the various field, laboratory, and computational phases. In addition, the data element must be representative of the spatial aspect of the study and must be representative of a specific short-term aspect; in other words, where and when to obtain the sample is very important. It is evident then that the quality of a specific element of sediment data may be affected by the following components:

1. Field methodology.
2. Field equipment.
3. Field operator.
4. Laboratory methodology.
5. Laboratory equipment.
6. Laboratory operator.
7. Computation methodology.
8. Computation equipment.
9. Computation operator.
10. Local spatial variation.
11. Short-term temporal variation.

Thus, in mathematical terms the overall standard error of estimate for the sample element is:

$$S_t = (S_1^2 + S_2^2 + S_3^2 + S_4^2 + S_5^2 + S_6^2 + S_7^2 + S_8^2 + S_9^2 + S_{10}^2 + S_{11}^2)^{0.5}. \qquad (3\text{-}13)$$

For all practical purposes, this formula cannot be used quantitatively because the components cannot be specifically measured. However, you can obtain perspective from this formula. Note that the standard error of estimate of individual items is squared; thus, one or two items that have a large error can cause an inordinately large reduction in the quality of the data element. An indication of the overall error for the sample element can be obtained for a given sampling condition by measuring the variation for a number of samples collected in rapid succession (Guy and Norman, 1970, p. 37–42). This kind of statistical analysis would integrate the effects of many of the individual components mentioned above.

Additional information on quality-control techniques is presented in Chapter 5, section H. These quality-control techniques will allow validation of the measurement process. With continued use they will develop the user's confidence in the analyst and the measurement process.

3.J.2. THE RECORD

The general quality of the sediment record depends on the quality or representativeness of the data with respect to the long-term climatic and environmental factors affecting sediment movement, as well as depending on the quality of the individual data elements. Each climatic and environmental factor pertinent to the sediment movement in an individual catchment may impart its standard error of estimate to the overall quality of the record. Control of this aspect of the general quality of the record then becomes a problem in decisionmaking or programing, whereas control of the quality of the individual data elements is a problem in operations.

Because sediment information must be economical as well as of good quality, error components in both the operational and programing aspects must be scrutinized in terms of cost effectiveness. Past experience shows that money spent for more observations to improve quality of the temporal and spatial components is usually more cost effective in improving the quality of the record than is money spent for more refinements in field, laboratory, or computational equipment. For this reason it is essential to maintain data-collection operations to assure that infrequently occurring runoff events are documented. The knowledge obtained from a block of sediment data can usually be increased if related data on streamflow and drainage basin characteristics are correlated with the sediment data.

Economic considerations in improving the quality of a sediment record require intensive planning for field, laboratory, and computation methodology because of the temporal and spatial variations involved. Planning for adequate and balanced methodology should not be a one-time effort, although the first effort is usually the most important. Experience with cost and variability of components obtained from a series of measurements should be used to fine tune the methodology and the equipment and operator on a periodic basis. Porterfield (1972, p.11) states, "A continuous evaluation of concentration data must be maintained to insure that sufficient samples are obtained and that the samples are of acceptable quality. The step-by-step preparation of records offers a continuing base for cross consultation among personnel responsible for records, laboratory, and field work to evaluate the overall efficiency of the sampling program and to determine if the quantity and quality of the basic data meet desired standards."

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3.L. APPENDIXES

3.L.1. REQUIREMENTS FOR THE SUSPENDED-SEDIMENT SAMPLERS AND THEIR COMPONENTS (SEC. 3.D.1.b.1.a.)

General

(1) The sample collected must be representative of the water-sediment mixture in the immediate vicinity of the sampling point or sampling zone at the time of sampling.
(2) The suspended sediment must not be separated from the waterflow lines at the point of entry into the sampler because of any sudden change of flow characteristics of the mixture: i.e., turbulence, velocity or direction of flow. Thus, the sampler must not appreciably disturb the flow causing the concentration of sediment in the sample collected to increase or decrease.
(3) The sample collected at a point must not be contaminated by water or sediment at other depths in the stream section. That is, the sampler should be arranged to open at the desired point and to close when filled.
(4) The volume of the sample must be sufficient to satisfy the laboratory requirements for the size-distribution analysis of the sediment as well as the concentration analysis.
(5) The sampler must be adaptable for use in streams of any depth and for sampling of any desired depth of the water from the surface to the bottom.
(6) The sampler should be portable and adaptable for use by an operator wading in a shallow stream or working from a boat or bridge in a deep river.
(7) The sampler should be constructed to allow the entire sampling operation at a cross section to be made in a minimum of time.
(8) The sampler should be streamlined and heavy enough so that in deep, swift streams its deflection from the vertical caused by drag is minimum.
(9) The sampler should be simply designed and constructed so that it is not prohibitively expensive and can be easily maintained and repaired in the field.
(10) The sample should be collected in a container that can be shipped to the laboratory. This would eliminate transferring the sample to another container and losing any of the sediment which might adhere to the original container.
(11) The sample should be collected in a transparent container so that the degree of settlement may be observed in the field and in the laboratory. However, in some streams it is necessary to protect glass containers from heavy suspended matter.
(12) The sampler can be designed to sample instantly or over a period of time.

Sampler Components

(1) *Nozzles Oriented Into The Stream.*

(a) To collect an accurate suspended-sediment sample containing sand-sized particles, the sampler must fill at such a rate that the velocity in the nozzle at the point of intake is equal to the local stream velocity at that point. If the velocity at the intake is less than stream velocity, the sediment concentration in the sample will be greater than the actual value; conversely, if the velocity at the intake is greater than the stream velocity, the concentration will be less than the actual value (U.S. Inter-Agency Reports, 1941A, 1952). The degree of error in each case increases with the extent of departure from an intake stream-velocity ratio of 1.0 and with the size of sediment particles in suspension. The following table shows how the sampling error is related to the relative sampling rate (intake stream-velocity ratio) for 0.45-mm sediment.

Relative sampling rate	*Error in concentration (percent)*
0.5	+29
.8	+5
1.0	0
1.2	-5
1.5	-11

To minimize field sampling errors, prototypes of new samplers should be laboratory checked to insure that the relative sampling rate is between 0.8 and 1.2 over a range of stream velocities from 0.5 m/s to at least 2 m/s. During the tests, water temperature should be held constant at 7° ± 1°C. Stream velocity should be measured with a current meter, and nozzle intake velocity may be computed from the filling rate of the sampler container. With the tolerance of ± 0.2 on relative sampling rates, the sediment sampling error should not exceed ± 5 percent for particles of standard fall diameter less than 0.45 mm. Every sampler subsequently patterned after the prototype should be laboratory checked at a minimum of one stream velocity and one temperature. Stream velocity of 1.1 ± 0.2 m/s and water temperature of 7°C are suggested. If temperature cannot be controlled, results should be corrected to 7°C from prototype tests by about 5 percent for each 5° fall in temperature from 21°-4°C (U.S. Inter-Agency Report, 1952, p. 78). For usual year-round sampling, the relative sampling rate should be nearly 1.0 at approximately 7°C. Between 0° and 21°C the rate should not be less than 0.9 nor more than 1.2 with a constant stream velocity of 1.1 m/s.

(b) Preferably, the shape of the leading edge of the nozzle should be gently rounded from the outside to the inside surfaces. However, nozzles may be beveled from the outside or the inside. The effective intake area should be taken as the area outlined by the extreme leading edge of the nozzle.

(c) Nozzle wall thickness should not exceed approximately 1.6 mm, but the nozzle must be sufficiently strong to withstand impact of debris usually found in natural streams.

(d) The inside diameter at the intake end should be at least 3.2 mm. Nozzles with inside diameters less than 3.2 mm sample erratically and have sampling-rate characteristics that are strongly affected by water temperature.

(e) The distance from the leading edge of the nozzle to the sampler body must be adequate to insure an undisturbed flow pattern at the intake. If the nozzle is supported by a rounded, well-streamlined body, a distance of about 25 mm is adequate.

(f) The inside surface of the nozzle should be straight and smooth to offer an unobstructed path for the flow of the water-sediment mixture.

(g) The nozzle material must be chemically inert if the samples are to be chemically analyzed. This requirement, particularly, is important if the samples are to be analyzed for pesticides or heavy metals.

(h) The nozzle must be supported so that the angle between the stream-velocity vector and the axis of the intake nozzle does not exceed 20°C. This requirement is not difficult to meet if the nozzle is attached to a fixed support; however, if the nozzle is part of a sampler that is to be lowered on a flexible line, then particular attention must be devoted to the stability of the sampler in turbulent flow.

(2) *Nozzles Oriented At Right Angles To The Flow.*

If at all possible, avoid using nozzles oriented at right angles to the flow because this orientation produces errors that are much larger than for upstream orientation. Criteria for this orientation have been formulated because recently developed, automatic-pumping samplers frequently are installed

behind fixed right-angle intakes mounted flush with the surface of a retaining wall or similar structure. This installation is necessary to eliminate the accumulation of trash around the mouth of the nozzle. Such installations must be at a location where the velocity is moderate to high throughout the full range of stages. The sampling error of the right-angle orientation is affected by the geometry of the support structure, stream velocity, intake velocity, nozzle size, and sediment size. In nearly every instance, the sediment concentration in the sample is less than the concentration in the stream at the sampling point (U.S. Inter-Agency Report, 1966). This difference occurs because particles approaching the nozzle must be accelerated at right angles to their line of travel if they are to enter the nozzle mouth. If a particle's combined approach velocity and mass are greater than a critical value, the particle momentum will cause it to separate from its associated water filament and continue downstream past the nozzle.

The following recommendations are based on test results of nozzles with inside diameters of 38 mm or less that were flush-mounted horizontally (U.S. Inter-Agency Report, 1966).

(a) The mean velocity in the intake should be equal to or greater than the stream velocity at the sampling point.
(b) The inside diameter of the nozzle should be at least 19 mm.
(c) The intake should be purged prior to sampling to expel accumulated sediment.

(3) *Conduit Between Nozzle And Sample Container.*

(a) The length of conduit should be as short as possible, and the inside surface should be smooth and free of obstructions that may impede movement of water and sediment.
(b) In long horizontal conduits, a mean velocity equal to or greater than 17 times the settling velocity of the largest particle will insure continuous suspension of all particles.
(c) In vertical conduits, the mean velocity of flow should be at least six times the settling velocity of the largest particle.

(4) *Sample Container.*

(a) The volume of the sample container must be large enough to accommodate a sufficient quantity of sample to satisfy laboratory requirements. For most routine sediment concentration determinations, sufficient sample can be collected in a 473-mL container. If samples are to be analyzed for substances, such as organics or heavy metals that are usually found in low concentrations, a 1,000-mL sample is generally considered a minimum. The sample container should be shaped to facilitate insertion and removal from the sampler body.
(b) The container must be made of a material that will not react chemically with the sample and interfere with laboratory analysis. For concentration and size analysis of sediment, low-sodium glass or plastic containers are adequate. This is the type usually used for milk bottles and other glass food containers. Additional container criteria are needed when samples are to be chemically analyzed.
(c) Samples should be collected and transported to the laboratory in the same container. Laboratory tests indicate that as much as 18 percent of the sediment may be lost when a sample is poured from one container to another. As expected, the errors are usually greater at low concentrations where the total amount of sediment is small.
(d) Containers should have a smooth inner surface free of sharp corners or ridges. Surface irregularities complicate the removal of sediment in the laboratory.
(e) Containers must be made of a material sufficiently strong to withstand the usual impacts encountered in the field, in transport, and in the laboratory. The material also should be hard enough to withstand repeated scrubbing without scratching.

(f) Container material should be transparent to facilitate visual inspection of the samples.
(g) Containers should be formed to receive caps that are relatively air tight. The caps should remain tight through temperature changes and handling impacts because cartons of sample containers may be dropped or shipped upside down, particularly when commercial carriers are used. Some samples may release carbon dioxide and other dissolved gases during storage.

(5) *Sampler Body And Suspension.*

The majority of samplers consist of a sample container, intake nozzle, air exhaust, valves, and plumbing, all mounted as one integral unit and usually lowered on a cable to the desired sampling point. The following requirements apply to samplers of this type.

(a) The intake nozzle and exhaust port should be made of noncorrosive material.
(b) The body of the sampler should be equipped with stabilizing fins so that the nozzle is oriented upstream prior to submergence. The fins must also exert sufficient stabilizing forces to hold the nozzle in an upstream orientation during the entire sampling interval. Instability causes a sampler to move back and forth across the flow, and thereby shifts the nozzle away from the optimum upstream orientation. Some instability can be tolerated provided the approach angle does not exceed 20° at stream velocities up to 2.4 m/s.
(c) The sampler should be balanced and streamlined so that it does not nose up or down more than about 5° at stream velocities up to 2.4 m/s with the sample container both full and empty. The sampler should be balanced so that when it leaves the water it does not spill the sample through the nozzle or other openings.
(d) The drag must be kept to a minimum to prevent excessive downstream drift at high stream velocities. Because drag forces on the suspension cable contribute significantly to drift, the cable diameter generally should be about 3 mm or less.
(e) The breaking strength of the suspension cable should be at least 25 times the weight of the sampler.
(f) The sampler should be light enough to permit transport by one or two men.
(g) The sampler should be shaped to permit sampling as close to the streambed as possible.
(h) The sample container should be easy to place and remove.

3.L.2. PROCEDURE FOR SUBSAMPLING WATER-SEDIMENT MIXTURES (14-LITER CHURN SPLITTERS)

[This procedure describes the USGS churn splitter and gives methods for splitting composited samples into representative subsamples required for analysis of several constituents. According to USGS Quality of Water Branch Technical Memorandum No. 76.24-T (Aug. 1976), this procedure makes it possible to obtain subsamples within 10 percent of the true concentration for sand concentrations up to 5,000 g/m^3.]

General

The water-quality laboratory may require 4 to 16 subsamples of a representative cross-section (transect) sample of the water-sediment mixture (streamflow) for water-quality analyses. The cross-section sample is collected in 1-pint or 1-quart bottles using suspended-sediment samplers at no fewer than three and preferably eight to ten verticals (EWI or EDI techniques). These samples are composited into one representative cross-section sample of the streamflow. This composited sample can then be split, using the churn splitter, into the required 4 to 16 representative subsamples as explained under Procedure. *Samples collected for organic analysis (e.g. organic carbon, pesticides) should not be composited in this container because of the possibility of contamination from the plastic.*

14-Liter Churn Splitter

The churn splitter is a 1/4 inch thick polyethylene cylinder, 10 inches in diameter and 12 inches deep with a lid. It has been manufactured for the Survey by a commercial manufacturer. The valve and spout are polypropylene. The stirring disk is a 3/8-inch thick polyethylene disk, 9 15/16 inches in diameter with 16 holes, 8 as scallops in the outer edge and 8 in an inner circle. The handle, a 1-inch diameter by 18-inch long polyethylene rod, is welded perpendicular to the center of the disk and supported by four ribs. A small "lip" on the disk alines with the valve, and a guide notch and rib are provided to maintain the correct alinement. Replacement valves and spouts are available from the Quality of Water Branch.

Procedure

This procedure requires a total sample volume of 8 to 14 liters, of which 4 to 10 liters are suitable for water-sediment mixture subsamples. The remaining 4 or more liters may be used for filtered subsamples if required by the analytical schedule. If not, they may be discarded. *This size churn splitter does not reliably produce representative water-sediment mixture subsamples when it contains less than about 4 liters.*

Before starting to collect the representative sample of the streamflow, label all the subsample containers to be used and determine the total sample volume needed. Add to this sample volume at least 10 percent to cover filter losses and spillage. It is less frustrating to throw away a small amount of sample than to have to go back and collect another cross-section sample.

Collect approximately one liter of water and thoroughly rinse the churn splitter.

Representative samples of the streamflow are collected by using standard EDI or EWI sampling techniques as described in "Field Methods for Measurement of Fluvial Sediment" TWRI Book 3, Chapter C2. Specific sample volumes cannot be obtained with sediment samplers, but properly collected pint bottles (approximately two-thirds full) will yield about 1/3 liter each. Only one sediment sample bottle is used over and over again in collecting the cross-section samples in order to minimize the amount of sediment lost in transferring samples from the bottles to the churn splitter. Each time the bottle is filled, the sample is poured into the splitter and the bottle is used again so that each succeeding sample washes the sediment left from the previous one into the splitter. Remember that the volume to be used for water-sediment mixture subsamples must be "on top of" the 4 liters of sample in the tank from which representative water-sediment mixture subsamples cannot be obtained.

Suspended-sediment concentration should always be determined whenever a sample is analyzed for total concentrations of chemical constituents. The sample for determination of suspended-sediment concentration can be collected: (1) as a separate cross-section sample as if no other sampling were required, or (2) it may be obtained as a single-bottle subsample from the churn splitter if the amount of sediment in a single bottle appears to be sufficient for the lab to obtain accurate weights of both the fine and sand fractions. The fieldman can decide whether (1) or (2) will be used by looking at the first bottle collected to see whether an appreciable amount of sand settles to the bottom of the bottle within 20 to 30 seconds; if so, (2) can be used. If in doubt, always use alternative (1).

When the required volume plus 10 percent for waste is in the churn splitter, place all water-sediment mixture subsample containers within easy reach, so that once started the stirring can be continuous. The sample should be stirred *at a uniform rate of approximately 9 inches per second.* As the volume of sample in the tank decreases the round trip frequency should increase so that the churning disk velocity remains the same. The *disk should touch the bottom of the tank on every stroke*, and the stroke length should be as long as possible *without breaking the water surface.* Before using the sample splitters for the first time, practice using tap water. Observe that, as the stroke length and/or disk velocity is increased beyond the recommended rate, there is a sudden change of sound and churning effort which is accompanied by the introduction of excessive air into the mixture. The introduction of excessive air into the sample is undesirable because it may tend to change the dissolved gases, bicarbonate, pH, and other characteristics. On the other hand, inadequate stirring may result in non-representative subsamples.

The sample in the splitter should be stirred at the uniform churning rate for about 10 strokes prior to the first withdrawal to establish the desired stirring rate of 9 inches per second and to assure uniform dispersion of the suspended matter. The churning must be continuous during the withdrawals; therefore, if a break in withdrawals is necessary, the stirring rate must be reestablished before continuing the withdrawals.

When all of the required water-sediment mixture subsamples have been obtained, the remaining portion of the sample is used as necessary for the filtered samples. It will be advantageous to allow the sediment to settle out in the mixing tank for a few minutes before pouring the sample into the filter apparatus. When all of the necessary filtered subsamples have been obtained, the mixing tank, churning disk, and filter apparatus should be cleaned thoroughly with deionized water. If deionized water will not remove all of the residue, clean by using a small amount of a detergent such as Alconox, rinse with a weak acid solution (4 mL of nitric acid per liter of water), rinse repeatedly with tap water, and then rinse with deionized water.

Equipment Not Furnished

1. A stand to support the mixing tank that will allow the subsample containers to be placed under the spout.
2. Small supports to hold various sizes of subsample containers such that the top or opening is at or near the mixing-tank spout.

3.L.3. LABORATORY PROCEDURE FOR EVAPORATION METHOD (SEC. 3.F.2.a.1.)

Equipment And Supplies

The following equipment and supplies will meet the minimum requirements for satisfactory analyses of samples to determine suspended-sediment concentration by the evaporation method. Other supplies incidental to the care of the equipment and handling of samples may be required.

a. Tared sample containers (glass milk bottles, 473 mL or 946 mL capacity, are used in most suspended-sediment samplers).
b. Distilled water.
c. A vacuum source.
d. Evaporating dishes of various sizes.
e. Convection-type drying oven.
f. Containers, 4,000 mL capacity or larger.
g. 100-mL pipet.

h. Desiccator.
i. Flocculating agent.
j. Balances, one accurate to 0.1 g and analytical balance (200-g capacity) accurate to 0.1 mg.

Analytical Procedure

a. Arrange samples in an orderly sequence according to location, station, and date and time of collection.
b. Prepare a set of consecutively numbered work sheets for each sampling location for recording data and making computations. The format may vary depending on the objectives.
c. Transfer date, time, gage height or discharge rate, sampling station, water temperature and remarks from sample bottle to the work sheets. In addition to the laboratory work sheets, some laboratories also keep a log book of all samples processed. Samples are entered in the log book when processing begins and the completion date is added when processing is completed. This provides a concise record of all samples collected and analyzed for a given location.
d. Weigh samples as soon as practical after they are received in the laboratory to avoid evaporation losses. Subtract the tare mass of container from the total mass of sample and container to determine sample mass. Record sample mass to 0.1 g on the laboratory work sheet.
e. If the sediment does not settle in 3 or 4 days, flocculate the sample (Guy, 1969, p. 11) by adding 0.4 mL of 0.2 molar solution of aluminum sulfate (alum) per liter of sample. The addition of flocculating agents complicates determining sample concentration and should be avoided if possible.
f. Decant excess supernate from the sample leaving about 30 mL. (This amount may vary but should be the same for all samples from a specific location, especially if a dissolved-solids correction is necessary.) The supernate from all samples for a location (gaging station) collected on the same date, during a runoff event, or during a relatively uniform hydrologic sequence is combined in a large container from which a dissolved-solids sample may be obtained, if needed (Guy, 1969, p. 12).
g. Using distilled water, wash the remaining portion, approximately 30 mL, of the sample into a tared (nearest 0.1 mg) numbered evaporating dish. Place the evaporation dish in the oven and dry overnight at 105°-110°C. Do not boil sediment out of the evaporation dish. This requires drying at temperatures slightly below the boiling point until all visible moisture has evaporated. Note, the sample may be dried in the sample container bottle if adequate drying and weighing facilities are available for the large vessels.
h. Remove the evaporation dish from the oven and place it in a desiccator until cool. When cool, weigh the sample immediately to nearest 0.1 mg.
i. Record gross and tare mass of the dried sample in space provided on laboratory work sheet. Compute net mass to nearest 0.1 mg and record.
j. If necessary, thoroughly mix all effluent from a group of samples (item g.) for a given location and withdraw 100 mL. Place it in tared evaporation dish and oven dry at 105°-110°C. Weigh residue and record to nearest 0.1 mg as dissolved solids on the laboratory work sheet. Compute net mass of dissolved solids to nearest 0.1 mg and record.
k. Compute correction factor for the group of samples by multiplying the net amount of dissolved solids (residue) from the 100 mL sample by 30 percent (30 mL of supernate evaporated with each sediment sample). Record on the laboratory work sheet.
l. Compute sediment concentration in parts per million as follows:

    1. Subtract correction factor for dissolved solids from net sediment mass.
    2. Divide oven-dry net mass of sediment by the net total mass of the water-sediment mixture and multiply by one million.

m. Many scientists and engineers now prefer to report sediment concentration in grams per cubic meter or in milligrams per liter. The computations are as follows:

$$\text{Concentration in g/m}^3 \text{ or mg/L} = A \left[\frac{\text{mass of sediment} \times 1{,}000{,}000}{\text{mass of water-sediment mixture}}\right]$$

The values of factor A, given in table 3-7, are based on the specific gravity of water and sediment as being 1.000 and 2.65 g/cm^3, respectively.

Table 3-7.—*Factors for converting sediment concentration in parts per million to grams per cubic meter or to milligrams per liter*

Range of concen-tration in 1,000 ppm	Multiply by	Range of concen-tration in 1,000 ppm	Multiply by	Range of concen-tration in 1,000 ppm	Multiply by
0 – 7.95	1.00	153–165	1.11	362–380	1.30
8.0– 23.7	1.01	166–178	1.12	381–398	1.32
23.8– 39.1	1.02	179–191	1.13	399–416	1.34
39.2– 54.3	1.03	192–209	1.14	417–434	1.36
54.4– 69.2	1.04	210–233	1.16	435–451	1.38
69.3– 83.7	1.05	234–256	1.18	452–467	1.40
83.8– 97.9	1.06	257–278	1.20	468–483	1.42
98.0–111	1.07	279–300	1.22	484–498	1.44
112 –125	1.08	301–321	1.24	499–513	1.46
126 –139	1.09	322–341	1.26	514–528	1.48
140 –152	1.10	342–361	1.28	529–542	1.50

3.L.4. LABORATORY PROCEDURE FOR FILTRATION METHOD (SEC. 3.F.2.a.2.)

Equipment And Supplies

The following equipment and supplies will meet the minimum requirements for sediment-concentration analysis by the filtration method.

a. Gooch crucibles, 25 mL capacity or larger, with perforated bottom which may be connected to a vacuum system.
b. A vacuum system.
c. Distilled water.
d. Convection type drying oven.
e. Desiccator.
f. Flocculating agent.
g. Balances, one accurate to 0.1 g and an analytical balance, 200-g capacity, accurate to 0.1 mg.
h. Evaporation beakers and other evaporation equipment.

Analytical Procedure

Since detailed instructions have been given for arranging the samples, making computations, and recording the data for the evaporation method, these items are omitted in the procedure for the filtration method.

a. Prepare a laboratory work sheet to record the data and make the computations.
b. Determine total net weight of the sample (water-sediment mixture).
c. Allow sample to remain undisturbed until solid material has settled. Flocculate by adding 0.4 mL of 0.2 molar solution of aluminum sulfate (alum) per liter of sample if necessary. When clear, decant excess liquid and transfer sample into a beaker. After transferring the sample, allow a short settling period and decant again if possible.
d. Install suitable filter in Gooch crucible and determine tare weight. Commercial glass fiber and cellulose filters are now available that are satisfactory for most types of sediments. An alternate method for some fine sediments is to use a glass or cellulose filter in conjunction with an asbestos mat.
e. Connect the crucible to the vacuum system. Transfer the sample to crucible. When filtration is complete, place crucible and contents in oven and dry at 105°-110°C. Remove from oven and place in desiccator until cool.
f. When cool, remove the crucible from desiccator, weigh immediately to nearest 0.1 mg and compute concentration. This procedure should be the same as used to determine the tare mass of the crucible.

3.L.5. LABORATORY PROCEDURE FOR SEPARATING FINES AND SANDS (SEC. 3.F.2.a.3.)

Analytical procedure

The following procedure is followed when the concentration of both the fines and sands is required. A typical laboratory work sheet is shown in figure 3-7.

a. Follow steps a through f as given for the evaporation method.
b. Separate the fines from the sands by wet sieving with distilled water through a 0.062-mm sieve.
c. Follow steps f through m as outlined for the evaporation method for the fines portion of the sample.
d. Remove sands from sieve and place in a tared evaporation dish. Oven dry the sample and record mass to nearest 0.1 mg.
e. Depending on the organic matter content, add 1 mL or more of 30-percent hydrogen peroxide solution per gram of the dry sand in the sample to about 40 mL of water. Allow to stand for a few hours to oxidize the organic matter. If no sediment is attached, remove floating organic matter by skimming. Destroy the hydrogen peroxide by slowly bringing sample to a boil.
f. Oven dry the sand sample and weigh to nearest 0.1 mg. Determine organic content by subtracting gross mass of sands from gross mass obtained in step d and record in the space provided on the laboratory work sheet, figure 3-7.
g. Record gross and tare sand mass from step f in space provided on the laboratory work sheet. Compute net sand mass and record to nearest 0.1 mg.
h. Subtract mass of organic matter from mass of sand and record on work sheet. Note, no correction is made for dissolved solids because the effluent was washed into the fines portion of the sample during wet sieving.

S. & W. C. RESEARCH DIVISION
Agricultural Research Service
SEDIMENT CONCENTRATION NOTES, DEPTH INTEGRATED SAMPLES

Sheet No. 2
Cataloged 4-28-69
Completed 5-7-69

Location Sta. 4C, Chews Creek, Holly Springs Miss. Computed by W.C.S. Checked by J. T.B.

	Date	4-5-69		4-5-69		4-5-69			
	Time	12:35A		12:37A		12:38A			
	G. H.	2.26		2.25		2.24			
	Samp. Sta.	1/4 1/R		2/4 1/R		3/4 1/R			
	Temp.	65°		65°		65°			
	Remarks	A.B.		A.B.		A.B.			
Sample	Gross	536.8		608.1		627.9			
	Tare	358.8		364.3		363.6			
	Net mass	178.0	Sand>.062	243.8	Sand>	264.3	Sand>		Sand>
Sediment	Container	497.0	38.0	498.0	39.0	499.0	40.0		
	Gross	60.4484	44.6157	56.3868	46.7192	68.0168	50.3103		
	Tare	60.2060	44.4876	55.9492	46.3116	67.5128	50.2181		
	Net mass	.2424	.1281	.4376	.4076	.5040	.0922		
	Corr.	-.0035	O.M.0050	-.0035	O.M.0061	-.0035	O.M.0057		
	Net mass	.2389	.1231	.4341	.4015	.5005	.0865		
	Conc. (ppm)	.1340	692	1,780	1,650	1,890	327		
Total Conc. (ppm)		2,032		3,430		2,220			

Dissolved solids:
Date 4-5-69
Container A-5
Gross 49.1236
Tare 49.1120
Net .0116
Corr. .0035

	Date										
	Time										
	G. H.										
	Samp. Sta.										
	Temp.										
	Remarks										
Sample	Gross										
	Tare										
	Net mass		Sand>		Sand>		Sand>		Sand>		Sand>
Sediment	Container										
	Gross										
	Tare										
	Net mass										
	Corr.										
	Net mass										
	Conc. (ppm)										
Total Conc. (ppm)											

Figure 3-7.—Sample laboratory work sheet for sediment-concentration analysis.

i. Compute the sand concentration in the manner prescribed in item 1 for the evaporation method.
j. Compute total concentration by totaling the concentration of the fines and sands.

3.L.6. LABORATORY PROCEDURE FOR PIPET METHOD (SEC. 3.F.2.1.b.)

Pipet Method

The pipet method is based on Stokes law, which states that thoroughly dispersed particles of a given size in a suspending medium will settle below a given point of withdrawal in given time. Thus the pipet method is applicable for particles less than 0.062 mm.

Predetermined depths and times of withdrawal are given in table 3-8 for various sediment size ranges.

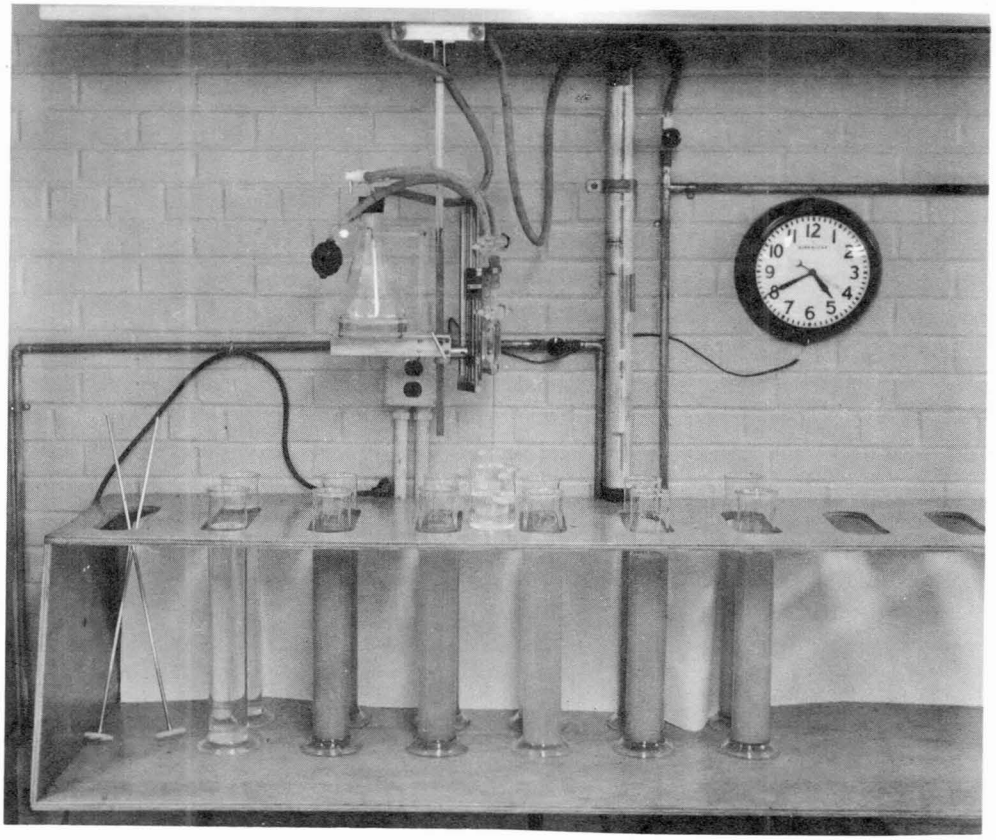
Table 3-8.—*Time of pipet withdrawal for given temperature, depth of withdrawal, and diameter of particles (after ASCE, 1975)**

Diameter of particle (mm)	0.062	0.031		0.016		0.008		0.004		0.002	
Depth of withdrawal (mm)	150	150		100		100		50		50	
Temperature	Time of withdrawal										
(°C)	(sec)	(min)	(sec)	(min)	(sec)	(min)	(sec)	(min)	(sec)	(hr)	(min)
20	44	2	52	7	40	30	40	61	19	4	5
21	42	2	48	7	29	29	58	59	50	4	0
22	41	2	45	7	18	29	13	58	22	3	54
23	40	2	41	7	8	28	34	57	5	3	48
24	39	2	38	6	58	27	52	55	41	3	43
25	38	2	34	6	48	27	14	54	25	3	38
26	37	2	30	6	39	26	38	52	2	3	33
27	36	2	27	6	31	26	2	52	2	3	28
28	36	2	23	6	22	25	28	50	52	3	24
29	35	2	19	6	13	24	53	49	42	3	19
30	34	2	16	6	6	24	22	48	42	3	15

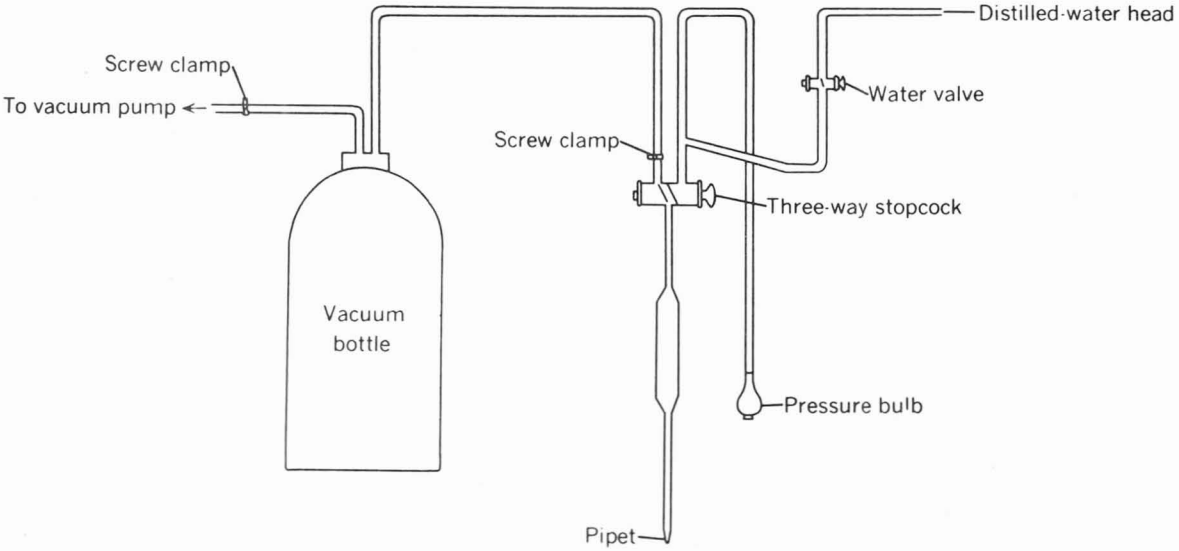
*The values in this table are based on particles of assumed spherical shape with an average specific gravity of 2.65, the constant of acceleration due to gravity = 980, and viscosity varying from 0.010087 at 20°C to 0.008004 at 30°C.

Equipment And Supplies

a. A 25-mL pipet apparatus that can be raised or lowered (fig. 3-8) mounted on a movable carriage.
b. A vacuum source.



A) Laboratory arrangements.



B) Diagram.

Figure 3-8.—Pipet apparatus for determining particle size of fine sediments: A) Laboratory arrangements with vertical moving rack and horizontal moving carriage for pipetting among several cylinders. B) Diagram showing relationship of components (after ASCE, 1975).

c. Distilled water.
d. Sedimentation cylinders, 1,000 mL capacity, with rubber stoppers.
e. Stirring rods made from 6.4-mm by 6.0-mm brass rods with a perforated plastic disk 50 mm in diameter attached to one end.
f. Thermometers.
g. Evaporating dishes.
h. Desiccators.
i. Stopwatch.
j. Laboratory work sheets.
k. No. 230 (0.062-mm) sieve.

Preparation Of The Sample

Many samples will require removing organic matter and soluble salts prior to pipet analysis.

Organic Matter

Remove organic matter by adding approximately 1 mL of 30-percent hydrogen peroxide solution for each gram of dry sample to 40 mL of water. Stir thoroughly and allow to stand for a few hours. If free of sediment, large floating particles of organic matter may be removed by decanting or skimming. Some samples may require heating and additional hydrogen peroxide to oxidize all organic matter. After the reaction has stopped, destroy the hydrogen peroxide by boiling or washing the sediment with distilled water.

Soluble Salts

The presence of magnesium and calcium carbonates and exchangeable divalent cations causes flocculation of soil particles. To remove carbonates, add 50 mL of buffer solution (Sodium Acetate) to each 5 mL of sample and bring to suspension by stirring with a glass rod (policeman). Digestion is aided by placing the beaker in a near-boiling sand or water bath for 30 minutes. Wash the suspension by filtering with a Pasteur-Chamberland filter. Some samples may require two or more treatments.

Filtration

After soluble salts and organic matter have been removed from the sample, filtration is required. Remove excess liquid with the Pasteur-Chamberland filter. When the filter candle becomes coated with soil, reverse the stopcock and apply pressure with the rubber bulb, touching the candle lightly against the inner wall of the beaker to dislodge the soil from the candle. Resume filtration, removing the coatings frequently to reduce impedance of flow.

After free water has been removed, add distilled water and mix the suspension by a jet of water. Filter again and repeat the mixing and filtering several times. After filtering is completed, apply pressure to the filter candle as before to dislodge as much soil as possible, and wash remainder back into the beaker with a water jet using a rubber stopper on a policeman to dislodge particles. Remove filter and proceed as outlined below.

Note: The procedure described below will not provide a record of the quantity of organic matter and soluble salts in the sample. The proportions in the various particle-size ranges are computed on an organic and soluble salt-free basis. If the quantity of organic matter and soluble salts is required, the supernate is removed, the sample is dried, and the net dry mass is determined before these items are removed.

a. If necessary, pretreat the sample in accordance with procedures given under "Preparation of sample." After pretreatment remove excess water, place the sample in a tared evaporation dish, dry at 100°-110°C, and weigh to nearest 0.1 mg. (Note: If sample to be analyzed is a suspended-sediment sample and both concentration and particle size are required, determine the net mass of the water-sediment mixture to the nearest 0.1 g before beginning sample processing.)

b. Flocculation of fine sediments, mainly clays, often increases the settling rate. Flocculation is prevented by adding a dispersing agent such as 10 mL of calgon solution (40.0 g of sodium metaphosphate and 8.0 g of sodium bicarbonate in distilled water diluted to 1.0 L) per gram of sample. After adding the dispersing agent, (1) transfer the sample to a 250-mL shaker bottle, adding distilled water to bring the volume to 180 mL, and shake overnight in a horizontal reciprocating shaker, or (2) stir with a mechanical analysis stirrer (malt machine) for 2 to 5 minutes.

   Determining the dissolved-solids correction for each new solution of the dispersing agent is necessary. Transfer a 25-mL pipet sample to a tared evaporation dish, dry overnight at 105°-110°C, and weigh the dish and contents to the nearest 0.1 mg. The net mass of the dissolved solids is subsequently subtracted from the net mass of sediment-solids mixture of each pipet withdrawal.

   Although in most analyses to determine the ultimate particle size the sample must be dispersed, it may be desirable to make some analyses in native water to include the effects of flocculation. This would determine the fall velocity characteristics most closely resembling those in the stream. In other cases the concentration of chemical constituents may be so low that dispersion is not required.

c. Weigh each empty sedimentation cylinder, fill with distilled water, and weigh again at least three times. Do the same for each 25-mL pipet. The ratio of the mean mass of the water in the cylinder to the mean mass of the water in the pipet is subsequently used as a volume ratio in computing the results of the withdrawals.

d. Select particle-size determinations to be made, and using table 3-8 (page 3-92), set up a schedule for time of withdrawal and depth from which withdrawal is to be made.

e. Using a no. 230 (0.062-mm) sieve and distilled water, wet the sieve and the dispersed sample and transfer all the material passing through the sieve to a sedimentation cylinder. Dilute the sample to 1 L with distilled water. Place the sands portion of the sample in a tared evaporation dish, dry in the oven, weigh to nearest 0.1 mg, and determine net mass.

f. When ready for pipetting, place a rubber stopper in the pouring end of the sedimentation cylinder. Suspend the material in the water by vigorously shaking the cylinder while turning it end over end. Then stir the sample for 1 minute with an up-and-down motion of the stirring rod.

g. After stirring, lower the pipet 100 mm into the sample and immediately take a "zero time" withdrawal for computing the total concentration of the fines. Take the temperature and

stir the sample again for 1 minute. After this, proceed with subsequent withdrawals according to the time and depth schedule selected in item d.

h. The initial withdrawal together with one distilled-water pipet flushing and all subsequent withdrawals are emptied into numbered and tared evaporating dishes. After each flushing, the pressure bulb may be used to blow any remaining droplets from the pipet tip.

i. Oven dry the pipet withdrawals overnight at 105°-110°C, cool in a desiccator, weigh on an analytical balance to the nearest 0.1 mg, and determine net sediment mass.

Reporting The Data

A pipet form, such as shown in figure 3-9, is used to report the results. Enter sample location, date, time, and other information at the top of the form. Record gross, tare, and net masses of the total sample, sands portion, and dispersing agent in spaces provided. Prior to pipetting, record the temperature of the suspension, the depth of withdrawal, settling time, and the masses of the numbered containers for each withdrawal. The calculations are carried out as follows:

a. From the initial zero-time withdrawal, determine the net mass of the fines in the suspension and record. Make a dissolved-solids correction if a dispersing agent was used prior to pipetting. Compute the total mass of the fines by multiplying the mass of fines in the suspension by the volume ratio.

b. Determine the net dry mass of the sediment in each subsequent pipet withdrawal and multiply by the volume ratio. This gives the mass of sediment in suspension finer than the size indicated for the given time and depth of withdrawal.

c. To obtain the fraction of total sediment finer than the desired size, divide the mass of sediment in the sample finer than this size (indicated for the given time and depth of withdrawal) by the dry mass of the total sediment in the sample.

d. To obtain the concentration of the fines, sands, and total sample in parts per million or grams per millimeter, divide the total net mass of each part by the total net mass of the total sample (water-sediment mixture) and multiply by one million. Record on the form.

3.L.7. LABORATORY PROCEDURE FOR SIEVING AND OPERATING VISUAL-ACCUMULATION TUBE (SEC. 3.F.2.b.2.a. AND b.)

Equipment And Supplies For Wet Stirring

a. A set of sieves with openings of the required size.
b. Ceramic dishes.
c. Wash bottles.
d. Tared containers for drying the sample fractions.
e. A drying oven.
f. Distilled water.
g. Balances for weighing the samples.

Equipment And Supplies For Dry Sieving

a. A series of sieves of sufficient size to hold the sample.
b. A mechanical shaker.
c. Tared containers to hold the size fractions.
d. Balances for weighing the samples.

Sample Data

Stream or Station: Lab. Ck.
Location: Oxford Miss.
G.H.: 3.20
Date: 4-15-69
Time: 10:15 P.M.
Composite: _____ No. Bottles: 1
Sample Weight: Gross: 463.6 g.
Tare: 358.6 g.
Net: 105.0 g.
Remarks: _____

Dispersing Agent Correction

Vol.: 25 cc.
Dish No.: 241
Gross: 45.6389 g.
Tare: 45.6293 g.
Net: .0096 g.

By: L.L.M.

Fines <.062 mm.:*

Gross: 0 g.
Tare: 0 g.
Net: .9823 g.
Conc.: 9,355 ppm

Sand >.062 mm.:

Dish No.: 242
Gross: 41.4886 g.
Tare: 41.3378 g.
Net: .1508 g.
Conc.: 1,436 ppm

Total Sediment

Beaker No.: 52
Gross: 103.1467 g.
Tare: 102.0000 g.
O.M.: .0136 g.
Net: 1.1331 g.
Conc.: 10,791 ppm

PIPET SIZES

Pipet No.: 22B Volume: 25 ml. Volume Ratio: 40.51

Size mm.		Conc.	<0.062	<0.031	<0.016	<0.008	<0.004	<0.002
Clock time		8:30		8:33	8:37	8:57	9:24	12:08
Temperature		25		25	25	25	25	25
Fall distance		10		15	10	10	5	5
Setting time		0		2-34	6-48	27-14	54-25	3hr.-38
Container No.		A-1		A-5	349	A-10	B-10	D-13
Mass - g.	Gross	46.6719		47.8425	47.8545	47.8644	45.6213	58.0282
	Tare	45.6381		47.8126	47.8269	47.8432	45.6008	58.0088
	Net pipet	.0338		.0299	.0276	.0212	.0205	.0194
	D.S. corr.	.0096		.0096	.0096	.0096	.0096	.0096
	Net sediment	.0242		.0203	.0180	.0116	.0109	.0098
	Finer than		.9803**	.8224	.7292	.4699	.4416	.3970
% Finer than			86.5	72.6	64.4	41.5	39.0	35.0

* Fines by difference, i.e., total O.M. free sediment minus sand.
** Fines by immediate withdrawal, i.e., "zero time".

Note: Fines by difference and fines by immediate withdrawal should not differ by more than 5 or 10 percent.

Figure 3-9.—Sample laboratory worksheet for pipet analysis.

Wet Sieving

a. Immerse the sieve with the coarsest screen in a ceramic dish containing distilled water until the water is about 0.6 cm above the screen.
b. Wash the sample onto the sieve with distilled water and shake vigorously until all particles smaller than the sieve opening have fallen through.
c. Pour the material with the wash water onto the next smaller sieve and repeat the process until the 0.062-mm or the smallest size sieve is reached.
d. Transfer the material retained on each sieve into a tared container. Dry and weigh each fraction.
e. Analyze all material passing the smallest sieve, usually 0.062 mm, by one of the fall velocity methods.

Dry Sieving

a. In dry sieving, set up a nest of sieves on a mechanical shaker with the coarsest sieve on top and the finest on the bottom.
b. Place the sample on the coarsest sieve and obtain simulataneous separation of fractions by shaking for about 10 minutes on a mechanical shaker and tapping machine. The masses of material for each size fraction are determined in the manner prescribed for wet sieving.

Reporting The Data

Analyze sediment smaller and larger than the sieving range by other methods and enter their masses entered on a suitable work sheet as single entries. Determine the masses and percentages of material for each sieved fraction and enter on the work sheet. Compute the concentration of each size in parts per million or milligrams per liter if desired.

Equipment And Supplies Needed For VA Tube Operation

a. VA apparatus as shown in figure 3-10.
b. Tubes for VA apparatus of all sizes (ASCE, 1975).
c. VA recording charts.
d. Special funnel for VA apparatus.
e. Stirring rod for use in mixing chamber.
f. Evaporating dishes and drying oven.
g. Sieves for separating the fines and materials larger than 2.0 mm for the VA sample.

Analytical Procedure

a. Prepare the sample by wet sieving all materials smaller than 0.053 mm and all materials larger than 2.0 mm. After sieving, treat the sample with 30-percent hydrogen peroxide solution to remove organic matter and to destroy algae growth. Add dispersing agent if necessary to obtain complete particle separation. Before the sample is poured into the VA-tube funnel, distilled water of the same temperature as the water in the tube, ±2°C, should be added to the sample until about 40 mL of mixture is obtained.
b. The appropriate size VA tube is based on sample mass and volume and the maximum particle diameter (ASCE, 1975). The height of the column of settled materials in the tube should not exceed 120 mm. A good practice is to start with samples containing the

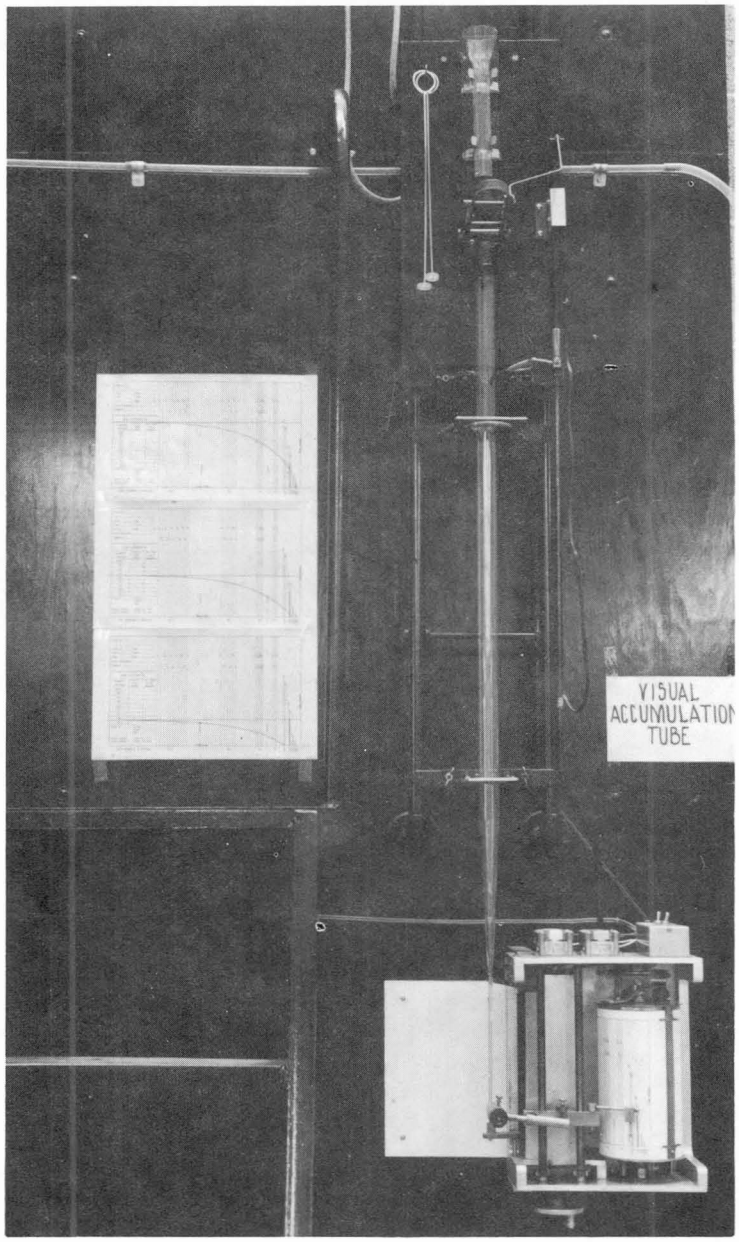


Figure 3-10.—Visual-accumulation tube apparatus for determining size distribution of sand-size particles.

smallest quantity of materials and change the tubes as necessary as the amounts of material increase. If the correct size is not selected the first time, the sample can be rerun.

c. Set the tube in place and fill it with distilled water, read and record the temperature of the water, and turn on the main switch of the apparatus.

d. Place the chart on the drum. (Note: The 1.2-m and 1.8-m tubes require different charts because settling distances are unequal.) With the release lever, free the drum and rotate it until the pen is to the right of the origin or zero-time line. Free the release lever so that the drum is engaged with the timing motor drive.

e. Place the pen against the chart and bring it exactly onto the baseline with the hand wheel. To take the slack out of the drive, bring the pen up to the origin line by turning on the forward drive. When the pen is situated exactly on the time origin and baseline intersection, turn off the forward switch.
f. Adjust the telescope so that the crosshair is at the top of the tube plug.
g. Close the valve in the sedimentation column and transfer the sample to the mixing chamber. Fill the chamber to the reference mark on the funnel with distilled water of the same temperature as that in the sedimentation tube.
h. Turn on the forward switch. Agitate the mixture with the stirring rod with a brisk up-and-down motion. After agitating, remove the plunger and open the valve fully, which automatically starts the drum so that chart time and particle settling begin simultaneously.
i. With the hand wheel, keep the crosshairs of the telescope on the water-sediment interface as the particles accumulate at the bottom of the tube. Tracking should be continuous as long as the sediment column rises or until the pen has passed the 0.062-mm size on the chart.
j. Turn off the forward switch when the maximum height of sand accumulation is reached, and extend the height across the chart by releasing the drum and turning the chart backward to the time origin.
k. Remove the chart from the drum. Make sure that the temperature of the water in the sedimentation tube, sample identification, time, name of operator, and size and number of VA tube are all marked on the chart.
l. To remove the sample from the tube, place a beaker under the end of the tube and remove the plug. Open the valve and allow about 50 mL of water and the sediment column to drain out. Close the valve and wash any sediment from the tube plug into the sample container. Dry and weigh the sample.
m. If the above procedure cleans the tube sufficiently, subsequent samples may be analyzed without further drainage.

Reporting The Data

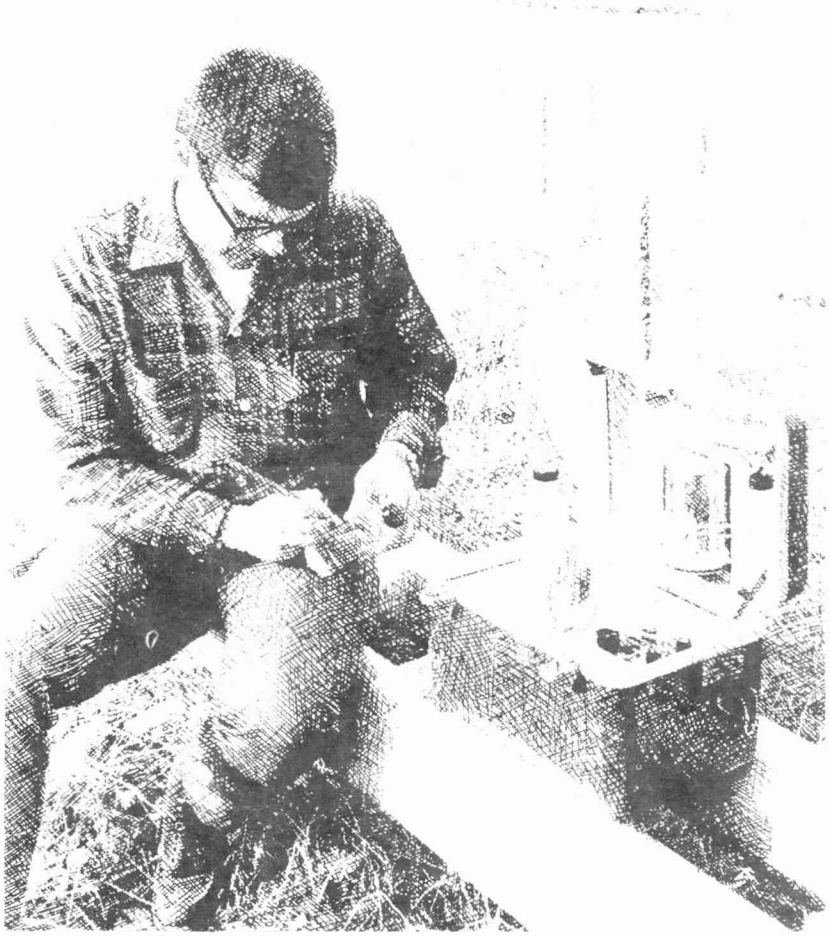
The charts have temperature lines and certain definite sizes printed on them. It is usually sufficient to record the percentages finer (or coarser) than the sizes printed on the chart. If other size divisions are desired, it is possible to obtain them by interpolating between the temperatures of the size lines printed. In reading the percentages finer (or coarser) than a given size, a scale calibrated from 0 to 100 is used. To reach percentages finer than a given size, place the scale on the chart so that the 0 mark coincides with the total accumulation level and the 100 mark coincides with the baseline. Maintaining this position, move the scale horizontally until the accumulation curve intersects the desired size and temperature line. The scale reading at the point of intersection then gives the percentage of the sample which is finer than the size for which the reading is made.

In most cases the VA sample will only be a portion of the total sample. If desired, the above procedure can be modified so that the readings will be in percentages finer than the specified size for the total sample. For example, if 50 percent of the sample is removed as fines and coarser material, the 50 mark can be placed on the base mark and the 0 mark on the total accumulation line. The scale reading at the desired intersection will then be the percentage of the total sample finer than the specified amount.

To obtain the percentage coarser, the scale is inverted and the same procedure followed. A space is provided on the chart for listing the percentages found by this method.

Chapter 4

Biologic and Microbiologic Quality of Surface and Ground Water



CHAPTER 4 - BIOLOGICAL AND MICROBIOLOGICAL QUALITY OF WATER

Prepared by
Work Group 4 on Biological and Microbiological Quality of Water
May 1983

WORK GROUP ON BIOLOGICAL AND MICROBIOLOGICAL QUALITY OF WATER

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COMMENTS ON CHAPTER 4

National Handbook of Recommended Methods for Water-Data Acquisition

I found this "National Handbook" chapter to be useful. Comments:

_____

_____

_____

I found the following method to be unsatisfactory: _____

Method _____

Reference _____

The method is unsatisfactory for the following reason(s): _____

_____

_____

_____

Submitted by (Name): _____

(Organization): _____

(Address): _____

(Telephone): _____

Date: _____

_____

Thank you for your views on Chapter 4 of the "National Handbook." Your comments will be considered in revising the "National Handbook" to benefit all users. Please mail this form to:

Office of Water Data Coordination
U.S. Geological Survey
MS 417, National Center
Reston, VA 22092

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CHAPTER 4 - BIOLOGICAL AND MICROBIOLOGICAL QUALITY OF WATER

4.A. INTRODUCTION

4.A.1. SCOPE

Chapter 4 contains methods for assessing the biological and microbiological quality of water. The chapter describes techniques to collect, preserve, and prepare samples; count and identify organisms; measure biomass and metabolic rates; handle and interpret data; and assure quality of data. Methods are provided for all major communities of aquatic organisms—including the phytoplankton, zooplankton, periphyton, macrophyton, macroinvertebrates, and fish—and for the viruses and bacteria. One or more methods are included for each of the basic properties of the communities, including standing crop, community structure, and community metabolism.

4.A.2. SOURCES OF METHODS

Methods were selected principally from widely-used references, such as Weber (1973), American Public Health Association and others (1976), Greeson and others (1977), and Bordner and others (1978). Other widely-used references were cited if they provided valuable supporting information or if the previously-mentioned sources did not contain a particular method.

4.A.3. DESCRIPTIONS OF METHODS

Only a brief overview of each method is provided to assist the user in determining the scope and application of the method. The description consists of the following elements: summary; application; interferences and special considerations; sample preservation and storage; analysis; calculations; and data reporting and precision. For detailed information about the methods, the user must consult the appropriate references.

4.A.4. REVISIONS OF METHODS

The development and standardization of biological methods are extremely dynamic. Existing methods are constantly evolving, and new methods are appearing with ever increasing frequency. To keep pace with new developments in this field, the state-of-the-art of the methodology will be continually monitored and the Handbook will be updated as appropriate.

4.A.5. QUALITY ASSURANCE

The quality and utility of biological data depend upon many factors, which include adequate program planning, the experience and skill of the staff, the availability of adequate facilities and state-of-the-art equipment, and the quality control exercised throughout the process of sample collection and analysis. A detailed discussion of quality assurance is presented in section 4.B.5.

4.A.6. DESIGNING THE PROJECT AND COLLECTING THE SAMPLES

Before biological samples are collected, the historical biological, chemical, and physical (especially hydrological) data should be examined and a study design must be formulated.

Examining historical biological and chemical data often reveals some areas that warrant intensive sampling and other areas where periodic or seasonal sampling will suffice. Physical data also are extremely useful in designing biological studies; of particular importance are data concerning volume of flow, stream gradient, currents, prevailing wind direction, temperature, turbidity (light penetration), depths of reservoir penstock releases, and estuarine salinity "wedges."

After historical data have been examined, a preliminary project design should be developed with the aid of a bio-statistician and experts in other disciplines. The study sites should be visited for reconnaissance and preliminary sampling. Based on the results of this reconnaissance and on the preliminary data, the project design can be modified to better fulfill project objectives and to facilitate efficient sampling (Weber, 1973).

Site selection on small streams is generally limited to sampling stations located above a study area and to sampling stations located as far downstream of the study area as may be affected by the source of pollution. On rivers, sampling stations are located at several points on a transect across the river. Plankton sampling at several points in the cross section is necessary because lateral and vertical mixings are usually incomplete.

Sampling stations in lakes, reservoirs, and estuaries generally are located in grid networks or along longitudinal transects as described in Greeson and others (1977), American Public Health Association and others (1976), Edmondson and Winberg (1971), Schwoerbel (1970), Pennak (1953), Unesco Press (1968), and Welch (1948).

The type of sampling equipment to use depends upon where and how the sample is to be taken (that is, from a small lake, large deep lake, small stream, large stream, from the shore, from a bridge, from a small boat, or from a large boat) and how it is to be used.

Information on the identity and history of each sample must be attached to or placed in the sample container or recorded in a field logbook referenced to the sample by an identifying number. In the latter instance, the logbook becomes a permanent part of the data. The sample information should include purpose or name of study; exact place, time, and date of collection; depth; method of collection; original volume; amount and type of preservative; and name of collector. Notes on relevant field observations or other associated data are often desirable. Labels and field logs should be waterproof and the information should be recorded in soft-lead pencil or permanent waterproof ink.

4.A.7. REFERENCES

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4.B. BIOLOGICAL METHODS

4.B.1. COMMUNITY STRUCTURE

4.B.1.a. PLANKTON

4.B.1.a.1. INTRODUCTION

Plankton consists of an assemblage of microscopic plants (phytoplankton) and animals (zooplankton) that have essentially neutral buoyancy and drift passively with the currents. The composition and abundance of species of plankton are directly related to water quality. Complex interrelationships exist among the various components of the planktonic community.

The phytoplankton consist of algae, bacteria, and fungi. Chlorophyll-bearing plants, such as algae, usually constitute the greatest part of the biomass of the plankton. However, the bacteria and other non-chlorophyllous plants may be very numerous. The algae use the energy of sunlight to metabolize inorganic nutrients and convert them into complex organic materials. The phytoplankton directly affect the composition of water—notably the dissolved oxygen, pH, and concentration of certain solutes—and the optical properties of water. At times the abundance or presence of particular species of phytoplankton results in nuisance conditions.

Zooplankton are secondary consumers that feed upon phytoplankton and organic detritus and are, in turn, consumed by larger organisms. Because they are the grazers in the aquatic environment, the zooplankton are a vital part of the food web in that they pass energy along to larger and usually more complex organisms, such as macroinvertebrates and fish. Although many species of zooplankton are restricted to standing bodies of water, some forms are common in streams.

Some devices used to sample the plankton, water bottles, for example, collect all suspended particulate matter in the water, including the phytoplankton, zooplankton, organic detritus, and inorganic materials. These suspended materials are collectively termed "seston."

4.B.1.a.2. SESTON

Seston is the total particulate matter, both inorganic and organic, suspended in water (Hutchinson, 1967). The composition of the seston frequently determines the apparent color of water. The inorganic components generally impart a brown color. Planktonic algae are responsible for several hues—abundant bluegreen algae impart a faded green color, diatoms give a yellowish or yellow-brown color, and green algae convey a grass-green appearance. Some phytoplankton and zooplankton, particularly flagellates and certain microcrustaceans, may tint the water red.

Measurements of seston include the total suspended particulate matter (dry weight), the dehydrated inorganic part of the suspended particulate matter (ash weight), and the suspended particulate organic matter (ash-free dry weight).

4.B.1.a.2.a. Gravimetric (Ash-Free Dry Weight of Organic Matter)

Summary of Method

A known volume of sample is concentrated by filtration or centrifugation and is dried at 105° C (Weber, 1973b; Greeson and others, 1977). The increase in weight over the tared filter weight is the dry weight of the seston. After ashing at 500° C, the sample is rewet and redried. The difference between the final dry weight and the ash weight (that is, the ash-free weight or weight lost on ignition) is assumed to be the biomass (organic weight) of the sample, but may include the weight of some volatile inorganic substances.

Application

The method is suitable for both fresh and saline waters.

Interferences and Special Considerations

The method is generally free from interferences. All sample-collecting equipment and bottles must be clean

and free of particulate matter. Saline samples must be washed thoroughly with distilled water to remove dissolved substances.

Preservation and Storage

The seston concentrate may be stored for several weeks at 1–4° C. Samples that cannot be concentrated without delay should be preserved with 40 mg Hg^{2+}/L (1 mL of the mercuric chloride solution per liter of sample). This method for seston preservation will stabilize the seston content of samples for at least 8 days. However, the results of analyses of preserved samples are not necessarily the same as those obtained by immediate filtration.

Analysis

Refer to Weber (1973b) and Greeson and others (1977).

Calculations

Refer to Weber (1973b) and Greeson and others (1977).

Data Reporting and Precision

Report seston concentrations to the nearest 0.1 mg/liter. No numerical precision data are available.

4.B.1.a.2.b. Adenosine Triphosphate (ATP)

Determination of adenosine triphosphate (ATP) is the only available method of measuring total viable plankton biomass. ATP is an energy-mediating compound that occurs in every form of living matter. For many species of bacteria, algae, and zooplankton, the ratio of ATP to cellular organic carbon is relatively constant (within an order of magnitude) (Weber 1973a). Furthermore, the concentration of ATP remains relatively constant during all phases of a growth cycle. ATP has a short survival time after the death of a cell and is, therefore, specific for living biomass.

Summary of Method

ATP is extracted from the organisms in a water sample. The sample may be filtered if concentration is necessary. The cell extract (containing the ATP) is injected into a reagent solution. A flash of light is produced and measured with a photometer. The amount of light produced is proportional to the ATP concentration; one photon of light is emitted for each molecule of ATP reacted.

Application

The method is suitable for all waters, including effluents.

Interferences and Special Considerations

Several metals (such as Hg^{+2}, Cd^{+2}) and high concentrations of salts in general will inhibit the reaction. Marine samples must be diluted (or filtered) to avoid an underestimation of ATP, which can result from the inhibition of luciferase by high salt concentrations. If the sample is filtered, it is advisable to wash the filter with distilled water immediately after filtration to remove most of the dissolved salts.

Preservation and Storage

Storing a plankton sample may result in a significant change in ATP concentration. Consequently, it is best to extract the ATP from the cells immediately after the sample has been collected. The sample may be kept for a few hours if it is maintained at approximately the same temperature and light intensity as when sampled. Once the ATP is extracted, the ATP concentrate may be stored frozen for at least 30 days.

Analysis

Several instruments are available for measuring ATP. Some measure the peak height of the emitted light flash, others integrate the area under the light-decay curve, and some instruments measure both peak heights and decay curves.

All methods utilize the firefly lantern enzyme system (luciferin-luciferase) to catalyze the reaction. At pres-

ent, two general luciferase preparations, one relatively impure and the other highly purified, are available. The crude preparation is inexpensive, but lacks specificity for ATP (because it contains enzymes other than luciferase that react with ATP), produces a high background, and is less sensitive than a more purified preparation. In contrast, the more purified preparation costs more, is specific for ATP, produces a low background, and is substantially more sensitive. Assay and extraction procedures can be found in Greeson and others (1977), SAI Technology Company (1975), Cheer and others (1974), Dupont Corporation (1974), JRB Associates (1974), and American Instrument Company (1973).

Calculations

Refer to Greeson and others (1977).

Data Reporting and Precision

Report ATP concentration in μg/L (micrograms per liter) of original water sample to the nearest 0.1 μg/L. Reproducibility is approximately ± 10 percent (single operator).

4.B.1.a.3. PHYTOPLANKTON

4.B.1.a.3.a. Collection

There is no single standard method for collecting and enumerating the phytoplankton. The organisms may be so greatly concentrated that the sample must be diluted for enumeration, or there may be so few organisms in a sample that many counts must be made. Morphological differences between living phytoplankton and preserved organisms are additional factors that influence the selection of a method to count phytoplankton (Greeson and others, 1977).

Many types of sampling devices can be used to sample phytoplankton. Most samplers collect water at only one depth; thus, the samples collected in such a way are referred to as "point" or "grab" samples. Grab samples should be collected with minimal disturbance to the surrounding water. Cylindrical samplers of the Kemmerer, Juday, or Van Dorn design operate in such a manner and are available in a variety of sizes and materials. For sampling in deep waters, the Nansen reversing water bottle is often used from a boat equipped with a winch (Weber, 1973b).

Phytoplankton may also be collected by pump and hose. While it is possible to collect large volumes in this manner, the hose must be flushed between samples and delicate forms of phytoplankton may be harmed by passage through the pump.

Using a net to collect phytoplankton is not recommended for quantitative work because nannoplankton and some larger algae, such as pennate diatoms, are thin enough to pass through a net. A net can be used for qualitative work, however.

4.B.1.a.3.b. Counting and Identification

4.B.1.a.3.b.1. Sedgwick-Rafter Counting Method—The Sedgwick-Rafter counting cell is one of the most widely used devices for determining the concentration of phytoplankton. The method is easily performed and provides reasonably reproducible information when used with a calibrated microscope equipped with a measuring device such as the Whipple ocular micrometer (American Public Health Association and others, 1976; Greeson and others, 1977).

Summary of Method

A 1-mL aliquot of phytoplankton sample is placed in a Sedgwick-Rafter counting cell and is examined microscopically with the aid of a Whipple ocular micrometer. The number of algal units present in random fields or in scanned strips is counted. The concentration of phytoplankton in the sample is calculated as number of units per milliliter.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Large concentrations of suspended sediment may obscure the phytoplankton cells in the sample. If the phytoplankton sample contains a great number of cells, as typically occurs in eutrophic waters, the sample must be diluted. Refer to Greeson and others (1977) for the dilution procedure. Samples with very few cells must be concentrated before the microscopic examination. Common concentrating procedures include sedimentation, centrifugation, and filtration. Refer to Greeson and others (1977) or Weber (1973b) for concentration procedures.

Preservation and Storage

Live samples should be examined within 2 or 3 hours after collection (Greeson and others, 1977). A phytoplankton sample may be maintained for 24 hours at 3–4° C (Greeson and others, 1977), but for extended storage, the sample must be preserved. If samples are to be stored for less than 1 year, Lugol's solution (potassium iodide and iodine, frequently with merthiolate) (Vollenweider, 1969) or merthiolate (Weber, 1968; 1973b) may be used as preservatives. If samples are to be stored for more than 1 year, preserve with formalin (Weber, 1973b; Greeson and others, 1977).

Analysis

Refer to American Public Health Association and others (1976), Greeson and others (1977), or Weber (1973b).

Calculations

Refer to American Public Health Association and others (1976), Greeson and others (1977), or Weber (1973b).

Data Reporting and Precision

Report phytoplankton concentration to two significant figures as units per milliliter (Greeson and others, 1977). The literature contains conflicting evidence concerning randomness at all stages of plankton sampling and enumeration (Greeson and others, 1977). Each investigator should evaluate the statistical characteristics of the particular sampling and counting methods being used (Committee on Oceanography, Biological Methods Panel, 1969). The difference between counts is significant if the confidence limits do not overlap. The difference is not significant if one actual count lies within the confidence limits of the other (Lund and others, 1958).

4.B.1.a.3.b.2. Palmer-Maloney Counting Method—The Palmer-Maloney cell was designed for enumerating nannoplankton (Palmer and Maloney, 1954) with a high-dry (45×) microscope objective. Although the method is useful for examining samples containing a high percentage of nannoplankton, it may require more counts to obtain a valid estimate of larger, and frequently less numerous, organisms present (Weber, 1973b). The Palmer-Maloney nannoplankton cell is not recommended for routine counting of samples.

Summary of Method

An aliquot of a well-mixed sample is pipetted into the nannoplankton cell and is examined microscopically with the aid of a Whipple ocular micrometer. The number of algal units in random fields is counted. The concentration of phytoplankton in the sample is calculated as number of units per milliliter.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Large concentrations of suspended sediment may obscure the phytoplankton cells in the sample. Samples generally have to be concentrated before microscopic examination. Common concentrating procedures include sedimentation, centrifugation, and filtration. Refer to Greeson and others (1977) or Weber (1973b) for concentration procedures.

Preservation and Storage

Live samples should occupy no more than one-half the volume of the container and should be examined within 2 or 3 hours after collection (Greeson and others, 1977). A phytoplankton sample may be maintained for 24 hours at 3–4° C (Greeson and others, 1977), but for extended storage, the sample must be preserved.

If samples are to be stored for less than 1 year, preserve with Lugol's solution (Vollenweider, 1969) or merthiolate (Weber, 1968; 1973b); for storage of more than 1 year, preserve with formalin (Weber, 1973b; Greeson and others, 1977).

Analysis

Refer to Weber (1973b).

Calculations

Refer to Weber (1973b).

Data Reporting and Precision

Report phytoplankton concentration to two significant figures as units per milliliter (Greeson and others, 1977). The literature contains conflicting evidence concerning randomness at all stages of plankton sampling and enumeration (Greeson and others, 1977). Each investigator should evaluate the statistical characteristics of the particular sampling and counting methods being used (Committee on Oceanography, Biological Methods Panel, 1969). The difference between counts is significant if the confidence limits do not overlap. The difference is not significant if one actual count lies within the confidence limits of the other (Lund and others, 1958).

4.B.1.a.3.b.3. Inverted-Microscope Counting Method—This technique involves the following:

Summary of Method

An aliquot of a preserved phytoplankton sample is placed in a counting chamber. The algae are allowed to settle to the bottom of the chamber. The algae are identified and enumerated in a known area of the chamber and the concentration in the sample is calculated.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Suspended sediment may obscure the algae in a plankton sample.

Preservation and Storage

Formaldehyde (often with detergent, cupric sulfate, or both) and Lugol's solution are the two most commonly utilized fixatives. Formaldehyde is effective indefinitely, but causes many flagellated forms of phytoplankton to shed flagella and may distort or destroy some forms. Lugol's solution generally does not cause the loss of flagella, but it decomposes slowly so that fresh fixative must be added at 6–12 month intervals (Weber, 1968; Committee on Oceanography, Biological Methods Panel, 1969; Weber, 1973b; Greeson and others, 1977).

Analysis

Refer to Greeson and others (1977).

Calculations

Calculate the units per milliliter by correcting for the percentage of chamber area counted and any dilution or concentration steps. Refer to Greeson and others (1977).

Data Reporting and Precision

Report phytoplankton concentration to two significant figures as units per milliliter. Precision is dependent upon the size of the count.

4.B.1.a.3.b.4. Membrane Filter Counting Method—An advantage of the membrane-filter method is that the phytoplankton sample is reduced to a semi-permanent microscope slide that can be retained for later examination.

Summary of Method

A fresh or preserved sample is filtered. Organisms from a fresh sample that are retained on the membrane are fixed with formaldehyde. The filter is rendered transparent, mounted on a microscope slide, and the concentration of cells is calculated from random-area microscopic counts.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Large amounts of inorganic sediment, detritus, or organic and inorganic precipitates may clog the filter (Greeson and others, 1977). Significant amounts of suspended matter may obscure or crush the organisms (Weber, 1973b). Experience is required to determine the proper amount of water to be filtered.

Saline samples must be washed with distilled water to remove salt (Weber, 1973b).

Preservation and Storage

Live samples should occupy no more than one-half the volume of the container and should be examined within 2 or 3 hours after collection (Greeson and others, 1977). A phytoplankton sample may be maintained for 24 hours at 3–4° C (Greeson and others, 1977), but for extended storage, the sample must be preserved. If samples are to be stored for less than 1 year, Lugol's solution (Vollenweider, 1969) or merthiolate (Weber, 1968; 1973b) may be used as a preservative. If samples are to be stored for more than 1 year, preserve with formalin (Weber, 1973b; Greeson and others, 1977). Add 3–5 mL of 40-percent formaldehyde solution (neutralized with sodium tetraborate to pH 7.0–7.3), 0.5 mL of 20-percent surgical-detergent solution, and 5 to 6 drops of concentrated cupric sulfate solution to each 100 mL of sample (Weber, 1973b; Greeson and others, 1977). To prepare Lugol's solution, dissolve 10 g iodine crystals and 20 g potassium iodide in 200 mL distilled water; add 20 mL glacial acetic acid a few days before use and store in amber glass bottles (Vollenweider, 1969).

Analysis

Refer to American Public Health Association and others (1967), Greeson and others (1977), or Weber (1973a). Greeson and others (1977) give a detailed description of the steps in the analytical procedure.

Calculations

Refer to American Public Health Association and others (1976) or Greeson and others (1977).

Data Reporting and Precision

Report phytoplankton concentration to two significant figures as units per milliliter (Greeson and others, 1977). The literature contains conflicting evidence concerning randomness at all stages of plankton sampling and enumeration (Greeson and others, 1977). Each investigator should evaluate the statistical characteristics of the particular sampling and counting methods being used (Committee on Oceanography, Biological Methods Panel, 1969). The difference between counts is significant if the confidence limits do not overlap. The difference is not significant if one actual count lies within the confidence limits of the other (Lund and others, 1958).

4.B.1.a.3.b.5. Diatom Species Proportional Counting Method—Study objectives often require specific identification of diatoms and information about the relative abundance of each species. Since the taxonomy of diatoms is based on frustule characteristics, low-power magnification is seldom sufficient, and permanent diatom mounts are prepared and examined under oil immersion (Weber, 1973b).

Summary of Method

The diatoms in a sample are concentrated, the organic matter is removed by chemical or pyrrolic oxidation and a permanent mount is prepared. The mount is examined microscopically, and the number of diatom taxa is calculated from strip counts.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Particulate matter and high concentrations of dissolved solids in the sample may obscure the structural details of the diatom cell walls. Differential phase interference optical systems (Normarski optics) with 1,000× magnification are recommended for identifying diatom species. Small centric diatoms and other extremely small microorganisms in periphyton samples are best identified under a scanning electron microscope (SEM), but preparing samples for an SEM is much more time consuming. "Mini" SEMs are available at modest cost and are becoming standard laboratory equipment.

Preservation and Storage

Samples should be preserved in 5-percent formalin when collected (Weber, 1973b; Greeson and others, 1977). Cells mounted in resin can be stored indefinitely.

Analysis

Refer to Greeson and others (1977) and Weber (1973b).

Calculations

Refer to Greeson and others (1977) and Weber (1973b).

Data Reporting and Precision

Report the percentage abundance of each species to the nearest 0.1 percent. Report the number of taxa and, where necessary, the number of organisms per taxa. The precision of the counts increases as the size of the tallies increases. The standard deviation is approximately equal to the square root of the mean tally.

4.B.1.a.3.c. Cell Volume Measurement

Because of the great variation in the size of phytoplankton, cell numbers may not provide a true evaluation of biomass. Measurements of algal cell volume may be used to estimate the total biomass of phytoplankton standing crop or the relative biomass of individual taxa. However, the method is generally too time consuming for routine use.

Summary

An aliquot of phytoplankton sample is examined with a calibrated microscope and ocular micrometer. The mean volume for each taxon (usually determined in advance) is multiplied by the number of individuals of that taxon in the aliquot. Results are reported in terms of algal volume per volume of water or as wet weight per volume of water, assuming a density of 1.0 for planktonic organisms.

Application

The method is suitable for all waters.

Interferences and Special Considerations

The microscope should be equipped with a calibrated micrometer. Because the method involves measuring three dimensions, the work is much slower than enumeration methods. The estimate of the vertical dimension or thickness of organisms is often subject to considerable error.

Preservation and Storage

Cell volume determinations can be made on live samples examined within 2 or 3 hours of collection or on samples preserved as described in American Public Health Association and others (1976), Weber (1973b), and Greeson and others (1977).

Analysis

The cells are enumerated using the Sedgwick-Rafter (or other) counting method. At least 20 representative individuals of each significant taxon encountered during the enumeration process are measured with the aid of the ocular micrometer and, if necessary, the calibrated fine adjustment. The mean cell volume, in cubic micrometers (μm^3), is determined for each taxon, and is multiplied by the number of cells present. Refer to Welch (1948), American Public Health Association and others (1976), and Vollenweider (1969).

Calculations

Refer to Welch (1948), American Public Health Association and others (1976), and Vollenweider (1969).

Data Reporting and Precision

Report phytoplankton volumes in cubic millimeters per liter. The estimate of algal volume can be converted into an estimate of wet weight by assuming a phytoplankton density of 1.0 (Vollenweider, 1969; Schwoerbel, 1970). No numerical precision data are available.

4.B.1.a.3.d. Pigment Determination

All algae contain chlorophyll *a*, and measuring this pigment can yield some insight into the relative amount of algal standing crop. Certain algae also contain chlorophyll *b* and *c*. Since the chlorophyll concentration varies with species and with environmental and nutritional factors that do not necessarily affect the standing crop, biomass estimates based on chlorophyll measurements are relatively imprecise.

4.B.1.a.3.d.1. Chlorophyll By Spectrophotometry—Spectrophotometry measures the chlorophylls without separating them from other cellular contents or from related precursors and degradation products.

Summary of Method

The algae in a water sample are concentrated and the algal cells are mechanically disrupted in acetone or dimethyl sulfoxide. The chlorophylls are solubilized and the sample is centrifuged to remove particulate matter. The concentration of chlorophylls is determined by absorbance at a specific wavelength. The sample is then acidified and the concentration of pheophytin, a degradation product of chlorophyll, is determined by spectrophotometric measurement (Lorenzen, 1965).

Application

The method is suitable for all waters.

Interferences and Special Considerations

The presence of any compound that absorbs at the same wavelength as chlorophyll is likely to cause an overestimation of chlorophyll. Degradation products of the chlorophylls, such as the pheophytins, chlorophyllides, and pheophorbides, will interfere when present. If pheophytin *a* is the primary degradation product, the chlorophyll *a* value may be corrected by measuring absorbance before and after acidification of the sample (Weber, 1973b). Exposure to light or acid at any stage of storage and analysis can result in photochemical and chemical degradation of the chlorophylls (Greeson and others, 1977).

Preservation and Storage

Changes in the chlorophyll content can be minimized by storing the filtered material in the dark at 1° C or less. Chlorophyll may degrade somewhat during storage, but this change is generally small when the sample is stored under the above conditions for 2 weeks or less. Samples stored more than 2 weeks should be held at −20° C.

Analysis

Refer to Greeson and others (1977), American Public Health Association and others (1976), or Weber (1973b).

Calculations

Refer to Greeson and others (1977) or Jeffrey and Humphrey (1975).

Data Reporting and Precision

Report chlorophyll *a*, *b*, and *c* in micrograms per liter to three significant figures. The precision of chlorophyll determinations is influenced by the volume of water filtered, the range of chlorophyll values found, the volume of extraction solvent, and the length of the light-path of the spectrophotometer cells.

4.B.1.a.3.d.2. Chlorophyll By Fluorometry—Fluorometry also measures the chlorophylls without separating them from other cellular contents or from related precursors and degradation products.

Summary of Method

The algae in a water sample are concentrated and are mechanically disrupted in acetone or dimethyl sulfoxide. The chlorophylls are solubilized and the sample is centrifuged to remove particulate matter. The concentration of chlorophylls is determined by fluorescence.

Application

The method is suitable for all waters.

Interferences and Special Considerations

The presence of any compound that fluoresces at the same wavelength as chlorophyll is likely to cause an overestimation of chlorophyll. Precursors and degradation products of the chlorophylls, such as the pheophytins, chlorophyllides, and pheophorbides, will interfere when present. Exposure to light or acid at any stage of storage and analysis can result in photochemical and chemical degradation of the chlorophylls (Lorenzen, 1965; Weber, 1973b; Greeson and others, 1977).

Preservation and Storage

Changes in the chlorophyll content can be minimized by storing the filtered material in the dark at 1° C or less. Chlorophyll may degrade somewhat during storage, but this change is generally small when the sample is stored under the above conditions for 2 weeks or less. Samples stored more than 2 weeks should be held at −20° C.

Analysis

Refer to American Public Health Association and others (1976) and Weber (1973b).

Calculations

Refer to American Public Health Association and others (1976).

Data Reporting and Precision

Report chlorophyll *a*, *b*, and *c* in micrograms per liter to three significant figures. The precision of chlorophyll determinations is influenced by the volume of water filtered, the range of chlorophyll values found, the volume of extraction solvent, and the light-path length of the cells.

4.B.1.a.3.d.3. Chlorophyll By Chromatography—Many precursors and degradation products of plant pigments can interfere with the determination of chlorophylls. Chlorophyll *a* and *b* can be separated from other cellular contents and from closely related precursors and degradation products by thin-layer chromatography. Chlorophylls then are measured by spectrophotometry or by fluorometry.

Summary of Method

The sample is concentrated, the cells are disrupted, and the chlorophylls are extracted. The chlorophylls are separated from each other and from closely related substances by thin-layer chromatography. Chlorophylls are eluted and are measured with a spectrophotometer or fluorometer.

Application

The method is suitable for all waters, but cannot be used for the determination of chlorophyll *c*.

Interferences and Special Considerations

Exposure to light or acid at any stage of storage and analysis can result in photochemical and chemical degradation of the chlorophylls (Weber, 1973b; Greeson and others, 1977). The method is very time consuming and is not recommended for general use.

Preservation

Algae concentrate should be stored in darkness at −20° C, preferably in a dessicator if extraction is delayed. Storage should not exceed 1 month (Greeson and others, 1977). Chlorophyll may degrade somewhat during storage, but any changes are usually small when the sample is stored under the above conditions.

Analysis

Refer to Greeson and others (1977). Revised spectrophotometric equations are found in Jeffrey and Humphrey (1975).

Calculations

Refer to Greeson and others (1977).

Data Reporting and Precision

Report chlorophyll *a* or *b* in micrograms per liter of original water sample to three significant figures. No precision data are available.

4.B.1.a.4. ZOOPLANKTON

4.B.1.a.4.a. Collection

Many factors affect the distribution of zooplankton. Water currents may cause lateral as well as vertical movement. Many zooplankton migrate vertically, approaching the surface at night and sinking to lower depths at dawn. Thus, representative samples from lakes, reservoirs, and estuaries should include the entire water column in order to minimize the effects of vertical plankton migrations that might occur during the course of a survey. The study of zooplankton must consider their ability to avoid sampling devices. No single method can conclusively and accurately sample the entire zooplankton community. A number of methods for the collection of zooplankton, as well as procedures for determining their grazing rates and production, are found in the references.

On rivers, sampling stations need to be located at several points in the cross section as well as upstream and downstream of a study area. Sampling at several points in the cross section is necessary because lateral and vertical mixing are usually incomplete.

Zooplankton sampling stations in lakes, reservoirs, and estuaries are generally located in grid networks or along longitudinal transects as described in Greeson and others (1977), American Public Health Association and others (1976), Edmondson and Winberg (1971), Schwoerbel (1970), Pennak (1953), Unesco Press (1968), and Welch (1948).

4.B.1.a.4.b. Sampling Devices

Quantitative samples of zooplankton may be collected by a messenger-operated water bottle, plankton trap, or metered plankton net. Semi-quantitative samples may be obtained by filtering water samples through a fine mesh net or an unmetered plankton net. A simple plankton net may be towed through the water to obtain zooplankton. Refer to American Public Health Association and others (1976), Greeson and others (1977), Weber (1973b), Barkley (1964; 1972), and Aron and others (1965) for details.

Choosing the appropriate size of the mesh and the other design attributes of a zooplankton net depends on the abundance of organisms in the water and on the expected towing speed of the net. See Barkley (1972) for a discussion of towed-net samplers. Additional considerations in selecting nets for various applications are given in Edmondson and Winberg (1971), Unesco Press (1968), and Dycus and Wade (1977).

4.B.1.a.4.c. Counting And Identification

4.B.1.a.4.c.1. Counting-Chamber Method—Larger zooplankton are frequently concentrated by allowing the organisms to settle to the bottom of a container before analysis. After concentration, an aliquot is selected for taxonomic identification and enumeration, which are carried out in a suitable chamber. Zooplankton are more accessible in open chambers, but such chambers are difficult to move without disturbing settled organisms. Identification of some species may require dissection and examination under a compound microscope (Pennak, 1953).

Summary of Method

In this method, an aliquot of the entire concentrate is transferred to a gridded culture dish. Enumeration is made under relatively low power under a dissecting microscope. If identification is required, many forms will have to be dissected and examined under a compound microscope (Pennak, 1953).

Application

The method is suitable for all waters.

Interferences and Special Considerations

Suspended materials in the water may interfere with the collection and microscopic examination of zooplankton. Sampling may be difficult in very swift water (Dycus and Wade, 1977).

Preservation and Storage

Zooplankton samples should be preserved with 5-percent neutralized formalin (add sodium tetraborate to obtain a pH of 7.0 to 7.3). Drying of the sample can be avoided by adding 5-percent glycerol (Weber, 1973b). The addition of 0.04-percent Rose Bengal is useful to differentiate zooplankton from detritus in certain samples.

Analysis

Refer to Weber (1973b) for analytical details.

Calculations

Refer to Weber (1973b).

Data Reporting and Precision

Report the zooplankton density as total number of organisms per cubic meter to two significant figures. No numerical precision data are available.

4.B.1.a.4.d. Biomass Determination

4.B.1.a.4.d.1. Gravimetric—The biomass is expressed as an estimate of the total assemblage of organisms in the sample, which may include bacteria, algae, and other forms besides zooplankton. It is difficult to obtain quantitative values for each of the components because of their heterogeneous distribution in the water column (Weber, 1973b).

Summary of Method

Samples of the zooplankton community are collected from known volumes of water. The dry and ash weight are determined, and the weight of organic matter per unit volume of the water sample is calculated.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Suspended materials in the water may interfere with sample collection. The presence of phytoplankton and nonliving organic matter in the sample will cause erroneously high ash-free weights.

Preservation and Storage

Wash the zooplankton by dipping the sample in distilled water several times, place the sample in a plastic bag, and preserve it in the field by freezing with dry ice. Keep frozen until gravimetric determinations can be made (Committee on Oceanography, Biological Methods Panel, 1969). If the samples cannot be kept frozen, preserve them in 2-percent neutralized formaldehyde solution (5-percent formalin). Label each sample with the volume of water filtered or with the information needed to determine this value.

Analysis

Refer to Greeson and others (1977) or Weber (1973b) for details of the procedure.

Calculations

Refer to Greeson and others (1977) or to Weber (1973b).

Data Reporting and Precision

Report biomass to two significant figures. No numerical precision data are available.

4.B.1.a.4.d.2. Volumetric—The volume of zooplankton can be estimated by water displacement. This method is useful for relatively large volumes of plankton, but cannot be used for samples having small numbers of zooplankton.

Summary of Method

The sample is separated from preservatives by pouring it through No. 20 mesh nylon bolting cloth. The drained zooplankton are placed in a graduated cylinder of appropriate size, and a known volume of water is added. The volume of zooplankton is determined from the difference between the known volume of water added and the volume of water plus the zooplankton.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Suspended sediment and other nonliving particulate matter cause overestimation of the true biomass. Bacteria, algae, and fungi, if present, also result in the overestimation of the zooplankton biomass. If the sample is preserved prior to analysis, some change in organism volume is likely.

Preservation and Storage

If the sample cannot be analyzed in the field, wash the zooplankton several times in distilled water, place the sample in a plastic bag, and preserve it immediately by freezing with dry ice. Keep frozen until analysis can be made (Committee on Oceanography, Biological Methods Panel, 1969). If the samples cannot be kept frozen, preserve them in 2-percent neutralized formaldehyde (5-percent formalin). Label each sample to indicate the volume of water filtered.

Analysis

Refer to Weber (1973b) for details of the procedure.

Calculations

Refer to Weber (1973b) for calculation procedure.

Data Reporting and Precision

Report the volume of zooplankton in milliliters per cubic meter of sample to two significant figures. No precision data are available.

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4.B.1.b. PERIPHYTON

4.B.1.b.1. INTRODUCTION

The periphyton consist of microscopic plants and animals, such as algae, protozoa, bacteria, and fungi, that grow on submerged surfaces. The organisms that live among the attached forms and are captured when the attached forms are collected are also considered to be periphyton.

The periphyton are important in the aquatic food web and may strongly affect the levels of dissolved minerals, organic matter, and gases in water. Their abundance (numbers and biomass), species composition and diversity, and physiological rates are useful indices of water quality.

Properties of periphyton communities may be used to model stream recovery, re-aeration rates, and assimilative capacity; to monitor long-term trends in water quality, which may be affected by point and nonpoint sources of pollution; to measure the immediate effects of discharges on receiving waters; and to detect the presence of low levels of toxicants through biomagnification processes.

4.B.1.b.2. COLLECTION

Stations may be employed singularly, as in the case of ambient water-quality monitoring and biomagnification studies, or may be established above and below point and nonpoint sources of pollution, to determine the effects of the pollutants on communities of indigenous aquatic organisms in the receiving waters.

Qualitative samples may be collected for studies of species composition and diversity by scraping the periphyton from rocks, sticks, aquatic plants, and other submersed surfaces. Studies of long-term trends in periphyton community structure and biomass at a single station or comparisons at stations above and below pollution sources must be based on collections from similar substrates in waters with comparable velocities. No reliable, practical methods are available to collect quantitative samples from natural substrates.

Artificial substrates offer the easiest and most reliable method of collecting quantitative samples from comparable surfaces. Substrates commonly employed are glass and Plexiglas[R]. Glass microscope slides (25 × 75 mm) collect sufficient material and are inexpensive and easy to obtain.

Colonization rates are affected by water temperature, nutrient concentrations, and illumination level. Optimum exposure time at temperatures above 20° C is 2–4 weeks. The same exposure time must be employed at all the stations that will be compared during a given period.

Substrates should be oriented in a vertical plane to prevent accumulation of silt and should be placed immediately below the surface of the water to eliminate the effects of turbidity on the light reaching the periphyton.

4.B.1.b.3. COUNTING AND IDENTIFICATION

4.B.1.b.3.a. Sedgwick-Rafter Counting Method

The Sedgwick-Rafter counting method for periphyton is similar to that discussed for the phytoplankton.

Summary of Method

The periphyton are removed from the substrate and, using a blender, are mechanically dispersed in the sample. A 1-mL aliquot is transferred to a Sedgwick-Rafter chamber and is examined with a microscope at 200×. The cells are counted in several randomly-selected fields or scanned strips, and the number of cells per square millimeter of substrate is determined.

Application

The method is suitable for all fresh waters. This method has not been used sufficiently in estuarine and marine waters to determine its applicability there.

Interferences and Special Considerations

Periphyton samples contain more filamentous algae than do plankton samples. Taxonomic references for these filamentous forms are more widely scattered in the scientific literature, and the organisms are more difficult to identify. Consequently, processing the samples takes more time.

Preservation and Storage

Samples that are not chemically preserved should be chilled to 4° C immediately, stored in the dark, and examined within 24 hours of collection. If held longer, preserve in 5-percent formalin.

Analysis

Refer to American Public Health Association and others (1976), Greeson and others (1977), and Weber (1973b). Identification should be carried out to the species and variety level whenever possible. Most mathematical indices of community structure that are of any value require identification to species. The environmental requirements and pollution tolerance of species often vary widely, even within the same genus. Also, identification to species permits the use of the large amount of published data on the water-quality requirements of aquatic organisms, which adds greatly to the information obtained from the samples and the inferences that can be drawn from the data. Therefore, identifications at the genus level and above are of very limited value.

Calculations

Refer to American Public Health Association and others (1976), Greeson and others (1977), and Weber (1973b).

Data Reporting and Precision

Report periphyton data to three significant figures as cells per square millimeter of substrate surface (Weber, 1973b). The precision of the data increases as the size of the tallies increases. The standard deviation of the count is approximately equal to the square root of the mean tally.

4.B.1.b.3.b. Diatom Species Proportional Counting Method

Diatoms are very useful water-quality indicator organisms because of the extensive knowledge of their water-quality requirements and pollution tolerance. Also, diatoms can be identified to species with greater certainty than most other algae. Therefore, the use of diatom species proportional counts is strongly recommended.

Summary of Method

The diatoms in the sample are concentrated by centrifugation, the organic matter is removed from the cells by chemical or heat treatment, and the cleaned cells are mounted in resin and are counted and identified at 1,000×.

Application

The method is suitable for all waters.

Interferences and Special Consideration

Particulate matter and high concentrations of dissolved solids in the sample may obscure the structural details of the diatom cell walls.

Preservation and Storage

Samples should be preserved in 5-percent formalin when collected (Weber, 1973b; Greeson and others, 1977). Cells mounted in resin can be stored indefinitely.

Analysis

Refer to Greeson and others (1977) and Weber (1973b).

Calculations

Refer to Greeson and others (1977) and Weber (1973b).

Data Reporting and Precision

Report the percentage abundance of each species to the nearest 0.1 percent. Report the number of taxa and, where necessary, the number of organisms per taxa. The precision of the counts increases as the size of the tallies increases. The standard deviation is approximately equal to the square root of the mean tally.

The chlorophyll content of the periphyton is used to estimate the algal biomass and as an indicator of the nutrient content (or trophic status) or toxicity of the water and the taxonomic composition of the community. Periphyton growing in surface water relatively free of organic pollution consist largely of algae, which contain approximately 1 to 2 percent chlorophyll *a* by dry weight. If dissolved or particulate organic matter is present in high concentrations, large populations of filamentous bacteria, stalked protozoa, and other nonchlorophyll bearing microorganisms develop and the percentage of chlorophyll *a* is then reduced. If the biomass-chlorophyll *a* relationship is expressed as a ratio (the autotrophic index), values greater than 100 may result from organic pollution (Weber, 1973b).

4.B.1.b.4.a. Chlorophyll By Spectrophotometry

Summary

The periphyton scrapings are mechanically disrupted in acetone or dimethyl sulfoxide. The chlorophylls are solubilized and the sample is centrifuged to remove particulate matter. The concentration of chlorophylls is determined by absorbance at specific wavelengths. The sample is then acidified and the pheophytin concentration is determined by spectrophotometric measurement (Lorenzen, 1965).

Application

The method is suitable for all waters.

Interferences and Special Considerations

The presence of any compound that absorbs at the same wavelength as chlorophyll is likely to cause an overestimation of chlorophyll. Degradation products of the chlorophylls, such as the pheophytins, chlorophyllides, and pheophorbides, will interfere when present. If pheophytin *a* is the primary degradation product, the chlorophyll *a* value may be corrected by measuring absorbance before and after acidification of the sample (Weber, 1973b). Exposure to light or acid at any stage of storage and analysis can result in photochemical and chemical degradation of the chlorophylls (Greeson and others, 1977).

Preservation and Storage

Changes in the chlorophyll content can be minimized by storing the filtered material in the dark at 1° C or less. Chlorophyll may degrade somewhat during storage, but this change is generally small when the sample is stored under the above conditions for 2 weeks or less. Samples stored more than 2 weeks should be held at −20° C.

Analysis

Refer to Greeson and others (1977), American Public Health Association and others (1976), or Weber (1973b).

Calculations

Refer to Greeson and others (1977) or Jeffrey and Humphrey (1975).

Data Reporting and Precision

Report chlorophyll *a*, *b*, and *c* in milligrams per square meter to three significant figures. The precision of chlorophyll determinations is influenced by the area of substrate sampled, the range of chlorophyll values found, the volume of extraction solvent, and the light-path of the spectrophotometer cells.

4.B.1.b.4.b. Chlorophyll By Fluorometry

Summary

The algae in a water sample are concentrated and are mechanically disrupted in acetone or dimethyl sulfoxide. The chlorophylls are solubilized and the sample is centrifuged to remove particulate matter. The concentration of chlorophylls is determined by fluorescence.

Application

The method is suitable for all waters.

Interferences and Special Considerations

The presence of any compound that fluoresces at the same wavelength as chlorophyll is likely to cause an overestimation of chlorophyll. Precursors and degradation products of the chlorophylls, such as the pheophytins, chlorophyllides, and pheophorbides will interfere when present. Exposure to light or acid at any stage of storage and analysis can result in photochemical and chemical degradation of the chlorophylls (Weber, 1973b; Greeson and others, 1977).

Preservation and Storage

Changes in the chlorophyll content can be minimized by storing the filtered material in the dark at 1° C or less. Chlorophyll may degrade somewhat during storage, but this change is generally small when the sample is stored under the above conditions for 2 weeks or less. Samples stored more than 2 weeks should be held at −20° C.

Analysis

Refer to American Public Health Association and others (1976) and Weber (1973b).

Calculations

Refer to American Public Health Association and others (1976).

Data Reporting and Precision

Report chlorophyll *a*, *b*, and *c* in milligrams per square meter to three significant figures. The precision of chlorophyll determinations is influenced by the area of substrate sampled, the range of chlorophyll values found, the volume of extraction solvent, and the light-path length of the cells.

4.B.1.b.4.c. Chlorophyll By Chromatography

Many precursors and degradation products of plant pigments can interfere with the determination of chlorophylls. Chlorophyll *a* and *b* can be separated from other cellular contents and from closely related precursors and degradation products by thin-layer chromatography. Chlorophylls then are measured by spectrophotometry or by fluorometry.

Summary

The periphyton scrapings are disrupted and the chlorophylls are extracted. The chlorophylls are separated from each other and from closely related substances by thin-layer chromatography. Chlorophylls are eluted and are measured with a spectrophotometer or fluorometer.

Application

The method is suitable for all waters, but cannot be used for the determination of chlorophyll *c*.

Interferences and Special Considerations

Exposure to light or acid at any stage of storage and analysis can result in photochemical and chemical degradation of the chlorophylls (Weber, 1973b; Greeson and others, 1977). The method is very time consuming and is not recommended for general use.

Preservation

Algae concentrate should be stored in darkness at −20° C, preferably in a dessicator if extraction is delayed. Storage should not exceed 1 month (Greeson and others, 1977). Chlorophyll may degrade somewhat during storage, but any changes are usually small when the sample is stored under the above conditions.

Analysis

Refer to Greeson and others (1977). Revised spectrophotometric equations are found in Jeffrey and Humphrey (1975).

Calculations

Refer to Greeson and others (1977).

Data Reporting and Precision

Report chlorophyll *a* and *b* in milligrams per square meter to three significant figures of substrate sampled. No precision data are available.

4.B.1.b.5. BIOMASS

4.B.1.b.5.a. Cell Volume

Cell volume is a more accurate estimate of periphyton biomass than cell counts because of the variation in cell size. However, unless preestablished factors are available to convert cell counts to cell volumes and biomass, the method is too time consuming for routine use.

Summary

A 1-milliliter aliquot of sample is transferred to a Sedgwick-Rafter cell and the sample is counted as described in section 4.B.1.b.3.a. The mean volume of each taxon is determined and is multiplied by the number of individuals of that taxon.

Application

The method is suitable for all fresh waters.

Interferences and Special Considerations

Cell volume measurements are very tedious, time consuming, and costly. Also, estimates of the vertical dimensions or thickness of organisms are often subject to considerable error.

Preservation and Storage

Refer to Greeson and others (1977) and Weber (1973b).

Analysis

At least 20 representative individuals of each significant taxa in the sample are measured with the aid of the ocular micrometer and calibrated fine focal adjustment of the microscope. Cell volumes are determined in cubic micrometers. The mean cell volume for each taxon is multiplied by the number of individuals. Refer to Welch (1948), American Public Health Association and others (1976), and Vollenweider (1969).

Calculations

Refer to Welch (1948), American Public Health Association and others (1976), and Vollenweider (1969).

Data Reporting

Report periphyton volumes in cubic millimeters per square meter. The cell volume estimate can be converted to wet weight by assuming a density of 1.0 (Vollenweider, 1969; Schwoerbel, 1970). No precision data are available.

4.B.1.b.5.b. Dry Weight Of Organic Matter

4.B.1.b.5.b.1. Gravimetric—The dry weight of organic matter in the periphyton is a useful index of the nutrient loading of the water body, and, if depressed, may also indicate the presence of toxicity. By coupling the weight of organic matter with the chlorophyll *a* content of the periphyton, information can be obtained about the taxonomic composition (Autotrophic Index) (Weber, 1973a).

Summary of Method

An aliquot of the sample is concentrated by filtration or centrifugation, dried at 105° C, combusted at 500° C, rewet, and redried at 105° C. The difference between the initial dry weight and the final weight of the redried ash is termed the ash-free dry weight and is an estimate of the living biomass of the periphyton.

Application

The method is suitable for all waters.

Interferences and Special Considerations

The presence of large amounts of dead or decaying cellular material will give falsely-high estimates of the total biomass.

Preservation and Storage

Refer to Greeson and others (1977) and Weber (1973b).

Analysis

Refer to Greeson and others (1977) and Weber (1973b).

Data Reporting and Precision

Report ash-free weight as milligrams per square meter of substrate. The error using 3–4 replicate substrates per sample is 5–20 percent.

4.B.1.b.6. AUTOTROPHIC INDEX

The Autotrophic Index is useful as a water quality index for evaluating the ratio between the chlorophyllous and nonchlorophyllous organisms in the periphyton. Periphyton growing in surface waters that are relatively free of degradable organic matter consist largely of algae, which contain approximately 1–2 percent chlorophyll *a* based on dry weight of organic matter (ash-free weight). If elevated concentrations of dissolved or particulate organic matter are present in the water, large populations of filamentous bacteria, stalked protozoa, and other non-chlorophyllous microorganisms develop on the substrates, and the percentage of chlorophyll *a* in the periphyton is reduced. If the relationship between biomass (ash-free weight) and chlorophyll *a* is expressed as a ratio (Autotrophic Index), values greater than 100 may result from organic pollution (Weber and McFarland, 1969; Weber, 1973a, 1973b).

Summary of Method

The chlorophyll *a* and ash-free dry weight of the sample are determined, and the biomass is divided by the chlorophyll *a*.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Refer to the gravimetric (4.B.1.b.5.b.1) and chlorophyll (4.B.1.b.4) methods.

Preservation and Storage

Refer to the gravimetric (4.B.1.b.5.b.1) and chlorophyll (4.B.1.b.4) methods.

Analysis

Refer to the gravimetric and chlorophyll methods.

Calculations

The ash-free dry weight (biomass) in milligrams per square meter is divided by the chlorophyll *a* content in milligrams per square meter (Weber and McFarland, 1969; Weber, 1973a, 1973b).

Data Reporting and Precision

The Autotrophic Index is a dimensionless value that ranges from 50–100 in unpolluted waters, and reaches values of 1,000 or more in waters containing elevated concentrations of degradable organic matter. The precision for samples consisting of four replicates is approximately 5–20 percent.

4.B.1.b.7. REFERENCES

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4.B.1.c. MACROPHYTON

4.B.1.c.1. INTRODUCTION

In this handbook, "macrophyte" refers to plants of macroscopic size that contain chlorophyll and occur in a predominately aquatic environment and includes species of algae, bryophytes, and vascular plants. Macro-

phytes are found in many different habitats (for example, streams, ponds, lakes, canals, reservoirs, seas, and oceans) and occupy various niches in aquatic ecosystems. Macrophytes may be grouped on the basis of growth form into those species that are attached to the substrate, such as the elodeas, cattails, and water lilies, and those that are free-floating, having no attachment to the substrate, such as duckweeds and water hyacinth. The group of attached species may be further divided into emersed, submersed, and floating-leaved forms. Emersed species include those that are attached to the substrate and grow on soils that are saturated or submersed for most of the growing season. These include cattails, grasses, sedges, and water-tolerant shrubs and trees. Submersed species include plants that are attached to the substrate and grow underwater (except for aerial reproductive organs), such as the elodeas, certain pondweeds, and naiads. Floating-leaved species occur on submersed soils and grow attached to the substrate, but have predominately broad, floating leaves. These include water lilies and broad-leaved pondweeds.

As with all plants, macrophytes grow in communities that reflect the structural and functional characteristics of the species populations that comprise them. The sum of all the communities of an area is referred to as the area's vegetation.

The study of macrophytes has been intensified in recent years because their importance in the overall functions of aquatic ecosystems has been realized. This has led to the consideration of macrophyte communities in environmental assessments, land-use planning decisions, and pollution studies. An equally significant factor contributing to the increased interest and study of macrophytes is that certain species (mostly introduced) cause severe water-use problems by clogging waterways, impeding navigation, interfering with water sports and recreation, fouling water intake systems, and providing breeding habitat for pestiferous insects.

4.B.1.c.2. METHODS

Any biological study should be designed to answer certain specific questions. The complexity of the questions dictates the extent of sampling and sophistication of the study methods used to answer them. Most questions involving the structure of aquatic macrophyte communities may be answered by employing one or a combination of the following methods—reconnaissance, floristic survey, qualitative vegetational analysis, and quantitative vegetational analysis.

4.B.1.c.2.a. Reconnaissance

Summary of Method

The initial step in determining the structure of macrophyte communities is to conduct a reconnaissance of the study area noting the dominant species, their location, and the general characteristics of the habitat. Reconnaissance may involve the use of aerial photography, ground surveys, and underwater surveys using scuba (self-contained underwater breathing apparatus). For detailed discussions of aerial, surface, and subsurface methods see Weber (1973).

Application

This method is suitable for all waters.

Interferences and Special Considerations

Surveys should be conducted during periods of peak plant biomass.

Preservation and Storage

Species not identified in the field should be preserved using standard techniques (Wood, 1975) until proper identification can be made.

Analysis

Manuals helpful in the identification of macrophytes include Muencher (1964), Fassett (1960), Cook (1974), Beal (1977), Correll and Correll (1972), Mason (1969), and Godfrey and Wooten (1979).

Calculations

Not applicable.

Data Reporting and Precision

A description of the habitat, location and extent of vegetation, dominant species, and a partial list of species present should be reported.

4.B.1.c.2.b. Floristic Survey

Summary of Method

A floristic survey provides a complete list of species found in the study area. It is compiled from observations and collections made during periodic surveys conducted throughout the growing season. Voucher specimens should be collected and maintained to verify the presence and proper identification of the species listed.

Application

This method is suitable for all waters.

Interferences and Special Considerations

Surveys should be conducted at various times during the growing season to insure a complete cataloging of species present. This is necessary because all species do not appear in an identifiable state at any particular time.

Preservation and Storage

Voucher specimens should be processed according to standard methods (Wood, 1975).

Analysis

Not applicable.

Calculations

Not applicable.

Data Reporting and Precision

The species list should be arranged either phylogenetically by family or alphabetically by scientific name. Common names may be included, but only in addition to and not in place of the scientific name.

4.B.1.c.2.c. Qualitative Vegetational Analysis

Summary of Method

A qualitative vegetational analysis provides a description of the physiognomic, structural, functional, and compositional characteristics of the macrophyte communities of an area and delimits the general occurrence of each individual community. A detailed explanation of these characteristics is found in Shimwell (1972). Photointerpretation of low altitude, large-scale aerial photography, combined with ground-truth surveys, is an effective method of determining the distribution of macrophyte communities. Underwater surveys using scuba techniques may be required in certain situations. Refer to Weber (1973) for further discussion of aerial, surface, and subsurface methods.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Surveys should be conducted seasonally to observe seasonal changes in vegetation. Aerial photographs should be made at a scale appropriate for the level of detail required by the study.

Analysis

Refer to Weber (1973) and Shimwell (1972).

Calculations

Not applicable.

Data Reporting and Precision

Results may be reported as vegetation maps, life-form association diagrams, or written descriptions.

4.B.1.c.2.d. Quantitative Vegetational Analysis

Summary of Method

A quantitative vegetational analysis provides a detailed description of the various macrophyte communities of an area based on parameters—such as population density, cover, frequency, biomass, productivity, and diversity—sampled in a systematic manner most commonly using transects or quadrats. The data are analyzed mathematically and are often correlated with environmental parameters of the habitat.

Application

The method is suitable for intensive investigations of areas of limited size in all waters.

Interferences and Special Considerations

Surveys should be conducted seasonally or at periods of peak plant biomass. The size of the area to be studied will be limited by time and resources, as application of these methods on a large scale becomes quite expensive. Decisions on what parameters to sample must be based on study objectives and habitat characteristics. Location of transects and quadrats, as well as sample size, shape, and number, must be considered based on study objectives, time, and resources. Refer to Weber (1973), Shimwell (1972), and Phillips (1959) for detailed discussion.

Analysis

Data may be analyzed using standard statistical tests such as "t" test, multiple range tests, analysis of variance, and regression analysis (Sokol and Rohl, 1969). Clustering analysis and ordination techniques are also useful in analyzing relationships and may be used to empirically define the community types based on one or more of the parameters considered. Refer to Sneath and Sokal (1973) for a discussion of the merits of these two types of analysis and Rohlf (1972) for comparisons of different types of ordination techniques.

Calculations

Parameters commonly used in quantitative analyses of macrophyte communities are density, cover, frequency, biomass, and productivity. Each may be defined as follows (consult references cited for details of calculations):

1. Density is a measure of abundance and is usually expressed as the average number of individuals per area sampled (Oosting, 1956).
2. Cover is a measure of the area occupied by a species (Phillipps, 1959).
3. Frequency is a measure of the distribution of a species and is usually expressed as the percentage of sample plots in which a species occurs (Oosting, 1956).
4. Biomass is the total quantity of a particular species within a system and is usually expressed as weight per unit area (Wood, 1975; Weber, 1973).
5. Productivity is a measure of the organic matter synthesized by a quantity of plants per unit time and is usually expressed as weight per square meter per day (Wood, 1975).
6. Diversity is a measure of the number of species per unit area (Wood, 1975). Diversity may also be expressed according to various indices (Odum, 1971).

Data Reporting and Precision

Report data in the form and to the precision appropriate for each type of analysis referenced above.

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4.B.1.d. MACROINVERTEBRATES

4.B.1.d.1. INTRODUCTION

In this handbook, aquatic macroinvertebrates are defined as animals that are large enough to be seen by the unaided eye and to be retained by U.S. Standard No. 30 sieve (28 meshes per inch, 0.595-mm openings).

The major taxonomic groups that fresh-water macroinvertebrates include are the insects, annelids, molluscs, flatworms, roundworms, and crustaceans. The major groups that salt-water macroinvertebrates include are the molluscs, annelids, crustaceans, coelenterates, porifers and bryozoa.

The macroinvertebrates are important members of the food web, and their well-being is reflected in the well-being of the higher life forms, such as fish. Many invertebrates, such as the marine and fresh-water shellfish, are important commercial and recreational species. Some, such as mosquitoes, black flies, biting midges, and Asiatic clams, are significant to public health or are simple pests. Many forms are important for digesting organic material and recycling nutrients (Weber, 1973).

Because macroinvertebrates have limited mobility and are sensitive to environmental perturbations, data on the structure and function of the macroinvertebrate community provide a direct measure of the quality of aquatic ecosystems. As a result of "biological magnification," potentially toxic materials which are only periodically discharged or which are present at undetectable levels in the water may be detected by chemical analyses of selected components of the macroinvertebrate fauna.

Many macroinvertebrates have a life span of months or years, which allows them to integrate water quality over long periods of time. Moreover, many benthic invertebrates inhabit specific types of environments, and if the environment changes, the composition of the benthic community changes (Hynes, 1970). In general, a varied benthic fauna, without excessively large numbers of any one group, is considered to be characteristic of good quality water (Greeson and others, 1977). As conditions change, for example, in the presence of organic pollution, the number of species decreases, but the number of individuals of the remaining species may increase. Toxic pollutants may eliminate all benthic organisms. Thus, knowledge of the kinds and abundance of benthic invertebrates helps to indicate trends in the condition of the aquatic environment. The extensive literature on interpretation of benthic invertebrate data with regard to water quality has been reviewed by Hynes (1960, 1970), Warren (1971), Cairns and Dickson (1973), Hart and Fuller (1974), and Weber (1973).

There is no universally accepted method for sampling the benthos. However, if the objective is to obtain a representative collection of the aquatic organisms, no habitat should be overlooked, and different habitats may require different sampling methods. The success of the chosen method will depend on the experience and skill of the collector.

4.B.1.d.2.a. Site Selection and Sampling Strategy

Sample sites may be selected systematically or by various randomization procedures (Elliot, 1971; Weber, 1973; Greeson and others, 1977).

For reconnaissance and synoptic surveys, some type of systematic sampling is frequently used (Weber, 1973). One form of systematic sampling that is useful for mapping and delimiting habitat types involves sampling points selected at discrete intervals on a line transect. Another form of systematic sampling is one in which the investigator selects and, using a variety of gear, intensively samples all recognizable habitat types in the study area.

For quantitative studies, some type of randomization procedure must be employed (Weber, 1973). Because the characteristics of macroinvertebrate communities are so closely tied to physical variables, it is generally best to utilize a stratified random-sampling scheme (Weber, 1973; Greeson and others, 1977).

Confounding abiotic variables that may be used as strata in the statistical design include substrate type, stream velocity, depth, and salinity. Methods for measuring these variables are presented in Weber (1973).

4.B.1.d.2.b. Sampling Devices

1. *Grabs* - For discussions of various types of grabs—their usefulness and limitations—refer to American Public Health Association and others (1976), Holme and McIntyre (1971), Greeson and others (1977), Weber (1973), and Welch (1948).
2. *Screens and Nets* - Refer to Welch (1948), Greeson and others (1977), and Weber (1973).
3. *Corers* - Refer to Welch (1948), Greeson and others (1977), Weber (1973), Holme and McIntyre (1971), and American Public Health Association and others (1976).
4. *Artificial Substrates* - Refer to American Public Health Association and others (1976) and Weber (1973).
5. *Drift Nets* - Refer to Elliot (1971), American Public Health Association and others (1976), and Weber (1973).
6. *Other* - Gear for qualitative sampling is only limited by the imagination of the investigator and the habitat to be sampled. Gear that has been used includes dip nets, oyster tongs, rakes, bare hands, and forceps (Weber, 1973).

4.B.1.d.3. COUNTING, IDENTIFICATION, AND BIOMASS

Refer to American Public Health Association and others (1976), Greeson and others (1977), or Weber (1973).

Summary of Method

Samples collected by a device suitable to the substrate and study objectives are sieved in the field, preserved, and returned to the laboratory for processing. In the laboratory, the organisms are separated from the inert materials (sand, gravel, detritus, and so on), identified, enumerated, and, where necessary, weighed. The numeric and gravimetric data are tabulated and subjected to various analyses appropriate to the objectives of the study.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Physical factors, such as stream velocity, substrate type, and depth of water, may interfere with sampling. Most samples contain relatively large amounts of sediment and plant debris from which the organisms must be separated. The principal difficulty with quantitative sampling is the heterogeneity of the spatial distribution of the invertebrate communities (Greeson and others, 1977).

Preservation and Storage

Refer to American Public Health Association and others (1976), Greeson and others (1977), and Weber (1973).

Analysis

Refer to Greeson and others (1977) and Weber (1973).

Calculations

Refer to Greeson and others (1977).

Data Reporting and Precision

Report the number of taxa present as individuals per square meter or individuals per sample. Report the percentage composition of each taxon in the sample to the nearest 0.1 percent. Report biomass to three significant figures. No numerical precision data are available.

4.B.1.d.4. REFERENCES

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4.B.1.e. FISH

4.B.1.e.1. INTRODUCTION

The principal characteristics of fish populations that are of interest in field studies include: (1) species present, (2) relative and absolute abundance of each species, (3) size distribution, (4) growth rate, (5) condition, (6) success of reproduction, (7) incidence of disease and parasitism, and (8) palatability (Weber, 1973).

Comprehensive investigations of the changes in fish populations induced by changes in water quality require various types of sampling equipment and sampling strategies. The choice of equipment is limited by the habitat to be sampled and the efficiency of the particular gear in that habitat. Consistency in both adaptation and use of types of gear is essential to compare sets of data over time. Changes in population characteristics as a

result of migration, diurnal and seasonal movements, food availability, and temperature gradients may, at any given time, mask the effects of water-quality changes.

Two approaches to assessing fish populations for indications of water quality are (1) population evaluations and (2) growth and maintenance determinations. Both types of assessments can be conducted using any one type of gear or a combination of gear.

Population evaluations involve determining species composition, standing stock, biomass, and relative abundance of each species.

Scale samples and other life history information taken from individual samples yield growth and maintenance information, such as age class distribution, growth rate, and condition.

Analyses of sport-fishing and commercial catch data can reveal some characteristics of important economic and recreational fisheries.

4.B.1.e.2. COLLECTION

4.B.1.e.2.a. Sampling Strategy

Selecting the type of gear and the methods to be used for fish investigations depends on the objectives of the particular study, the investigator's knowledge of the use of the gear, the selectivity of the gear, and the particular waters involved. The sizes and kinds of fish to be sampled also influence the selection of sampling gear. Each type of gear has some selectivity associated with design and construction (Funk, 1958; Barkley, 1972; Hamley, 1975). In comprehensive investigations, more than one type of gear is required to obtain representative samples from all segments of the fish populations.

Sampling frequency varies according to the type of activity under investigation. Intensive collection effort is usually scheduled to coincide with annual or seasonal occurrences of highest biomass of the particular life stages under investigation or with most favorable collecting conditions.

In large bodies of water, collecting and measuring all fish is virtually impossible. Therefore, a sample is taken, assuming that the characteristics measured in the sample are representative of the whole population. Prior knowledge of the population attributes of a fishery is essential for developing good sampling systems.

Even with the best sampling strategy, calculated estimates of population characteristics may have very large errors. Unbiased sampling procedures or procedures with known estimates of bias should be employed whenever possible. Properly designed sampling systems yield frequency distributions with estimates of variance and reliability (Ricker, 1968; 1969).

1.B.1.e.2.b. Sampling Techniques and Types of Gear

Various types of sampling techniques and types of gear are available for studying fish populations. The choice of techniques and gear depends on the type of habitat and the efficacy of the gear in a particular habitat (table 4–1).

1. Entangling gear: gill nets and trammel nets.

Refer to Carlander (1953), Hamley (1975), Food and Agriculture Organization (1959), and Moyle (1950) for discussions on usefulness and adaptations of entangling gear.

2. Entrapping gear: hoop nets, basket traps, trap nets, and fyke and wing nets.

Refer to Food and Agriculture Organization (1959), Grinstead (1968), and Hargis (1967) for discussions of application and adaptation of entrapping gear.

3. Encircling gear: haul seine, purse seine, bay seine, and Danish seine.

Refer to Food and Agriculture Organization (1959) for instruction on the use of encircling gear.

4. Electroshocking gear: boat shockers, backpack shockers, and electric seines.

See Food and Agriculture Organization (1959), Novotny and Priegel (1972). Vincent (1971), and Funk (1947) for discussions on the development and utilization of electroshocking devices.

5. Toxicants: rotenone and antimycin.

Refer to Hall (1974), Burress (1971), and Finucane (1969) for application and usage of toxicants.

TABLE 4–1.—Fisheries Equipment Selection

Equipment	Habitat					Efficacy	
	Small Stream	Large Stream	Lake	Reservoir	Ocean Estuary	Good	Fair
Trammel net			X	X		X	
Hoop net		X					X
Gill net		X	X	X	X		X
Fyke net		X	X	X			X
Seine	X			X			X
Purse seine			X		X	X	
Electroshockers	X	X	X	X			X
Rotenone	X	X	X	X		X	
Antimycin	X	X					X

4.B.1.e.3. POPULATION EVALUATION

Even though the various methods of sampling fish populations differ greatly in their precision and expenditure of effort required, the diversity of fishes present still can serve as an index to the water-quality situation (Lagler, 1956).

Summary of Method

Fish collected by any one of the above sampling methods are identified to species, grouped in length classes, and weighed. If numbers of fish collected are sufficiently large, individuals of each length class may be weighed collectively.

Application

This method is suitable for all waters and all sampling strategies.

Interferences and Special Considerations

It is important for the investigator to identify and record the location (with a physical description) and time of the collection, area and volume sampled, gear used (mesh size, hoop size, and other pertinent characteristics), and environmental conditions (such as dissolved oxygen, pH, temperature, and conductivity) that may identify sources of sampling bias.

Preservation and Storage

A 10-percent formalin solution may be used as a fish preservative. Fish longer than 3 inches should be cut to expose the body cavity to allow penetration of the preservative. For long-term preservation the 10-percent formalin may be replaced with fresh 5-percent formalin. Borax (5 g/L) may be added to buffer the formalin and prevent shrinkage of the preserved fish. Samples may also be iced or placed in dry ice for preservation.

Analysis

Refer to Good (1953), Ricker (1968; 1971), and White and others (1977).

Calculations

Refer to Lloyd and others (1968) and Ricker (1968).

Data Reporting and Precision

Refer to Ricker (1968).

A comparison of the rates of fish growth in different water bodies may serve as an indicator of environmental conditions. A fish population heavily weighted to a young or an old age group extreme may show a growing population or a declining population, respectively.

Summary of Method

Scale samples and information on the length, weight, sex, and maturity of individuals are taken from fishes captured in the sample. In spiny-rayed fishes, scales are taken from *below* the lateral line below the origin of the dorsal spine. In soft-rayed fishes, scales are removed in the same manner from *above* the lateral line. Scales are stored in individual envelopes with the information listed above recorded on the outside of the envelope for reading in the laboratory. In the laboratory, scales are cleaned and mounted for magnification and counting of the growth rings.

Application

This method is suitable for all waters.

Interferences and Special Considerations

In some species, such as the catfishes (*Ictaluridae*), a cross section of the dorsal spine is read. Similarly, in some species, for example, the fresh-water drum (*Aplodinotus grenniens*), otiliths may be treated and measured instead of scales.

Preservation and Storage

Whole scales may be permanently mounted on various media: sodium silicate (waterglass), glycerin-waterglass mixture, balsam, and so forth. Another method is to use strong pressure to impress the scale markings on cellulose acetate.

Analysis

Annuli or year marks are read to determine the age of the fish. The identity of the annuli as true age marks must be established. Perhaps the easiest way to do this is by comparing annuli with those of a fish of known age. Data determined from inspection of the enlarged scales are: the age of the fish in years, the approximate length attained by the fish at the end of each year of life, and the rate of growth for each year of life (Lagler, 1956).

Calculations

Length at the end of each year of life is most simply calculated as a direct proportion (Dahl, 1909). The Dahl-Lea method determines growth in each year by relating body length to scale length multiplied by a constant. Refer to Lagler (1956).

Data Reporting and Precision

Refer to Dahl (1909), Hile (1941), Carlander (1945), Lagler (1956), and Ricker (1968).

4.B.1.e.5. FISH KILLS

Standard procedures for investigating fish kills have been recommended by the Pollution Committee, American Fisheries Society, Southern Division (1970). A list of pertinent observations on moribund fish is given in Federal Water Pollution Control Administration (1970).

4.B.1.e.6. REFERENCES

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4.B.2. COMMUNITY METABOLISM

4.B.2.a. INTRODUCTION

Biological communities are groups of species that inhabit a common environment and interact with one another through food or trophic relationships. The physiological condition of aquatic communities and the rates of metabolic processes within the communities often provide a better understanding of the ecosystem than do measurements of community structure.

This section includes methods to measure community metabolism that are based on photosynthetic production of oxygen, photosynthetic assimilation of carbon, respiratory uptake of oxygen, respiratory release of carbon, and biological fixation of nitrogen.

Primary productivity is the rate at which new organic matter is formed and accumulated within the system under study. The basic process involved in the creation of new organic matter is photosynthesis, in which carbon dioxide is assimilated and oxygen is released according to the following general reaction:

$$6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2.$$

Respiration may be thought of as the reverse reaction, in which oxygen is consumed and carbon dioxide is released. The rate at which the reactions take place provides a means for estimating the rate at which new organic matter is being synthesized.

The rate of photosynthesis customarily is determined by measuring the amount of oxygen produced or the amount of carbon dioxide consumed. In practice, primary productivity may be measured by one of two different approaches: by measuring isolated samples of natural communities or by directly measuring nonisolated communities in the natural environment. Refer to Vollenweider (1969) for a discussion of the general principles, advantages, and limitations of each approach.

Primary productivity is related to water quality. In general, high daily or annual rates of primary productivity indicate eutrophic (fertile) environments, and low rates indicate oligotrophic (infertile) environments. Primary productivity may be increased or decreased by pollution. Very high productivity rates may indicate nuisance algal blooms, whereas very low rates may indicate certain toxic conditions.

4.B.2.b.1. PHYTOPLANKTON

4.B.2.b.1.a. Oxygen Light And Dark Bottle

Summary of Method

Light (clear) and dark (blackened) bottles filled with the water under study are suspended at several depths within the euphotic zone for a known period of time. The concentration of dissolved oxygen in each bottle is measured at the beginning and at the end of the exposure period. Changes in oxygen concentrations within the bottles are interpreted in terms of photosynthesis and respiration. Productivity is calculated on the basis of one carbon atom assimilated for each oxygen molecule released. From samples collected and exposed at various depths, the depth-profile of primary productivity below a unit area of surface can be determined.

Application

The method is suitable for standing or slowly moving waters, both fresh and saline. Estimates of gross and net primary productivity and respiration are provided. Best results are obtained in eutrophic waters in which the production rate is between about 3 and 200 milligrams of carbon per cubic meter per hour (mg $C/m^3/hr$) of photoperiod (Strickland and Parsons, 1968).

Interferences and Special Considerations

Isolated samples of water and plankton are used to indicate the response of the natural system. When collecting and handling the samples and when exposing them to light, care must be taken not to injure the organisms or to alter the concentration of dissolved oxygen in the bottles. Refer to Committee on Oceanography, Biological Methods Panel (1969), Strickland and Parsons (1968), and Vollenweider (1969).

Preservation and Storage

Keep the samples in subdued light at all times to avoid light injury to the organisms. Transfer the water sample from each depth to a polyethylene bottle of appropriate size, and let stand for 15–30 minutes (but not more than 1 or 2 hours) at a temperature slightly higher than the water temperature. Shake the bottles occasionally to eliminate oxygen supersaturation. For each depth sampled, fill four light and two dark BOD bottles. It is important that all bottles have the same initial oxygen content.

Immediately add the reagents for the Winkler method to two light BOD bottles from each depth. These samples, designated IB, are used for determining the initial dissolved oxygen concentration. Titration may be delayed several hours, if necessary, if the samples are kept cool and dark.

As quickly as possible after incubation, add the first two Winkler reagents to each bottle to arrest biological activity and to fix the dissolved oxygen. Refer to Strickland and Parsons (1968), Committee on Oceanography, Biological Methods Panel (1969), and Vollenweider (1969).

Analysis

Refer to Strickland and Parsons (1968), Committee on Oceanography, Biological Methods Panel (1969), Vollenweider (1969), American Public Health Association and others (1976), Greeson and others (1977), Weber (1973), or Lind (1974). Greeson and others (1977) give a detailed description of steps in the analytical procedure.

Calculations

Refer to Greeson and others (1977).

Data Reporting and Precision

Report primary productivity as follows: less than 10 mg, one decimal; 10 mg and above, two significant figures (Greeson and others, 1977). Precision estimates are given by Strickland and Parsons (1968).

4.B.2.b.1.b. Carbon-14 Light And Dark Bottle

Summary of Method

Light (clear) and dark (blackened) bottles filled with the water under study are spiked with known amounts of radioactive carbonate. The bottles are suspended at several depths within the euphotic zone for a known period of time. The total inorganic carbonate is determined from an aliquot of each sample. After incubation, the samples are filtered through membrane filters, and the retained plankton cells are washed to remove inorganic carbon-14. Radioactivity retained by the cells is measured by liquid scintillation or other counting equipment. The quantity of carbon fixed in the organic matter of the phytoplankton approximates net primary productivity for incubation periods of 1 to 4 hours. From samples collected and exposed at various depths, the depth-profile of primary productivity below a unit area of surface can be determined.

Application

The method is suitable for standing or slowly moving fresh or saline waters. Because of the sensitivity of the carbon-14 method, it is the method of choice in oligotrophic waters. The range of production rates reported by Strickland and Parsons (1968) is from about 0.05 to 100 mg $C/m^3/hr$ of photoperiod. However, these authors state that there is virtually no upper limit and the lower limit could probably be reduced to 0.01 mg $C/m^3/hr$ by using great care in the radiochemical procedure.

Interferences and Special Considerations

Isolated samples of water and plankton are used to indicate the response of the natural system. When collecting and handling the samples and when exposing them to light, care must be taken not to injure the organisms. Refer to Committee on Oceanography, Biological Methods Panel (1969), Strickland and Parsons (1968), Vollenweider (1969), Nalewajko and Lean (1972), and McMahon (1973).

Preservation and Storage

Following sample exposure and filtration, the membrane filters may be dried in a dessicator for 12 hours and then stored indefinitely. Although Pugh (1973) found no significant losses in radioactivity during the first 24 hours of dry filter storage, Wallen and Geen (1968) did report significant losses. The filter drying step is eliminated in liquid scintillation counting. Refer to Wolfe and Schelske (1967), Wallen and Geen (1968), Committee on Oceanography, Biological Methods Panel (1969), American Public Health Association and others (1976), and Pugh (1973).

Analysis

Refer to Strickland and Parsons (1968), Committee on Oceanography, Biological Methods Panel (1969), Schindler and others (1972), American Public Health Association and others (1976), Janzer and others (1973), Greeson and others (1977), Weber (1973), or Lind (1974). Janzer and others (1973), Lind (1974), and Greeson and others (1977) give detailed descriptions of the steps in the analytical procedure.

Calculations

Refer to Greeson and others (1977).

Data Reporting and Precision

Report radiocarbon-measured primary productivity as follows: less than 10 mg, one decimal; 10 mg and above, two significant figures (Greeson and others, 1977). Precision estimates are given by Strickland and Parsons (1968).

4.B.2.b.2. PERIPHYTON

4.B.2.b.2.a. In Situ Oxygen Method

Summary of Method

Known areas of natural or artificial substrates containing living periphyton are isolated in light and dark chambers. Natural conditions are simulated as closely as possible. In standing waters, bell jars or open-ended plastic chambers can be inserted into the substratum to isolate the periphyton. In flowing waters, provision must be made to circulate water in the chambers. The concentration of dissolved oxygen in the chambers is determined at the beginning and at the end of the exposure period. Changes in oxygen concentration are interpreted in terms of photosynthesis and respiration per unit area of periphyton. Productivity is calculated on the basis of one carbon atom assimilated for each oxygen molecule released.

Application

The method is most suitable for shallow streams, ponds, and the littoral zones of lakes where light penetration is sufficient for photosynthesis. Best results will be in eutrophic waters in which the production rate is equivalent to about 3–200 mg $C/m^3/hr$ of photoperiod (Strickland and Parsons, 1968, p. 263). Measurements of productivity of stream periphyton in static cultures may provide useful comparative values, but are undoubtedly too low in absolute terms because photosynthesis is suppressed in the absence of current (Wetzel, 1964).

Interferences and Special Considerations

The method uses isolated samples of periphyton to indicate the response of the natural system. When collecting and handling the samples and when exposing them to light, care must be taken not to injure the organisms. Photosynthesis and respiration of plankton in the chambers may cause errors in the estimation of periphyton metabolism. The metabolism of periphyton from flowing waters will be greatly suppressed unless current is provided in the chambers (Whitford, 1960; Whitford and Schumacher, 1961). Refer to American Public Health Association and others (1976), Greeson and others (1977), Vollenweider (1969), Wetzel (1964; 1965).

Preservation and Storage

Keep periphyton samples in subdued light at all times to avoid light injury to the organisms. Immediately after water samples are drawn for the initial determination of dissolved oxygen, add the reagents for the Winkler method. Titration may be delayed several hours, if necessary, if the samples are kept cool and dark. As quickly as possible after the exposure period, add the first two Winkler reagents to another set of water samples to fix the dissolved oxygen.

Analysis

Refer to American Public Health Association and others (1976), Greeson and others (1977), Vollenweider (1969), Thomas and O'Connell (1966), McIntire and others (1964), Hansmann and others (1971), and Pfeifer and McDiffett (1975). Greeson and others (1977) give a detailed description of steps in the analytical procedure.

Calculations

Refer to Greeson and others (1977)

Data Reporting and Precision

Report primary productivity as follows: less than 10 mg, one decimal; 10 mg and above, two significant figures (Greeson and others, 1977).

No numerical precision data are available.

4.B.2.b.2.b. In Situ Carbon-14 Method

Summary of Method

Known areas of natural or artificial substrates containing living periphyton are isolated in light and dark chambers. In standing waters, bell jars or open-ended plastic chambers can be inserted into the substratum to isolate the periphyton. In flowing waters, provision must be made to circulate water in the chambers. Carbon 14-labeled sodium carbonate is injected, mixed, and allowed to incubate with the periphyton for a known time. The concentration of dissolved inorganic carbon available for photosynthesis is determined. Following incubation, the periphyton is separated from the substrate and is assayed for carbon-14.

Application

The method is most suitable for shallow streams, ponds, and the littoral zones of lakes where light penetration is sufficient for photosynthesis. It may be used in oligotrophic or eutrophic waters. Measurements of productivity of stream periphyton in static cultures may provide useful comparative values, but are undoubtedly too low in absolute terms because photosynthesis is suppressed in the absence of current (Wetzel, 1964).

Interferences and Special Considerations

The method uses isolated samples of periphyton to indicate the response of the natural system. When collecting and handling the samples and when exposing them to light, care must be taken not to injure the organisms. Metabolism of periphyton from flowing waters will be greatly suppressed unless current is provided (Whitford, 1960; Whitford and Schumacher, 1961). Refer to American Public Health Association and others (1976), Wetzel (1964; 1965), and Vollenweider (1969).

Preservation and Storage

Keep periphyton samples in subdued light at all times to avoid light injury to the organisms. For treatment of periphyton following incubation, refer to American Public Health Association and others (1976), Wetzel (1964, 1965), and Vollenweider (1969).

Analysis

Refer to American Public Health Association and others (1976), Wetzel (1964; 1965), Vollenweider (1969), Thomas and O'Connell (1966), McIntire and others (1964), Hansmann and others (1971), and Pfeifer and McDiffett (1975).

Calculations

Refer to American Public Health Association and others (1976).

Data Reporting and Precision

Report radiocarbon-measured net primary productivity as follows: less than 10 mg, one decimal; 10 mg and above, two significant figures (Greeson and others, 1977).

No numerical precision data are available.

4.B.2.b.2.c. Bottle Method

Summary of Method

Samples of periphyton on known areas of natural or artificial substrates, or periphyton removed from known areas of substrate are placed in light (clear) and dark (blackened) bottles of prefiltered water, inoculated with carbon 14-labeled sodium carbonate, and incubated at the depth from which the samples were taken. Following incubation, the periphyton is assayed for carbon-14.

Application

The method is most suitable for ponds and littoral zones of lakes where light penetration is sufficient for photosynthesis. It may be used in oligotrophic or eutrophic waters. The method may be used for stream periphyton if circulation is provided during incubation (Backhaus, 1967; Schwoerbel, 1970). Measurements of stream periphyton in static cultures may provide useful comparative values, but are undoubtedly too low in absolute terms because photosynthesis is suppressed in the absence of current (Wetzel, 1964).

Interferences and Special Considerations

The method uses isolated samples of periphyton to indicate the response of the natural system. When collecting and handling the samples and exposing them to light, care must be taken not to injure the organisms. Metabolism of periphyton from flowing waters will be greatly suppressed unless current is provided (Whitford, 1960; Whitford and Schumacher, 1961). Refer to Wetzel (1964; 1965) and Vollenweider (1969).

Preservation and Storage

Keep periphyton samples in subdued light at all times to avoid light injury to the organisms. For treatment of periphyton following incubation refer to American Public Health Association and others (1976), Wetzel (1964; 1965), Vollenweider (1969), and Schwoerbel (1970).

Analysis

Refer to American Public Health Association and others (1976).

Calculations

Refer to American Public Health Association and others (1976).

Data Reporting and Precision

Report radiocarbon-measured net primary productivity as follows: less than 10 mg, one decimal; 10 mg and above, two significant figures (Greeson and others, 1977).

No numerical precision data are available.

4.B.2.b.3. MACROPHYTON

4.B.2.b.3.a. In Situ Oxygen Method

Summary of Method

Experimental chambers are placed over growing submersed plants, then are gently forced into the substratum. Next the enclosed volume is noted. Changes in dissolved oxygen in transparent and opaque enclosures are measured to determine metabolism of submersed macrophytes. Productivity is calculated on the basis of one carbon atom assimilated for each oxygen molecule released.

Application

The method is suitable for standing or flowing waters in which light penetration is sufficient for photosynthesis. Estimates of gross and net primary productivity and respiration are provided. Best results are obtained in eutrophic waters in which the production rate is between 3–200 mg $C/m^3/hr$ of photoperiod (Strickland and Parsons, 1968).

Interferences and Special Considerations

There are many difficulties that seriously limit the use of dissolved oxygen changes for estimating macrophyte metabolism. During incubation, especially if it lasts longer than 6 hours, the growth of bacteria and other enclosed organisms may significantly alter the oxygen content of the chambers. An important source of error results from the internal (lacunal) storage and utilization of oxygen produced in photosynthesis. Metabolism of macrophytes from flowing waters will be greatly suppressed unless current is provided. Refer to Vollenweider (1969), Wetzel (1964, 1965, 1969), Hartman and Brown (1967), Hough (1974), and Hough and Wetzel (1975) for additional discussion of the limitations and interferences in the use of this method.

Preservation and Storage

Determining dissolved oxygen changes in the chambers may be accomplished using an electrode or by withdrawing small samples. If the latter is used, add the reagents for the Winkler method. Titration may be delayed several hours, if necessary, if the samples are kept cool and dark. After incubation remove the entire plants including roots, wash free of sediment, blot, and place in polyethylene bags. Quick freeze between blocks of solid carbon dioxide. Refer to Vollenweider (1969).

Analysis

Refer to Wetzel (1964; 1965) and Vollenweider (1969).

Calculations

Refer to Wetzel (1964; 1965) and Vollenweider (1969).

Data Reporting and Precision

Report primary productivity as follows: less than 10 mg, one decimal; 10 mg and above, two significant figures (Greeson and others, 1977).

No numerical precision data are available.

4.B.2.b.3.b. In Situ Carbon-14 Method

Summary of Method

Transparent and opaque experimental chambers are placed over growing submersed plants, then are gently forced into the substratum. Next the enclosed volume is noted. Carbon 14-labeled sodium carbonate is injected, mixed, and allowed to incubate with the plants for a known time. The concentration of dissolved inorganic carbon available for photosynthesis is determined. Following incubation, the plants, including the roots, are separated from the substrate and are assayed for carbon-14.

Application

The method is suitable for standing or flowing waters in which light penetration is sufficient for photosynthesis. It may be used in oligotrophic or eutrophic waters to estimate net primary productivity. Refer to Vollenweider (1969) and Hough (1974).

Interferences and Special Considerations

Rapid self-absorption of the weak beta radiation by the plant tissues necessitates changes in radioassay from the method usually employed for phytoplankton. The excretion of organic matter, especially carbohydrates, during macrophyte photosynthesis may be a significant source of error. Metabolism of macrophytes from flowing waters will be greatly affected unless current is provided. Refer to Wetzel (1964, 1965, 1969), Vollenweider (1969), Hough (1974), and Hough and Wetzel (1975).

Preservation and Storage

After incubation remove the entire plants including roots, wash free of sediment, blot, and place in polyethylene bags. Quick freeze between blocks of solid carbon dioxide. Refer to Vollenweider (1969).

Analysis

Refer to Wetzel (1964, 1965), and Vollenweider (1969).

Calculations

Refer to Wetzel (1964, 1965), and Vollenweider (1969).

Data Reporting and Precision

Report radiocarbon-measured net primary productivity as follows: less than 10 mg, one decimal; 10 mg and above, two significant figures (Greeson and others, 1977).

No numerical precision data are available.

4.B.2.b.3.c. Isolated-Shoot Method

Summary of Method

Apical portions of macrophyte shoots are incubated in light and dark flasks of known volume for definite periods of time. Macrophyte metabolism is estimated from changes in oxygen concentration or from the amount of carbon-14 fixed.

Application

The method is suitable for standing or flowing waters in which light penetration is sufficient for photosynthesis. The carbon-14 method may be used in oligotrophic or eutrophic waters to estimate net primary productivity. Best results with the oxygen method are obtained in eutrophic waters in which the production rate is between about 3–200 mg $C/m^3/hr$ of photoperiod (Strickland and Parsons, 1968). Estimates of gross and net primary productivity and respiration are provided. Refer to Vollenweider (1969) and Hough (1974).

Interferences and Special Considerations

Separation of shoots and roots may affect nutrient uptake and metabolism, and even attached roots may behave differently when removed from the substratum. Transport and handling of the plants, especially if they are exposed to high light intensities, may alter their normal metabolism. Use of only apical portions of plants weights the results towards greater production. Refer to Vollenweider (1969). Additional limitations and interferences are discussed by Wetzel (1964; 1965; 1969), Hartman and Brown (1967), Hough (1974), and Hough and Wetzel (1975).

Preservation and Storage

Keep apical shoots in subdued light at all times to avoid light injury. Determining dissolved oxygen changes in the chambers may be accomplished using an electrode or by withdrawing small samples. If the latter is used, add the reagents for the Winkler method. Titration may be delayed several hours, if necessary, if the samples are kept cool and dark. After incubation remove the shoots, blot, and place in polyethylene bags. Quick freeze between blocks of solid carbon dioxide. Refer to Vollenweider (1969).

Analysis

Refer to Wetzel (1964; 1965), and Vollenweider (1969).

Calculations

Refer to Wetzel (1964; 1965), and Vollenweider (1969).

Data Reporting and Precision

Report primary productivity measured by the oxygen method or net primary productivity measured by the radiocarbon technique as follows: less than 10 mg, one decimal; 10 mg and above, two significant figures (Greeson and others, 1977).

No numerical precision data are available.

4.B.2.b.4.a. Unstratified Waters

Summary of Method

Changes in the dissolved oxygen concentration in a body of water are a result of photosynthesis, respiration, diffusion, and inflowing surface and ground water. If it is known how these factors affect the oxygen concentration in the study area, a dissolved-oxygen curve can be established and the primary productivity of the community can be determined. According to Odum (1956) and Owens (1965), the formula for the oxygen curve may be given as:

$$Q = P - R \pm D + A \tag{1}$$

where

Q is the rate of change (gain or loss) of dissolved oxygen per unit area.

P is the area of community gross primary productivity per unit area.

R is the rate of oxygen utilization (respiration) per unit area.

D is the rate of oxygen uptake or loss by diffusion per unit area (depending on whether the water is undersaturated or oversaturated with oxygen with respect to the air).

A is the rate of supply of oxygen from drainage accrual.

If possible, the area selected for study is one in which accrual has a negligible effect on the oxygen concentration as compared with the other components. Dissolved oxygen concentration and water temperature are determined in the open water continuously or at 1- to 3-hour intervals for at least 24 hours. Diffusion (D) is calculated or measured and gross primary productivity and respiration of the community are estimated from rates of oxygen change after correction for the exchange of oxygen between water and the atmosphere.

Application

The method is applicable to unstratified eutrophic bays, estuaries, lakes and streams. If the incoming water of a flowing water system has a metabolic history similar to the outflowing water, the single station analysis may be made. If the metabolic characteristics of the inflowing water are unknown or are not similar to the outflowing water, the two station analysis should be made. If complete vertical mixing occurs within a bay, estuary, or lake, a series of single station analyses may be sufficient to characterize the oxygen regime within the water. Refer to Odum (1956), American Public Health Association and others (1976), and Greeson and others (1977).

Interferences and Special Considerations

Undetected advection, accrual of surface or ground water, and loss of oxygen from the water in the form of bubbles are possible sources of error. The limited sensitivity of the method precludes its use in unproductive waters. In shallow, turbulent streams the rate of oxygen equilibration between water and the atmosphere is too rapid for the method to be used.

Preservation and Storage

Refer to American Public Health Association and others (1976) and Greeson and others (1977) for treatment of samples for dissolved oxygen determination.

Analysis

Refer to Odum (1956), Owens (1965), Vollenweider (1969), American Public Health Association and others (1976), and Greeson and others (1977). Greeson and others give a detailed description of steps in the analytical procedure.

Calculations

Refer to Greeson and others (1977).

Data Reporting and Precision

Report community metabolism as follows: less than 10 g O_2/day, one decimal; 10 g and above, two significant figures (Greeson and others, 1977).

No numerical precision data are available.

4.B.2.b.4.b. Stratified Waters

Summary of Method

Changes in the dissolved oxygen concentration in a body of water are a result of photosynthesis, respiration, diffusion, and inflowing surface and ground water. If it is known how these factors affect the oxygen concentration in the study area, a dissolved-oxygen curve can be established and the primary productivity of the community can be determined. According to Odom (1956) and Owens (1965), the formula for the oxygen curve may be given as eq 1 (section 4.B.2.b.4.a).

In stratified waters, a vertical variation in dissolved oxygen may exist—concentration may vary from near saturation at the surface to near zero at the bottom. Under these conditions, production of oxygen is limited to the euphotic zone, and an oxygen deficit exists in the lower or hypolimnetic water. From average values for temperature, dissolved oxygen, and, if appropriate, salinity, an average rate of change of dissolved oxygen is calculated for the entire water body. Average dissolved oxygen values for the surface-water layer are corrected for diffusion. The resulting curve of diel changes in the *in situ* concentrations of dissolved oxygen is used to estimate the primary productivity of the entire aquatic plant community.

Application

The method is applicable to eutrophic estuaries, lakes and other stratified bodies of water in which a vertical variation in dissolved oxygen exists. The lower limit for measurable oxygen production occurs when phytoplankton densities, expressed as chlorophyll *a*, fall below 1 mg/m^3 (Vollenweider, 1969).

Interferences and Special Considerations

Undetected advection, accrual of surface or ground water, and loss of oxygen from the water in the form of bubbles are possible sources of error. The limited sensitivity of the method precludes its use in unproductive waters. The method should be used in waters of comparative horizontal homogeneity.

Preservation and Storage

Refer to American Public Health Association and others (1976) and Greeson and others (1977) for treatment of samples for dissolved oxygen determination.

Analysis

Refer to Greeson and others (1977), Vollenweider (1969), Odum (1965), and American Public Health Association and others (1976). Greeson and others give a detailed description of steps in the analytical procedure.

Calculations

Refer to Greeson and others (1977).

Data Reporting and Precision

Report community metabolism as follows: less than 10 g O_2/day, one decimal; 10 g and above, two significant figures (Greeson and others, 1977).

No numerical precision data are available.

4.B.2.b.5. REFERENCES

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4.B.2.c. NITROGEN FIXATION

4.B.2.c.1. INTRODUCTION

Nitrogen is a major cell constituent, and its abundance is an important factor determining the productivity of aquatic ecosystems. Accurate data on nitrogen budgets of surface waters, therefore, are essential for effective water resource management. Elemental nitrogen is known to be fixed by more than 20 species of blue-green

algae and 15 genera of bacteria (Fogg, 1962; Stewart, 1967). Hence, biological fixation of elemental nitrogen may be an important source of combined nitrogen in surface waters.

Elemental nitrogen is reduced to ammonia by the nitrogenase enzyme system in the presence of ATP and magnesium ions according to the general reaction:

$$N_2 + 6e \xrightarrow[\text{ATP} + Mg^{++}]{\text{Nitrogenase}} 2\ NH_3$$

Nitrogen fixation in surface waters has been estimated from Kjeldahl measurements of the gain in bound nitrogen in the seston (Hutchison, 1941; Mortimer, 1939); from cell counts of nitrogen-fixing bacteria and blue-green algae (Kusnezow, 1959); from radioactive nitrogen, ^{13}N, or the stable nitrogen isotope, ^{15}N; and from changes in the argon:nitrogen ratio in the gas above cultures ventilated with a 1:2 mixture of argon and nitrogen (Fay and Fogg, 1962). Until recently, the use of nitrogen-15 was considered the most convenient, sensitive and reliable method of estimating rates of nitrogen fixation in the laboratory on *in situ* flask tests (Neess and others, 1962; Fogg and Horne, 1967).

The nitrogenase enzyme system also reduces acetylene to ethylene. Use of acetylene reduction to estimate rates of nitrogen fixation was first adapted to the *in situ* measurement of nitrogen fixation rates by Stewart and others (1967), who quantitated the evolved ethylene by gas chromatography. The rate of acetylene reduction in bacteria ranges from 20 to 40 nanomoles C_2H_4/mg protein/min, and is one or two orders of magnitude greater than the rate for blue-green algae, which ranges from 0.1 to 4.7 nanomoles C_2H_4/mg protein/min (Dilworth, 1966; Stewart and others, 1967).

Photosynthesis is essential for nitrogen fixation by algae. If nitrogen-fixing algae are placed in the dark, they lose their ability to fix nitrogen within approximately 1 hour. However, if returned to the light, they quickly resume nitrogen reduction. Similarly, natural plankton populations taken from the surface of a lake and incubated in the aphotic zone fix less nitrogen than if incubated near the surface. The rate of nitrogen fixation in phytoplankton incubated *in situ* near the surface follows a diel pattern similar to that of photosynthesis, which is reduced as a result of photoinhibition during midday.

Because the rate of nitrogen fixation varies greatly with different types of organisms and with the concentration of combined nitrogen in the water, it is not possible to use nitrogen fixation rates to estimate the biomass of nitrogen-fixing microorganisms in surface waters. However, the acetylene reduction method may be very useful in measuring nitrogen budgets and in bioassays (Weber, 1973).

4.B.2.c.2. ACETYLENE REDUCTION METHOD

The acetylene reduction method is rapid and inexpensive, and permits the use of incubation periods of 5 seconds to 30 minutes, compared to 24 hours required for the nitrogen-15 method. As little as 1 picomole of acetylene can be detected, making the method a thousand times more sensitive than the nitrogen-15 method and a million times more sensitive than the Kjeldahl method.

The reduction of nitrogen to ammonia requires six electrons, whereas the reduction of acetylene to ethylene requires only two electrons:

$$C_2H_2 + 2e \xrightarrow{\text{Nitrogenase}} C_2H_4$$

On the basis of the energy requirements, the theoretical yield of this reaction would be a ratio of 3 moles of ethylene produced to 1 mole of nitrogen reduced. Reported ratios range from 2.4 to 8.6, but most values fall between three and five.

The acetylene reduction technique has also been used to determine phosphorus availability in surface waters by Stewart and others (1970), who measured the rate of ethylene production in phosphorus-starved *Anabaena flosaquae* incubated in test water and in culture media containing several levels of orthophosphate (0.00, 0.010, 0.025, 0.050, and 0.100 mg P/liter). The rate of nitrogen fixation was found to be directly proportional to the amount of phosphorus added, up to a concentration of 0.100 mg P/liter.

Summary of Method

A water sample is placed in a small bottle or vial and covered with a serum-type rubber cap. A known quantity of acetylene is injected into the air space above the water using a syringe and needle, and the sample is well mixed. The sample is incubated at the desired temperature and illumination for 1–30 minutes. An aliquot of the gas above the sample is withdrawn with a syringe and the ethylene is measured by gas chromatography.

Application

The method is applicable to all waters.

Interferences and Special Considerations

Water samples should be collected with a non-metallic sampler. If samples are used to indicate the response of the natural system, they should be maintained at the same temperature and level of illumination as the point from which they were taken from the water body. Measurements should be made immediately or within 2 hours.

Analysis

Refer to Stewart and others (1967, 1970), and Brezonik and Harper (1969).

Data Reporting and Precision

Results are generally reported as micrograms of nitrogen fixed per liter per hour (or per day) or as milligrams of nitrogen fixed per square meter per day. The precision of the method is unknown.

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4.B.3. BIOASSAY

4.B.3.a. INTRODUCTION

The term bioassay includes any test in which organisms are used to detect or measure the presence or effect of one or more substances or conditions that may be biostimulatory or bioinhibitory (toxic). These tests measure organism responses including mortality, growth rate, standing crop (biomass), reproduction, stimulation or inhibition of metabolic or enzyme systems, changes in behavior, histopathology, and flesh tainting (in shellfish and fish). The ultimate purpose of bioassays is to predict the effect of pollutants or adverse physical conditions

on populations of aquatic organisms in receiving waters. Whenever possible, therefore, tests should be carried out with species that are native (indigenous) to the receiving waters.

Bioassays have several advantages. The success of water-pollution control programs must be judged in terms of the health of the indigenous communities of aquatic organisms in receiving waters. Bioassays, therefore, are an essential part of water-pollution control programs. Also, in many cases, bioassays are very sensitive measures of the presence of biostimulatory or toxic substances and may be more cost effective than chemical analyses.

Although bioassay data are useful in detecting toxicity and other properties of pollutants and in predicting the effects of these substances on receiving waters, the user should remember the ultimate proof that aquatic life is adequately protected must come from studies of the effects of pollutants on the abundance, species composition, and condition of the natural (indigenous) aquatic communities in the receiving waters.

The general principles and methods of conducting bioassays presented in Weber (1973), U.S. Environmental Protection Agency (1975), American Public Health Association and others (1976), and Peltier (1978), apply to most bioassays, and can be used with many types of aquatic organisms with only slight modification.

4.B.3.b. ALGAL GROWTH POTENTIAL TEST

Algal growth potential is defined as the algal biomass or maximum growth rate that can be produced in a water sample under standardized laboratory conditions. Algal growth potential measurements are designed to determine the trophic status of surface waters, growth-limiting nutrients, and the influence and source of growth-promoting nutrients to improve means for predicting and controlling excessive algal growth in aquatic habitats.

Measurements of optical density, oxygen production, carbon dioxide uptake, cell numbers, and cell mass have been used for determining algal growth, but these methods are not sensitive when the number of cells is low. The measurement of carbon-14 uptake is sensitive but time consuming. The measurement of chlorophyll (*in vivo* or extracted) by fluorescence is also sensitive, but the chlorophyll-to-cell-mass ratio may vary with growth in water samples of differing chemical composition and with the age of the culture within a given flask. The electronic particle counter is both a sensitive and rapid method for counting and sizing non-filamentous algae in algal growth potential tests.

Summary of Method

A water sample is autoclaved, filtered, or both, then is placed in a covered vessel, inoculated with the test algal species, and incubated under controlled temperature and light intensity. Growth is measured daily until the rate of growth is less than 5 percent per day. The algal mass or maximum growth rate is used as an estimate of algal growth potential.

Application

The method is suitable for all waters.

Interferences and Special Considerations

Non-algal particles in the culture medium (sample), such as dust or lint, may block the aperture of the counting apparatus or give false counts when the electronic particle counter is used. These interferences may be avoided by careful filtration of the water sample prior to inoculation. Autoclaving may cause irreversible precipitation of certain constituents in the sample.

Preservation and Storage

The sample should be autoclaved and filtered, then may be stored in the dark at 0–5° C. The assay should be done within 1 week. Changes in water samples may occur during storage regardless of conditions. The extent and nature of these changes may be complex and may vary from sample to sample. Changes can be minimized by keeping the samples cool and dark and by avoiding air spaces in the container.

Analysis

Refer to Weber (1973).

Data Reporting and Precision

Report algal growth potential as standing crop (mg dry weight/L) or maximum specific growth rate (units/day). Refer to Weiss and Helms (1971) for precision data.

4.B.3.c. TOXICITY TESTS

Toxic substances are defined in Section 502(13), Public Law 95–217, as "any pollutants. . .which cause death, disease, behavior abnormalities, cancer, genetic mutations, physiological malfunctions or physical deformations in *any* organism."

4.B.3.c.1. ACUTE TOXICITY

Acute toxicity is generally defined as a relatively short-term lethal effect, usually occurring within 4 days for fish and macroinvertebrates (American Public Health Association and others, 1976).

4.B.3.c.1.a. In-Situ Method

Summary of Method

Aquatic organisms (generally fish or macroinvertebrates) are confined in cages placed at stations above and below the source of pollution for 24–96 hours. The organisms are checked at frequent intervals and mortality is recorded (Basch, 1971).

Application

The method is suitable for all waters, and is used to determine the toxicity of wastes after they have been discharged into receiving waters.

Interferences and Special Considerations

If multiple discharges are located close together, segregating the effects of the individual effluents may not be possible. The morphology of the water body may interfere with station selection, and adverse hydrologic conditions may destroy sampling equipment. Seasonal changes in ambient air and water temperatures may restrict field work to the summer season.

Analysis

Refer to Basch (1971).

Data Reporting and Precision

The results are reported as the percentage of mortality within the specified period of time. The precision of the test is unknown.

4.B.3.c.1.b. Laboratory Method

Summary of Method

Organisms are generally exposed to several concentrations of pure compounds or effluent for a specified period of time (generally 96 hours) under static or flow-through conditions and at a constant temperature. Organisms used in tests include algae, zooplankton, aquatic weeds, macroinvertebrates and fish. Tests may be conducted in fixed or mobile laboratories (U.S. Environmental Protection Agency, 1975; Peltier, 1978).

Application

The test is applicable for determining the toxicity of pure compounds, complex wastes or surface waters, or for determining the adverse effects of elevated water temperatures, turbidity, or other physical stress.

Interferences and Special Considerations

Rapid degradation of the test material may prevent accurate determinations of its toxicity. Also, the biochemical oxygen demand created during degradation of the test substance may rapidly deplete the dissolved oxygen and cause mortality, especially in static bioassays. Large amounts of dilution water and toxicants required by the flow-through system may in many cases preclude the use of such a system.

Analysis

Refer to Peltier (1978) and U.S. Environmental Protection Agency (1975).

Data Reporting and Precision

Results are reported as the concentration of pure compound (mg/L) or percentage of effluent that kills 50 percent of the test organisms within the prescribed test period. This is termed the LC50 (LC = lethal concentration). If death is not easily determined, such as with invertebrates, some "effect" other than death is used, and the results are expressed as the EC50 (EC = effective concentration). This is the concentration at which 50 percent of the test organisms show the selected effect within the time period used.

4.B.3.c.2. CHRONIC TOXICITY

Chronic toxicity is defined as long-term effects, which may include changes in appetite, growth, metabolism and reproduction and even death or mutations (American Public Health Association and others, 1976).

4.B.3.c.2.a. Long-Term Test

Summary of Method

The test organisms are exposed to several concentrations of toxicant or several levels of adverse physical conditions over a long period of time (generally at least one entire life cycle) in a flow-through system. The test organisms are observed to determine the maximum concentration of toxicant (or maximum level of adverse physical conditions) at which no adverse effects are seen in reproduction, behavior, physiology, morphology, growth rate, and so on (Weber, 1973; American Public Health Association and others, 1976).

Application

The test may be used with pure compounds or complex wastes to establish water-quality standards and effluent limitations related to specific pollutants or physical conditions.

Interferences and Special Considerations

Many organisms are extremely difficult to culture for the long periods of time (one or more life cycles) required for the test. Generally, the more sensitive the organism is to environmental stress, the more difficult it is to culture. Also, the test requires extremely large amounts of dilution water and highly-controlled laboratory conditions.

Analysis

Refer to Weber (1973).

Data Reporting and Precision

Refer to Weber (1973).

4.B.3.c.2.b. Short-Term Test

Summary of Method

Fish or macroinvertebrates are subjected to several levels of toxicant (or other stress) for several hours to determine the concentration or level at which significant changes occur in locomotor activity, respiration rate, heart rate, coughing response, and so forth.

Application

This approach provides a very sensitive and rapid test for the presence of toxicity in effluents and is useful in estimating the maximum acceptable toxicant concentration (MATC) of pure compounds or effluents.

Interferences and Special Considerations

Refer to American Public Health Association and others (1976).

Analysis

Refer to American Public Health Association and others (1976).

Data Reporting and Precision

Results are expressed as the MATC in mg/L or μg/liter. The precision of the test is unknown.

4.B.3.d. REFERENCES

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4.B.4. DATA MANAGEMENT

4.B.4.a. BENCH SHEETS AND RECORDS

Field and laboratory data should be entered immediately in bound record books or on bench sheets designed to organize the data in a functional manner. Examples of data sheets for many types of biological samples and analyses are included in Weber (1973).

4.B.4.b. DATA EVALUATION

The evaluation and interpretation of data should be attempted only by an experienced biologist with the aid of a bio-statistician and experts in other disciplines, as appropriate, and should involve the use of both subjective and quantitative tools and standards.

4.B.4.b.1. COMMUNITY STRUCTURE

Evaluation of community structure involves the use of quantitative data on the biomass (weight) and numbers of organisms per sampling unit and qualitative data on the species present and their environmental requirements and pollution tolerances. In interpreting the data, the biologist must rely primarily on his personal experience and knowledge of the published literature. However, guidelines for identifying organisms and evaluating data on community structure are presented in Weber (1973) and U.S. Environmental Protection Agency (1975a, 1977).

4.B.4.b.2. COMMUNITY METABOLISM

Evaluation of community metabolism generally involves the comparison of measured rates of primary productivity, respiration, or nitrogen fixation with previous data, for trend analysis, or with data from other surface waters to determine the relative rate of metabolic activity. A table relating productivity to trophic status is presented in U.S. Environmental Protection Agency (1975a).

4.B.4.c. COMPUTER STORAGE AND MANIPULATION

The use of computerized data management systems has many advantages, including quality-assurance features and cost-saving factors, such as:

1. Reducing the cost of, and relieving the biologist from, carrying out repetitive arithmetical calculations such as the conversion of tallies (sample counts) to final reported values. This allows the biologist to use his time more productively and reduces the human errors inherent in manual data handling.
2. Carrying out edit checks on the data using established ranges and logical comparisons with other (physical and chemical) data.
3. Use of more powerful statistical analyses than those that are normally available or those that can be carried out manually.
4. Correlation of biological data with physical and chemical data (especially if they reside in the same system) to provide greater insight in the cause-and-effect relationships among these data.
5. Development and use of mathematical models to predict the effects of environmental perturbations on aquatic life.

4.B.4.c.1. STORET

The U.S. Environmental Protection Agency operates an extensive data management system called STORET (U.S. Environmental Protection Agency, 1975b). The data base consists largely of physical and chemical water-quality data, but also includes approximately 360 biological parameters identified by a 5-digit numerical parameter code. The data system is managed by the Office of Water and Hazardous Materials, Washington, D.C., and operates on an IBM 370/168 computer.

Authorized users can store, retrieve and analyze data via remote low- or high-speed terminals through a dedicated telecommunications network. Several statistical software packages are available in the system.

STORET lacks an open-ended, hierarchical taxonomic coding system, and, therefore, is limited in its capability of handling biological data.

4.B.4.c.2. BIO-STORET

The U.S. Environmental Protection Agency has designed and implemented a new biological data management system on a pilot basis. BIO-STORET will serve as a companion to the physical and chemical water-quality data base of STORET, will be supported by the same office as STORET, and will operate in the same computer main frame (IBM 370/168).

BIO-STORET has an open-ended, hierarchical taxonomic code, which currently includes approximately 12,000 species of aquatic organisms (Weber and others, 1981). The system will accommodate data on biomass, species composition, toxic substances in tissues, and bioassays for all communities of aquatic organisms, including the phytoplankton, zooplankton, periphyton, macrophyton, macroinvertebrates, and fish. For further information see Nacht and Weber (1976).

4.B.4.d. REFERENCES

Nacht, L., and Weber, C. I., 1976, BIO-STORET final design specifications: Cincinnati, Ohio, U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency, 1975a, Model state water monitoring program: Washington, D.C., U.S. Environmental Protection Agency.

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4.B.5. QUALITY ASSURANCE

A successful quality-assurance program in aquatic biology is based on the following essential elements:

1. *Staff Commitment* – a staff with an understanding and acceptance of the importance of quality control and a commitment to fully integrate quality-control practices into field and laboratory operations.

   To establish and maintain an effective quality-assurance program in aquatic biology, the supervisor must actively support and frequently monitor the use of quality-control practices in all aquatic biology activities. This will require the commitment of 10–15 percent of the total personnel resources. The supervisor must frequently review field and laboratory operations with his staff to ensure that quality-assurance practices are followed and properly documented.

2. *Staff* – a staff with adequate formal training and experience and proper specialization to meet program needs.

   The quality and reliability of the data rest heavily on the competence of the staff that collects and analyzes them. The range of aquatic organisms studied by biological programs is very broad, and each community requires unique skills in sample collection and analysis and data interpretation. Several disciplines, therefore, must be represented on the staff to deal effectively with the taxonomy and ecology of the major groups of aquatic organisms, which include the phytoplankton, zooplankton, periphyton, macrophyton, macroinvertebrates and fish.

3. *Facilities* – adequate field equipment, storage and laboratory space, instrumentation, and taxonomic references.

   The quality of the data also depends upon the adequacy of storage and laboratory space and the availability and performance of equipment. Sampling gear, current meters, spectrophotometers, microscopes, and the like must be available and must meet performance standards related to the biological parameters being measured. Laboratory instrumentation must provide the sensitivity and accuracy required by the state-of-the-art in sample analysis.

4. *Advance Planning* – careful advance preparation and design of field and laboratory studies.

   Thorough advance planning of field and laboratory projects is necessary to maintain the required control over the technical aspects of the project and to ensure the collection of meaningful data. Factors that should be considered include the objectives of the study, parameters to be measured, station selection, sampling frequency and replication, seasonal cycles in the properties of communities of aquatic organisms, and quality-control measures to be incorporated into the various phases of the project.

5. *Use of Approved Methodology* – strict adherence to approved methodology, where available, and careful consideration of the technical defensibility of the methods and their application.

   All methods used should be proven as acceptable for the particular application intended; should be completely described in available literature; and should have been subjected to peer review. All the methods references in this Handbook generally meet these criteria. If program activities require methods for parameters not covered in recommended references, the techniques used should be fully documented and retained as a permanent record.

6. *Replication* – use of replication in sample collection and analysis, where feasible, and determination of the accuracy and precision of the data.

   Comparisons of biological parameters measured in "control" and "affected" regions of water bodies, and in laboratory experiments, may be meaningless if the precision of the results is not known. Preliminary measurements must be made in each study to determine the scatter in the data and to establish the number of replicate samples required to achieve the level of precision required to detect differences in the responses measured.

7. *Instrument Calibration and Maintenance* – frequent calibration of field and laboratory instruments.

   Sampling equipment and laboratory instrumentation with mechanical metering devices and electronic components must be calibrated on a regularly scheduled basis to ensure the accuracy of the data. Standards, such as NBS-certified thermometers for temperature-measuring devices, Class S weights for balances, and absorption filters for spectrophotometers, should be obtained. Records of the calibrations, regular performance checks and service for each device should be maintained in a bound logbook so that the history of the performance of the instrument may be easily reviewed. Analytical reagents should be labelled and dated when received, and should be protected from deterioration if labile. The expected shelf life of each reagent must be recorded on the label and the material should not be used after the expiration date.

8. *Sample Labelling* – proper identification and handling of samples to prevent misidentification or intermixing of samples.

   Samples should be securely labelled in the field and recorded in a bound logbook. Information on the label should include the station, time and date of collection, depth and other relevant information. A unique (lot) number should be assigned to the sample and recorded on the label. Waterproof paper and ink must be used for the labels, and are recommended for the field logs. Depending on requirements, labels can be placed inside samples such as macroinvertebrates.

9. *Quality Control Samples* – use of "blind," split or other control samples to evaluate performance.

   The accuracy of the data from routine analyses such as organism counts and identifications, and chlorophyll and biomass measurements are determined by introducing "blind," split or reference samples in the sampling processing stream. These samples are prepared by the supervisory aquatic biologist, or Laboratory Quality Control Officer. The results are discussed at regularly scheduled staff meetings and any problems are discussed and corrected.

10. *Organism Identification and Reference Specimens* – development and regular use of inhouse reference specimen collections, and use of outside taxonomic experts to confirm or provide identifications for "problem" specimens.

    Accurate identification of aquatic organisms to the species level is essential to the interpretation of biological data. Within each laboratory, a set of reference specimens should be established as taxonomic (identification) "standards" for processing samples and for training new personnel. The set should be representative of the aquatic organisms collected by the program and each specimen should embody the morphological characteristics essential to the identification of that taxon. The identity of these specimens is verified by outside taxonomic experts, who also examine organisms that pose unusually difficult identification problems in routine sample analysis.

11. *Data Records, Editing (Proofing), and Review* – meticulous, dual-level review of the results of manual arithmetic data manipulations and transcription before the data are used in reports or placed in computer files.

    Data collected manually should be entered in a bound log or on specialized bench sheets that fully describe the origin and nature of the sample. The entries should be maintained in a binder or file. Source data on organism abundance, metabolic rates, chlorophyll, and so forth, which are manually or electronically manipulated or transcribed from one record to another, should be double-checked by a second person. All manual calculations and all electronic calculations where data are manually keyboarded, should be carried out twice, except where the source (input) data are included in the output and can be proofed. Keypunched data should be carefully proofed before they are submitted for computer manipulation.

12. *Interlaboratory Methods Studies* – participation in formal interlaboratory aquatic biology methods studies, and use of certified biological reference materials.

    The aquatic biology program should participate in formal interlaboratory biological methods studies such as those carried out by the U.S. Environmental Protection Agency's Environmental Monitoring Support Laboratory in Cincinnati, Ohio.

13. *Documentation of Quality Assurance Program* – documentation of methodology and quality-control practices employed in the program.

    A laboratory operations manual describing the scope of the program, organizational structure, qualifications of the staff, available space and equipment, methodology employed for sample collection and analysis, and quality-control procedures should be prepared.

4.B.5.a. REFERENCES

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4.C. MICROBIOLOGICAL METHODS

4.C.1. VIRUSES

4.C.1.a. INTRODUCTION

4.C.1.a.1. SOURCE AND SURVIVAL

The human viruses most likely to be present in the aquatic environment are those that multiply in the gastrointestinal tract of infected individuals and are excreted in large numbers in the feces of these individuals. Approximately 100 such "enteric viruses" have been identified. Various members of this group usually dominate in a community until the number of susceptible individuals (usually the young) is reduced below the number required to maintain the viral transmission. The enteric viruses characteristically produce overt disease symptoms in only a small percentage of the individuals infected. Therefore, a very high infection rate (and excretion rate) may exist in a community without becoming apparent to local physicians and health officials (Evans, 1977).

The enteric viruses abound in raw sewage and enter the water resources of populated areas primarily through sewage effluents. Since viruses can only reproduce within susceptible living cells, they do not multiply in such wastewater. In fact, good secondary sewage treatment reduces their number considerably (Berg, 1973a).

The viruses are further reduced in the receiving waters through dilution and naturally-occurring degradation of organic matter. For example, oxidation is important in the destruction of virion integrity at temperatures of about 37° C but not at temperatures of most natural waters (Akin and others, 1971). In fact, enteric viruses are relatively resistant to inactivating factors at temperatures below 37° C and are protected by some types of organic matter present in contaminated water. Viruses survive longer with decreasing temperature and may remain infectious for days to weeks in surface waters at temperatures that prevail during the colder months. Interestingly, more enteric virus excretion occurs during the warmer months of later summer and early fall. Important virus survival factors other than temperature have not been clearly defined. Although these factors are ill defined, obviously the exposed protein and nucleic acid molecules comprising the virion cannot maintain their integrity for extended periods in the hostile environment. Perhaps the fact that enteric viruses readily adsorb to most types of natural particulate matter (especially in the presence of cations) and the possibility that they may be embedded in minute particles of fecal matter, may explain their longevity in the aquatic environment (Britton, 1975). The ability of large-volume virus recovery procedures to isolate enteric viruses from surface waters distant from known pollution sources attests to the durability of these viruses (Berg, 1973b).

4.C.1.a.2. ISOLATION AND ENUMERATION

Viruses are present in contaminated water at levels such that concentration procedures are required to detect their presence in all samples with the possible exception of raw sewage. Most virus concentration procedures are based on the adsorption and elution characteristics of the amphoteric virus particles. In the presence of cations or an acid pH, the enteric viruses will adsorb to a wide variety of materials. This property is utilized in the flow-through virus concentration procedure whereby large volumes of water may be sampled on site and a small volume of concentrate (eluate) can be returned to the laboratory for testing. Investigators have evaluated various materials in an effort to find an efficient virus adsorbent that would also allow the elution of infectious virus under defined conditions (Sobsey, 1976). Viruses of all three subgroups of the enteric viruses group (entero, adeno and reo) have been recovered from contaminated waters using techniques based on this principal. Enteric viral agents that cause Hepatitis A and non-bacterial gastroenteritis have not been isolated from environmental samples using these procedures. The lack of cell culture systems or satisfactory laboratory animals to grow the viruses has precluded the evaluation of concentration procedures for recovery of these viruses.

To detect viruses in the sample concentrate, the sample is added to *in vitro* cultures of animal cells. Typically a volume of sample is allowed to adsorb to a monolayer of cells growing on one surface of a glass or plastic container. One of two techniques can then be employed: (1) a liquid nutrient medium can be added to the container and the cells observed microscopically for morphological changes indicative of viral replication, called cytopathic effect (CPE), or (2) a semisolid overlay medium containing a vital dye can be placed over the cell

monolayer. The monolayer is then observed macroscopically for the appearance of areas of cell destruction (plaques) indicative of viral replication within confined areas of the monolayer. The plaque method has the advantages of requiring less technical skill and allowing quantitation of the virus particles in the sample. However, all viruses do not produce plaques with standard overlay procedures and the presence of such viruses could go undetected. The "all-or-none" CPE procedure is believed by some to be more sensitive with low numbers of viral particles than the plaque procedure. However, a highly "trained eye" is required to detect the CPE produced by some viruses.

No single cell type will support the replication of all enteric viruses. A combination of three or more cell types from human or lower-primate origin may be required to support the growth of most of the approximately 100 enteric virus types (Lee and others, 1965). Some of the enteroviruses may require the inoculation of intact laboratory animals to demonstrate their presence.

4.C.1.b. DETECTION IN SURFACE AND DRINKING WATERS

Summary of Method

The method has been described as basically a two-stage procedure (American Public Health Association and others, 1976; Bordner and others, 1978). In the first stage, the water is adjusted to pH 3.5 with hydrochloric acid, and any chlorine that may be present is neutralized with sodium thiosulfate. These additives are introduced into the sampling stream by a hydraulically-operated proportioning pump. The water and additives enter a mixing chamber before passing through one of several acceptable virus-adsorbing filter media (American Public Health Association and others 1976; Farrah, Gerba and others, 1976; Farrah and others, 1977). When the required volume of water has been sampled, the filter medium is eluted with an alkaline glycine buffer to produce the primary eluate. In the second stage, the primary eluate is reconcentrated by adjusting the pH to 3.5, adding cations, and readsorbing with smaller-sized virus-adsorbing filters. The virus is then re-eluted from the filters.

A beef extract solution may be used for primary elution (Katzenelson and others, 1976). In this case, reconcentration of viruses from the primary eluate is accomplished by adjusting the eluate to pH 3.5 and centrifuging the resulting floc. The floc, with the associated viruses, is redissolved in a small volume of phosphate buffer to produce the final concentrate.

Application

The method is suitable for surface and drinking waters. Routine monitoring of water supplies is not advocated, but the method is recommended in special circumstances, such as wastewater reclamation, disease outbreaks, or research studies, and should be employed by competent virologists having adequate facilities.

Interferences and Special Considerations

At acid pH, organic compounds may be deposited on the virus-adsorbing filter medium (Farrah, Goyal and others, 1976). These compounds could interfere with virus adsorption and elution and reconcentration. The addition of cations in the form of magnesium or aluminum chloride may be indicated in these circumstances to enhance primary virus adsorption (Wallis, Henderson, and Melrick, 1972). If a precipitate forms in the primary eluate when using alkaline glycine buffer elution, difficulty may be encountered during filtration reconcentration. In this instance, elution and reconcentration by the organic flocculation technique may be desirable.

Suspended particulates (clays, metal complexes, and so on) could clog the primary filter and thus decrease the volume of sample that may be processed. Clarifying filters (Wallis, Homma, and Melnick, 1972) may be used only if absolutely necessary to obtain the required sample volume (generally, up to 400 liters for raw surface waters, and up to 1900 liters for treated drinking waters). The use of clarifying filters, while increasing the volume that may be conveniently sampled, could decrease the recovery efficiency. The efficiency of the chosen sampler configuration should be determined with a given water through controlled virus-seeded experimentation. In the collection and processing of samples for indigenous viruses, precautions should be taken to assure the integrity of the sample (Akin and Jakubowski, 1976).

Preservation and Storage

The concentrate is adjusted to physiological pH and salt content, and protective protein is added. The concentrate may be filtered through a protein-treated bacteriological filter or appropriate antibiotics may be added to control bacterial and fungal growth. Concentrates are stored at −70° C until assayed.

Analysis

Refer to American Public Health Association and others (1976) and Bordner and others (1978) for discussions of appropriate virus assay systems.

Calculations

For relatively unpolluted surface waters and for drinking waters, the entire sample concentrate should be assayed. Virus levels in these samples should not be calculated based upon examination of a portion of the total concentrate.

Data Reporting and Precision

All isolates obtained from raw waters should be confirmed as viral. All isolates obtained from drinking water should be confirmed as viral and identified as to type by appropriate procedures. Report confirmed or identified viruses as number of plaque-forming units (PFU) per volume of water sampled. If the CPE technique or animals are used, report as number of isolates per volume of water sampled. In either case, detailed information on tissue culture types; animal species; the number of assay tubes, flasks, or animals employed; inoculum volume; and assay conditions should be included. As there are over 100 enteric viruses that may be found in water, and there are infinite variations in water quality, only limited data are available on recovery efficiency and sensitivity. Comparisions done by Jakubowski and others (1975) and by Hill and others (1976) indicated a mean recovery efficiency of poliovirus 1 from drinking waters of 35 percent, and a detection reliability of 66 percent at virus levels of 1 to 2 PFU/380 liters when 1900 liters were sampled.

4.C.1.c. DETECTION IN SEWAGE

Summary of Method

A disc adsorption virus-elution procedure has been developed for concentrating viruses associated with sewage (Wallis and Melnick, 1967; Rao and others, 1972). In this method sewage is clarified by filtration through a 293 mm AP 20 prefilter and 0.45 μm membrane that have been pretreated with 500 mL of 0.1 percent Tween 80, and washed with two liters of sterile distilled water. This pretreatment removes bacteria and solid material. To each liter of filtrate is added 1.2 grams of $MgCl_2 \cdot 6H_2O$. The salt-supplemented filtrate is adjusted to pH 3.5 with concentrated hydrochloric acid and filtered through a 142 mm 0.45 μm membrane (Dahling and others, 1974). Virus is eluted from the membrane with 40 mL of 3 percent beef extract. The beef extract is allowed to remain in contact with the virus-adsorbing membrane for 30 minutes before being forced through the membrane. The eluate is inoculated at 1 mL per culture bottle. The BGM continuous cell line is used to detect the presence of viruses (Dahling and others, 1974). Isolated viruses are identified by assaying against antisera pools (Melnick and Hempil, 1970).

Application

The method is suitable for all sewages and all heavily polluted waters. The method is recommended for monitoring wastewater treatment plants and heavily polluted waters used in spray irrigation. The concentration procedure requires skilled technicians fully trained in aseptic techniques. Virus assay is performed in a well-equipped laboratory by competent environmental virologists.

Interferences and Special Considerations

Solids present in water may clog the prefilter and virus adsorbing filter. When clogged, prefilters are either replaced or the size of the test sample is reduced. Viruses may attach to solids on prefilters. Elution of these solids with 10 percent buffered beef extract is often necessary (Wolf and others, 1974).

Organics present in water may interfere with virus adsorption and thus lower recoveries may be experienced. Seeding experiments can provide data on the relative efficiency of virus recoveries.

Preservation and Storage

Samples should be processed at time of collection. Resulting eluate should be either immediately inoculated into tissue culture or refrigerated at 4° C and maintained at that temperature until the eluate is assayed for virus. If assay for virus cannot be undertaken within 8 hours, store processed eluate immediately at −70° C. Samples that must be shipped should be iced for no longer than 24 hours before processing, otherwise they must be frozen at −70° C.

Analysis

Refer to American Public Health Association and others (1976) for discussions of appropriate virus assay systems.

Calculations

Whenever possible, the entire sample should be assayed. When only a portion of the sample is inoculated, store the remaining sample at −70° C for future reference. The plaque counting technique (Dulbecco and Vogt, 1954) is used to enumerate the number of viruses present, which are calculated on the basis of plaque forming units (PFU).

Data Reporting and Precision

Because of the many variables in wastewaters, no definitive statement regarding the precision of virus concentration procedures can be made. Repeatability is shown by preliminary testing with virus seeded into test waters.

Results should be calculated and recorded on protocol sheets. Positive results are reported after verification by cytopathic effects (CPE) in tissue culture tubes and without awaiting subsequent identification by typing against antisera pools.

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4.C.2. WATER-QUALITY INDICATOR ORGANISMS AND PATHOGENIC BACTERIA

4.C.2.a. INTRODUCTION

4.C.2.a.1. WATER QUALITY ANALYSES

Bacteriological analyses are the only measures of water quality that provide information on the sanitary quality of water and wastewater and the potential risks to public health from waterborne disease. Bacteriological tests are conducted to assure the safety of potable water; enforce water-quality standards; monitor ambient water for recreational, agricultural, industrial, and water-supply uses; determine the effectiveness of water and wastewater treatment; control the water quality in such industries as beverage, cosmetic, and pharmaceutical, identify the sources of bacterial pollutants; and develop water resources.

4.C.2.a.2. SOURCES OF MICROORGANISMS IN WATER

Some bacteria are indigenous to natural waters; others gain access to water from land, air, or human and animal wastes. For example, urban and rural runoff washes large numbers of microorganisms into water from natural vegetation and soil habitats, from decomposing organic materials, and from animal wastes deposited on land or concentrated in feedlots and barnyards. Treated and untreated sewage and wastes from such industries as dairy, food, meat, tanning, sugar, textile, pulp and paper, and shellfish processing contribute large numbers of bacteria directly to the receiving waters. Many of the bacteria found in these wastes cause disease or act as indicators of the sanitary quality of water and wastewater.

4.C.2.a.3. SURVIVAL FACTORS

The numbers and kinds of microorganisms in water depend on: the natural flora (the organisms that colonize in the water); the transient contaminants (the organisms that enter water and may multiply); and the ability of these groups to survive, grow, and reproduce. Survival, growth, and reproduction are a function of: (1) available nutrients; (2) the presence of toxic substances; (3) physical and chemical factors such as pH, temperature, turbidity, penetration of sunlight, hydrostatic pressure, oxygen tension, and salinity; (4) competition from other microorganisms; and (5) the action of predators, antagonistic protozoans and bacteriophages, and other microorganisms that produce antibiotic substances. Requirements for survival are less restrictive than those for growth. Some types of organisms survive better because they are more adaptable to variations in temperature, dissolved oxygen and pH, or more tolerant of low nutrients, high salinity, or toxic chemicals. Spore-forming bacteria and cocci survive particularly well under adverse conditions.

The size and nature of bacterial populations vary with the type of water (Carpenter, 1972; Frobisher and others, 1974). In general more species and fewer organisms per species occur in clean water; fewer species and higher densities occur in polluted water.

Surface waters, which result from precipitation that has collected in rivers, streams, lakes, and ponds, have extremely variable bacterial contents. A cold, pristine mountain stream contains low bacterial densities, mostly psychrophiles. Rivers contain many microorganisms derived from the soil and, in inhabited regions, are contaminated by domestic and industrial wastes. Total bacterial counts in rivers and streams range from several hundred to thousands of bacteria per milliliter. Since these waters are dynamic and always in motion, bacterial levels at any site vary greatly and may suddenly fluctuate because of rainfall, changes in streamflow, and other environmental factors. The continuous flow of streams replenishes nutrients and removes potentially toxic materials. Limited food supply, oxygenation, exposure to sunlight, settling out of the organisms, and the action of predators decrease the densities of microorganisms and tend to purify the water naturally.

Stationary waters such as lakes and ponds contain more stable microbial populations than streams because their physical and chemical characteristics and food supplies are more constant. Stored waters encourage the gradual settling of microorganisms. The populations of reservoirs, lakes, and ponds that do not receive sewage or nutrient pollution are relatively low. However, where static waters receive land runoff and domestic or industrial wastes, high bacterial counts occur along the shores. Microorganisms are concentrated at the interfaces at the surface of the water, a few centimeters above the bottom, in the underlying sediment, adhering to organic and inorganic particles, and attached to living plants and animals.

Springs, wells, and aquifers deep beneath the earth's surface are relatively free of microorganisms and ground water filtered through successive layers of soil, sand and clay may contain very few organisms. However, shallow wells and springs from unprotected runoff areas may be contaminated and produce unsafe water.

In marine and estuarine waters the zones along the shorelines and the sediments are most heavily populated by microorganisms, reflecting the higher levels of organic materials present. Large numbers of bacterial contaminants carried by rivers, streams and waste discharges are deposited in these areas and persist in seawater with a continued influx of organics. However, these transient organisms die off quickly in unpolluted seawater. In estuaries, fresh water is layered over salt water and the populations of each layer may differ significantly until the layers are mixed. In general bacterial densities decrease outward from the shore and downward from the surface. The open ocean contains low numbers of bacteria because of sedimentation, predators, sunlight and the high concentration of salt and minerals.

4.C.2.b. WATER-QUALITY INDICATOR ORGANISMS

Wastes from warm-blooded animals contribute a variety of bacterial genera and species that contaminate water (Geldreich, 1972). They include the coliform group and the genera *Streptococcus*, *Lactobacillus*, *Staphylococcus*, *Proteus*, *Pseudomonas* and *Clostridia*. In addition many other kinds of pathogenic microorganisms are present intermittently in the wastes. Their numbers vary with the local watershed, the intestinal diseases prevalent in the population, and the type and extent of waste treatment practiced. The most common pathogenic microorganisms include *Salmonella*, *Shigella*, enteropathogenic *Escherichia coli*, *Pasteurella*, *Vibrio*, *Mycobacteria*, human enteric viruses, cysts of *Entamoeba histolytica*, and hookworm larvae.

The direct approach to determine the safety or pollution level of water would be to test for pathogenic microorganisms. However, such testing is impractical because the densities of pathogens in feces vary too much and because pathogens are vastly outnumbered in polluted waters by other bacteria, which outgrow the pathogens in usual culturing techniques. Although *Salmonella* strains are easily isolated from sewage, streams, irrigation waters, wells, and estuaries, the methods used are not quantitative or standardized. Other pathogenic microorganisms are reported less frequently because their numbers are too low and variable and the methods of isolating and identifying them are complex, time consuming, and not available for routine use. Therefore, various groups of bacteria that are always present in the intestines of man or warm-blooded animals are used to indicate contamination from sewage, industrial wastes and land runoff, and the potential danger from disease-causing organisms. Total coliforms, fecal coliforms, and fecal streptococci are the most widely used indicators

of pollution. Other possible candidates are *Clostridium perfringens*, *Bifidobacterium bifidus*, *Bacteroides* and lactobacilli (Geldrich, 1978).

The results from water-quality analyses are only as valid as the sample. Microbiological samples must be collected aseptically and must be representative of the water or wastewater being sampled. Strict adherence to sample temperature and holding limits is critical for bacteriological analyses because no chemical preservative is available. The samples should be iced or refrigerated at 1–4° C during transport to the laboratory and analyzed as soon as possible after collection, preferably within 6 hours. However, potable water samples that must be mailed to the laboratory are permitted a maximum of 30 hours transit time before examination (American Public Health Association and others, 1976). The bacterial densities in water and wastewater samples range from none or few organisms in drinking water to millions per 100 mL in untreated sewage. High density samples of polluted water, wastewater or other material must be diluted to reduce the number of bacterial cells to measureable levels. The standard plate count, membrane filter and most probable number procedures are the basic methods used to isolate and enumerate bacteria important to water quality.

In the standard plate count method (also known as the pour plate method) the analyst dilutes the bacterial density in a sample through a series of dilution water blanks until the original bacterial population is reduced to a countable level. Aliquots of the diluted sample are added to sterile petri dishes and mixed with melted agar. After the agar solidifies, the plates are inverted and incubated at a specified temperature for a specified time. Surface or subsurface colonies that develop in the agar plates are counted to provide a measure of the bacteria in the original sample.

In the membrane-filter method the sample or a dilution of the sample is filtered through the membrane. The membrane filter is placed on a general nutrient medium or one selective for the bacteria being tested. The bacteria retained on the surface of the membrane develop into visible colonies after incubation under the specified conditions and are counted to provide a quantitative value for bacteria being tested. The medium and the temperature of incubation influence the kinds of bacteria that develop.

In the most probable number (MPN) method (also called the multiple-tube procedure) decimal dilutions of samples are inoculated into a series of liquid tube media selective for the bacteria being measured. Growth, fermentative gas production, or both indicate positive tests. The number of bacteria in water and wastewater is estimated by the use of probability tables based on combinations of positive and negative tube results.

The MPN procedure may be carried to two stages of completion: the confirmed test and the completed test. Before the first stage, a presumptive step in minimally-restrictive tube media is used to improve recovery of stressed organisms. The results of this step are never used without further analyses. The first stage is the *Confirmed Test*, which involves transferring growth from each positive presumptive tube into a more selective inhibitory medium. The positive confirmed tubes are recorded, and the index is calculated from the MPN table. The second stage is the *Completed Test*. Positive tubes from the confirmed test are submitted to additional tests to verify the identity of the isolated microorganisms. This stage may be used to further substantiate the confirmed test and to provide quality-control checks on the MPN procedure.

4.C.2.b.1. TOTAL BACTERIA

4.C.2.b.1.a. Standard Plate Count Method

The standard plate count (SPC) method provides a direct quantitative measurement of the viable aerobic and facultative anaerobic bacteria in water that will grow on a general-growth agar plating medium under defined test conditions.

Summary of Method

An aliquot or dilution of the sample is pipetted into a sterile petri dish, melted plate-count agar is added, and the plate is rotated to evenly distribute the bacteria. The agar is allowed to harden and the plate is incubated in an inverted position at 35° C for 48 hours. The resultant colonies are counted and recorded.

Application

The standard plate count provides a way to monitor changes in the bacteriological quality of finished water throughout a distribution system, thus indicating the effectiveness of chlorine residual in the system as well as

the possible existence of cross-connections, sediment accumulations and other problems within the distribution lines. The procedure may also be used to determine the quality of bottled water or emergency water supplies, to monitor the effectiveness of chlorination in swimming pools, and, when supplemented by other data, to estimate the aerobic, heterotrophic bacterial populations in water-supply impoundments and other natural waters.

Interferences and Special Considerations

The standard plate count does not provide a true total bacterial count. Theoretically, each bacterial cell present in a sample develops into a visible colony in or on the agar. However, no counting procedure can enumerate the entire population present because all viable bacterial cells in the water sample cannot reproduce under a single set of cultural conditions. This procedure does not allow the more fastidious aerobes or obligate anaerobes to develop.

Some species may produce a spreading growth that covers the entire plate, obscures other colonies and interferes with the count. Clumps of organisms may result in underestimates of bacterial density because an aggregate of cells appears as one colony on the growth medium. Reduced counts due to "heat shock" from the melted agar are possible. The pour plate technique is limited to an inoculum volume of 1–2 mL.

Sample Preservation and Storage

For samples containing chlorine, a dechlorinating agent must be added to the sample bottle prior to sterilization. Samples should be iced or refrigerated at a temperature of 1–4°C during transit to the laboratory. Samples should be examined as soon as possible after collection, and they should not be held longer than 6 hours between collection and analysis. Samples exceeding these limits should not be analyzed.

Analysis

Refer to Bordner and others (1978) and American Public Health Association and others (1976, p. 908–913).

Calculations

Select pour plates with 30–300 colonies and count immediately. Compute the bacterial count per milliliter by multiplying the number of colonies per plate by the dilution used according to the formula:

$$\text{SPC/mL} = \frac{\text{total number of colonies}}{\text{volume (mL) of original sample plated}}$$

If all plates have no colonies, fewer than 30 colonies, greater than 300 colonies, or colonies too numerous to count, an estimated count based on the volume analyzed is provided. Refer to Bordner and others (1978) and American Public Health Association and others (1976).

Data Reporting and Precision

Report counts as standard plate count per milliliter.

The standard deviation of individual counts from 30–300 will vary from 0–20 percent. This plating error is 10 percent for plate counts within the 100–300 range. A dilution error of about 3 percent for each dilution stage is incurred. Therefore, large variations can be expected from high density samples for which several dilutions are required.

Each analyst should be able to duplicate counts on the same plate within 5 percent. The counts of more than one analyst should agree within 10 percent.

4.C.2.b.1.b. Membrane-Filter Method

Summary of Method

An appropriate volume or dilution of the sample is passed through a membrane filter using a vacuum. The filter, which retains the bacteria present in the sample, is placed on m-SPC medium (Taylor and Geldreich, 1979) and incubated in an inverted position at 35° C for 48 hours. The resultant colonies are counted under low magnification and reported as the standard plate count (MF) per milliliter.

Application

The application is the same as the standard plate count method (section 4.C.2.b.1.a). The membrane-filter technique offers the advantages of examining larger, more representative sample volumes; being more adaptable to field studies; and saving time, labor, supplies, and equipment.

Interferences and Special Considerations

Interferences and special considerations are the same as those described for the standard plate count method, first paragraph.

Although most water samples can be tested by the membrane-filter method, some samples contain colloidal materials, suspended solids, or algae that can clog the filter pores or cause the development of spreading bacterial colonies. With samples having high bacterial densities, smaller volumes or higher sample dilutions can be tested. The membrane-filter method may be used with turbid samples by filtering several smaller, replicate sample volumes and combining the results. However, the membrane-filter method may not be applicable to water with high turbidity and low bacterial count.

Sample Preservation and Storage

Same as standard plate count procedure.

Analysis

Refer to Taylor and Geldreich (1979) for a specific method and to Bordner and others (1978) and American Public Health Association and others (1976) for the general membrane-filter procedure.

Calculations

Select membranes with 20–200 colonies and count immediately. Compute the bacterial count per milliliter by multiplying the number of colonies per membrane by the dilution used according to the formula:

$$\text{SPC(MF)/mL} = \frac{\text{total number of colonies}}{\text{volume (mL) of original sample filtered}}$$

If all counts are zero, below 20, or greater than 200, or if colonies are too numerous to count, estimated results are provided, with appropriate explanatory remarks. Refer to Bordner and others (1978) for general counting procedures.

Data Reporting and Precision

Report counts as standard plate count (MF) per milliliter. If there is no result because of confluency or laboratory accident, report as "no result" and specify the reason.

No established precision data are available.

Each analyst should be able to duplicate counts on the same membrane within 5 percent and the counts of other analysts within 10 percent.

4.C.2.b.2. TOTAL COLIFORMS

Total coliforms belong to the enteric bacteria group, Enterobacteriaceae, and consist of various species found in the environment and in the intestinal tract of warm-blooded animals. The coliform group is defined as the aerobic and facultative anaerobic, gram-negative, nonspore-forming, rod-shaped bacteria that ferment lactose with gas formation within 48 hours at 35° C.

4.C.2.b.2.a. Membrane-Filter Methods

Membrane-filter (MF) methods include the single-step, two-step enrichment, and delayed-incubation methods.

For the purpose of the methods described below, the coliform group is defined as those organisms that produce colonies with a golden-green metallic sheen on M-Endo medium within 24 hours when incubated at 35°C.

Summary of Methods

In the single-step procedure, an appropriate volume or dilution of a water sample is passed through a membrane filter using a vacuum. The filter retaining the bacteria is placed on a nutrient medium (M-Endo agar, LES M-Endo agar or M-Endo broth) designed to promote the growth of the coliform group and suppress the growth of most non-coliforms. After incubation at 35° C for 24 hours the sheen colonies that have developed are counted under low magnification and reported as the number of total coliforms.

In the two-step enrichment procedure, the filter retaining the microorganisms is placed on an absorbent pad saturated with lauryl tryptose broth. After incubation for 2 hours at 35° C, the filter is transferred to an absorbent pad saturated with M-Endo broth, M-Endo agar, or LES M-Endo agar, and incubated for an additional 20–22 hours at 35° C. Sheen colonies are counted and reported.

In the delayed-incubation procedure, the filter retaining the microorganisms is placed on an absorbent pad saturated with M-Endo preservative medium in a tight-lidded petri dish and is transported from the field site to the laboratory. In the laboratory, the filter is transferred to M-Endo growth medium and incubated at 35° C for 24 hours. Sheen colonies are counted and reported.

Application

The total coliform test is the primary indicator of bacteriological quality for potable water, distribution-system waters, and public water supplies because this more inclusive measure of contamination provides a greater safety factor. The method is not recommended for natural waters. Although it still is used to monitor water quality for shellfish, it is being gradually replaced by the fecal coliform test.

Most water and wastewater samples can be examined for total coliforms by the single-step membrane-filter procedure. However, if the membrane-filter method is used to measure total coliforms in chlorinated secondary or tertiary sewage effluents, the two-step enrichment procedure is required. Also, some potable water samples may require the enrichment provided by the two-step method for improved recovery of coliforms.

The delayed-incubation membrane-filter method is useful in field surveys or emergency situations when time and temperature limits for sample storage cannot be met. The method simplifies field processing and equipment needs.

The membrane-filter technique offers the advantages of examining larger, more representative sample volumes than the most probable number procedure; being adaptable to field studies; and saving time, labor, supplies, and equipment.

Interferences and Special Considerations

Although the majority of water samples can be tested by membrane filtration, some samples contain colloidal materials, suspended solids or algae that can clog the filter pores or cause the development of spreading bacterial colonies. When the bacterial counts of such samples are high, smaller volumes or higher sample dilutions can be tested. The membrane filter method may be used with turbid samples by filtering several smaller replicate sample volumes and combining the results. However, with waters of high turbidity and low bacterial counts, saline samples, or industrial wastes with toxicity, the membrane-filter method may not be applicable and the MPN procedure should be used. Recovering indicator organisms that are stressed in the environment may require an enrichment step. In addition, membrane-filter analyses require that MPN tube media be prepared for verification.

In the total coliform test large non-coliform populations may mask the appearance of indicators on membrane-filter medium.

Sample Preservation and Storage

For samples containing chlorine, a dechlorinating agent must be added to the sample bottle prior to sterilization. Samples should be iced or refrigerated at a temperature of 1–4° C during transit to the laboratory. Samples should be examined as soon as possible after collection, and they should not be held longer than 6 hours between collection and analysis. However, potable water samples that must be mailed to the laboratory are permitted a maximum of 30 hours transit time before examination. Samples exceeding these limits should not be analyzed.

Analysis

Refer to Bordner and others (1978), Greeson and others (1977), and American Public Health Association and others (1976, p. 928–937).

Calculations

Those membranes containing 20–80 golden-green, metallic sheen colonies and less than 200 total bacterial colonies are selected for counting. The colonies are counted using a microscope of 10–15× magnification and a fluorescent lamp. Compute the coliform count according to the formula:

$$\text{Total coliforms/100 mL} = \frac{\text{total number of coliform colonies}}{\text{volume (mL) original sample filtered}} \times 100$$

If all counts are zero, below 20, or greater than 80, or if colonies are too numerous to count, estimated results are provided, with appropriate explanatory remarks. Refer to Bordner and others (1978) for specific counting rules.

Data Reporting and Precision

Report total coliform densities per 100 mL of sample. If there is no result because of confluency or laboratory accident, report as "no result" and specify the reason.

No established precision and accuracy data are available at this time. Each analyst should be able to duplicate counts on the same membrane within 5 percent and the counts of other analysts within 10 percent.

4.C.2.b.2.b. Most Probable Number Method

The MPN test measures coliforms as the aerobic and facultative anaerobic, gram-negative, nonspore-forming, rod-shaped bacteria that ferment lactose with gas formation within 48 hours at 35° C.

Summary of Method

Decimal dilutions of a sample are inoculated into fermentation tube media selective for total coliforms. Five replicate portions are tested in each dilution. The method has two stages: the confirmed test and the completed test. Prior to the confirmed test, a series of fermentation tubes containing lauryl tryptose broth are inoculated with decimal dilutions of the sample. The formation of gas in these presumptive tubes at 35° C within 48 hours tentatively indicates the total coliform group. However, the MPN procedure must be carried through the confirmed test for valid results.

In the confirmed test, inocula from positive presumptive tubes are transferred to tubes of brilliant green lactose bile (BGLB) broth. Gas production in the tubes after incubation for 24 or 48 hours at 35° C constitutes a positive confirmed test and is the point at which most MPN tests are terminated.

In the completed test, growth from the positive BGLB tubes is streaked onto eosin methylene blue (EMB) plates and the plates are incubated for 24 hours at 35° C. Typical and atypical colonies are picked into lauryl tryptose broth fermentation tubes and onto a nutrient agar slant. The formation of gas after 48 hours at 35° C and confirmation of gram-negative rods constitute a positive completed test for total coliforms. The MPN per 100 mL is calculated from the MPN table based upon the confirmed or completed test results.

Application

Because the MPN procedure is a tube-dilution method using a nutrient-rich medium, it is less sensitive to toxicity than the membrane-filter method and supports the growth of environmentally-stressed organisms. The method is applicable to the examination of total coliforms in chlorinated primary effluents and under other stressed conditions. The MPN procedure is also better suited for examining turbid samples, muds, sediments, or sludges because particulates do not interfere visibly with the test. It is applicable to fresh and saline waters.

Interferences and Special Considerations

The MPN procedure is ordinarily limited to a maximum sample volume of 10 mL per tube. The time required for the test may be as long as 96 hours for a confirmed test result. The man-hour requirements to prepare

glassware and media and to perform the tests are significant. Relatively large amounts of bench space, incubator space and tube/rack storage space are required. The procedure is not as convenient for field work as the membrane-filter method. Certain non-coliform bacteria may suppress coliforms or act synergistically to ferment lauryl tryptose broth and yield false positive results. False positives are more common in sediments. Background organisms or toxic constituents in 10-mL volumes of marine water can interfere with coliform growth.

A significant number of false positive results can also occur in the brilliant green bile broth when chlorinated primary effluents are tested, especially when stormwater is mixed with sewage.

Sample Preservation and Storage

Refer to total coliform membrane-filter method (section 4.C.2.b.2.a).

Analysis

Refer to Bordner and others (1978), Greeson and others (1977), and American Public Health Association and others (1976, p. 913–921).

Calculations

The MPN for the confirmed or completed test is calculated from the number of positive tubes among the sample volumes tested. If more than three sample volumes are inoculated, the three significant dilutions are selected following established guidelines referred to under *Analysis* above. The number of positive tubes from three significant dilutions provide a code of three numbers, for example, 5–3–0. The code is located in the MPN table and the corresponding index is obtained. Because the table is based on sample volumes of 10, 1, and 0.1 mL, the MPN value for other than these volumes is calculated according to the formula:

$$\text{MPN/100 mL} = \text{MPN (from table)} \times \frac{10}{\text{largest quantity tested}}$$

The MPN can also be computed for each sample based on the positive and negative tubes according to the following formula:

$$\text{MPN/100 mL} = \frac{\text{number of positive tubes} \times 100}{\sqrt{(\text{volume (mL) in negative tubes}) \times (\text{volume (mL) in all tubes})}}$$

Data Reporting and Precision

Report the MPN value as total coliforms per 100 mL of original sample.

The MPN table contains probability calculations that inherently have poor precision and have a 23 percent positive bias at the five tube, three dilution levels normally used. The precision of the MPN value increases with increased numbers of replicates tested. A five tube, five dilution MPN is recommended for natural and waste waters. Only a five tube, single volume series is required for potable water. The 95 percent confidence limits for various combinations of positive and negative results are given in the MPN tables.

4.C.2.b.3. FECAL COLIFORMS

Fecal coliforms are enteric bacteria that represent those members of the total coliform group always found in the intestines and feces of warm-blooded animals.

4.C.2.b.3.a. Membrane-Filter Method

Membrane filter (MF) procedures include the immediate and delayed-incubation methods.

For the purpose of the methods described below, the fecal coliform group is defined as all organisms that produce blue colonies on M-FC medium within 24 hours when incubated at 44.5° ± 0.2° C.

Summary of Methods

In the immediate method, an appropriate volume or dilution of a water sample is passed through a membrane filter using a vacuum. The filter retaining the bacteria is placed on an absorbent pad saturated with a nutrient medium (M-FC broth or M-FC agar) designed to promote the growth of this group and suppress the development of non-fecal coliforms. After incubation at 44.5° C for 24 hours the typical blue colonies are counted under low magnification and reported as the number of fecal coliforms.

In the delayed-incubation method, selected sample volumes are passed through the filter. The filter retaining the bacteria is placed on a minimum growth medium (M-VFC broth) and is transported from the field site to the laboratory. In the laboratory, the filter is transferred to the standard M-FC medium and incubated at 44.5° C for 24 hours. Blue colonies are counted as fecal coliforms.

Application

The fecal coliform test is applicable to most waters: lakes and reservoirs, wells and springs, public water supplies, natural bathing waters, secondary nonchlorinated effluents from sewage treatment plants, farm ponds, stormwater runoff, raw municipal sewage, and feedlot runoff. The membrane-filter test has been used with varied success in marine waters.

The delayed-incubation method is useful in survey monitoring or emergency situations when the standard fecal coliform test cannot be performed at the sample site, or when time and temperature limits for sample storage cannot be met. The method reduces field processing and equipment needs.

The membrane filter technique offers the advantages of examining larger, more representative sample volumes; being more adaptable to field studies; and saving time, labor, supplies, and equipment.

Interferences and Special Considerations

The interferences and special considerations described under total coliforms for the membrane-filter procedure (section 4.C.2.b.2.a) in general apply to this procedure. Recovery of fecal coliforms from chlorinated effluents or toxic materials may be lower with the MPN procedure. Since chlorination stresses fecal coliforms and significantly reduces their recovery, the single step method should not be used with chlorinated wastewater.

Sample Preservation and Storage

Refer to standard plate count method (section 4.C.2.b.1.a).

Analysis

Refer to Bordner and others (1978), Greeson and others (1977), and American Public Health Association and others (1976, p. 937–941).

Sample Preservation and Storage

Refer to standard plate count method.

Analysis

Refer to Bordner and others (1978), Greeson and others (1977), and American Public Health Association and others (1976, p. 937–941).

Calculations

Those membranes containing 20–60 blue colonies are selected for counting. Non-fecal colonies are gray, buff or colorless and are not counted. Pinpoint blue colonies should be counted and confirmed. The colonies are counted using a microscope of 10–15× magnification and a fluorescent lamp. Compute the fecal coliform count according to the formula:

$$\text{Fecal coliforms/100 mL} = \frac{\text{number of fecal coliform colonies}}{\text{volume (mL) original sample filtered}} \times 100$$

If all counts are zero, below 20, greater than 60, or if colonies are too numerous to count, estimated results are provided, with appropriate explanatory remarks. Refer to Bordner and others (1978) for specific counting rules.

Data Reporting and Precision

Report fecal coliform densities per 100 mL of sample. If there is no result because of confluency or laboratory accident, report "no result" and specify the reason.

No established precision and accuracy data are available at this time. Each analyst should be able to duplicate counts on the same membrane within 5 percent and the counts of other analysts within 10 percent.

4.C.2.b.3.b. Most Probable Number Method

For the purpose of the test described below, fecal coliforms are defined as bacteria that are positive in presumptive tubes and ferment lactose in 24 hours at 44.5° C with gas formation.

Summary of Method

Decimal dilutions of multiple sample aliquots are inoculated into fermentation tube media selective for fecal coliforms. In the presumptive step, a series of fermentation tubes containing lauryl tryptose broth are inoculated with decimal dilutions of the sample. The formation of gas at 35° C within 48 hours constitutes positive presumptive tubes. This is the same presumptive step used in the total coliform MPN procedure. The MPN must be carried through the confirmed test for valid results. In this test, inocula from positive presumptive tubes are transferred to tubes of EC broth and incubated at 44.5° C for 24 hours. Formation of gas in any quantity in the inverted vial is a positive reaction confirming fecal coliforms. Fecal coliform densities are calculated from the MPN table on the basis of the positive EC tubes.

Application

Refer to total coliform MPN method (section 4.C.2.b.2.b).

Interferences and Special Considerations

Refer to total coliform MPN method. The time required for the fecal coliform MPN test may be as long as 72 hours.

Sample Preservation and Storage

Refer to standard plate count method (section 4.C.2.b.1.a).

Analysis

Refer to Bordner and others (1978), Greeson and others (1977), and American Public Health Association and others (1976, p. 922–927).

Calculations

The MPN value for the fecal coliform test is based on the number of positive tubes among the sample volumes tested in EC medium. The calculations are the same as those described for the total coliform MPN procedure.

Data Reporting and Precision

Report the MPN value as fecal coliforms per 100 mL of original sample.

Refer to Total Coliform MPN method.

4.C.2.b.4. FECAL STREPTOCOCCI

For the purposes of the following procedures, the fecal streptococcal group consists of the streptococci that indicate the sanitary quality of water and wastewater. The group includes the enterococcus subgroup (*S. faecalis*, *S. faecalis* subsp. *liquefaciens*, *S. faecalis* subsp. *zymogenes*, and *S. faecium*), *S. bovis*, *S. equinus*, and *S. avium*.

4.C.2.b.4.a. Membrane-Filter Method

Summary of Method

An appropriate volume or dilution of sample is filtered through the membrane filter using a vacuum. The filter retaining the bacteria is placed on KF Streptococcus agar and incubated at 35° C for 48 hours. Red and pink colonies are counted and reported as the number of fecal streptococci.

Application

Fecal streptococci are measured in fresh and marine waters, municipal sewage, wastewaters from food processing plants, slaughter houses, canneries, sugar processing plants, dairy plants, feedlots and farmland runoff. In combination with data on coliform bacteria, data on fecal streptococci are used in sanitary evaluations to supplement data on fecal coliforms when a more precise determination of sources of contamination is necessary. Data on fecal streptococci also may provide additional information concerning the recency and probable origin of pollution. The occurrence of fecal streptococci in water indicates fecal contamination by warm-blooded animals because these bacteria are not known to multiply in the environment.

The membrane-filter technique offers the advantages of examining larger, more representative sample volumes than the MPN procedure; being adaptable to field studies; and saving time, labor, supplies, and equipment.

Interferences and Special Considerations

The interferences and special considerations described under total coliforms for the membrane-filter procedure (section 4.C.2.b.2.a) apply in general to this method.

Fecal streptococci strains may be stressed in the water environment and particularly in chlorinated wastewaters. The membrane-filter procedure should be used for these types of samples only after sufficient parallel testing demonstrates equivalency to the alternative plate count and MPN procedures (Geldreich, 1976).

Although fecal streptococci can be used independently, they are usually used in addition to fecal coliforms and other indicators, primarily because the group includes a broad spectrum of strains that have different survival rates and are present in the feces of specific animal groups in varying numbers. Further, two subgroups limit the sanitary significance of fecal streptococci. One subgroup, *S. bovis* and *S. equinus*, is a specific indicator of human or warm-blooded animal pollution but dies off rapidly outside the intestinal tract. The other, *S. faecalis* subsp. *liquefaciens*, represents a significant portion of the fecal streptococcal population in waters of good quality and therefore has limited sanitary significance because of its ubiquity (Geldreich, 1976). If the results from fecal streptococci analyses are followed by species identification, the biochemical tests required are cumbersome and time-consuming.

When both fecal coliforms and fecal streptococci are measured in a water sample, the ratio of fecal coliforms to fecal streptococci may provide information on pollution sources. However, this ratio must be carefully applied according to guidelines provided in Bordner and others (1978) and Geldreich (1976).

Sample Preservation and Storage

Refer to standard plate count method (section 4.c.2.b.1.a).

Analysis

Refer to Bordner and others (1978), Greeson and others (1977), and American Public Health Association and others (1976, p. 944–945). Further identification of types of streptococci present in the sample may be obtained by biochemical characterization. Procedures are described in the three references listed above.

Calculations

Those plates containing 20–100 pink to dark red colonies are selected for counting. The colonies may range in size from barely visible to about 2 mm in diameter. Colonies of other colors are not counted. Count the colonies using a microscope of 10–15× magnification and a fluorescent lamp. Compute the fecal streptococci density according to the formula:

$$\text{Fecal streptococci/100 mL} = \frac{\text{number of fecal streptococci colonies}}{\text{volume (mL) original sample filtered}} \times 100$$

If all counts are zero, below 20, greater than 100, or if colonies are too numerous to count, estimated results are provided, with appropriate explanatory remarks.

Data Reporting and Precision

Report fecal streptococci densities per 100 mL of sample. If there is no result because of confluency or laboratory accident, report as "no result" and specify the reason.

No established precision and accuracy data are available at this time. However, KF Streptococcus and PSE (Pfizer Selective Enterococcus) agar have been reported to be highly efficient in the recovery of fecal streptococci in the analyses of feces, sewage and foods (Kenner and others, 1960; Pavlova and others, 1972). KF yielded a high recovery of fecal streptococci with a low percentage (18.6) of non-fecal streptococci.

4.C.2.b.4.b. Most Probable Number Method

Summary of Method

Decimal dilutions of multiple sample aliquots are inoculated into broth tube media selective for fecal streptococci. The method has two stages: In the presumptive test, a series of azide dextrose broth tubes are inoculated with decimal dilutions of the sample. Growth, as indicated by turbidity after incubation at 35° C for 24–48 hours, constitutes a positive test. The MPN must be carried through the confirmed test for valid results.

In the confirmed test growth from positive presumptive tubes is streaked on esculin-azide agar (PSE or equivalent) plates and incubated at 35° C for 24 hours (Clausen and others, 1977). The presence of brownish-black colonies with brown halos confirms fecal streptococci. The MPN is computed on the basis of the confirmed test results read from the MPN table.

Application

Refer to the membrane-filter method for fecal streptococci (section 4.C.2.b.4.a), paragraph 1 for a discussion on the application of tests for fecal streptococci.

Because the MPN procedure is a tube-dilution method using a nutrient-rich medium, it is less sensitive to toxicity and supports the growth of environmentally-stressed organisms. The method is applicable to the examination of fecal streptococci under stressed conditions. The MPN procedure is also better suited for examining turbid samples, muds, sediments, or sludges because particulates do not interfere visibly with the test. It is applicable to fresh and saline waters.

Interferences and Special Considerations

The MPN procedure is ordinarily limited to a sample volume of 10 mL per tube. The time required for the test may be as long as 72 hours for a confirmed test result. The man-hour requirements to prepare glassware and media and to perform the tests are significant. Relatively large amounts of bench space, incubator space and tube/rack storage space are required. The procedure is not as convenient for field work as the membrane-filter method.

This procedure is more time-consuming, less convenient and less direct than the membrane-filter or standard plate count procedures. It must be used for samples that cannot be examined by the membrane-filter or direct plating techniques because of turbidity, high numbers of background bacteria, metallic compounds, the presence of coagulants, the chlorination of sewage effluents or sample volume limitations of the plating technique.

Sample Preservation and Storage

Refer to standard plate count method (section 4.C.2.b.1.a).

Analysis

Refer to Bordner and others (1978) and American Public Health Association and others (1976, p. 943–944).

Calculations

The MPN value for the fecal streptococci is based on the number of positive confirmed tests from the esculin-azide agar plates using the MPN table. The calculations are the same as those described for the total coliform MPN procedure (section 4.C.2.b.2.b).

Data Reporting and Precision

Report the MPN value as fecal streptococci per 100 mL of original sample.

Refer to total coliform MPN method.

4.C.2.b.4.c. Plate Count Method

Summary of Method

An aliquot or dilution of the sample is pipetted into a sterile petri dish to which melted, tempered PSE agar, equivalent esculine-azide agar, or KF agar is added and thoroughly mixed. The plate is rotated to evenly distribute the bacteria and the agar is allowed to harden. PSE or esculin-azide agar plates are incubated 18–24 hours at 35° C. Brownish-black colonies 1 mm in diameter with brown halos are counted and reported as fecal streptococci. On KF agar plates incubated 48 hours at 35° C, red or pink colonies are counted and reported as fecal streptococci.

Application

The application is the same as the membrane-filter procedure for fecal streptococci (section 4.c.2.b.4.a). The plate count method is recommended as an alternate procedure to the membrane-filter technique when chlorinated sewage effluent and water samples with high turbidity are encountered. PSE agar, the medium of choice, has the following advantages: (1) it requires only 24 hours incubation compared to 48 hours for other media, and (2) it exhibits consistent recovery, regardless of sources.

Interferences and Special Considerations

Only small volumes (1–2 mL) of sample may be analyzed with the plate count technique. This is a disadvantage when the fecal streptococcal density is low and a large volume of sample would be required for an accurate density determination. Consequently, the membrane-filter technique should be used unless the water is so turbid that filtration is impossible.

Sample Preservation and Storage

Refer to standard plate count method (section 4.c.2.b.1.a).

Analysis

Refer to Bordner and others (1977) and American Public Health Association and others (1976, p. 947–948).

Calculations

After the specified incubation period, select those plates with 30–300 fecal streptococcal colonies. Fecal streptococci on PSE agar are brownish-black colonies, about 1 mm in diameter with brown halos. On KF agar, fecal streptococci are pink to red and of various sizes. Count colonies in the plates with the aid of a colony counter (10–15× magnification) equipped with a grid. Compute the fecal streptococci density according to the formula:

$$\text{Fecal streptococci/100 mL} = \frac{\text{number of fecal streptococci colonies}}{\text{volume (mL) original sample plated}} \times 100$$

If all plates have no colonies, fewer than 30 colonies, or greater than 300 colonies an estimated count based on the volume analyzed is provided. Refer to Bordner and others (1978) and American Public Health Association and others (1976).

Data Reporting and Precision

Report counts as fecal streptococci per 100 mL.

No established precision and accuracy data are available at this time.

4.C.2.b.5. *PSEUDOMONAS AERUGINOSA*

Ps. aeruginosa is a rod-shaped species of bacteria that is aerobic, gram-negative, nonspore-forming, and usually pigment-producing and has an oxidative metabolism capable of using a wide variety of organic compounds as carbon and energy sources.

4.C.2.b.5.a. Membrane-Filter Method

Summary of Method

An appropriate volume or dilution of the sample is filtered through the membrane using a vacuum source. The filter retaining the bacteria is placed on a culture medium (M-PA agar) designed to promote the growth of *Ps. aeruginosa* and suppress the growth of most other microorganisms. After incubation at 41.5° C for 48 hours, flat colonies that are brown to greenish-black are counted under low magnification and reported as the number of *Ps. aeruginosa.*

Application

Ps. aeruginosa is an indicator significant to public health in swimming pools; recreational, potable, fresh and marine surface waters; and sewage. This organism uses a wide variety of carbohydrates, fats, proteins and other organic compounds. It is also an opportunistic pathogen, infecting individuals whose natural resistance is lowered. Pseudomonads have been implicated in urinary tract and middle ear infections; diarrhea in newborn infants and debilitated adults; and ulcer, wound, burn and blood system infections in hospital patients.

The membrane-filter technique offers the advantages of examining large representative sample volumes; being adaptable to field studies; and saving time, labor, supplies, and equipment. It is more precise than the MPN procedure and permits the use of colonial characteristics to differentiate *Ps. aeruginosa* from other organisms.

Interferences and Special Considerations

Refer to total coliform membrane filter method (section 4.c.2.b.2.a).

Sample Preservation and Storage

Refer to standard plant count method (section 4.c.2.b.1.a).

Analysis

Refer to Levin and Gabelli (1972) and American Public Health Association and others (1976, p. 980).

Calculations

Membranes containing 20–80 colonies that are flat with light outer rims and brown to greenish-black centers are selected for counting. These colonies are typically 0.8 to 2.2 mm in diameter. They are counted using a microscope of 10–15 × magnification and a fluorescent lamp. Compute the count according to the formula:

$$\textit{Ps. aeruginosa}/100\text{ mL} = \frac{\text{number of } \textit{Ps. aeruginosa} \text{ colonies}}{\text{volume (mL) original sample filtered}} \times 100$$

If all counts are zero, below 20, greater than 80, or if colonies are too numerous to count, estimated results are provided, with appropriate explanatory remarks. Refer to Bordner and others (1978).

Data Reporting and Precision

Report *Ps. aeruginosa* densities per 100 mL of sample. If there is no result because of confluency or laboratory accident, report as "no result" and specify the reason.

No established precision and accuracy data are available at this time. Analysts should be able to duplicate their own counts on the same membrane within 5 percent and the counts of other analysts within 10 percent.

4.C.2.c. PATHOGENIC BACTERIA

4.C.2.c.1. *SALMONELLA*

Salmonella belong to the same enteric group as the coliform bacteria. They are gram-negative, nonspore-forming rods closely resembling coliforms in appearance, but do not generally ferment lactose. These two genera can be isolated from water by similar methods and distinguished from other enterics and from each other by a series of biochemical and serological tests. However, *Salmonella* are much more difficult to isolate directly from water than the indicator organisms because these pathogens are usually present in small numbers and the methods for their detection and identification are much more cumbersome and time-consuming.

The more common diseases caused by *Salmonella* include typhoid and para-typhoid fever in humans and salmonellosis, an acute gastroenteritis with diarrhea and abdominal cramps, in humans and animals. Salmonellae have a wide host range and infect a large number of mammals and birds.

Summary of Method

Because of the low incidence of pathogenic bacteria in most waters, the organisms must be concentrated by immersing gauze swabs at the sampling site or by filtering large volumes of the sample through diatomaceous earth, membrane filters, or cartridge filters. The bacteria-laden swabs, diatomaceous earth plugs, or filters are divided into equal parts for inoculation into selected enrichment media. Selenite and tetrathionate broths are the enrichment media used to grow *Salmonella* and to suppress the growth of other microorganisms. After incubation of the enrichment media at 41.5° C or 35° C growth is streaked on selective agar at 24 hour intervals for up to 5 days. Colonies showing typical *Salmonella* characteristics on the selective media are purified and classified further by biochemical reactions. Commercially-available multitest systems are convenient for this purpose. The cultures that have been identified biochemically are then confirmed serologically.

Application

Routine examination of water and wastewater for pathogenic microorganisms such as *Salmonella* cannot be recommended at this time. No single procedure can be used to isolate and identify these microorganisms. Therefore, optional methods are described. Salmonellae are extremely common in the environment and are probably responsible for most recognized outbreaks of waterborne disease. However, isolation techniques for these ubiquitous organisms require relatively complicated procedures that exceed the capabilities of many water laboratories because they lack adequate methods, trained personnel, facilities, time, and funds.

The method is applicable to recreational, potable, fresh, estuarine and marine waters and wastewaters.

Interferences and Special Considerations

Special preparations for sampling are required because it is necessary to concentrate and analyze large volumes of samples. The sampler must be trained in aseptic techniques and in handling potentially disease-causing materials. The membrane filter is useful to concentrate large sample volumes but may not be applicable to waters that contain significant amounts of suspended solids. Many bacteria other than *Salmonella* may grow in the enrichment media and false positives may grow on the selective plating media, complicating isolation and identification procedures. Cultures for biochemical and serological confirmation must be pure; otherwise false results will be obtained.

The analyst must be thoroughly trained and experienced in isolation, biochemical, and serological techniques for these pathogens. The collector and analyst should be inoculated against typhoid fever. No single enrichment or selective plating medium will give optimum growth of *Salmonella*; therefore, it is necessary to inoculate more than one medium and follow more than one method to successfully detect these microorganisms. The selection of media and incubation temperature are interrelated; more than one temperature may be necessary. The biochemical and serological identification of *Salmonella* involves complex, highly specialized procedures. The procedures provided by the Centers for Disease Control, Atlanta, Georgia, are recommended (U.S. Public Health Service, 1970).

The occurrence of *Salmonella* in water and wastewater is highly variable and the procedures recommended vary in their ability to detect the over 1,200 *Salmonella* serotypes. A negative result by any of these methods does not assure the absence of these genera. These methods are qualitative and do not determine the numbers of pathogens in the original sample.

Sample Preservation and Storage

Refer to standard plate count method (section 4.c.2.b.1.a).

Analysis

Refer to Bordner and others (1978), Greeson and others (1977), and American Public Health Association and others (1976).

Calculations

The procedure is not quantitative.

Data Reporting and Precision

Report the biochemically- and serologically-verified presence of *Salmonella*. If speciation has been done, report species and numbers of species found in the sample.

No precision data are available.

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4.C.3. NATIVE MARINE BACTERIA AND YEASTS

4.C.3.a. BACTERIA

4.C.3.a.1. INTRODUCTION

This section contains methods for sample collection, isolation, and enumeration of bacteria and yeasts in the estuarine and marine environment. Procedures are provided for the microorganisms of primary interest in determining water quality, conducting ecological studies, investigating nutrient cycles, and identifying organisms of public health and economic impact.

4.C.3.a.2. COLLECTION

Since sterility is a necessary requirement for collecting aquatic microorganisms. it is advisable to use sampling devices that can be sterilized. Several different types of microbiological sampling devices are in general use (Sorokin and Kadata, 1969; Colwell and others, 1975). They include bottle samplers, rubber bulb samplers, plastic bag samplers, syringe-type samplers, and sediment samplers.

4.C.3.a.3. ENUMERATION

Quantitative examination of samples can be by (1) direct counts of the organisms, or by (2) cultures of the "viable" organisms, employing dilution or spread plate techniques (Wood, 1967).

a. *Direct counts*: An aliquot of the sample is placed on a slide or counting chamber, and counts are made using high power, phase contrast or fluorescence microscopy.

b. *Viable counts:* Counts are made by either spread plating or by dilution cultures. Dilution blanks are used for both methods. The plate method employs solid media. The plates are incubated 3–5 days at 25° C or a specific temperature for enrichment, selection, and so forth, and the plates containing 10 to 100 colonies per plate are counted. In dilution cultures, the tubes of the greatest dilution containing the required organism are recorded and the total population is calculated.

4.C.3.a.4. DISTRIBUTION, MORPHOLOGY, AND CHARACTERIZATION

4.C.3.a.4.a. Thiobacillus

Thiobacteria belong to a group of microorganisms that generally grow autotrophically on sulfur and sulfur compounds. They actively oxidize hydrogen sulfide in water masses. Some species, however, are capable of growing heterotrophically. Thiobacilli occur in sea water, marine mud, soil, fresh water, acid mine waters, sewage, sulfur springs and in and near sulfur deposits. When contamination from industrial and domestic sewage occurs in water masses, the thiobacilli are active in the "self-purification process" of such waters.

Since various species of thiobacilli have different metabolic characteristics, different energy requirements, and different pH demands, the specific features of water masses under study must be considered so that the proper medium can be chosen. Often it is advisable to inoculate several kinds of media.

4.C.3.a.4.b. Vibrio

Vibrios are ubiquitous in the marine environment and are also found in the alimentary canal of man and animals Two species of Vibrios are of current interest to marine microbiologists: *V. paraheomolyticus* and *V. anguillarum*. *V. parahaemolyticus*, since its initial isolation in 1953, has received considerable attention, being one of the causative agents of food poisoning arising from the ingestion of contaminated seafood.

4.C.3.a.4.c. Clostridium

The predominant bacteria in sea water are gram-negative rods, but sea-bottom deposits, particularly near large land masses, can be a source of spore-forming organisms of the genera *Clostridium*. Clostridia also occur in soil and in the intestinal content of man and animals.

In marine microbiology the most important members of the genera are *C. perfringens, C. tetani* and *C. botulinum*. Available data suggest that *C. perfringens* is more widely spaced than any other pathogenic bacterium, occurring extensively in marine sediment. In recent years most marine studies of *Clostridium botulinum* have been concerned more with type E than with other types of *Clostridium botulinum*.

4.C.3.b. YEASTS

4.C.3.b.1. INTRODUCTION

The bacterial flora of the oceans have been studied extensively. Our knowledge of the marine-occurring yeasts, however, was fairly limited until a group of Russian microbiologists produced a series of reports on the quantitative distribution of yeasts in the Black Sea, the Okhotsk Sea, the Pacific Ocean, and the Arctic (Kriss, 1955; Kriss and Lambina, 1955; Novozkelova, 1955).

Marine yeasts have been defined as all the yeasts and yeast-like organisms that are capable of building up self-perpetuating populations in marine environments. This definition does not exclude yeasts that are also capable of occupying non-marine ecological niches or those that may prefer to do so.

The presence of yeast in the marine environment is extensive, occurring in estuaries and inland waters, in deep sea sediments, in weeds and algae, and in fish and invertebrates. Available data suggest that yeast populations reach their highest densities in inland waters, and their lowest densities in the open sea (Van Uden and Fill, 1968).

An important morphological feature in the classification of yeasts (Lodder and others, 1952) is their characteristic vegetative reproduction, which takes place by budding or by division. Both modes may take place together. The shape of the cells may be round, oval, elongated oval, cylindrical, lemon-shaped, flask-shaped, three-cornered or teardrop-shaped. In aquatic yeast, a pseudomycelium often develops from an elongation of cells that fails to detach. Yeasts cells are approximately $2.5 \times 4 \times 6\ \mu m$.

4.C.3.b.2. ISOLATION AND CULTURE

Probably the most satisfactory method for isolating yeast from water samples is by culturing them on membrane filters (Kriss, 1959). A known volume of the sample is filtered through a boiled cellulose acetate membrane, which is placed on a growth media (Van Uden and Fill, 1968).

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Chapter 5

Chemical and Physical Quality of Water and Sediment

CHAPTER 5—CHEMICAL AND PHYSICAL QUALITY OF WATER AND SEDIMENT

Prepared by
Work Group 5 on Chemical and Physical Quality of Water
March 1982

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National Handbook of Recommended Methods for Water-Data Acquisition

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CHAPTER 5—CHEMICAL AND PHYSICAL QUALITY OF WATER AND SEDIMENT

5.A. INTRODUCTION

5.A.1. SCOPE OF CHAPTER 5

The analytical methods recommended in this chapter have been selected on the basis of their wide applicability and their general acceptability. The chapter describes methods for both the laboratory and the field. These methods encompass certain physical characteristics, such as specific conductance and turbidity; the major inorganic ions and many of the trace elements; phenols, pesticides, oil and grease, and other organic substances; and radioactive constituents. At least one method is given for all constituents. Several reliable and suitable methods are included for some constituents.

The chapter also describes methods for continuous field monitoring of certain significant water-quality characteristics and constituents. These methods encompass those parameters for which dependable sensors are available.

5.A.2. SOURCES OF METHODS

In selecting methods for this chapter, the work group consulted authoritative, widely used references. "Standard Methods for the Examination of Water and Wastewater," published jointly by the American Public Health Association, the American Water Works Association, and the Water Pollution Control Federation (1980), is well known in the field of water analysis. Another reference is the "Annual Book of ASTM Standards, Part 31, Water," revised and published annually by the American Society for Testing and Materials (1981). A third reference used extensively in this chapter is the Environmental Protection Agency's (1979) "Methods for Chemical Analysis of Water and Wastes." Other references are cited when a suitable method for a particular constituent does not appear in one of these widely used manuals.

This chapter briefly outlines each analytical procedure, not the full method, because the information given here is intended only as an aid in selecting a method. For details of each method, the user must consult the appropriate reference. Reliable data can be obtained if the detailed instructions in the reference are carefully followed by a competent analyst.

5.A.3. DEFINITIONS

So that everyone understands the terms used in this chapter, here are their definitions:

Atmospheric deposition.—The sum of wet and dry deposition.

Brackish water.—Water having a dissolved material content in the range of 1,000 to 30,000 mg/L (milligrams per liter), but not necessarily corresponding to ocean water with respect to ionic ratios.

Brine.—Water having more than 30,000 mg/L dissolved material, but not necessarily corresponding to ocean water with respect to ionic ratios.

Dissolved material.—All material that passes through a filter having a pore size of 0.45 m.

Dry deposition.—The surface flux of all quantities, including gases, small particles, and those larger particles that fall under the influence of gravity.

Fresh water.—Water having less than 1,000 mg/L dissolved material.

Ocean water.—Water having between 20,000 and 40,000 mg/L dissolved material whose ionic ratios correspond closely to those specified in "Standard Specification for Substitute Ocean Water," ASTM Method D 1141-75 (1981).

Particulate material.—Material that is retained by a filter having a pore size of 0.45 m.

Precipitation.—All forms of water particles, liquid or solid, that fall from the atmosphere and reach the ground.

Suspended material.—Same as particulate material.

Suspended residue.—The material retained by a filter. The characteristics of the filter are specified in the method.

Total material.—The quantity of a given material present in an unfiltered water sample regardless of the form or nature of the material's occurrence.

Total recoverable material.—The total quantity of all dissolved forms of a given material plus that which is brought into solution and into an analytically determinable form, usually by means of an acid-digestion pretreatment or an acid-oxidation-digestion pretreatment of the sample. The exact conditions of the digestion pretreatment must be specified. (Includes mainly dissolved material plus that material which is sorbed on particulate matter. Also includes all or a portion of that which is present as a constituent part of the particulate matter.)

Wet deposition.—Same as precipitation.

5.A.4. RECOMMENDED METHODS

Recommended procedures for acquiring data on the chemical and physical quality of water are described in sections 5.C. through 5.F. of this chapter. The descriptions are organized by the particular constituents or characteristics being measured (physical, inorganic, radioactive). Each description consists of at least three elements: Sample, Analysis, and Reporting.

The *sample* element includes sampling precautions that may be required, type of sample container to be used, preliminary treatment required, and specific steps that must be taken during both sampling and storage to maintain the integrity of the sample. This part also describes the types of samples for which the recommended method can be used.

For details about the factors that must be considered in designing and operating a satisfactory sampling program for evaluating the physical and chemical quality of surface water, ground water, and atmospheric deposition, see section 5.B. of this chapter.

The *analysis* element gives information on the recommended analytical method, the range of concentration within which a method is applicable, the precision that can be expected, and the references containing the detailed procedure.

The *reporting* element indicates the preferred form and units for reporting the parameter or constituent measured and the significant figures commensurate with the accuracy and precision of the method.

5.A.4.a. APPLICABILITY OF METHODS

The methods included in sections 5.C. through 5.F. of this chapter are applicable to the analysis of fresh water samples and to other types of samples as indicated for the individual constituents. Those organic methods listed as having "Applicability. . .General" are probably useful for all fresh waters and most industrial waters.

A method's upper limit of determinable concentration can usually be extended by diluting the sample before analysis; however, the extent of dilution must be a matter of the analyst's judgment. Factors that must be considered include the chemical characteristics of the constituent(s) being sought, the concentrations of other solutes, possible interferences, and the general capability of the method.

Most of the atmospheric deposition methods use flame atomic absorption spectrophotometry (FAAS). With some samples, the concentration of a constituent will be below the FAAS method's lower limit of detection. In these cases, the analyst should consider methods with lower detection limits, such as graphite furnace atomic absorption spectrophotometry (GFAAS).

Some of the fresh water methods are applicable to the analysis of brackish waters and brines, some are applicable with modification, and some are not applicable. Unless a method is specifically designated as being suitable, the analyst must determine the precision and accuracy of the method to be used for analyzing saline waters.

5.A.4.b. UNITS AND SIGNIFICANT FIGURES

The form and units for reporting values of physical and chemical water-quality parameters and constituents are specified for all methods. For data on concentration, the reporting units are mg/L (milligrams per liter) and g/L (micrograms per liter) rather than ppm (parts per million) and ppb (parts per billion). For data on sediment, the reporting units are g/g (micrograms per gram) or mg/kg (milligrams per kilogram). This practice conforms to present analytical techniques and to current procedures in most water analysis laboratories.

The proper number of significant figures for reporting analytical measurements are specified to indicate the confidence level that the data user may expect. In any reported data, an uncertainty of one unit in the last significant figure may be expected. The precision specified for any given determination indicates the probable repeatability of the measurement.

5.A.5 CONSTITUENTS AND PARAMETERS DESCRIBED

5.A.5.a. PHYSICAL CHARACTERISTICS

Methods are included for determining the most commonly analyzed physical characteristics of water, including color, specific conductance, turbidity, and residue.

5.A.5.b. INORGANIC CONSTITUENTS

Methods are included for determining commonly analyzed inorganic constituents. The recommended methods are mostly intended for acquiring data on natural waters. If the method can be used to analyze other types of samples, such as wastewaters or atmospheric deposition, that is indicated in the description of the method. Information on the precision and range of the method is provided when available. Some methods contain no precision data, but are included because they are considered to be the best methods currently at hand.

Two publications by Federal agencies were used in selecting inorganic methods. One of these publications is "Methods for Determination of Inorganic Substances in Water and Fluvial Sediments," by M. W. Skougstad and others (1979). The second publication is the Environmental Protection Agency's (1979) "Methods for Chemical Analysis of Water and Wastes."

5.A.5.c. ORGANIC CONSTITUENTS

The methods included for determining organic constituents are not comprehensive; however, methods are given (where reliable, proven methods exist) for most compounds of current concern. Methods for determining other constituents will be added as the need arises and as acceptable routine methods become available.

Organic methods have been selected from the "Annual Book of ASTM Standards," by the American Society for Testing and Materials (1981); guidelines published by the Environmental Protection Agency in the *Federal Register* (1979); and other generally accepted references whenever possible. However, the number of constituents that can be determined by these methods is limited, and other publications are used frequently. The user of any method listed should verify the recovery and precision limits in his laboratory.

Multiresidue methods are included for most pesticides, explosives, and other organic compounds whenever possible. This approach is efficient, but it can lead to serious qualitative and quantitative errors if the interferences noted in each method are not considered.

Some methods listed in section 5.E. contain no precision data, but are included because they are considered to be the best methods currently available. The provisional Environmental Protection Agency priority pollutant analyses cited in the *Federal Register* fall within this category.

Sampling can be a considerable source of error in low-level organic analysis. An excellent discussion on sampling for pesticides is presented in "Guidelines on Sampling and Statistical Methodologies for Ambient Pesticide Monitoring," by the Monitoring Panel of the Federal Working Group on Pest Management (1974). The Panel's report covers sampling, preservation, and storage in a section just before the organic summaries.

A very good discussion of methods for pesticides is presented in "Guidelines on Analytical Methodology for Pesticide Residue Monitoring," also published by the Federal Working Group on Pest Management (1975), and a good reference on pesticides is "Farm Chemicals Handbook," published annually by Meister Publishing Company (1980). Two excellent books on trace organic analyses are "Trace Organic Analysis: A New Frontier in Analytical Chemistry" (Hertz and Chester, 1979) and "Identificaton and Analyses of Organic Pollutants in Water" (Keith, 1976).

5.A.5.d. RADIOACTIVE CONSTITUENTS

Several methods for radiochemical analyses, including methods for determining most important radionuclides, are provided.

Whenever possible, the radiochemical methods have been selected from the "Annual Book of ASTM Standards," by the American Society for Testing and Materials (1981) and "Methods for Determination of Radioactive Substances in Water and Fluvial Sediments" (Thatcher and Janzer, 1977). Unfortunately, the number of radiochemical procedures from such references is limited so other publications are used also. In some cases the methods cited have not been widely used or subjected to interlaboratory comparison. Such methods are labeled tentative and are included because they offer somewhat better sensitivity or are the only available procedures. If a tentative method is to be used, the user should verify the method by radioactive tracer techniques or by comparison with any available alternative methods.

Procedures for determining gross-alpha, -beta, and -gamma radiation in water are included. Their inclusion should not be interpreted as a recommendation for gross measurements instead of individual radionuclide determinations. Gross-counting data should be used and intepreted with caution and their inherent limitations should be recognized. Gross counting may be useful to screen which samples should be analyzed in greater detail as to their radionuclide composition and concentration. Gross counting also may help detect trends in samples collected at the same location over time.

Gamma spectrometry is included as a method and can be used to directly determine gamma-emitting radionuclides without prior chemical separation. High-resolution gamma spectrometry with a Ge(Li) detector is a powerful method, but does not offer the sensitivity of other counting methods when using reasonable counting times. For very low levels of radioactivity, a chemical separation from large-volume samples followed by beta or gamma counting with a NaI(Tl) detector is somewhat more sensitive.

The radiochemical procedures in this chapter are for total dissolved material unless otherwise noted. Samples should be acidified as soon as possible after collection by adding 2 percent concentrated HCl or HNO_3 by volume. Acidifying a sample is particularly important when the sample must be stored because radionuclides may settle on the container walls otherwise. Acidifying unfiltered water samples may cause radioactivity to leach from suspended material and, thus, may give somewhat higher results than do filtered samples. If unfiltered samples are not acidified because such a leaching effect is undesirable, the problem of radionuclide loss on container walls should be considered. If the distribution of radionuclides between filterable and non-filterable fractions is to be determined, the sample should be filtered in the field when it is collected and the filtrate should be acidified with concentrated HCl or HNO_3. The filtrate and filters then can be analyzed separately.

In the abstracts for radiochemical methods (section 5.F.), specific information from the published procedure is cited whenever possible. In some cases, the specific information needed is not available, so the reviewers have inferred it from statements in the paper or from estimates using tabulated data. A blank space indicates that no direct or indirect information is available from which the reviewers could draw conclusions. The range of a method is not given since it extends from the detection limit to some activity at which the instrumental response deviates from linearity, generally due to coincidence losses or to a level artificially and subjectively imposed due to concern for contamination, radiation levels, and other factors.

In the analytical methods in section 5.F., three of the categories of information reported are treated as follows:

Detection Limit: When not stated in the published procedure, the detection limit of a species is that concentration yielding a count rate at which twice the counting error (¢) of the sample is equal to a total error of 100 percent.

Precision: In the absence of specific information in the published procedure, a precision of 20 percent at the 95 percent confidence level has been selected, and the corresponding activity concentration at which the counting error is 20 percent at the 95 percent confidence level has been computed using the assumptions given for the Detection Limit.

Significant Figures: The number of significant figures used for reporting data relates directly to the precision of the analysis. In radiometric analyses, the precision varies widely and depends primarily on the total number of counts, which in turn is a function of the sample size, the concentration of activity in the sample, and the variables listed for the Detection Limit. Therefore, the statement given for significant figures is: Retain the number of significant figures justified by twice the relative standard deviation of the determination.

5.A.6. INSTRUMENTATION

The calibration of all instruments, such as spectrophotometers, pH meters, and conductivity meters, should be checked against standards before and after use each day and more frequently if large numbers of samples are being analyzed. Additional guidelines on calibration and standardization are given in section 5.G. of this chapter. Since some models or brands of instruments are more sensitive than others, considering the method of analysis and consulting other analysts is advisable before purchasing new equipment.

5.A.7. FIELD INSTRUMENTATION TECHNIQUES

The section on field instrumentation techniques (5.G.) is divided into two specific field applications, automatic water-quality monitors and oceanographic monitoring techniques. A future section on portable instruments is being developed.

Electrochemical and electrophysical types of automatic water-quality monitors are the most economical means of obtaining continuous or time-series reporting of certain water-quality characteristics. Because of the widespread use of automatic monitors, section 5.G. gives criteria for operating the instruments so that the data generated will meet acceptable levels of accuracy. The system-performance requirements outlined in section 5.G., however, are not engineering specifications. The reader should recognize that to meet specific needs of operation, enforcement, or management, data sometimes must be collected under more rigorous criteria of accuracy and transient response than those prescribed here.

5.A.8. QUALITY CONTROL

The continued output of high-quality, reliable water-quality data depends not only on the use of acceptable analytical methods by competent and conscientious analysts, but also on some prescribed program of regular quality control. A suggested minimum program of quality control for laboratories performing routine and research water analyses is presented in section 5.H. Section 5.H. also discusses the theory of quality control for water analysis laboratories and the philosophy of quality-control programs in laboratory operations.

5.A.9. REVISIONS AND UPDATES

All recommendations published in this chapter are continuously reviewed. Deletions, revisions and updates will be issued regularly as new methods which are more sensitive, more precise, or faster become available. The Work Group intends to cite readily available published methods and related material. In the absence of any suitable and acceptable published method or material, the Work Group itself may prepare recommended methods for this chapter. Analytical methods that the work group recommends for publication include documented statistical data describing the precision and sensitivity of the method. If these data are not immediately available, the method either will be updated to include such data within 2 years of first approval, be reapproved as published, or be withdrawn as a recommended method.

5.A.10. REFERENCES CITED

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_____1979b, Guidelines establishing test procedures for the analysis of pollutants: *Federal Register*, v. 44, no. 233, p. 69464–69575.

5.B. SAMPLING

5.B.1. REPRESENTATIVE SAMPLES

Sampling is the process of collecting a representative portion of the environment to learn about the whole environment. A representative sample is one that typifies the rest of the environment. To collect representative samples, one must standardize sampling bias related to site selection; sampling frequency; sample collection; sampling devices; and sample handling, preservation, and identification.

Collecting a representative sample and maintaining its integrity until it is analyzed is important because the validity of each measurement begins with the sample. Regardless of scrutiny and quality control applied during laboratory analyses, reported data are no better than the confidence that can be placed in the representativeness of the samples (Feltz and Culbertson, 1972). This section recommends techniques for obtaining representative samples of atmospheric deposition, surface water, water-sediment mixtures, and bottom material. Sampling of wells and springs is discussed in chapter 2 of this handbook.

5.B.2. SITE SELECTION

5.B.2.a. ATMOSPHERIC DEPOSITION

Several factors should be considered in selecting a sampling site for atmospheric deposition: study objectives, accessibility, physical characteristics, sources of contamination, and personnel and equipment available for conducting a study.

5.B.2.a.1. OBJECTIVES

Most studies of atmospheric deposition are designed to quantify the temporal and spatial variation of the quality of atmospheric deposition as it relates to various human activities and natural events.

In studies designed to assess the quality of regional deposition or to establish long-term trends, the most important factor in site selection is to avoid or minimize local sources of contamination. However, if the study objective is to determine the relationship between a specific source or sources of contamination and the quality of deposition, site selection becomes more complex. This objective requires that dispersion modeling be conducted to optimize site locations (Haszpra, 1980; Jones and others, 1979; Karol and Mijatch, 1972).

5.B.2.a.2. ACCESSIBILITY

Accessibility to the sampling site is a requirement that is often directly related to sampling costs. Roadways, trails, and helipads that are usable and negotiable with conventional equipment are essential to meet site visitation schedules.

5.B.2.a.3. PHYSICAL CHARACTERISTICS

If a region is typified by a certain type of land use, the sampling site should reflect this use. For example, if agriculture is the dominant regional land use, then locating a sampling site within, adjacent to, or downwind of that activity is acceptable. Conversely, if wilderness is the dominant regional land use, all sources of manmade contamination should be avoided when locating the site.

5.B.2.a.4. MINIMIZING UNDESIRABLE EFFECTS

Where regional quality of atmospheric deposition is the study objective, the following actions are suggested to minimize undesirable effects:

1. Avoid sources of contamination from air, ground, or water traffic.

2. Avoid surface storage of agricultural products, fuels, or other foreign materials.

3. Avoid continuous sources of contamination within 50 km upwind of the site and 30 km in other directions.

4. Install samplers over undisturbed land.

5.B.2.a.5. PERSONNEL AND EQUIPMENT

Properly trained personnel with sufficient time to collect good samples and properly conduct field activities are essential to a meaningful study.

Before sampling begins, all possible preparations should be made from a centrally located field office where a workshop is available for repairing and adjusting sampling equipment and vehicles.

5.B.2.b. SURFACE WATER

Many factors are involved in selecting a sampling site for surface water: study objectives; accessibility; flow, mixing, and other physical characteristics of the water body; point and diffuse sources of contamination; and personnel and equipment available to conduct the study. In the case of dissolved constituents, dispersion depends on the vertical and lateral mixing within the cross section of a body of water. The hydrologist collecting samples, therefore, not only must know the mixing characteristics of streams and lakes, but also must understand the role of fluvial-sediment transport, deposition, and chemical sorption. Chapter 3 discusses sediment transport and sampling procedures in-depth.

5.B.2.b.1. OBJECTIVES

Different agencies have different objectives for assessing the water quality of streams, lakes, and reservoirs. Most monitoring studies of streams and lakes aim to assess the effects of overland runoff, ground-water inflow, or waste disposal into waterways. Therefore, such studies can usually be tied to the physiographic features of the area under consideration., In most cases, the quality of the water flowing into a lake or past a particular point along a stream can be related directly to inputs within the drainage basin, including the entire drainage area upstream of a selected point.

Whether the basic objective for the program is reconnaissance, evaluating long-term trends, or solving specific problems, the first step in a study is to define the hydrologic boundaries and then establish the sampling site locations above, within, or below these boundaries.

5.B.2.b.2. ACCESSIBILITY

Accessibility to any sampling site is a requirement that is often directly related to sampling costs. Bridges are the first choice for locating a sampling station on a stream because bridges provide ready access and also permit the hydrologist to sample any point across the stream. A boat may be needed to sample locations on lakes and reservoirs, as well as those on larger rivers. Frequently, however, a boat will take longer to cross a water body and will hinder manipulation of the sampling equipment.

5.B.2.b.3. PHYSICAL CHARACTERISTICS

The ideal sampling site for a stream is a cross section that would yield the same concentrations of each constituent at all points along the cross section and at all sampling times (Kittrell, 1969). This situation never persists in nature, which reinforces the need for careful site selection in order to ensure, as nearly as possible, that samples are taken where uniform flow and good mixing conditions exist.

The availability of streamflow and sediment discharge records can be an important consideration in choosing sampling sites on streams. Adequate streamflow data are essential for estimating the total loads carried by

the stream. If a gaging station is not conveniently located on a selected stream, the hydrologist should explore the possibility of obtaining streamflow data by direct or indirect methods.

5.B.2.b.4. SOURCES OF CONTAMINATION

The hydrologist must know the locations of point and nonpoint sources of contaminants from industrial complexes, sewage outfalls, and agricultural areas to select sampling sites that will yield the data needed to meet program objectives. Obtaining a representative sample from a main stream immediately below a source of chemical inflow or a tributary is difficult because the inflow frequently follows a stream bank with little lateral mixing for some distance. Sampling alternatives to overcome this situation are: (1) select a site above the chemical source or tributary, (2) move the site far enough downstream to allow for adequate mixing, or (3) collect integrated samples in a cross section.

5.B.2.b.5. PERSONNEL AND EQUIPMENT

The people who collect the samples will visit the stream or lake under investigation more than anyone else involved in a study. Experienced, observant, and conscientious field personnel are essential to any monitoring study. Anyone who wants to be proficient in planning and conducting monitoring programs will be well-advised to spend a reasonable apprenticeship collecting samples.

Before sampling begins, all possible preparations should be made from a centrally located field office where a workshop is available for repairing or adjusting sampling equipment, boats, outboard motors, and vehicles.

5.B.3. SAMPLING FREQUENCY

5.B.3.a. ATMOSPHERIC DEPOSITION

The frequency of sampling for a study of atmospheric deposition is largely determined by the objectives of the study. Source-related studies often necessitate short-term event sampling, whereas long-term trends and averages can be determined by weekly, biweekly, monthly, or seasonal sampling. In the United States, participants in the National Atmospheric Deposition Program (NADP) are collecting and analyzing wet deposition samples weekly and are collecting dry deposition samples bimonthly (Huston and others, 1976).

5.B.3.b. SURFACE WATER

For reconnaissance studies (defined here as short-term, one-time evaluations), both the bottom material and the overlying water should be sampled at each site. For monitoring, which consists of repetitive, continuing measurements to define variations and trends at a given location, water samples should be collected at least monthly and during droughts and floods. Samples of bottom material should be collected from fresh deposits at least yearly, and preferably during both spring and fall seasons. Additional sampling related to other flow conditions may be desirable.

The variability in available water-quality data should be evaluated before deciding on the number and collection frequency of samples required to maintain an effective monitoring program.

5.B.4. SAMPLE COLLECTION

5.B.4.a. ATMOSPHERIC DEPOSITION

Samples of atmospheric deposition are usually collected in either cylindrical plastic or glass containers (Galloway and Likens, 1976). Plastic containers are used for inorganic analyses and glass containers are used for organic constituents. Sample containers may be continually exposed to collect an integrated wet and dry sample

(bulk collectors) or may be preferentially exposed to allow the wet and dry components to separate (Bogen and others, 1980; de Pena and others, 1980).

5.B.4.b. SURFACE WATER

5.B.4.b.1. STREAMS AND RIVERS

Ways to collect samples from streams and rivers vary from the simplest of hand sampling procedures at a single point to the more sophisticated multipoint sampling techniques known as the equal-width-increment (EWI) method or the equal-discharge-increment (EDI) method (chapter 3).

Generally, the number and types of samples to be taken depend on the river's width, depth, and discharge and on the suspended sediment the river transports. The more individual points that are sampled, the more the composite sample will represent the water.

Water is often sampled by filling a container held just beneath the surface of the water (a dip or grab sample). Published data and discussions with investigators reveal that a high percentage of samples have been collected this way. Concentrations of constituents measured in grab samples are limited to the concentrations near the surface of the water and may represent only a fraction of the total concentration that is distributed throughout the water column and in the cross section. Therefore, one should get samples that represent both dissolved and suspended constituents and both vertical and horizontal distributions.

Many organic compounds are only slightly water soluble and tend to be adsorbed by particulate matter. Nitrogen, phosphorus, and the heavy metals may also be transported by particulates (Feltz, 1980). Collect samples with a representative amount of suspended material and do not transfer water from the sampling container without transferring a proportionate amount of the suspended material.

Using a weighted holder that allows a sample bottle to be lowered to any desired depth, opened for filling, closed, and returned to the surface, improves on a dip or grab sample. If an open bottle is lowered to the bottom and raised to the surface at a uniform rate so that the bottle is just filled on reaching the surface, the resulting sample will roughly approach what is known as a depth-integrated sample. However, the open-mouth weighted-bottle sampler does not collect a truly representative sample in a flowing stream if many particles coarser than about 0.062 mm are carried in suspension. Another disadvantage in using an open-mouth weighted-bottle sampler in flowing streams is that knowing when the bottle is filled is impossible. Thus, whether the sample truly represents the distribution of both dissolved and suspended material in the water column that has been sampled is uncertain.

Depth integration is used to collect a water-sediment sample that is weighted according to velocity at each increment of depth. This means that the water-sediment mixture must enter the sample bottle at the same velocity as the flow passing the intake of the sampler. If a depth-integrating sampler is lowered from the surface to the bed and back at the same rate, each increment of flow in that vertical is sampled proportionately to the velocity.

All stream samples should be collected by depth-integrating methods using either a hand-held or a cable-and-reel suspended sampler whenever practical. The only exception might be in shallow streams where the depth is insufficient for true depth integration. In such cases, dip samples collected at one or more verticals across the stream are appropriate; however, the sample container should be held carefully just beneath the water surface to avoid disturbing the streambed.

One method of collecting depth-integrated samples currently accepted by hydrologists is the EWI technique. With this technique, depth-integrating suspended-sediment samplers are used to collect a velocity-weighted sample. Samples are taken at several equally spaced verticals in the cross section. The number of verticals depends on the width of the stream. The transit rate of the sampler, which is how fast the sampler moves from the surface to the bed and back to the surface, is the same in all verticals. The samples collected in each vertical are then composited into a single sample representative of the entire flow in the cross section. In this manner, the composite sample of the water-sediment mixture flowing in the cross section is both velocity- and discharge-weighted.

The person actually collecting the samples usually decides the number of verticals to be sampled. For small streams, a depth-integrated sample taken at the centroid of flow is usually adequate. Larger streams require

sampling of several verticals at equal width increments or at centroids of equal discharge. The number of verticals required for the EWI method depends on the streamflow and sediment characteristics at the time of sampling as well as on the desired accuracy of sampling. Generally, 10 to 20 verticals will give an accurate discharge-weighted concentration by the EWI method.

The streamflow distribution in the cross section must be known before sampling verticals can be selected for the equal-discharge-increment (EDI) method. To make an EDI measurement when prior streamflow data are not available, one must first determine the total discharge across the stream channel (see chapter 1) and then subdivide the cross section according to incremental discharges.

Obviously, the multipoint sampling techniques can become very time-consuming and, consequently, expensive. An alternate method often used involves sampling at the quarter points or other equal intervals across the width of the stream. Composite samples obtained from individual samples collected at the quarter points can be fairly representative, providing the stream cross section is properly located.

Regardless of the techniques used to collect samples in a cross section of a stream, the compositing and subsampling process should be the same; that is, homogenizing all the individual samples from the cross section and then splitting the water-sediment mixture into the number of subsamples required to perform the analyses of interest. A churn splitter is a practical means for splitting composited samples into representative subsamples, as described in appendix 3.L.2. of chapter 3 of this handbook.

One should consider the advantages and disadvantages of the several sampling techniques. The EDI method has these advantages: variable transit rates may be used, fewer verticals need to be sampled, and cross-section discharge information is obtained. The primary disadvantage of the method is that the streamflow distribution in the cross section must be known or measured each time before sampling.

The EWI method has these advantages: discharge measurements are not needed, the technique is learned easily, and the technique is preferred for streams with shifting beds. The main disadvantages are that the procedure is time consuming for large streams and does not provide cross-section discharge information. Furthermore, the EWI method requires sampling at equally spaced verticals and use of identical transit rates within each vertical.

5.B.4.b.2. LAKES AND RESERVOIRS

The number of sampling sites on a lake or reservoir will vary with the size and shape of the basin. In shallow lakes having a circular basin, a single site in the deepest part of the lake may be sufficient to describe the distribution and abundance of the constituents in solution. In natural lakes, the deepest point is often near the center of the lake, and, in reservoirs, the deepest area is near the dam. In lakes with irregular shapes and with several arms and bays that are protected from the wind, additional sampling sites may be needed to define the water quality adequately (Britton and others, 1975).

Many lake measurements are now made *in situ* using sensors and automatic readout or recording devices. Single and multiparameter instruments are available for measuring temperature, depth, pH, oxidation-reduction potential (ORP), specific conductance, dissolved oxygen, some cations and anions, and light penetration.

Samples of lake water may be collected at any desired depth with a Kemmerer-type sampler and brought to the surface for filtering or other pre-analysis treatment. Nonuniform vertical mixing of chemical constituents often occurs because of wind and temperature changes, the shape of the lake basin, biological activity, and other factors. Therefore, water samples should be collected from several points in the water column and from the surface to the bed.

5.B.4.c. BOTTOM MATERIAL

Samples of bottom material are usually collected at the same verticals at which samples of water are collected. A bottom-material sample may consist of a single scoop or core or may be a composite of several individual samples in the cross section.

Chemical constituents associated with bottom material may reflect an integration of chemical and biological processes. Bottom samples reflect the historical input to streams, lakes, and estuaries with respect to time, application of chemicals, and land use. Because the heavier fluvial materials settle to the bottom during

low flow in streams or calm conditions in lakes and add to solids that have accumulated on streambeds or in lake bottoms, periodic sampling of the water overlying these deposits might not reveal the presence of sorbed constituents; however, nitrogen, phosphorus, heavy metals, and organic compounds may be found in the bottom material, which acts as a sink and reservoir (Feltz, 1980).

The loss of low-density deposits must be minimized during any sampling process, which requires a bottom-material sampler that can collect and retain the "fines," which often contain the highest concentration of sorbed constituents.

5.B.5. SAMPLING DEVICES

5.B.5.a. ATMOSPHERIC DEPOSITION

Glass or plastic containers located 1 to 2 m above the ground are recommended for collecting bulk deposition samples. To minimize evaporative loss, use funnel collectors fitted with U-tubes. In areas where rainfall is light or where snowfall is collected, large containers are needed to collect an amount sufficient for analysis. Bulk deposition devices are simple to use, do not usually require electricity, and are adequate for many studies.

Glass or plastic containers located 1 to 2 m above the ground are also used for collecting wet and dry deposition samples. To overcome evaporative loss and to minimize wet-sample contamination, sampling equipment has been designed to effectively seal either the wet or dry sampling bucket when the other is being used. The most commonly used device is the Aero-Chem Metrics collector.

Designed originally by the Atomic Energy Commission to collect atmospheric radionuclides, this device consists of two sampling buckets and a movable cover (Volchok and Graveson, 1976). Under dry conditions, the dry bucket is exposed while the wet bucket is sealed by the cover. During rain or snow, a heated sensor activated by precipitation exposes the wet bucket and covers the dry bucket. Following the wet event, the dry bucket is exposed again. These collectors require either direct or alternating electrical current to operate. The size of the sample bucket or bottle will depend on the volume of sample required for analysis and the amount of deposition expected over the sampling period. To ensure comparability of data, the Aero-Chem Metrics device is used in most existing networks.

5.B.5.b. SURFACE WATER

Several depth-integrating samplers that have been specifically designed and thoroughly tested are available and suitable for collecting representative samples (see chapter 3).

In shallow streams and wetlands that can be waded, the US DH-48 suspended-sediment sampler can be used successfully. The US DH-59 suspended-sediment sampler was designed to be suspended by a hand-held rope in streams too deep to be waded. Both of these samplers are simple and use a container that is easily inserted into position and is held firmly by a spring. The US D-49 suspended-sediment sampler has also been used for many years to collect depth-integrated samples in large streams and rivers. It accommodates a 473-mL bottle and has a choice of nozzles (3.2-mm, 4.8-mm, and 6.4-mm in diameter) with which the rate of inflow of the water-sediment mixture can be controlled. The D-49 sampler, which weighs about 27 kg, is suspended on a cable and operated with a reel attached to a boom. The US D-74 sampler is a modified D-49 sampler that accommodates either a 473-mL or 946-mL bottle. The US D-74 AL sampler is also a modified D-49 sampler, but is cast from aluminum and weighs approximately 13.6 kg. This sampler can be used with a handline in slower moving streams.

For sampling under ice, one may use the DH-75P sampler, which holds a 500-mL plastic bottle; the DH-75Q sampler, which accommodates a 1,000-mL bottle; or the DH-75H sampler, which holds a 2,000-mL container. The US DH-76 sampler is a modified DH-59 sampler that accommodates a 946-mL bottle and is available in the regular or trace-metal series. A 3-liter sampler, the US D-77, designed to overcome problems encountered during freezing conditions, has been field tested and is now available. A newer sampler based on the D-77 design is being field tested. This sampler, designated DH-80, will accommodate either a 473-mL or 946-mL Mason jar. The intake nozzle with air exhaust ports is a single-piece head molded from polypropylene. Contaminated or frozen heads can be replaced quickly and easily.

The open-mouth weighted bottle sampler, which is available in many sizes, is acceptable for lakes and slow moving streams (less than 0.5 m/s) having little suspended sediment. The sample bottle is inserted into a weighted holder that is suspended by a rope. The P–61 sampler, which can be opened and closed electrically at any given depth, is also quite useful in sluggish streams and lakes. It may be held open and used as a depth-integrating sampler to overcome the 5.5-m depth sampling limit of other models. Kemmerer (Foerst) or van Dorn samplers may be used to obtain point samples at any desired depth.

Continuous and automatic samplers for rivers and streams have been designed to collect water samples at a rate proportional to either streamflow or time.

Sampling treated waters is best accomplished at the treatment plant. Samples can be collected using a pipeline drip device or they can be collected at regular intervals (hourly, every shift, or other interval) by one of the plant operators. These samples usually have a small volume, and thus are composited for analysis.

5.B.5.c. BOTTOM MATERIAL

Sampling bottom deposits is more difficult than sampling the water column in streams or lakes, primarily because of the varying firmness of the deposits. The US BMH–60 sampler is a 13.6-kg impact-type sampler designed primarily for sand-bed streams. However, it works equally well for firm and partially consolidated bottom material. One person can collect samples with this sampler under most conditions. The bucket takes a bottom material sample that is approximately 56 by 127 by 43 mm. This sampler can be used in about 75 percent of the river miles and in many small lakes and reservoirs across the United States.

For small lakes and farm ponds, using boats equipped with heavy sampling devices is impractical in most cases. An alternative is to use a hand sampler such as the US BMH–53 or one of the clamshell types (Culbertson and others, 1972). The hydrologist wades out from shore as far as possible, being cautious not to disturb the material near the point of collection, and carefully collects a sample of the uppermost layers of the bottom deposits.

In large lakes or estuaries, the bottom material may be sampled with any one of the various types of dredges, including the Petersen and Shipek designs. The Petersen dredge can collect samples from fairly hard bottoms such as sand, gravel, or marl. The Shipek dredge is a spring-loaded sampler for use on all types of bottoms, but is especially useful in collecting and retaining the "fines" obtained from deposits of sand, silt, or clay.

Some investigators prefer to collect core samples when they are interested primarily in obtaining historical data and if the bed is sufficiently compacted to be sampled with a coring device. Although the value of core samples should not be minimized, sampling fresh deposits is of prime importance in a continuous evaluation of the occurrence, distribution, and movement of chemical constituents.

Most core samplers lack positive seals to hold a core or moist sample in place as the sampler is withdrawn from the water. A controlled-depth volumetric bottom sampler described by Jackson (1970), and a core sampler for *in situ* freezing of benthic deposits designed by Gleason and Ohlmacher (1965), are examples of efforts to overcome the drawbacks of the common core sampler and to provide the investigator with reliable equipment.

Little progress has been made in developing equipment to collect representative samples at the liquid-solid interface because sampling without disturbing the interface is difficult. The Gleason core sampler offers an advantage in sampling this interface because it can be used as a point sampler. The hydrosol sampler designed by Lawrence may be used in some sampling situations (Feltz and Culbertson, 1972).

5.B.6. SAMPLE HANDLING AND PRESERVATION

5.B.6.a. CONTAINERS

Thoroughly cleansed plastic or glass bottles fitted with screw caps may be used for water samples collected with depth-integrating samplers or atmospheric deposition samplers. Plastic containers are generally preferred for inorganic samples and glass containers are preferred for organic samples. Bottom materials can be placed in clean, wide-mouth plastic or glass bottles with Teflon-lined caps, depending on whether inorganic or organic analyses will be performed. Plastic bottles must not be used for samples of organics and certain trace metals because plastic introduces interferences and has sorption characteristics. Most water samples for organic

analyses must remain in the collection container until analysis is begun because the laboratory procedure often includes a method for rinsing the sample container with the extraction solvent. A sufficient volume of sample should be collected to satisfy the requirements of each analysis and to analyze duplicate and fortified samples. Glass sample bottles should be shipped in expanded polystyrene molds so that they do not break.

5.B.6.b. PRESERVATION

Deteriorated samples negate all the efforts and cost expended in obtaining good samples. In general, the shorter the elapsed time between collection and analysis, the more reliable the analytical results. For certain chemical constituents and physical values, immediate analysis in the field is required to obtain reliable results because the composition of the sample almost certainly will change before it arrives at the laboratory.

5.B.6.b.1. ATMOSPHERIC DEPOSITION

Preferably, measurements of the pH and conductivity of precipitation should be made in the field and also immediately when the samples arrive in the laboratory. Following pH and conductivity measurements in the laboratory, the remainder of the sample should be filtered through a 0.45 m polycarbonate or Teflon membrane directly into the sample storage bottle. In some cases, the filters may be stored and retrieved for subsequent analysis of the residue. Deionized water is added to leach dry samples, which also are filtered (Stensland and others, 1980). Samples should be stored at 4°C in the dark until analyses are performed. No preservatives should be added. Because of the potential changes in phosphate, nitrate, and ammonia concentration, all samples should be analyzed as soon as possible after collection.

5.B.6.b.2. SURFACE WATER

Temperature, pH, specific conductance, and dissolved-gases should be measured in the field. Samples for metal analysis can be preserved by adding nitric acid; samples for organic constituent determinations, by chilling or freezing; and samples for determination of biodegradable substances (such as nitrates, phosphates, and surfactants), by chilling the sample immediately in an ice bath and storing the sample in the dark at a temperature just above freezing. Select a preservative that does not interfere with the analytical measurements. Samples for determining certain dissolved inorganic and organic species must not be frozen because it is not always possible to reconstitute the sample. Particulars appropriate for each measurement are given in sections 5.C. through 5.F.

5.B.6.c. FILTRATION

5.B.6.c.1. ATMOSPHERIC DEPOSITION

See Sec. 5.B.6.b.1.

5.B.6.c.2. SURFACE WATER

When the objective is to determine concentrations of dissolved inorganic constituents in a water system, the sample must be filtered through a non-metallic 0.45 m membrane immediately after collection. Discard the first 150 to 200 mL of filtrate to rinse the filter and filtration apparatus of any contaminants. This technique minimizes the risk of altering the composition of the samples by the filtering operation. The filtrate, collected in a suitable bottle (usually polyethylene), is immediately acidified to pH 2.0 or less with nitric acid whose purity is consistent with the measurement to be made. Acidifying the filtrate (sample) minimizes the risk of dissolved constituents precipitating and also inhibits constituents from adsorbing onto walls of the bottle. Samples treated in this manner can be used for determining dissolved metallic constituents. Inorganic anionic constituents may be determined using a portion of the filtrate that has not been acidified.

When filtering samples for analyzing organic constituents, use a glass-fiber or metal-membrane filter and collect the sample in a suitable container, usually glass. Because most organic analyses require extraction of the entire sample, do not discard any of it. After filtering, the membrane containing the suspended fraction can be sealed in a glass container and analyzed separately as soon as practicable.

Total recoverable inorganic constituents may be determined using a second, unfiltered sample collected at the same time as the sample for dissolved constituents. Acidify this sample to avoid precipitation and adsorption unless selective extraction techniques are to be used. Portions of an unfiltered, acidified sample may be used to determine total or total recoverable metals, depending on the techniques used to bring the metals or other constituents into solution or on the analytical techniques used for their determination.

A procedure sometimes used to determine suspended inorganic materials is to digest the material collected on the membrane filter in nitric or hydrochloric acid, or both. All or most of the particulate matter is thus brought into solution. The resulting digestate may be analyzed by the usual means to determine either total suspended inorganic constituents or inorganic constituents recoverable by dilute acid digestion of the suspended matter. Such treatment of the suspended particulate matter obviously doubles the amount of analytical work required, and, consequently, an analysis of an unfiltered acidified sample is usually performed when information on more than just dissolved material is desired.

In the strict sense, the total concentrations of all inorganic constituents in a water-suspended sediment mixture cannot truly be determined unless the particulate matter is completely dissolved, as by fusion and solution, or unless an analytical technique that does not discriminate between the chemical or physical forms of the constituents present in the sample is used.

5.B.6.d. STORAGE

Samples for metal analysis that are preserved with nitric acid may be stored for several months. Chilled or refrigerated samples are also generally stable if no sediment is present; however, most samples should be analyzed as soon as possible within the time limitations specified in each analytical method. A good practice is always to store samples in a cool place out of direct sunlight. Store all samples in containers compatible with analysis for the desired constituents.

5.B.7. SAMPLE IDENTIFICATION

Identify the samples with detailed and accurate descriptions. Record every sample collected; identify every bottle, preferably by attaching an appropriately inscribed tag or label. Clearly write the name of the person collecting the sample.

5.B.7.a. ATMOSPHERIC DEPOSITION

The recommended minimum information to accompany atmospheric-deposition samples includes: sample number, site number, date and time of collection, name of observer, amount of precipitation (as function of time, if possible), unusual conditions (high dust levels, forest fires, malfunctions, and so on), condition of sample (good or contaminated by bugs, bird droppings, leaves, and so forth), field pH, and field conductivity. Reference a recording rain gage and associated meteorological records.

5.B.7.b. SURFACE WATER

The recommended minimum information required for surface-water samples includes: geographic name of the source, exact location of the sampling site and point of collection, date and time of collection, name of observer, gage height or water discharge (if available), water temperature and other field measurements, sample appearance, weather conditions, and any other observations that may assist in interpreting water-quality data.

5.B.7.c. GROUND WATER

The recommended minimum information to accompany ground-water samples includes: exact location of well or source, point and method of collection, name of observer, depth and diameter of well, casing record, screened intervals and type of screens, water-bearing formation(s), water level, rate of discharge and duration of pumping before sampling, water temperature and other field measurements, date and time of collection, appearance, and any other relevant observations, such as use of the water, that may assist in interpreting water-quality data (see chapter 2).

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15.C. MEASUREMENT OF PHYSICAL PROPERTIES

5.C.1. SPECIFIED TESTS

Color (true)
Conductance, specific
Residue
Resistivity
Specific gravity
Turbidity

5.C.2. REFERENCES CITED

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5.C.3. ANALYTICAL METHODS

List of Abbreviations

Estimate of Precision

RSD - relative standard deviation
SD - standard deviation
ST - interlaboratory overall precision
X - concentration

Form[1]

d - dissolved
s - suspended
t - total
t.v. - total volatile

[1]Consult specific reference for exact definition of form.

Color (true)

I. APPLICATION: The methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass.
FIELD TREATMENT: None required.
PRESERVATIVE: None required. (Refrigeration at 4°C recommended to minimize biologic changes.)
STORAGE: Store in dark place and analyze within 24 hours.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Visual comparison	2	204A	0 to 70 color units	Not available	d
	3	I-1250-78	0 to 70 color units	Not available	d
	4	110.2	0 to 70 color units	Not available	d

IV. REPORTING: Data should be reported in PCU (platinum-cobalt units). The number of significant figures should be as follows: 1–50, nearest one unit; 51–100, nearest 5 units; 101–250, nearest 10 units; 251–500, nearest 20 units.

Date Approved: May 1, 1981

Conductance, specific

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brines (Refs. 1 and 4).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: None required.
PRESERVATIVE: None required. Protect against gain or loss of gases.
STORAGE: Should be determined in situ or at time of collection.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION
A. Wheatstone Bridge	1	D1125-77(C)	μmho/cm	Not available
	2	205	μmho/cm	RSD = 8% at 150–230 μmho/cm
	3	I-780-78	μmho/cm	Not available
	4	120.1	μmho/cm	SD = 6% at 536 μmho/cm

IV. REPORTING: Data should be reported in units of μmho/cm or μS/cm which are identical. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: Methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat samples as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Analyze as soon as possible.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Gravimetric	2	209A	2.5 to 200 mg	SD = 4 at 25 mg/L	t
	3	I-3750-78	Not available	RSD = >11% at 63 mg/L	t
	4	160.3	10 to 20,000 mg/L	Not available	t
	2	209B	2.5 to 200 mg	Not available	d
	3	I-1750-78	<200 mg	ST = 0.034X + 4.81	d
	3	I-1749-78	<200 mg	RSD = >5% at 116 mg/L	d
	4	160.1	10 to 20,000 mg/L	Not available	d
	2	209E	Not available	SD = 11 at 170 mg/L	t.v.
	3	I-3753-78	Not available	Not available	t.v.
	4	160.4	Not available	SD = 11 at 170 mg/L	t.v.
	2	209D	2.5 to 200 mg	SD = 5 at 15 mg/L	s
	3	I-3765-78	Not available	Not available	s
	4	160.2	4 to 20,000 mg/L	Not available	s

IV. REPORTING: Data should be reported in units of mg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Resistivity

I. APPLICATION: These methods generally are applicable for the analysis of fresh water and brines.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Instrumental					
1. Wheatstone bridge	1	D1125-77(C)	0.01 to 10 ohm-meters	Not available	d
	5	pp. 17-19	0.01 to 10 ohm-meters	Not available	d
	6	pp. 32-35	0.01 to 10 ohm-meters	Not available	d

IV. REPORTING: Data should be reported in ohm-meters. The number of significant figures for less than 0.2 ohm-meter is three decimal places, 0.2 to two ohm-meters is two decimal places, and greater than two ohm-meters is one decimal place.

Date Approved: May 1, 1981

Specific gravity

I. APPLICATION: Methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brines–A. (D1429–76B), C. (D1429–76D), D. (D1429–76A); Sediments–B. (D1429–76C).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: None.
PRESERVATIVE: None.
STORAGE: Analyze as soon as possible.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Balance	1	D1429–76(B)	0.1 mg to limit of balance	±0.003 g/mL	d
B. Erlenmeyer Flask	1	D1429–76(C)	0.1 mg to limit of balance	±0.005 g/mL	d,s,t
	2	210	0.1 mg to limit of balance	Not available	d,s,t
C. Hydrometer	1	D1429–76(D)	hydrometer range dependent	±0.004 g/mL	d,s,t
D. Pycnometer	1	D1429–76(A)	0.1 mg to limit of balance	±0.002 g/mL	d
	3	I–1312–78	0.1 mg to limit of balance	±0.005 g/mL	d

IV. REPORTING: Data should be reported in units of specific gravity or density per unit volume (g/mL). The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Turbidity

I. APPLICATION: The methods generally are applicable for the analysis of fresh water, ocean water, brines, industrial water, and waste water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: None.
PRESERVATIVE: None.
STORAGE: Cool to 4°C, analyze as soon as possible.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Jackson Candle Turbidity	1	D1889–71	25 to 1000 JTU	Not available	s
	2	214B	5 to 1000 JTU	Not available	s
B. Nephelometric	1	D1889–71	0 to 100 NTU	Not available	s
	2	214A	0 to 40 NTU	Not available	s
	3	I–3860–78	0 to 40 NTU	RSD = 2% at 0.26 NTU	s
	4	180.1	0 to 40 NTU	SD = +0.94 at 41 NTU	s

IV. REPORTING: Data should be reported in units of JTU or NTU for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

5.D. DETERMINATION OF INORGANIC CONSTITUENTS

5.D.1. CONSTITUENTS SPECIFIED

Acidity
Alkalinity
Aluminum (Al)
Antimony (Sb)
Arsenic (As)
Barium (Ba)
Beryllium (Be)
Bicarbonate (HCO_3)
Biochemical oxygen demand (BOD_5)
Boron (B)
Bromide (Br)
Cadmium (Cd)
Calcium (Ca)
Carbonate (CO_3)
Chloride (Cl)
Chlorine, residual
Chromium (Cr)
Chromium (Cr), hexavalent
Cobalt (Co)
Copper (Cu)
Cyanide (CN)
Fluoride (F)
Hardness
Hydroxide (OH)
Iodide (I)
Iron (Fe)
Lead (Pb)
Lithium (Li)
Magnesium (Mg)
Manganese (Mn)
Mercury (Hg)
Molybdenum (Mo)
Nickel (Ni)
Nitrogen (N_2)
Nitrogen, ammonia (NH_3-N)
Nitrogen, nitrate (NO_3-N)
Nitrogen, nitrite (NO_2-N)
Nitrogen, nitrite plus nitrate ($NO_2 + NO_3$-N)
Nitrogen, Total Kjeldahl (NH_3 plus organic-N)
Oxidation reduction potential (ORP)
Oxygen, dissolved (DO)
pH
Phosphorus (P)
Potassium (K)
Selenium (Se)
Silica (SiO_2)
Silver (Ag)
Sodium (NA)
Strontium (Sr)
Sulfate (SO_4)
Sulfide (S)
Sulfite (SO_3)
Thallium (Tl)
Tin (Sn)
Vanadium (V)
Zinc (Zn)

5.D.2. REFERENCES CITED

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5.D.3. ANALYTICAL METHODS

List of Abbreviations

Estimate of Precision

RD - relative deviation
RSD - relative standard deviation
SC - single laboratory precision
SD - standard deviation
S - single operator precision
ST - interlaboratory overall precision
V - volume
X - concentration

Form[1]

c - combined
d - dissolved
f - free
s - suspended
t - total
t.r. - total recoverable

[1]Consult specific reference for exact definition of form.

Acidity

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines (Ref. 5).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Analyze as soon as possible, or within 24 hours.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Titrimetric	1	D1067-70(B)	Not available	Not available	t.
	2	402	Not available	SD = 1.8 at 20 mg/L	t.
	3	I-1020-78	Not available	Not available	t.
	4	305.1	Not available	SD = 10 up to 2000 mg/L	t.
	5	p. 22	Not available	Not available	t.

IV. REPORTING: Data should be reported in units of mg/L or milliequivalents per liter for water (Ref. A.1). The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Alkalinity

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines-A. (D3875-80, Refs. 5 and 9).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Analyze as soon as possible, or within 24 hours.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Titrimetric	1	D1067-70(B)	Not available	Not available	t.
	1	D3875-80	Not available	ST = 0.005X + 2.8	t.
	2	403	Not available	SD = 5 at 120 mg/L	t.
	3	I-1030-78	Not available	ST = 0.082X + 0.73	t.
	3	I-2030-78[1]	Not available	RSD = 7% at 20 mg/L; 12% at 151 mg/L	t.
	4	310.1	Not available	SD = 5.36 at 119 mg/L	t.
	5	pp. 8-9	Not available	approximately 3% value	t.
	9	pp. 37-39	Not available	approximately 3% value	t.
B. Colorimetric	4	310.2	10 to 200 mg/L	SD = 0.5 at 15, 57, and 193 mg/L	t.r.

IV. REPORTING: Data should be reported in units of mg/L or milliequivalents per liter for water (Ref. A.1). The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Sediment-A.1. (I-5051-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Nitric acid to pH 2.0 or less is required.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D857-79(D)	0.1 to 5.0 mg/L	See fig. 1,2	t.r.,d
	1	D857-79(E)	10 to 300 μg/L	See fig. 3,4	t.r.,d
	2	303C	5 to 100 mg/L	Not available	t,s,d
	2	303D	Not available	RSD = 22.2% at 300 μg/L	t,s,d
	3	I-1051-78	100 to 5000 μg/L	ST = 0.158X + 35.3	d
	3	I-1052-78	10 to 1000 μg/L	ST = 0.073X + 14.97	d
	3	I-3051-78	100 to 5000 μg/L	Not available	t.r.
	3	I-3052-78	10 to 1000 μg/L	Not available	t.r.
	3	I-5051-78	10 to 5000 μg/g	Not available	t.r.
	4	202.1	5 to 50 mg/L	SD = 391 at 1004 μg/L; 108 at 35 μg/L	t,s,d
2. Furnace	4	202.2	20 to 200 μg/L	Not available	t,s,d
B. Colorimetric					
1. 8-quinolinol	1	D857-79(B)	0.00 to 0.50 mg/L	So = 0.9/V	t
2. Eriochrome cyanine R	2	306B	20 to 300 μg/L	RSD = 38.5% at 50 μg/L	t,s,d
3. Ferron	1	D857-79(C)	0 to 2 mg/L	So = 0.035	d
	3	I-1050-78	100 to 3000 μg/L	ST = 0.077X + 27.33	d
C. Fluorometric					
1. Morin	1	D857-79(A)	0 to 5 μg/L	SC = (7.9-1.1X)/V	d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Sediment-A.1. (I-5055-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Nitric acid to pH 2.0 or less is required.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3697-78(D)	1 to 15 μg/L	See figs. 2 and 3 in reference	t.r.,d
	2	303A	1 to 40 mg/L	Not available	t,s,d
	3	I-1055-78	1 to 15 μg/L	RSD = 4% at 4.3 μg/L; 3% at 20.3 μg/L	d
	3	I-3055-78	1 to 15 μg/L	Not available	t
	3	I-5055-78	1 to 15 μg/g	Not available	t
	4	204.1	1 to 40 mg/L	SD = 0.08 at 5 mg/L; 0.1 at 15 mg/L	t,s,d
2. Furnace	4	204.2	20 to 300 μg/L	Not available	t,s,d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Sediment–A.1. (I–5062–78, I–6062–78) and B.1. (I–5060–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Nitric acid to pH 2.0 or less is required.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D2972–78(B)	1 to 20 μg/L	ST = 1.8 at 8.8 μg/L	t.r.,d
	2	303E	2 to 20 μg/L	RSD = 6.0% at 10 μg/L	t.s,d
	3	I–1062–78	1 to 20 μg/L	ST = 0.082X + 1.94	d
	3	I–2062–78[1]	1 to 15 μg/L	RD = 5% at 5.8 to 15.5 μg/L	d
	3	I–3062–78	1 to 20 μg/L	RD = 58% at 4.3 μg/L; 19% at 17.8 μg/L	t
	3	I–4062–78[1]	1 to 15 μg/L	RD = > 5%	t
	3	I–5062–78	1 to 10 μg/g	RD = 58% at 1 μg/g; 19% at 10 μg/g	t
	3	I–6062–78[1]	1 to 15 μg/g	RD = > 5%	t
	4	206.3	2 to 20 μg/L	SD = 0.3 at 5 μg/L; 0.9 at 10 μg/L; 1.1 at 20 μg/L	t,s,d
2. Furnace	4	206.2	5 to 100 μg/L	SD = 1.1 at 50 μg/L, 1.6 at 100 μg/L	t,s,d
B. Colorimetric					
1. Silver diethyldithio-carbamate	1	D2972–78(A)	5 to 250 μg/L	ST = 4.2 at 98 μg/L	t.r.,d
	2	307B	≥ 30 μg/L	RSD = 13.8% at 40 μg/L	t
	3	I–1060–78	5 to 200 μg/L	ST = 0.230X + 2.11	d
	3	I–3060–78	5 to 200 μg/L	RD = > 42% at 9.8; 24% at 109 μg/L	t
	3	I–5060–78	5 to 200 μg/g	RD = > 42% at lower range	t
	4	206.4	≥ 10 μg/L	RSD = 13.8% at 40 μg/L	t,s,d
2. Mercuricbromide	2	307C	≥ 30 μg/L	RSD = 75% at 50 μg/L	t

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.1. (D3651–78, D3986–81, Refs. 6 and 9) and B.1. (Refs. 5 and 9); Sediments–A.1. (I–5084–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Hydrochloric acid to pH 3.0 or less is required for A.1. (Refs. 6 and 9); B.1. (Refs. 5 and 9); all others require nitric acid to pH 2.0 or less.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3651–78	1 to 5 mg/L	See figure 1	d
	2	303C	1 to 20 mg/L	RSD = 10.0% at 500 μg/L	t
	3	I–1084–78	100 to 5000 μg/L	ST = 0.069X + 69.1	d
	3	I–3084–78	100 to 5000 μg/L	RD = 38% at 62 μg/L	t.r.
	3	I–5084–78	2.5 to 50,000 μg/g	RD = 38% at lower range	t.r.
	4	208.1	1 to 20 mg/L	SC = 0.043 at 0.40 mg/L; 0.13 at 2.0 mg/L	t,s,d
	6	pp. 2–10	≥0.2 mg/L	Not available	d
	9	pp. 77–78	≥0.2 mg/L	SD = 0.25 at 3.18 mg/L	d
2. Furnace	4	208.2	10 to 200 μg/L	SD = 2.5 at 500 μg/L; 2.2 at 1000 μg/L	s,d
B. Atomic emission					
1. DC plasma	1	D3986–81	10 to 20 mg/L	See fig. 1 in reference	d,t.r.
	5	pp. 39–41	≥0.5 mg/L	RSD = approx. 3% throughout range	d
	9	pp. 83–89	≥0.5 mg/L	RSD = approx. 3%	d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brine-B.1. (Refs. 5 and 9); Sediment-A.1. (I-5095-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Nitric acid to pH 2.0 or less is required.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3645-78	10 to 500 μg/L	SD = 6 at 100 μg/L; 16 at 350 μg/L	t.r.,d
	2	309A	0.05 to 2 mg/L	Not available	t,s,d
	2	309A	Not available	RSD = 34.0% at 5 μg/L	t,s,d
	3	I-1095-78	10 to 200 μg/L	ST = −0.015X + 5.62	d
	3	I-3095-78	10 to 200 μg/L	RD = 19% at 27 μg/L	t.r.
	3	I-5095-78	>2.5 μg/g	Not available	t.r.
	4	210.1	0.05 to 2 mg/L	SD = 0.001 at 0.01 mg/L; 0.002 at 0.25 mg/L	t,s,d
2. Furnace	4	210.2	1 to 30 μg/L	Not available	s,d
B. Atomic emission					
1. DC plasma	5	pp. 41-43	≥0.2 μg/L	RSD = approx. 3%	d
	9	pp. 89-90	≥0.2 μg/L	RSD = approx. 3%	d
C. Colorimetric					
1. Aluminon	2	309B	≥5 μg/L	RSD = 7.13% at 250 μg/L	t,d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Bicarbonate (HCO_3)

I. APPLICATION: This method generally is applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: None required.
PRESERVATIVE: None required.
STORAGE: Analyze immediately.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Titrimetric	1	D513-71(C)	Not available	approximate precision = 1 mg/L at <100 mg/L; 2 mg/L at 100-200 mg/L	t.r.

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: This method is applicable to waste waters, effluents and polluted waters. It is of only limited value in measuring the oxygen demand of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Neutralize to pH 7.0 for samples containing caustic alkalinity or acidity with 1 N H_2SO_4 or NaOH. Destroy high chlorine residuals with Na_2SO_3.
PRESERVATIVE: None required.
STORAGE: Store at 4°C; analyze within 24 hours.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Oxygen depletion	2	507	≥1 mg/L	SD = 37 at 300 mg/L;	t.r.
	4	405.1	Not available	SD = 0.7 at 2.1 mg/L; 26 at 175 mg/L	t.r.

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Boron (B)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brines–A.1. (Ref. 5), B.1. (Ref. 5), and C. (Refs. 5 and 9); Sediment–B.1. (I-5111-78), B.3. (I-5110-78 and I-5114-78).

II. SAMPLE:

CONTAINER: Boron-free glass or plastic.
FIELD TREATMENT: Treat samples according to form desired as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Approximately 6 months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic emission					
1. Plasma arc	5	pp. 39–41	≥2 mg/L	RSD = 5% to 6%	d
	9	pp. 83–89	≥2 mg/L	Not available	d
B. Colorimetric					
1. Carminic acid	1	D3082-79(A)	0.1 to 10 mg/L	ST = 0.0125X + 0.074	d
	2	404B	1 to 10 mg/L	RSD = 35.5% at 0.18 mg/L	t.r.
	3	I-1111-78	500 to 10,000 μg/L	RSD = 14% at 522 μg/L	d
	3	I-3111-78	500 to 10,000 μg/L	RD = 14% at 522 μg/L	t.r.
	3	I-5111-78	≥10 μg/g	Not available	t.r.
	5	pp. 32–33	2 to 20 mg/L	SD = 0.4 at 4 mg/L	d
2. Curcumin	1	D3082-79(C)	0.1 to 10 mg/L	ST = 0.03X + 0.02	d
	2	404A	0.1 to 1 mg/L	RSD = 22.8% at 0.24 mg/L	t.r.
	3	I-1112-78	100 to 1000 μg/L	ST = 0.034X + 42.4	d
	3	I-3112-78	100 to 1000 μg/L	RD = 13% at 380 μg/L	t.r.
	4	212.3	0.1 to 1.0 mg/L	Same as Ref. 2	t,d,s
3. Dianthrimide	3	I-1110-78	20 to 1000 μg/L	ST = 0.079X + 17.11	d
	3	I-3110-78	20 to 1000 μg/L	RD = 12% at 530 μg/L	t.r.
	3	I-5110-78	≥10 μg/g	RD = 68% at lower range	t.r.
	3	I-5114-78	≥10 μg/g	RD = 68% at lower range	t
C. Titrimetric	1	D3082-79(B)	1 to 100 mg/L	ST = 0.0244X + 0.0248	D
	5	p. 33	2 to 1000 mg/L	Not available	t.r.
	9	pp. 37–39	2 to 1000 mg/L	Not available	t.r.

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Bromide (Br)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brines -A.1. (Ref. 5), B. (Refs. 5 and 9).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat samples according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Approximately six months; cap bottle tightly and store in cool place out of direct sunlight.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Chromium trioxide oxidation	1	D3869-79(D)	40 to 6500 mg/L	ST = 0.092X − 2.47	d
	5	pp. 35-36	≥5 mg/L	RSD = 4%-5% at 200 mg/L to 400 mg/L	d
2. Permanganate oxidation	1	D1246-77(B)	<100 μg/L	ST = 0.0767X + 1.48	d
	3	I-1127-78	0.01 to 0.10 mg/L	RSD = <4% over range	d
3. Phenol red	2	405	0.1 to 1.0 mg/L	Not available	d
B. Titrimetric	1	D1246-77(C)	≥5.0 mg/L	So = 0.0044X	d
	1	D3869-79(A)	5 to 6500 mg/L	See figure 2.	d
	3	I-1125-78	≥1.0 mg/L	So = 0.0044X	d
	4	320.1	2 to 20 mg/L	SC = 0.37 at 0.44 mg/L	d
	5	pp. 36-37	0.1 to 50 mg/L	about 3% of amount present	d
	9	pp. 45-47	0.1 to 50 mg/L	Not available	d

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Cadmium (Cd)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Brines-A.1. (D3557-78(B), 301A III, I-1136-78); Sediment-A.1. (I-5135-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat samples according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify water samples to pH 2.0 or less with HNO_3.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3557-78(A)	50 to 2000 μg/L	See Fig. 1 in reference	d,t.r.
	1	D3557-78(B)	5 to 200 μg/L	See Fig. 2 in reference	d,t.r.
	2	310A	0.05 to 2 mg/L	RSD = 21.6% at 50 μg/L	d,t.r.,t
	2	310A	Not available	RSD = 43.8% at 50 μg/L	d,t.r.,t
	3	I-1135-78	10 to 250 μg/L	RSD = 31% at 14 μg/L	d
	3	I-1136-78	1 to 50 μg/L	ST = 0.192X + 0.093	d
	3	I-3135-78	10 to 250 μg/L	RD ≥ 49% at 12 μg/L	t.r.
	3	I-3136-78	1 to 50 μg/L	RD ≥ 17% at 10.2 μg/L	t.r.
	3	I-5135-78	≥1 μg/g	RD ≥ 31% at lower range	t.r.
	4	213.1	0.05 to 2 mg/L	SD = 21 at 71 μg/L	d,s,t
2. Furnace	4	213.2	0.5 to 10 μg/L	SD = 0.10 at 2.5 μg/L; 0.16 at 5.0 μg/L; 0.33 at 10.0 μg/L	d,s,t

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brines-A.1. (D511-77(C)), B. (D511-77(B)); Brines-A.1. (Refs. 6 and 9), B. (Refs. 5, 7, and 8); Sediment-A.1. (I-5152-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Immediately acidify sample to pH 2.0 with HNO_3.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D511-77(C)	0.3 to 15 mg/L	ST = 0.07X + 0.007	d,t.r.
			250 to 25000 mg/L	So = 253	d,t.r.
	2	311A	0.2 to 20 mg/L	Not available	d,s,t,t.r.
	3	I-1152-78	0.1 to 60 mg/L	ST = 0.057X + 0.343	d
	3	I-3152-78	0.1 to 60 mg/L	RD ≥ 7% at 12.6 mg/L	t.r.
	3	I-5152-78	≥ 10 mg/kg	RD ≥ 7%	t.r.
	4	215.1	0.2 to 7 mg/L	SD = 0.3 at 9 mg/L; 0.6 at 36 mg/L	d,t.r.
	6	pp. 2-10	≥ 0.1 mg/L	Not available	d
	9	pp. 72-74	≥ 0.1 mg/L	SD = 0.025 mg/L; at 0.828 mg/L	d
B. Titrimetric	1	D511-77(B)	1 to 1000 mg/L	ST = 0.009X + 0.58	d,t.r.
	2	311B	< 250 mg/L	RSD = 3.5% at 108 mg/L	d
	4	215.2	Not available	RSD = 9.2% at 108 mg/L	d,t.r.
	5	pp. 10-11	≥ 0.1 mg/L	1-2% of amount present	d
	7	Sec. 7. pp. 18-21	≥ 0.1 mg/L	Not available	d
	8	pp. 44-46	≥ 0.1 mg/L	Not available	d

IV. REPORTING: Data should be reported in units of mg/L for water and mg/kg for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Carbonate (CO_3)

I. APPLICATION: This method generally is applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: None.
PRESERVATIVE: None.
STORAGE: Analyze immediately.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Titrimetric	1	D513-80(A)	Not available	Not available	t.r.

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Atmospheric deposition–A.1., and B. (all with range less than 1 mg/L); Brines–B. (Refs. 5, 7, 8, and 9).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Ferricyanide	1	D512-80(C)	0.1 to 10 mg/L	ST = 0.054X − 0.002	d
	3	I-1187-78	0.1 to 10 mg/L	RSD = 33% at 1.4 mg/L	d
	3	I-2187-78[1]	0.1 to 100 mg/L	ST = 0.057X − 0.25	d
	4	325.2[1]	1 to 200 mg/L	Not available	d
B. Titrimetric	1	D512-80(A)	≥0.2 mg/L	ST = 0.023X + 0.43	d
	1	D512-80(B)	≥5 mg/L	ST = 0.013X + 0.70	d
	2	407A	1.5 to 100 mg/L	RSD = 4.2% at 241 mg/L	d
	2	407B	Not available	RSD = 3.3% at 241 mg/L	d
	3	I-1183-78	10 to 2000 mg/L	ST = 0.034X + 0.33	d
	3	I-1184-78	≥0.1 mg/L	ST = 0.045X + 0.43	d
	4	325.3	<400 mg/L	RSD = 3.3% at 241 mg/L	d
	5	p. 16	≥0.2 mg/L	approx. 1% of amount present	d
	7	Sec. 10, pp. 27–30	≥0.2 mg/L	Not available	d
	7	Sec. 11, pp. 30–32	Not available	Not available	d
	8	pp. 60–62	Not available	Not available	d
	9	pp. 44–45	Not available	Not available	d

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: None.
PRESERVATIVE: None.
STORAGE: Analyze within five minutes of collection. Keep samples out of direct sunlight.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. N, N-diethyl -p-phenylene-diamine (DPD)	2	408E	0.05 to 4 mg/L	Not available	f,t
	4	330.5	0.2 to 4 mg/L	RSD = 27.6% at 0.66 mg/L	t
2. Leuco crystal violet	2	408F	Not available	Not available	c,f,t
B. Titrimetric	1	D1253-76(A)	0.01 to 10 mg/L	So = 3X/V	c,f,t
	1	D1253-76(B)	≥0.1 mg/L	So = 4/V	t
	2	408A	≥1.0 mg/L	Not available	t
	2	408B	>1.0 mg/L	Not available	t
	2	408C	<2 mg/L	Not available	c,f,t
	2	408D	Not available	Not available	c,f,t
	4	330.1	Not available	RSD = 24.8% at 0.64 mg/L; 12.5% at 1.83 mg/L	t
	4	330.2	Not available	RSD = 4.3% at 0.8 mg/L	t
	4	330.3	≥1.0 mg/L	RSD = 23.6% at 1.83 mg/L	t
	4	330.4	≥1.0 mg/L	RSD = 9.4% at 1.83 mg/L	t

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brine-A.1. 312A, I-1238-78, 218.3); Sediment-A.1. (I-5236-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with HNO_3.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D1687-77(D)	0.1 to 10 mg/L	ST = 0.097X + 0.01	d,t.r.
	2	312	Not available	Not available	d,s,t,t.r.
	2	312A	Not available	Not available	d,s,t,t.r.
	3	I-1236-78	10 to 400 mg/L	ST = 0.173X + 2.44	d
	3	I-1238-78	1 to 25 μg/L	ST = 1.005X − 5.36	d
	3	I-3236-78	10 to 400 μg/L	RD = 27% at 22 μg/L	t.r.
	3	I-5236-78	≥1 μg/g	RD = 27% at lower range	t.r.
	4	218.1	0.5 to 10 μg/L	Not available	d,s,t,t.r.
	4	218.3	1 to 25 μg/L	Not available	d
	4	218.2	5 to 100 μg/L	SD = 0.1 at 19 μg/L; 0.8 at 77 μg/L	d,s,t,t.r.
B. Colorimetric					
1. Diphenylcarbazide	1	D1687-77(A)	0.5 to 50 mg/L	SD = 0.10 at 6 mg/L	d,t.r.
	1	D1687-77(B)	0.5 to 50 mg/L	SD = 0.12 at 6 mg/L	d,t.r.
	1	D1687-77(C)	0.5 to 50 mg/L	ST = 0.0052X + 0.025	d,t.r.
	2	312B	Not available	RSD = 47.8% at 110 μg/L	d,t
	3	I-1237-78	50 to 4000 μg/L	Not available	d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Chromium (Cr), hexavalent

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special application is: Brine-A.1.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with HNO_3.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	3	I-1232-78	1 to 25 μg/L	RD = 25% at 8 μg/L	d
	4	218.4	1 to 25 μg/L	Not available	d
B. Colorimetric					
1. Diphenylcarbazide	2	312B	Not available	RSD = 47.8% at 110 μg/L	d
	3	I-1230-78	50 to 4000 μg/L	RSD = 5% at 810 μg/L	d

IV. REPORTING: Data should be reported in units of μg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.1. (D3558–77(B), and I–1240–78); Sediment–A.1. (I–5239–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with nitric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3558–77(A)	0.1 to 10 mg/L	See fig. 1 in reference	t.r.,d
	1	D3558–77(B)	10 to 1000 μg/L	See fig. 2 in reference	t.r.,d
	2	303A	0.5 to 10 mg/L	Not available	t.r.,d
	3	I–1239–78	50 to 1000 μg/L	Not available	d
	3	I–1240–78	1 to 50 μg/L	ST = 0.1X + 0.732	d
	3	I–3239–78	50 to 1000 μg/L	Not available	t.r.
	3	I–3240–78	1 to 50 μg/L	RD > 20% at 5 μg/L	t.r.
	3	I–5239–78	≥ 5 μg/g	Not available	t.r.
	4	219.1	0.5 to 5 mg/L	SD = 0.01 at 1 mg/L	d,t.r.
2. Furnace	4	219.2	5 to 100 μg/L	Not available	t.r.

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.1. (D1688–77(E), I–3271–78, Refs. 6 and 9); Sediments–A.1. (I–5270–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 with nitric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D1688–77(D)	0.02 to 5 mg/L	ST = 0.06X + 0.039	t.r.,d
	1	D1688–77(E)	2 to 500 μg/L	ST = 0.27X + 42	t.r.,d
	2	303A	0.2 to 10 mg/L	RSD = 11.2% at 1000 μg/L	t.r.,d
	3	I–1270–78	10 to 1000 μg/L	ST = 0.063X + 9.34	d
	3	I–1271–78	1 to 75 μg/L	RD = 23% at 25 μg/L	d
	3	I–3270–78	10 to 1000 μg/L	RD = >15% at 79 μg/L; >9% at 595 μg/L	t.r
	3	I–3271–78	1 to 75 μg/L	RD = 23% at 25 μg/L	t.r.
	3	I–5270–78	≥1 μg/g	RD ≥ 15% at lower range	t.r.
	4	220.1	0.2 to 5 mg/L	SD = 0.06 at 0.3 mg/L	t.r.,d
	6	pp. 10–11	≥5 μg/L	SD = 0.64 at 38 μg/L	d
	6	pp. 2–10	≥100 μg/L	Not available	d
	9	p. 80	≥100 μg/L	SD = 7 at 774 μg/L	d
2. Furnace	4	220.2	5 to 100 μg/L	Not available	t.r.,d
B. Colorimetric					
1. Neo-cuproine	7	Sec. 13, pp. 37–40	≥20 μg/L	Not available	d
	8	pp. 63–66	≥20 μg/L	Not available	d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.2. (I–1300–78); Sediments–A.2. (I–5300–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: None.
PRESERVATIVE: Adjust to pH 12 with NaOH.
STORAGE: Store at 4°C, analyze within 24 hours.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Pyridine-barbituric	1	D2036–81(A)	>0.03 mg/L	See Fig. 2 in reference	t
	2	412D	≥20 μg/L	ST = 0.115X + 0.031	t
	3	I–2302–78[1]	0.01 to 0.3 mg/L	RSD = 2% at 0.04 mg/L; 1% at 0.224 mg/L	d
	3	I–4302–78[1]	0.01 to 0.3 mg/L	RSD = 2% at 0.04 mg/L; 1% at 0.224 mg/L	t
	4	335.3[1]	5 to 500 μg/L	Not available	t
2. Pyridine-pyrazolone	3	I–1300–78	≥0.01 mg/L	ST = 0.115X + 0.031	d
	3	I–3300–78	≥0.01 mg/L	RSD = 27% at 0.2 mg/L	t
	3	I–5300–78	≥0.5 mg/Kg	Not available	t
	4	335.2	0.02 to 1 mg/L	SD = 0.03 at 0.28 mg/L See fig. 3	t
	2	412C	≥1 mg/L	RSD = 2% at 1 mg/L; 8% at 0.4 mg/L	t
	4	335.2	≥1 mg/L	Not available	t

IV. REPORTING: Data should be reported in units of μg/L for water and mg/kg for sediments. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. With distillation, these methods generally are applicable for the analysis of ocean water and brines.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Approximately six months (Ref. 3); and seven days (Ref. 4).

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Complexone	4	340.3	0.05 to 1.5 mg/L	SD = 0.018 at 0.15 mg/L	t,d
2. SPADNS with distillation	1	D1179-80(A)	0.00 to 1.4 mg/L	SD = 0.089 at 0.81 mg/L	t,d
	2	413C	0.05 to 1.4 mg/L	RSD = 8% at 0.83 mg/L	t,d
	4	340.1	0.1 to 2.5 mg/L	SD = 0.103 at 0.57 mg/L	t,d
B. Electrometric	1	D1179-80(B)	0.1 to 1000 mg/L	SD = 0.03 at 0.85 mg/L	t.r.,d
	2	413B	0.1 to 5.0 mg/L	Not available	t.r.,d
	4	340.2	0.1 to 1000 mg/L	SD = 0.036 at 0.75 mg/L	t.r.,d
C. Visual					
1. Alizarin with distillation	2	413D	0.05 to 1.4 mg/L	RSD = 4.9% at 0.83 mg/L	t,d

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Hardness

I. APPLICATION: These methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric	4	130.1[1]	10 to 400 mg/L	SD = 1.5 at 120 mg/L	t
B. Titrimetric	1	D1126-80	>0.5 mg/L	ST = 0.0082X + 1.2	t
	2	314B	1 to 300 mg/L	RSD = 2.9% at 610 mg/L	t
	3	I-1338-78	10 to 300 mg/L	ST = 0.14 + 1.75	t
	4	130.2	Not available	SD = 2.87 at 31 mg/L	t

IV. REPORTING: Data should be reported in units of mg/L as $CaCo_3$ for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

I. APPLICATION: This method generally is applicable for the analysis of fresh water and waste water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Analyze immediately.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Titrimetric	1	D514-80	<15 mg/L	So = 0.05 mg/L	t

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Iodide (I)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brine-B. (Refs. D1246-77(C), 5, 7, and 9), D. (Refs. 5 and 9); Brine-C. (Ref. 10).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Cool to 4°C and store in dark (see Ref. 4).
STORAGE: Analyze sample within 24 hours (see Ref. 4).

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Ceric	1	D1246-77(A)	≤100 μg/L	ST = 0.0790X + 0.194	t
	2	414B	<80 μg/L	SD = 0.3 at 14 μg/L	
2. Lauco Violet	2	414A	0.05 to 6 mg/L	Not available	t
B. Titrimetric	1	D1246-77(C)	>50 mg/L	S_o = 0.009X	t
	4	345.1	2 to 20 mg/L	SD = 0.1 at 6.6 mg/L	t
	5	pp. 36-37	≥0.1 mg/L	RSD = 3% at amount present	d
	7	pp. 15-18	≥0.1 mg/L	Not available	d
	9	pp. 45-47	≥0.1 mg/L	Not available	d
C. Electrometric	10	All	10 to 400 mg/L	Approximate RSD = 1 to 2%	d
D. Photometric	5	p. 36	≥0.5 mg/L	Approximate RSD = 1 to 2% at 10 mg/L	d
	9	pp. 110-111	≥0.5 mg/L	Not available	

IV. REPORTING: Data should be reported in units of mg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brines A.1. (Refs. 6 and 9), B.1. (Refs. 7 and 8), B.2. (I-2379-78), C.1. (Refs. 5 and 9); Sediments-A.1. (I-5381-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 with nitric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D1068-77(C)	0.05 to 5.0 mg/L	ST = 0.086X + 0.096	t.r.,d
	1	D1068-77(D)	5 to 500 μg/L	ST = 0.160X + 8.9	t,d
	2	303A	0.3 to 10 mg/L	RSD = 16.5% at 300 μg/L	t,d,s
	3	I-1381-78	10 to 1000 μg/L	ST = 0.056X + 23.9	d
	3	I-5381-78	1 to 1000 μg/g	RSD = 3% at 10 μg/g	s
	3	I-3381-78	10 to 1000 μg/L	RSD = >31% at 100 μg/L	t.r.
	4	236.1	0.3 to 5.0 mg/L	SD = 0.173 at 0.84 mg/L	t,d
	6	pp. 2-10	>0.1 mg/L	Not available	d
	6	pp. 10-11	≥10 μg/L	SD = 10 at 180 μg/L	d
	9	pp. 79-80	>0.1 mg/L	SD = 0.047 at 2.913 mg/L	d
2. Furnace	4	236.2	5.0 to 100 μg/L	Not available	d,s
B. Colorimetric					
1. Orthophenanthroline	1	D1068-77(A)	0.05 to 3.0 mg/L	See figure 1	t,d
	2	315B	0.02 to 4 mg/L	RSD = 25.5% at 300 μg/L	t,d
	7	pp. 51-54	≥20 μg/L	Not available	d
	8	pp. 69-71	≥20 μg/L	Not available	d
2. Bipyridine	3	I-2379-78[1]	10 to 5,000 μg/L	SD = 13 at 118 μg/L; 6 at 991 μg/L	d
	3	I-4379-78	10 to 5000 μg/L	RSD = >13% at 118 μg/L	t.r.
	3	I-6379-78[1]	1 to 5000 μg/g	RSD = >13%	s
3. Bathophenanthroline	1	D1068-77(B)	0.02 to 0.2 mg/L	ST = 0.039X + 1.47	t
C. Atomic emission					
1. Plasma arc	5	pp. 39-41	≥1.0 mg/L	RSD = approx. 5 to 6% of value	d
	9	pp. 83-89	≥1.0 mg/L	Not available	d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water and Brine–A.1. (D3559–78(B)); Sediment–A.1. (I–5399–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with nitric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3559–78(A)	1.0 to 10 mg/L	See fig. 1	d,t.r.
	1	D3559–78(B)	100 to 1000 mg/L	ST = 0.876X + 1.5	d,t.r.
	2	303A	1 to 20 mg/L	Not available	d,t.r.,t
	2	303B	Not available	RSD = 23.5% at 50 μg/L	d,t.r.
	3	I–1399–78	100 to 4000 μg/L	Not available	d
	3	I–3399–78	100 to 4000 μg/L	Not available	t.r.
	3	I–5399–78	10 to 4000 μg/g	Not available	t.r.
	3	I–1400–78	1 to 100 μg/L	ST = 0.097X + 1.45	d
	3	I–3400–78	1 to 100 μg/L	RD = > 10% at 45.6 μg/L	t.r.
	4	239.1	1 to 20 μg/L	SD = 46 at 101 μg/L	d,t.r.
	6	pp. 2–10	≥ 0.2 μg/L	Not available	d
	9	pp. 81–82	≥ 0.2 μg/L	SD = 0.25 at 1.57 μg/L	t.r.
	6	pp. 10–11	≥ 50 μg/L	SD = 53 at 350 μg/L	d,t.r.
	9	p. 82	≥ 50 μg/L	Not available	d,t.r.
2. Furnace	4	239.2	5 to 100 μg/L	SD = 1.6 at 50 μg/L	d,t.r.
B. Colorimetric					
1. Dithizone	2	316B	Not available	S_o = 6.8% at 0.01 mg/L	d,t.r.

IV. REPORTING: Data should be reported in units of μg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water–A.1. (D3561-77); Brine–A.1. (D3561-77, I-1425-78, I-3425-78, Refs. 6 and 9), B.1. (Refs. 2, 5, and 9).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with nitric or hydrochloric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3561-77	0.1 to 70,000 mg/L	ST = 0.0677X + 3.127	d
	3	I-1425-78	> 10 μg/L	ST = 0.048X + 4.84	d
	3	I-3425-78	10 to 1000 μg/L	RD = 9% at 54 μg/L 5% at 484 μg/L	t.r.
	3	I-5425-78	> 1 μg/g	RD = 9%	t.r.
	6	pp. 2-10	> 0.1 mg/L	Not available	d
	9	p. 68	> 0.1 mg/L	SD = 0.02 mg/L at 1.504 mg/L	d
B. Atomic emission					
1. Flame	2	317B	0.1 to 2 mg/L	SD = 0.1 at 0.7 mg/L	d,t.r.
	5	pp. 45-46	> 0.2 mg/L	approximately 3%	d
	9	pp. 54-56	> 0.2 mg/L	Not available	d

IV. REPORTING: Data should be reported in units of mg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Magnesium (Mg)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water–A.1. (D511-77(C)), B. (Ref. 7); Brines–A.1. (D511-77(C), I-1447-78, Refs. 6 and 9) and B. (Refs. 5 and 7); Sediment–A.1. (I-5447-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat samples according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Procedures A.1. (Refs. 6 and 9) and B. (Refs. 5 and 7) require HCl to pH 3.0 or less. All others require HNO_3 to pH 2.0 or less.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D511-77(C)	0.05 to 3.5 mg/L	ST = 0.078X + 0.03	t.r.,d
	2	303A	0.02 to 2 mg/L	RSD = 10.5% at 200 μg/L	t.r.,t,s,d
	3	I-1447-78	0.1 to 50 mg/L	ST = 0.043X + 0.134	d
	3	I-3447-78	0.1 to 50 mg/L	RD = > 9% at 1.98 mg/L	t.r.
	3	I-5447-78	≥ 10 mg/Kg	RD = > 9% at lower range	t.r.
	4	242.1	0.02 to 0.5 mg/L	SD = 0.1 at 2.1 mg/L	t,d,s
	6	pp. 2-10	≥ 0.02 mg/L	Not available	d
	9	pp. 71-72	≥ 0.02 mg/L	SD = 0.0016 at 0.345 mg/L	d
B. Titrimetric	1	D511-77(B)	1 to 1000 mg/L	ST = 0.017X + 0.85	t.r.,d
	5	pp. 10-11	≥ 0.1 mg/L	approximately 1-2%	d
	7	Sec. 7, pp. 18-21	≥ 0.1 mg/L	Not available	d

IV. REPORTING: Data should be reported in units of mg/L for water and mg/Kg for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.1. (I–1456–78, D858–77(B), Refs. 6 and 9), and B.1. (Refs. 5 and 9); Sediments–A.1. (I–5454–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat samples according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Procedure C. (Refs. 1 and 2) requires H_2SO_4; Procedure A.1. (Refs. 6 and 9) requires HCL; the rest require HNO_3 to pH 2.0 or less.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D858–77(B)	0.02 to 5 mg/L	See fig. 1, 2	t.r.,d
	1	D858–77(C)	2 to 500 μg/L	See fig. 3, 4	t.r.,d
	2	303A	0.1 to 10 mg/L	RSD = 13.5% at 50 μg/L	t,s
	3	I–1454–78	10 to 1000 μg/L	ST = 0.0497X + 9.59	d
	3	I–3454–78	10 to 1000 μg/L	RSD = >20% at 70.4 μg/L	t.r.
	3	I–1456–78	1 to 100 μg/L	Not available	d
	3	I–5454–78	≥1 μg/g	RD = >20%	t.r.
	4	243.1	0.1 to 3 mg/L	SD = 70 at 426 μg/L	t,d,s
	6	pp. 2–10	≥0.2 mg/L	SD = 0.03 at 1.51 mg/L	d
	9	pp. 78–79	≥0.2 mg/L	SD = 0.03 at 1.51 mg/L	d
2. Furnace	4	443.2	1 to 30 μg/L	Not available	t,d,s
B. Atomic emission:					
1. Plasma arc	5	pp. 39–41	≥1.0 mg/L	Not available	d
	9	pp. 83–89	≥1.0 mg/L	ST = 6% of measured value	d
C. Colorimetric					
1. Persulfate oxidation	1	D858–77(A)	0.025 to 15 mg/L	ST = 0.029X + 0.01	t.r.,d
	2	319B	50 to 1500 μg/L	RSD = 26.3% at 120 μg/L	t,d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.1. (D3223–79, I–1462–78, I–3462–78, 245.1, and 245.2); Sediments–A.1. (I–5462–78).

II. SAMPLE:

CONTAINER: Glass or high density-hard polyethylene bottles.
FIELD TREATMENT: Treat samples according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Nitric acid to pH 2.0 or less.
STORAGE: 38 days in glass; 13 days in hard plastic.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Cold vapor	1	D3223–79	0.2 to 10 μg/L	ST = 0.386X + 0.107	t.r.,d
	2	303F	Not available	RSD = 21.2% at 0.4 μg/L	t,s
	3	I–1462–78	0.5 to 10 μg/L	ST = 0.171X + 0.132	d
	3	I–2462–78[1]	0.1 to 8 μg/L	RD = 11% at 0.72 μg/L	d
	3	I–3462–78	0.5 to 10 μg/L	RD = >46% at 0.6 μg/L	t.r.
	3	I–5462–78	≥0.01 μg/g	RD = >18%	t.r.
	4	245.1	≥0.2 μg/L	SD = 0.39 at 0.60 μg/L	t,d,s
	4	245.2[1]	0.2 to 20 μg/L	SD = 0.04 at 0.5 μg/L	t,d,s

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

Molybdenum (Mo)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.1. (D3372–80); Sediment–A.1. (I–5490–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat samples according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Nitric acid to pH 2.0 or less.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3372–80	1 to 25 μg/L	ST = 0.072X + 0.45	t.r.,d
	3	I–1490–78	1 to 50 μg/L	RD = 36% at 2 μg/L; 11% at 29.7 μg/L	d
	3	I–3490–78	1 to 50 μg/L	RD = >30% at 2 μg/L	t.r.
	3	I–5490–78	≥0.25 μg/g	RD = >36% at lower range	t.r.
	4	246.1	0.1 to 40 mg/L	SD = 0.02 at 1.5 mg/L	t,d,s
2. Furnace	4	246.2	3 to 60 μg/L	Not available	t,d,s

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.1. (I–1500–78, D1886–77(C), D1886–77(D)); Sediment–A.1. (I–5499–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Nitric acid to pH 2.0 or less.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D1886–77(C)	0.1 to 10 mg/L	See fig. 1	t.r.,d
	1	D1886–77(D)	10 to 1000 μg/L	See fig. 2	t.r.,d
	2	303A	0.3 to 10 mg/L	Not available	t,s
	3	I–1499–78	100 to 1000 μg/L	Not available	d
	3	I–3499–78	100 to 1000 μg/L	Not available	t.r.
	3	I–5499–78	≥2.5 μg/g	Not available	t.r.
	3	I–1500–78	1 to 100 μg/L	ST = 0.187X + 1.45	d
	3	I–3500–78	1 to 100 μg/L	RD = >37% at 5.9 μg/L	t,r,d
	4	249.1	0.3 to 5 mg/L	SD = 0.011 at 0.20 mg/L	t,d,s
2. Furnace	4	249.2	5 to 100 μg/L	Not available	t,d,s
B. Colorimetric					
1. Carbamate	1	D1886–77(A)	0.001 to 0.05 mg/L	ST = 0.08X	t.r.,d
2. Glyoxime	1	D1886–77(B)	0.01 to 5 mg/L	ST = 0.06X	t.r.,d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.2. (D1426–79(A) and 350.2), A.1. (I–2523–78 and 350.1), C. (350.2, Refs. 5 and 9); Ocean water–A.2. (D1426–79(A)); Sediment–A.1. (I–6523–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: HCl to pH 1.5 or less is required for C. (Refs. 5 and 9); H_2SO_4 to a pH of 2.0 or less for all others.
STORAGE: Store at 4°C and analyze within 1 week.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Direct	1	D1426–79(B)	<0.1 mg-NH_3	SD = ±0.04 at ≤0.5 mg/L	d
	1	D1426–79(C)	0.01 to 2 mg/L	ST = 0.04X + 0.02	d
	2	417B	0.02 to 5 mg/L	RSD = 38% at 0.2 mg/L	d
	2	417C	0.01 to 0.5 mg/L	RSD = 39.2% at 0.2 mg/L	d
	3	I–2523–78[1]	0.01 to 5 mg/L	RD = >17% at 0.22 mg/L	d
	3	I–4523–78[1]	0.01 to 5 mg/L	RD = >17% at 0.22 mg/L	t
	3	I–6523–78[1]	≥0.2 mg/kg	RD = >17% at lower range	t,d
	4	350.1[1]	0.01 to 2 mg/L	SD = 0.005 at 1.41 mg/L	t,d
2. Distillation	1	D1426–79(A)	<.1 mg-NH_3	SD = ±0.03 at ≥0.5 mg/L	t.r.,d
	2	417B	0.02 to 5 mg/L	RSD = 46% at 0.2 mg/L	t.r.,d
	2	417C	0.01 to 0.5 mg/L	RSD = 15.1% at 0.2 mg/L	t.r.,d
	3	I–1520–78	0.01 to 2 mg/L	Not available	d
	3	I–3520–78	0.01 to 5 mg/L	Not available	t
	4	350.2 (8.2)	0.05 to 1 mg/L	SD = 0.07 at 0.26 mg/L	t,d
B. Potentiometric	1	D1426–79(D)	0.5 to 1000 mg/L	See Table 2	t.r.,d
	3	I–1524–78	≥0.10 mg/L	Not available	d
	3	I–3524–78	≥0.10 mg/L	Not available	t
	4	350.3	0.03 to 1400 mg/L	SD = 0.038 at 1.00 mg/L	t,d
C. Titrimetric	1	D1426–79(A)	≤5 mg/L	SD = 0.11 at 5 mg/L	t.r.,d
	2	417D	≤5 mg/L	SD = 69.8 at 0.20 mg/L	t.r.,d
	4	350.2 (8.1)	1 to 25 mg/L	Not available	t,d
	5	pp. 34–35	≥5 mg/L	Not available	d
	9	pp. 43–44	≥5 mg/L	2% of the amount present	d

IV. REPORTING: Data should be reported in units of mg/L for water and mg/kg for sediments. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

Nitrogen, (N_2)

I. APPLICATION: The method generally is applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass bottles such as for dissolved oxygen measurements.
FIELD TREATMENT: None.
PRESERVATIVE: Chill in ice-water bath near 0°C.
STORAGE: Sample should not be stored, analyze as soon as possible.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Gas chromatography	11	pp. 483–485	1 to 33 mg/L	SD = 0.01 at 1.0 mg/L	d

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines-A.1. (352.1).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended 5.B.6. (b and c).
PRESERVATIVE: H_2SO_4 to pH of 2.0 or less and chill to 4°C.
STORAGE: 48 hours.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Brucine-sulfuric acid	1	D992-71	1 to 50 mg/L	ST = 0.93	t.r.,d
	3	I-1530-78	0.1 to 1 mg/L	RSD = 22% at 0.2 mg/L	d
	4	352.1	0.1 to 2 mg/L	SD = 0.092 at 0.16 mg/L	t

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Nitrogen, nitrite (NO_2-N)

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines-A.1. (354.1 and I-2540-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Cool immediately to 4°C.
STORAGE: Analyze immediately or within 48 hours.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Diazotization	2	419	0.001 to 0.05 mg/L	Not available	d
	3	I-1540-78	0.01 to 0.6 mg/L	Not available	d
	3	I-2540-78[1]	0.01 to 1.0 mg/L	Not available	d
	3	I-4540-78[1]	0.01 to 1.0 mg/L	Not available	t
	4	354.1	0.01 to 1.0 mg/L	Not available	t

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines-A.1. (I-2545-78, 353.2, and 353.3); Sediments-A.1. (I-6545-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Cool immediately to 4°C.
PRESERVATIVE: Extended analytical time can be obtained by adding H_2SO_4 to pH 2.0.
STORAGE: Analyze within four weeks.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Cadmium reduction diazotization	1	D3867-79(A)[1]	0.05 to 1.0 mg/L	ST = 0.0437	d
	1	D3867-79(B)	0.05 to 1.0 mg/L	NO_2-N ST = 0.0901X + 0.035, NO_3-N ST = 0.057	d
	2	418C	0.01 to 1 mg/L	Not available	d
	3	I-2545-78[1]	0.1 to 5 mg/L	ST = .080X + .011	d
	3	I-4545-78[1]	0.1 to 5 mg/L	RD = >14% at 0.45 mg/L	t
	3	I-6545-78[1]	2 to 5 mg/kg	RD = >14%	t.r.
	4	353.2[1]	0.05 to 10 mg/L	SD = 0.012 at 0.29 mg/L	t
	4	353.3	0.01 to 1.0 mg/L	SD = 0.005 at 0.04 mg/L	t
2. Hydrazine reduction diazotization	4	353.1[1]	0.01 to 10 mg/L	SD = 0.02 at 0.39 mg/L	t

IV. REPORTING: Data should be reported in units of mg/L for water and mg/kg for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

Nitrogen, Total Kjeldahl
(NH_3 plus organic-N)

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines-A.1. (D3590-77, 420, I-1550-78, 351.3), A.2. (I-2551-78, I-4551-78, 351.1), B. (D3590-77, 351.3); C. (D3590-77, 420, and 351.3); Sediments-A.2. (I-6551-78) and A.3. (I-6552-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Cool to 4°C.
PRESERVATIVE: H_2SO_4 to pH 2.0. or less.
STORAGE: Analyze as soon as possible but within four weeks.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Nesslerization	1	D3590-77	≤1 mg/L	SD = 1.056 at 4.1 mg/L	t.r.
	2	420A	0.2 to 5 mg/L	RSD = 52% at 0.80 mg/L	t
	3	I-1550-78	0.01 to 2 mg/L	Not available	d
	4	351.3	≤1 mg/L	SD = 1.056 at 4.1 mg/L	t
2. Phenate	3	I-2551-78[1]	0.01 to 2 mg/L	Not available	d
	3	I-4551-78[1]	0.01 to 2 mg/L	Not available	t
	3	I-6551-78[1]	≥1 mg/kg	Not available	t.r.
	4	351.1[1]	0.05 to 2 mg/L	SD = 0.54 at 1.89 mg/L	t
3. Salicylate-hypochlorite	3	I-2552-78[1]	0.1 to 10 mg/L	RD = 18% at 0.38 mg/L	d
	3	I-4552-78[1]	0.1 to 10 mg/L	RD = 18% at 0.38 mg/L	t
	3	I-6552-78[1]	≥10 mg/Kg	RD = > 18%	t.r.
	4	351.2	0.1 to 20 mg/L	SD = 0.07 at 1.2 mg/L	t
B. Potentiometric	1	D3590-77	0.05 to 1400 mg/L	Not available	t.r.
	4	351.3	0.05 to 1400 mg/L	Not available	t
	4	351.4	0.03 to 25 mg/L	Not available	t
C. Titrimetric	1	D3590-77	≥1 mg/L	SD = 1.05 at 4.1 mg/L	t.r.
	2	420A	Not available	RSD = 55% at 1.5 mg/L	t
	4	351.3	≥1 mg/L	Not available	t

IV. REPORTING: Data should be reported in units of mg/L for water and mg/kg for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

Oxidation-reduction potential
(ORP)

I. APPLICATION: The method generally is applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: None required. Protect against gain or loss of gases.
PRESERVATIVE: None required.
STORAGE: This sample must not be stored. Analyze immediately.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Potentiometric	1	D1498-76	See Table 1	± 10 mV	t

IV. REPORTING: Data should be reported in units of mV for water. Report data to the nearest 10 mV.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water, brines, ocean water, and waste waters.

II. SAMPLE:

CONTAINER: Collect in glass and avoid aeration. (Procedure A).
FIELD TREATMENT: Analyze as soon as possible or preserve as described below in Procedure B.
PRESERVATIVE: Add manganous sulfate, alkali azide, and sulfuric acid reagents (Procedure B).
STORAGE: This sample must not be stored; analyze immediately after collection (Procedure A); store in a cool place, out of direct sunlight, and complete analysis within 8 hours after preservation (Procedure B).

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Electrometric: oxygen-probe electrode[1]	2	421F	Not available	±0.05 mg/L	d
	3	I-1577-78	≥0.1 mg/L	Not available	d
	4	360.1	0 to 20 mg/L	±0.05 mg/L	d
	7	Sec. 14, pp. 40–43	≥0.1 mg/L	Not available	d
B. Titrimetric: Alsterberg-azide modification of the Winkler method	1	D1589-80(A)	≥0.1 mg/L	Not available	d
	2	421B	Not available	SD = 20 μg/L to 100 μg/L	d
	3	I-1575-78	≥0.1 mg/L	Not available	d
	4	360.2	Not available	Approx. ±0.2 at 7.5 mg/L	d
	7	Sec. 15, pp. 44–47	≥0.1 mg/L	Not available	d
	8	pp. 75–81	≥0.1 mg/L	Not available	d

IV. REPORTING: Data should be reported in units of mg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. When precision is not known, two significant figures generally are applicable.

[1]See Section 5.G for electrode calibration procedure.

Date Approved: May 1, 1981

.pH

I. APPLICATION: The methods generally are applicable to the analysis of fresh water, brines, ocean water, and atmospheric deposition.

II. SAMPLE:

CONTAINER: Glass or plastic. For atmospheric deposition samples, use only polyethylene.
FIELD TREATMENT: None required.
PRESERVATIVE: None required.
STORAGE: Analyze immediately.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Electrometric: 1. Glass electrode[1]	1	D1293-78(A)	See table 1	±0.05 pH unit	t
	2	423	0 to 14	±0.02 pH unit	t
	3	I-1586-78	0 to 14	SD = 0.16 at pH 7.71; 0.22 at pH 8.10	t
	4	150.1	0 to 14	SD = 0.10 to 0.20; within range pH 3.5 to 8.0	t

IV. REPORTING: Data should be reported in pH units. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. When precision is not known, two significant figures generally are applicable.

[1]See Section 5.G for electrode calibration procedure.

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water, waste water, and atmospheric deposition. Special applications are: Ocean water and Brines-A. (Refs. 5 and 9).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat samples according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Add concentrated H_2SO_4 to pH less than 2.0 or H_gCl_2 to 40 mg/L, and cool to 4°C.
STORAGE: Analyze within 7 days.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM[2]
A. Colorimetric	1	D515-78(A)	0.01 to 0.5 mg/L	See Table 1.	d,t.r.
	1	D515-78(B)	0.1 to 3 mg/L	ST = 0.65X/V	d,t.r.
			0.03 to 1 mg/L	ST = (1.4X − 0.31)/V	d,t.r.
	1	D515-78(C)	1 to 10 mg PO_4/L	ST = (0.31X + 3.1)/V	
	2	424	0.01 to 6 mg/L	See Table 424: III	t,t.r.,d
	2	424G[1]	0.001 to 10.0 mg/L	SD = 0.019 to 0.087 at 0.040 to 0.300 mg/L	d
	3	I-1600-78	0.02 to 0.4 mg/L	RSD = 50% at 0.06 mg/L; 20% at 0.45 mg/L	d
	3	I-1601-78	0.02 to 0.4 mg/L	RSD = 22% at 0.036 mg/L; 6% at 0.326 mg/L	d
	3	I-1602-78	0.02 to 0.4 mg/L	RSD = >50% at 0.06 mg/L	d
	3	I-1603-78	0.02 to 0.4 mg/L	Not available	d
	3	I-2600-78[1]	0.01 to 2.0 mg/L	RSD = 12% at 0.197 mg/L; 3% at 0.670 mg/L	d
	3	I-2602-78[1]	0.01 to 2.0 mg/L	RSD = >12% at 0.20 mg/L	d
	3	I-4602-78[1]	0.01 to 2.0 mg/L	RSD = >12% at 0.20 mg/L	t
	3	I-2603-78[1]	0.01 to 2.0 mg/L	Not available	d
	3	I-4603-78[1]	0.01 to 2.0 mg/L	Not available	t
	3	I-2601-78[1]	0.01 to 2.0 mg/L	RSD = 20% at 0.050 mg/L 16% at 0.168 mg/L	d
	3	I-4601-78[1]	0.01 to 2.0 mg/L	RSD = 20% at 0.050 mg/L	t
	3	I-4600-78[1]	0.01 to 2.0 mg/L	RSD = 12% at 0.197 mg/L; 3% at 0.67 mg/L	t
	4	365.2	0.01 to 0.5 mg/L	SD = 0.033 at 0.110 mg/L (f) 0.023 at 0.383 mg/L (t)	t,d
	4	365.3	0.01 to 1.2 mg/L	Not available	t,d
	4	365.1[1]	0.001 to 1.0 mg/L	SD = 0.014 at 0.04 mg/L	t,d
	4	365.4[1]	0.01 to 20 mg/L	SD = 0.01 at 0.23 mg/L;	t
	5	p. 29	0.1 to 10 mg/L	RSD = approximately 5%	d
	9	pp. 105-107	0.1 to 10 mg/L	RSD = approximately 5%	d

IV. REPORTING: Data should be reported in units of mg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated
[2]see reference for specific speciation.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Brines–A.1. (D3561–77, Refs. 6 and 9) and B.1. (Refs. 5 and 9); Ocean water–A.1. (D3561–77, Refs. 6 and 9) and B.1. (Refs. 5 and 9); Waste water–A.1. (Refs. 3 and 4) and B.1. (D1428–64(A), Ref. 2).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3561–77	0.1 to 70,000 mg/L	ST = 0.1443X–2.317	d
	2	322A	0.1 to 2 mg/L	Not available	d
	3	I–1630–78	0.1 to 100 mg/L	RD = 14% at 0.8 mg/L; 11% at 5.2 mg/L	d
	3	I–3630–78	0.1 to 100 mg/L	RD = > 14% at 0.8 mg/L; 11% at 5.2 mg/L	t.r.
	4	258.1	0.1 to 2 mg/L	SD = 0.2 at 1.6 mg/L	d,t,s
	6	pp. 2–10	≥0.1 mg/L	Not available	d
	9	pp. 70–71	≥0.1 mg/L	SD = 25 at 456 mg/L; 325 at 5680 mg/L	d
B. Atomic Emission					
1. Flame	1	D1428–64(A)	1 to 100 mg/L	ST = 0.009X + 0.45	d,t
	2	322B	≥0.1 mg/L	RSD = 15.5% at 3.1 mg/L	d,t
	5	pp. 44–45	≥0.1 mg/L	Approx. 3% of amt. present	d
	9	pp. 58–59	≥0.1 mg/L	Approx. 3% of amt. present	d

IV. REPORTING: Data should be reported in units of mg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Selenium (Se)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Furnace	4	270.2	5 to 100 μg/L	RSD = 14.2% at 5 μg/L; 6.4% at 50 μg/L	d,t,s
2. Vapor	1	D3859-79	1 to 20 μg/L	ST = 0.146X + 0.49	d,t.r.
	2	323A	0.002 to 0.02 mg/L	RSD = 11% at 0.01 mg/L	d,t
	3	I-1667-78	≥1 μg/L	RSD = 29% at 3.5 μg/L; 27% at 8.5 μg/L; 47% at 18.6 μg/L	d
	3	I-3667-78	≥1 μg/L	RSD = 24% at 3.5 μg/L; 47% at 18.6 μg/L	t
	4	270.3	5 to 100 μg/L	SD = 0.6 at 5 μg/L; 1.2 at 10 μg/L	d,t,s
B. Colorimetric	2	323B,C	1 to 100 μg/L	RSD = 21.2% at 20 μg/L	d,t.r.

IV. REPORTING: Data should be reported in units of μg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Silica (SiO_2)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: None required.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption	2	425A	5 to 150 μg/L	Not available	d
	3	I-1702-78	0.5 to 35 mg/L	RSD = 22% at 3.9 mg/L; 9% at 11.0 mg/L; 4% at 16.5 mg/L	d
B. Colorimetric	1	D859-80(B)	20 to 1000 μg/L	ST = 0.03X + 1.3	d
	2	425D	>20 μg/L	RSD = 27.2% at 5.0 mg/L; 18.0% at 15.0 mg/L; 4.9% at 30.0 mg/L	d
	3	I-1700-78	0.1 to 100 mg/L	ST = 0.031X + 0.60	d
	3	I-2700-78[1]	0.1 to 60 mg/L	ST = 0.087X − 0.148	d
	4	370.1	2 to 35 mg/L	RSD = 14.3% at 5 mg/L	d
C. Gravimetric	1	D359-80(A)	>5 mg/L	ST = (0.0085X + 0.55)/V	t
	2	425B	≥20 mg/L	SD = ±0.2 mg/L	d,t

IV. REPORTING: Data should be reported in units of mg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify with nitric acid to pH 2.0 or less.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3866-80(B)	0.1 to 10 mg/L	ST = 0.0425X + 0.0004	d,t.r.
	2	324A	100 to 4000 μg/L	RSD = 17.5% at 550 μg/L	d,t.r.
	3	I-1720-78	1 to 10 μg/L	RSD = 14% at 3.2, 6.4, and 10.0 μg/L	d
	3	I-3720-78	1 to 10 μg/L	RSD = > 14%	t.r.
	4	272.1	100 to 4000 μg/L	SD = 8.8 at 50 μg/L	d,t
2. Furnace	1	D3866-80(A)	1 to 10 μg/L	See fig. 1, 2	d,t.r.
	4	272.3	1 to 25 μg/L	SD = 0.4 at 25 μg/L; = 0.7 at 50 μg/L	d,t

IV. REPORTING: Data should be reported in units of μg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Sodium (Na)

I. APPLICATION: Methods generally are applicable for the analysis of fresh water. Special applications are: Brines-A.1. (D3561-77, I-1735-78); B.1. (D1428-64(A) and (B), D3561-77); Sediments-A.1. (I-5735-78, I-3735-78, I-3736-78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 with nitric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D3561-77	0.1 to 70,000 mg/L	ST = 0.08905X + 729	d
	2	325A	0.03 to 1 mg/L	Not available	d,t
	3	I-1735-78	0.1 to 80 mg/L	ST = 0.039X + 0.448	d
	3	I-5735-78	≥ 10 mg/kg	RD = > 9% in lower range; > 4% in upper range	t.r.
	3	I-3735-78	0.1 to 80 mg/L	RD = > 9% at 3.44 mg/L	t.r.
	4	273.1	0.03 to 1.0 mg/L	SD = 0.8 at 52 mg/L	d,s,t
	6	pp. 2-10	≥ 0.1 mg/L	SD = 3.2 at 147.8 mg/L	d
	9	pp. 68-70	0.1 to 70,000 mg/L	SD = 3.2 at 147.8 mg/L	d
B. Atomic emission					
1. Flame	1	D1428-64(A)	1.0 to 100 mg/L	ST = 0.011X + 0.64	d
	1	D1428-64(B)	0.25 to 1000 μg/L	ST = 0.006X + 0.09	d
	2	325B	> 10 μg/L	RSD = 17.3% at 19.9 mg/L	d
	5	pp. 43-44	≥ 0.1 mg/L	3% of amount present	d

IV. REPORTING: Data should be reported in units of mg/L for water and mg/kg for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water–A.1. (D–3352–74, I–1800–78, I–5800–78) and B.1. (326B); Brines–A.1. (D3352–74, I–1800–78, I–5800–78, I–3800–78), B.1. (326B) and B.2. (Refs. 5 and 9); Sediments–A.1. (I–5800–78, I–3800–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 with nitric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	2	326A	0.03 to 5 mg/L	Not available	d,t
	1	D3352–74	5 to 2100 mg/L	ST = 0.0929X + 2.596	d
	3	I–1800–78	10 to 5000 μg/L	ST = 0.104X + 15.4	d
	3	I–5800–78	≥1.0 μg/g	RD = 9–34%	s
	3	I–3800–78	10 to 5000 μg/L	RD = 34% at 82 μg/L	t.r.
	6	pp. 2–10	≥0.2 mg/L	SD = 0.282 at 3.325 mg/L	d
	9	pp. 76–77	≥0.2 mg/L	SD = 0.282 at 3.325 mg/L	d
B. Atomic emission					
1. Flame	2	326B	>0.2 mg/L	SD = ±2 mg/L at 16 mg/L	d
2. Plasma arc	5	pp. 39–41	≥0.5 mg/L	2–3% of amount present	d
	9	pp. 83–89	Not available	Not available	d

IV. REPORTING: Data should be reported in units of mg/L for water and μg/g for sediment. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water–B.1. (Refs. 7 and 8) and D.1. (Ref. 8); Brines–B.1. (Refs. 5, 7, 8, and 9) and D.1. (Refs. 5 and 8).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat samples as recommended in 5.B.6. (b and c).
PRESERVATIVE: Cool to 4°C.
STORAGE: Approximately 7 days.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Chloroanilate	4	375.1[1]	10 to 400 mg/L	SD = 1.0 at 111 mg/L	d
2. Methylthymol blue	3	I-2822-77	5 to 300 mg/L	ST = 0.001X + 2.92	d
	4	375.2[1]	3 to 300 mg/L	SD = 1.6 at 110 mg/L	d
B. Gravimetric					
1. Precipitated barium sulfate	1	D516-68(A)	20 to 100 mg/L	1% of amount present	d,t.r.,t
	2	426A	≥ 10 mg/L	RSD = 4.7% at 259 mg/L	d,t.r.,t
	2	426B	≥ 10 mg/L	Not available	t.r.
	4	375.3	≥ 10 mg/L	RSD = 4.7% at 259 mg/L	d,t.r,t
	5	p. 14	≥ 10 mg/L	RSD = Approx. 1-2% at 2000 mg/L	d
	7	pp. 71-73	≥ 10 mg/L	RSD = Approx. 1-2% at 2000 mg/L	d
	8	pp. 94-96	≥ 10 mg/L	RSD = Approx. 1-2% at 2000 mg/L	d
	9	pp. 114-115	≥ 10 mg/L	RSD = Approx. 1-2% at 2000 mg/L	d
C. Titrimetric					
1. Thorin	1	D516-68(C)	5 to 1000 mg/L	SD = Approx. 0.7 at 5 to 100 mg/L	d
	3	I-1820-78	0.5 to 20 mg/L	ST = 0.046X + 0.575	d
D. Turbidimetric					
1. Barium sulfate suspension	1	D516-68(B)	10 to 100 mg/L	Approx. 5% of amount present	d
	2	426C	1 to 40 mg/L	RSD = 9.1% at 259 mg/L	d
	4	375.4	1 to 40 mg/L	RSD = 9.1% at 259 mg/L	d
	5	pp. 15-16	≥ 10 mg/L	2-3% in 100-100 mg/L range	d
	8	pp. 97-98	≥ 10 mg/L	2-3% in 100-1000 mg/L range	d

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

Sulfide (S)

I. APPLICATION: The methods generally are applicable for the analysis of fresh water. Special applications are: Ocean water–A.1. (D376.2) and B.1. (376.1); Brines–A.1. (376.2) and B.1. (376.1); Sediment–B.1. (I–3840–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: If acidic, neutralize with alkali immediately and add 2 grams zinc acetate per liter of sample.
STORAGE: Analyze as soon as possible.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Colorimetric					
1. Methylene blue	2	427C	>1 mg/L	Not available	d,t
	4	376.2	0.1 to 20 mg/L	Not available	d,t
B. Titrimetric	2	427D	≥0.1 mg/L	Varies with sample type	d,t
	3	I–3840–78	≥0.5 mg/L	Not available	t
	4	376.1	≥1.0 mg/L	Not available	d,t

IV. REPORTING: Data should be reported in units of mg/L. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Sulfite (SO_3)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Determine on sample.
PRESERVATIVE: None.
STORAGE: None.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Titrimetric					
1. Iodometric	1	D1339(A)	0.1 to 6.0 mg/L	ST = 0.2	t
	1	D1339(B)	≥6.0 mg/L	So = 0.12 at 10.3 mg/L	t
	1	D1339(C)	≥3.0 mg/L	So = 1.0 mg/L	t
	2	428	≥2.0 mg/L	Not available	t
	4	377.1	≥2 mg/L	Not available	t

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Thallium (Tl)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with nitric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	4	279.1	1 to 20 mg/L	SD = 0.05 at 3 mg/L	d,s,t
2. Furnace	4	279.2	5.0 to 100 μg/L	Not Available	d,s,t

IV. REPORTING: Data should be reported in units of mg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

Tin (Sn)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with HCl or HNO_3.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	2	303A	10–200 mg/L	Not available	t,d
	3	I-1850-78	100 to 10,000 μg/L	Not available	d
	3	I-3850-78	100 to 10,000 μg/L	Not available	t.r.
	4	282.1	10 to 300 mg/L	SD = 0.25 at 4.0 mg/L	d,s,t
2. Furnace	4	282.2	20 to 300 μg/L	Not available	d,s,t

IV. REPORTING: Data should be reported in units of μg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

Date Approved: May 1, 1981

I. APPLICATION: These methods generally are applicable for the analysis of fresh water.

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with HNO_3 only for Procedure A.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	2	327A	2–100 mg/L	Not available	d,t
	4	286.1	2 to 100 mg/L	SD = 0.1 at 10 mg/L	d,s
2. Furnace	4	286.2	10 to 200 μg/L	Not Available	d,s
B. Colorimetric					
1. Catalytic oxidation	1	D3373–80	1 to 8 μg/L	ST = 0.07X + 0.42	d
	2	327B	>2.0 μg/L	RSD = 20% at 6 μg/L	d
	3	I–1880–78	0.1 to 100 μg/L	ST = 0.069X + 0.422	d
	3	I–2880–78[1]	1 to 10 μg/L	Not available	d

IV. REPORTING: Data should be reported in units of μg/L for water. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

[1]automated

Date Approved: May 1, 1981

Zinc (Zn)

I. APPLICATION: These methods generally are applicable for the analysis of fresh water. Special applicatios are: Brines–A.1. (Ref. 6, pp. 2–11 and Ref. 9); Sediments–A.1. (I–5900–78).

II. SAMPLE:

CONTAINER: Glass or plastic.
FIELD TREATMENT: Treat sample according to desired form as recommended in 5.B.6. (b and c).
PRESERVATIVE: Acidify to pH 2.0 or less with nitric acid.
STORAGE: Approximately six months.

III. ANALYSIS:

PROCEDURE	REF.	METHOD	RANGE/UNITS	ESTIMATE OF PRECISION	FORM
A. Atomic absorption					
1. Flame	1	D1691–77(C)	0.01 to 2 mg/L	See figure 1	d,t.r.
	1	D1691–77(D)	1 to 200 μg/L	See figure 2	d,t.r.
	1	D2576–70	0.02 to 3.0 mg/L	ST = 0.05X + 0.01	d
	2	328A	0.05–2 mg/L	RSD = 8.2% at 500 μg/L	d,t.r.
	3	I–1900–78	10 to 500 μg/L	ST = 0.34X + 16.6	d
	3	I–5900–78	≥1.0 μg/g	RD = 7–55%	t.r.
	3	I–3900–78	10 to 500 μg/L	RSD = 35% at 41 μg/L; 7% at 437 μg/L	t.r.
	4	289.1	0.05 to 1 mg/L	SD = 0.097 at 0.284 mg/L	d,t.r.
	6	pp. 10–11	≥1.0 μg/L	SD = 0.54 at 12.2 μg/L	d
	6	pp. 2–10	≥0.2 mg/L	SD = 0.021 at 0.263 mg/L	d
	9	pp. 80–81	≥0.2 mg/L	SD = 0.021 at 0.263 mg/L	d
2. Furnace	4	289.2	0.05 to 4.0 μg/L	Not available	d,t.r.
B. Colorimetric					
1. Dithizone	2	328B	≥1 μg/L	RSD = 18.2% at 650 μg/L	d
	2	328C	≥2 μg/L	Not available	d
2. Zincon	1	D1691–77(A)	0.02 to 5 mg/L	ST = 0.05 mg/L	d,t.r.
	2	328D	>0.02 mg/L	RSD = 0.96% at 650 μg/L	d

IV. REPORTING: Data should be reported in units of μg/L for water and μg/g for sediments. The number of significant figures to be used in reporting data is related directly to the sensitivity and precision of the method of analysis. Where precision is not known, two significant figures generally are applicable.

5.E. DETERMINATION OF ORGANIC CONSTITUENTS

5.E.1. CONSTITUENTS SPECIFIED

Constituent Determined	*Class*
1. acenaphthene	hydrocarbons, polynuclear aromatic
2. acenaphthylene	hydrocarbons, polynuclear aromatic
3. acetonitrile	nitriles
4. acrolein	nitriles
5. acrylonitrile	nitriles
6. aldrin	insecticides, organochlorine
7. allyl chloride	hydrocarbons, halogenated
8. ametryn	herbicides, triazine
9. aminocarb (Matacil)	insecticides, carbamate
10. animal fats	oil and grease
11. anthracene	hydrocarbons, polynuclear aromatic
12. aroclor 1016, 1221, 1232, 1242, 1248, 1254, and 1260 (polychlorinated biphenyls, PCB's)	hydrocarbons, halogenated aromatic
13. arprocarb (Baygon, propoxur)	insecticides, carbamate
14. atraton	herbicide, triazine
15. atrazine	herbicides, triazine
16. azinphos-methyl (Guthion)	insecticides, organophosphorus
17. barban	herbicides, carbamate
18. Baygon (arprocarb, propoxur)	insecticides, carbamate
19. benzene	hydrocarbons, aromatic
20. benzene hexachloride (BHC)	insecticides, organochlorine
21. benzidine	hydrocarbons, halogenated aromatic amine
22. benzo[a]anthracene	hydrocarbons, polynuclear aromatic
23. benzo[b]fluoranthene	hydrocarbons, polynuclear aromatic
24. benzo[k]fluoranthene	hydrocarbons, polynuclear aromatic
25. 2,3-benofuran	hydrocarbons, aromatic
26. benzo[ghi]perylene	hydrocarbons, polynuclear aromatic
27. benzo[a]pyrene	hydrocarbons, polynuclear aromatic
28. benzyl butyl phthalate	esters, phthalate
29. BHC (benzene hexachloride)	insecticides, organochlorine
30. 1-BHC	insecticides, organochlorine
31. b-BHC	insecticides, organochlorine
32. s-BHC	insecticides, organochlorine
33. y-BHC	insecticides, organochlorine
34. bromobenzene	hydrocarbons, halogenated aromatic
35. bromochloromethane	hydrocarbons, halogenated
36. bromodichloromethane	hydrocarbons, halogenated
37. 4-bromofluorobenzene	hydrocarbons, halogenated aromatic
38. bromoform	hydrocarbons, halogenated
39. bromomethane	hydrocarbons, halogenated
40. 4-bromophenyl phenyl ether	ethers, halogenated aromatic
41. n-butylbenzene	hydrocarbons, aromatic
42. s-butylbenzene	hydrocarbons, aromatic
43. t-butylbenzene	hydrocarbons, aromatic
44. butyronitrile	nitriles
45. captan	fungicides, organochlorine
46. carbaryl (Sevin)	insecticides, carbamate

Constituent Determined	*Class*
47. carbofuran	insecticides, carbamate
48. carbon, all forms	carbon
49. carbon tetrachloride	hydrocarbons, halogenated
50. chlordane	insecticides, organochlorine
51. chlorobenzene	hydrocarbons, halogenated aromatic
52. chlorocyclohexane	hydrocarbons, halogenated
53. 1-chlorocyclohexene	hydrocarbons, halogenated
54. chlorodibromomethane	hydrocarbons, halogenated
55. chloroethane	hydrocarbons, halogenated
56. *bis* (2-chloroethoxy) methane	ethers, halogenated
57. *bis* (2-chloroethyl) ether	ethers, halogenated
58. 2-chloroethyl ethyl ether	ethers, halogenated
59. 2-chloroethyl vinyl ether	ethers, halogenated
60. chloroform	hydrocarbons, halogenated
61. *bis* (2-chloroisopropyl)	ethers, halogenated
62. chloromethane	hydrocarbons, halogenated
63. 4-chloro-3-methylphenol	phenols
64. 2-chloronaphthalene	hydrocarbons, halogenated aromatic
65. 2-chlorophenol	phenols
66. 4-chlorophenyl phenyl ether	ethers, halogenated aromatic
67. 2-chlorotoluene	hydrocarbons, halogenated aromatic
68. 4-chlorotoluene	hydrocarbons, halogenated aromatic
69. chlorpropham (CIPC)	herbicides, carbamate
70. chlorpyrifos	insecticides, organophosphorus
71. chrysene	hydrocarbons, polynuclear aromatic
72. CIPC (chlorpropham)	herbicides, carbamate
73. cresols	phenols
74. cyclopropylbenzene	hydrocarbons, aromatic
75. p-cymene (1-isopropyl-4-methylbenzene)	hydrocarbons, aromatic
76. 2, 4-D	herbicides, chlorinated phenoxy acid
77. DDD	insecticides, organochlorine
78. DDE	insecticides, organochlorine
79. DDT	insecticides, organochlorine
80. demeton	insecticides, organophosphorus
81. desmetryne	herbicides, triazine
82. diazinon	insecticides, organophosphorus
83. diazinon-oxon	insecticides, organophosphorus
84. dibenzo[a,h]anthracene	hydrocarbons, polynuclear aromatic
85. dibromochloromethane	hydrocarbons, halogenated
86. 1,2-dibromoethane	hydrocarbons, halogenated
87. dibromomethane	hydrocarbons, halogenated
88. di-n-butyl phthalate	esters, phthalate
89. dicamba	herbicides, chlorinated aromatic acid
90. 1, 2-dichlorobenzene	hydrocarbons, halogenated aromatic
91. 1, 3-dichlorobenzene	hydrocarbons, halogenated aromatic
92. 1, 4-dichlorobenzene	hydrocarbons, halogenated aromatic
93. 3, 3′-dichlorobenzidine	hydrocarbons, halogenated aromatic amine
94. dichlorodifluoromethane	hydrocarbons, halogenated
95. 1, 1-dichloroethane	hydrocarbons, halogenated
96. 1, 2-dichloroethene	hydrocarbons, halogenated
97. 1, 1-dichloroethene	hydrocarbons, halogenated
98. *cis*-1, 2-dichloroethene	hydrocarbons, halogenated

Constituent Determined	Class
99. *trans*-1, 2-dichloroethene	hydrocarbons, halogenated
100. dichloromethane	hydrocarbons, halogenated
101. 2, 3-dichlorophenol	hydrocarbons, halogenated phenols
102. dichlorophenols	phenols
103. 1, 2-dichloropropane	hydrocarbons, halogenated
104. 1, 3-dichloropropane	hydrocarbons, halogenated
105. 1, 1-dichloropropene	hydrocarbons, halogenated
106. *cis*-1, 3-dichloropropene	hydrocarbons, halogenated
107. *trans*-1, 3-dichloropropene	hydrocarbons, halogenated
108. 2, 3-dichloropropene	hydrocarbons, halogenated
109. dicloran (DCNA)	herbicides, organochlorine
110. dieldrin	insecticides, organochlorine
111. diethyl phthalate	esters, phthalate
112. dimethoate	insecticides, organophosphorus
113. 2, 4-dimethylphenol	phenols
114. dimethyl phthalate	esters, phthalate
115. dinitroglycerin (DNG)	explosives
116. 2, 4-dinitrophenol	phenols
117. 2, 4-dinitrotoluene	hydrocarbons, nitroaromatics
118. 2, 6-dinitrotoluene	hydrocarbons, nitroaromatics
119. di-n-octyl phthalate	esters, phthalate
120. disulfoton	insecticides, organophosphorus
121. Di-Syston	insecticides, organophosphorus
122. diuron	herbicides, carbamate
123. DNG (dinitroglycerin)	explosives
124. endosulfan	insecticides, organochlorine
125. endosulfan-I	insecticides, organochlorine
126. endosulfan-II	insecticides, organochlorine
127. endosulfan sulfate	insecticides, organochlorine
128. endrin	insecticides, organochlorine
129. EPN	insecticides, organophosphorus
130. ethion	insecticides, organophosphorus
131. ethylbenzene	hydrocarbons, aromatic
132. *bis* (2-ethylhexyl) phthalate	esters, phthalate
133. ethyl parathion	insecticides, organophosphorus
134. fats, animal	oil and grease
135. fenitrothion	insecticides, organophosphorus
136. fenuron	herbicides, carbamate
137. fluoranthene	hydrocarbons, polynuclear aromatic
138. fluorene	hydrocarbons, polynuclear aromatic
139. fluorotrichloromethane	hydrocarbons, halogenated
140. greases	oil and grease
141. GS-13529	herbicides, triazine
142. GS-14254	herbicides, triazine
143. Guthion (azinphos methyl)	insecticides, organophosphorus
144. heptachlor	insecticides, organochlorine
145. heptachlor epoxide	insecticides, organochlorine
146. hexachlorobenzene	fungicides, organochlorine
147. hexachlorobutadience	hydrocarbons, halogenated
148. hexachlorocyclopentadiene	hydrocarbons, halogenated
149. hexachloroethane	hydrocarbons, halogenated
150. hexachlorophene	phenols

Constituent Determined	*Class*
151. hydrocarbons: aliphatic and aromatic, C_1–C_{10}	hydrocarbons, petroleum
152. hydrocarbons: aliphatic, C_{10}–C_{22}	hydrocarbons, petroleum
153. hydrocarbons: aliphatic, C_{14}–C_{35}	hydrocarbons, petroleum
154. hydrocarbons: aromatic, 1- to 3-ring	hydrocarbons, petroleum, aromatic
155. hydrocarbons: aromatic, 3- to 6-ring	hydrocarbons, petroleum, aromatic
156. hydrocarbons: 2 percent soluble in water and boiling below 150°C	hydrocarbons, petroleum
157. hydrocarbons, relatively nonvolatile	oil and grease
158. indeno[1, 2, 3-cd]pyrene	hydrocarbons, polynuclear aromatic
159. IPC (propham)	herbicides, carbamate
160. isophorone	ketone, a,b-unsaturated
161. isopropylbenezene	hydrocarbons, aromatic
162. 3-ketocarbofuran	insecticides, carbamate
163. lindane	insecticides, organochlorine
164. linuron	herbicides, carbamate
165. malathion	insecticides, organophosphorus
166. Metacil (aminocarb)	insecticides, carbamate
167. Mesurol (methiocarb, metmercapturon)	insecticides, carbamate
168. methidathion	insecticides, organophosphorus
169. methiocarb (Mesurol, metmercapturon)	insecticides, carbamate
170. methoxy-acetonitrile	nitriles
171. methoxychlor	insecticides, organochlorine
172. 2-methyl-4, 6-dinitrophenol	phenols
173. methyl parathion	insecticides, organophosphorus
174. methylene blue active substances (MBAS)	surfactants (anionic)
175. methylene chloride	hydrocarbons, halogenated
176. metmercapturon (Mesurol, methiocarb)	insecticides, carbamate
177. mirex	insecticides, organochlorine
178. Mobam	insecticides, carbamate
179. monochlorophenols	phenols
180. monuron	herbicides, carbamate
181. naphthalene	hydrocarbons, polynuclear aromatic
182. neburon	herbicides, carbamate
183. NG (nitroglycerin)	explosives
184. nitrobenzene	hydrocarbons, nitroaromatic
185. 2-nitrophenol	phenols
186. 4-nitrophenol	phenols
187. N-nitrosodimethylamine	nitrosamines
188. N-nitrosodiphenylamine	nitrosamines
189. N-nitrosodi-n-propylamine	nitrosamines
190. organic matter, solvent extractable	organic matter
191. parathion	insecticides, organophosphorus
192. PCBs	hydrocarbons, halogenated aromatic
193. PCNB (Pentachloronitrobenzene)	fungicides, organochlorine
194. PCP (Pentachlorophenol)	phenols
195. pentachloroethane	hydrocarbons, halogenated
196. phenanthrane	hydrocarbons, polynuclear aromatic
197. phenol	phenols
198. phosalone	insecticides, organophosphorus
199. phosmet	insecticides, organophosphorus
200. B-phosphamidon	insecticides, organophosphorus
201. prometon	herbicides, triazine

Constituent Determined	*Class*
202. prometryn	herbicides, triazine
203. propazine	herbicides, triazine
204. propham (IPC)	herbicides, carbamate
205. propionitrile	nitriles
206. propoxur (Baygon, arprocarb)	insecticides, carbamate
207. n-propylbenzene	hydrocarbons, aromatic
208. pyrene	hydrocarbons, polynuclear
209. RDX	explosives
210. Ronnel	insecticides, organophosphorus
211. Ruelene	insecticides, organophosphorus
212. Sevin (carbaryl)	insecticides, carbamate
213. siduron	herbicides, carbamate
214. silvex	herbicides, chlorinated phenoxy acid
215. simazine	herbicides, triazine
216. simetryn	herbicides, triazine
217. soaps	oil and grease
218. solvents, halogenated	hydrocarbons, halogenated and hydrocarbons, halogenated aromatic
219. solvents, volatile organic	hydrocarbons, aromatic and hydrocarbons, halogenated
220. Strobane	insecticides, organochlorine
221. styrene	hydrocarbons, aromatic
222. swep	herbicides, carbamate
223. Systox	insecticides, organophosphorus
224. 2,4,5-T	herbicides, chlorinated phenoxy acid
225. tannin and lignin	hydrocarbons, aromatic alcohol
226. terbutryn	herbicides, triazine
227. 2,3,7,8-tetrachlorodibenzo-p-dioxin	hydrocarbons, halogenated aromatic
228. 1,1,1,2-tetrachloroethane	hydrocarbons, halogenated
229. 1,1,2,2-tetrachloroethane	hydrocarbons, halogenated
230. 1,1,2,2-tetrachloroethane	hydrocarbons, halogenated
231. TNT (2,4,6-trinitrotoluene)	explosives, hydrocarbons, nitroaromatics
232. toluene	hydrocarbons, aromatic
233. toxaphene	insecticides, organochlorine
234. 1,2,3-trichlorobenzene	hydrocarbons, halogenated aromatic
235. 1,2,4-trichlorobenzene	hydrocarbons, halogenated aromatic
236. 1,1,1-trichloroethane	hydrocarbons, halogenated
237. 1,1,2-trichloroethane	hydrocarbons, halogenated
238. 1,1,2-trichloroethane	hydrocarbons, halogenated
239. trichlorofluoromethane	hydrocarbons, halogenated
240. 2,4,6-trichlorophenol	phenols
241. 1,2,3-trichloropropane	hydrocarbons, halogenated
242. trifluorotoluene	hydrocarbons, halogenated aromatic
243. trifluralin	herbicides, halogenated
244. 1,2,4-trimethylbenzene	hydrocarbons, aromatic
245. 1,3,5-trimethylbenzene	hydrocarbons, aromatic
246. trinitroglycerin (TNT)	explosives
247. 2,4,6-trinitrotoluene	explosives, hydrocarbons, nitroaromatics
248. 1,3,5-trinitro-1,3,5-triazacyclohexane (RDX)	explosives
249. Urab	herbicides, carbamate
250. Urox	herbicides, carbamate
251. vegetable oils	oil and grease

Constituent Determined	*Class*
252. vinyl chloride	hydrocarbons, halogenated
253. waxes	oil and grease
254. o-xylene	hydrocarbons, aromatic
255. m-xylene	hydrocarbons, aromatic
256. p-xylene	hydrocarbons, aromatic
257. Zectran	insecticides, carbamate

5.E.2. REFERENCES CITED

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5.E.3. ANALYTICAL METHODS

Approved: 9/80

Class: *Hydrocarbons, polynuclear aromatic*

Acenaphthene, acenaphthylene, anthracene, benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(ghi)perylene, benzo (k)fluoranthene, chrysene, dibenzo(a,h)anthracene, fluoranthene, fluorene, indeno (1,2,3-cd)pyrene, naphthalene, phenanthrene, pyrene

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. The sample bottle must not be prewashed with sample before collection.*

Container ..... *Glass bottle with teflon-lined cap.*

Preliminary treatment ... *Ice samples from the time of collection until extraction. If samples will not be extracted within 48 hours of collection, adjust sample to a pH of 6.0 to 8.0 with sodium hydroxide or sulfuric acid and add 35 mg of sodium thiosulfate per part per million of free chlorine per liter.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator until ready for extraction. All samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Methylene chloride extraction followed by HPLC with fluorescence or UV detection; or gas chromatography.*

Range ..... *HPLC with UV detection; 0.1 μg/L and higher. HPLC with fluorescence detection; 0.042 μg/L and higher.*

Precision .....

Reference ..... *No. 29.*

III. REPORTING

Units ..... *μg/L without recovery data correction.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Hydrocarbons, petroleum* *Hydrocarbons: aliphatic, C_{10}–C_{22}; aromatic, 1- to 3-ring*

I. SAMPLE

Applicability	*Fresh water and brackish water.*
Collection	*Collect in a cleaned 4-liter bottle (glass) contained in a stainless steel frame.*
Container	*Glass.*
Preliminary treatment ...	*Add mixture of internal standard compounds for subsequent quantitation.*
Preservative	*Freeze on a bed of dry ice.*
Storage	*Keep frozen till time of analysis.*

II. ANALYSIS

Method	*GC/GC-MS: Dynamic headspace sampling with trapping on GC pre-column for analysis on glass SCOT analytical column.*
Range	*0.5 to 50 μg/L.*
Precision	*Average relative standard deviation of the mean a) for 9 samples in the 0.9 to 5 μg/kg range: 25 percent b) for 3 samples in the 7 to 12 μg/kg range: 3 percent.*
References	*No. 13.* *No. 25.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Maximum hydrocarbon content; individual species possible.*
Significant figures	*Two.*

Approved: 11/76

Class: *Hydrocarbons, petroleum* — *Hydrocarbons: aliphatic, C_{14}–C_{35}; aromatic, 1- to 3-ring*

I. SAMPLE

Applicability ..... *Fresh water and brackish water.*

Collection ..... *Collect in a clean weighted stainless steel pail or through a ship's sanitary pump line.*

Container ..... *Glass.*

Preliminary treatment ... *Extract 3 liters of water with 25 mL CCl_4 and decant most of the water, or add 25 mL CCl_4 as preservative and do not decant.*

Preservative ..... *CCl_4.*

Storage ..... *Store in refrigerator at 4°C until ready for extraction. All samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Infrared spectrometric: CCl_4 extraction; silica gel column chromatography.*

Range ..... *0.001 μg/L and greater.*

Precision ..... *± 10 relative percent for 0.002 μg/L hydrocarbons.*

References ..... *No. 8.*
No. 9.

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Total hydrocarbons or saturated hydrocarbons and aromatic hydrocarbons.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Hydrocarbons, petroleum* *Hydrocarbons: aromatic, 3- to 6-ring*

I. SAMPLE

Applicability ..... *Fresh water and brackish water.*

Collection ..... *Collect in a cleaned 4-liter bottle contained in a stainless steel frame.*

Container ..... *Glass.*

Preliminary treatment ... *Add mixture of internal standard compounds for subsequent quantitation.*

Preservative ..... *Freeze on bed of dry ice and keep frozen.*

Storage ..... *Indefinite if kept frozen.*

II. ANALYSIS

Method ..... *Liquid-chromatographic (254 nm ultraviolet detection); pump water sample through pellicular pre-column for analysis on micro-particulate analytical column.*

Range ..... *0.5 to 5.0 μg/L.*

Precision ..... *10 percent average relative standard deviation on spiked distilled water samples.*

References ..... *No. 13.*
No. 25.

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Aromatic hydrocarbons as phenanthrene equivalents.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Nitriles* — *Acetonitrile, acrylonitrile, butyronitrile, methoxy-acetonitrile, propionitrile, and others*

I. SAMPLE

Applicability	*General.*
Collection	*See Ref. no. 1: D 3370–76.*
Container	*Glass: narrow or wide mouth bottle with Teflon® -lined cap.*
Preliminary treatment	*Neutralize to pH 7 at time of collection.*
Preservative	*Freeze or ice; adjust pH to 7.*
Storage	*In freezer.*

II. ANALYSIS

Method	*Direct aqueous injection gas chromatography with flame ionization detector.*
Range	*1 mg/L and greater.*
Precision	*Acetonitrile: $S = 0.015\ (mg/L) + 0.9$; propionitrile: $S = 0.088\ (mg/L) - 0.6$; methoxy acetonitrile: $S = 0.097\ (mg/L) + 0.1$; butyronitrile: $S = 0.10\ (mg/L) - 0.4$.*
References	*No. 1, D 3371–79 and D 2908–74.*

III. REPORTING

Units	*mg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Class: *Nitriles* *Acrolein, acrylonitrile*

I. SAMPLE

Applicability	*General.*
Collection	*See ref. 29. Collect 500 mL sample. Fill a 40mL bottle to overflowing.*
Container	*Glass bottle with teflon-lined septum.*
Preliminary treatment ...	*Adjust pH of sample to 6.5 to 7.5 with 1:1 diluted H_2SO_4 or NaOH. If sample contains chlorine add 35 mg sodium thiosulfate per part per million of free chlorine per liter of sample.*
Preservative	*Refrigerate at 4°C.*
Storage	*Store in refrigerator until ready for use. Analyze within 3 days of collection.*

II. ANALYSIS

Method	*Inert gas purge followed by gas chromatographic separation and detection with flame ionization detector.*
Range	*1 μg/L and higher.*
Precision	
Reference	*No. 29.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Approved: 11/76

Class: *Insecticides, organochlorine* — *Aldrin, chlordane, DDD, DDE, DDT, dieldrin, endrin, heptachlor, heptachlor epoxide, lindane, methoxychlor, toxaphene*

I. SAMPLE

Applicability	*Fresh water.*
Collection	*See Section 5.B. of this Chapter. One liter of water is required.*
Container	*Glass bottles, 1 to 4 liters, narrow or widemouth, with Teflon® -lined caps.*
Preliminary treatment ...	*Ice or refrigerate in the field as soon as possible after collection and filter through glass-fiber or metal-membrane filter.*
Preservative	*Refrigeration is the only acceptable means of preservation.*
Storage	*Samples should be extracted immediately. If it becomes necessary to store them they should be refrigerated and kept in the dark. All samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Liquid-liquid extraction-gas chromatography, using electron capture, microcoulometric, and electrolytic conductivity detectors.*
Range	*0.005 μg/L and greater.*
Precision	*See references.*
References	*No. 1, D 3086–79.* *No. 3, p. 24–32; plus U.S. Geol. Survey Quality of Water Branch Memorandum 74.01, July 6, 1974.*

III. REPORTING

Units	*μg/L; include detection limit in report.*
Form(s)	*Parent compound.*
Significant figures	*One figure at lower limit; two figures are maximum justified.*

Approved: 9/80

Class: *Insecticides, organochlorine; and hydrocarbons, halogenated aromatic*

Aldrin, α-BHC, β-BHC, δ-BHC, λ-BHC, chlordane, 4,4'-DDD, 4-4'-DDE, 4-4'-DDT, dieldrin, endosulfan I, endosulfan II, endosulfan sulfate, PCBs

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. Do not prewash bottle with sample before collection.*

Container ..... *Glass bottles with teflon-lined cap.*

Preliminary treatment ... *Ice samples from time of collection until extraction. If samples will not be extracted within 48 hours of collection, the sample pH should be adjusted to 6.0 to 8.0 with sodium hydroxide or sulfuric acid.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator until ready for extraction. All samples should be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Methylene chloride extraction followed by gas chromatography with electron capture or halide specific detection.*

Range ..... *0.0002 μg/L and higher.*

Precision .....

Reference ..... *No. 29*

III. REPORTING

Units ..... *μg/L without recovery data correction.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Herbicides, triazine*

Ametryn, atraton, atrazine, GS-13529, GS-14254, prometon, prometryn, propazine, simazine

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See Section 5.B. of this Chapter. One liter of water is required.*

Container ..... *Glass.*

Preliminary treatment ... *None.*

Preservative ..... *Refrigeration is the only acceptable means of preservation.*

Storage ..... *Extract immediately if possible, or store in refrigerator at 4°C until extraction. Samples must be extracted within 2 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Gas chromatographic; liquid-liquid extraction with methylene chloride; cleanup by column chromatography; detection by gas chromatography, using an electolytic conductivity detector or thermionic detector.*

Range ..... *1 μg/L and greater.*

Precision ..... *At 10 μg/L: Prometon: $\sigma = 0.4$; atraton: $\sigma = 0.05$; atrazine: $\sigma = 0.3$; prometryn: $\sigma = 0.5$: simazine: $\sigma = 0.4$.*

Reference ..... *No. 21*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Oil and grease* — *Animal fats, greases, relatively nonvolatile hydrocarbons, soaps, vegetable oils, waxes, etc.*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter.*
Container	*Glass bottle: narrow neck with Teflon® or Polyseal® cap.*
Preliminary treatment	*None.*
Preservative	*If analysis is delayed more than a few hours, preserve sample by adding 5 mL H_2SO_4 or HCl at the time of collection.*
Storage	*Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Infrared spectrometric: Separatory funnel extraction with Freon 113.*
Range	*0.2 to 1,000 mg/L.*
Precision	*When 1-liter portions of sewage were dosed with 14.0 mg of a mixture of #2 fuel oil and cooking oil, recovery was 99 percent and standard deviation 1.4 mg.*
References	*No. 2, p. 516–517.* *No. 4, p. 232–235.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Oil and grease, total.*
Significant figures	*Two.*

Approved: 11/76

Class: *Oil and grease* — *Animal fats, greases, relatively nonvolatile hydrocarbons, soaps, vegetable oils, waxes, etc.*

I. SAMPLE

Applicability	*General (except wastewater with high asphaltic content).*
Collection	*See Section 5.B. of this Chapter.*
Container	*Glass bottle: narrow neck with Teflon® or Polyseal® cap.*
Preliminary treatment	*None.*
Preservative	*If analysis is delayed more than a few hours, preserve sample by adding 5 mL* H_2SO_4 *at time of collection.*
Storage	*Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Gravimetric: separatory funnel extraction with Freon 113 or filtration and soxhlet extraction with Freon 113.*
Range	*5 to 1,000 mg/L.*
Precision	*When 1-liter portions of sewage were dosed with 14.0 mg of a mixture of #2 fuel oil and cooking oil, recovery was 90 percent and standard deviation was 1 mg.*
References	*No. 2, p. 515–516, 518–519.* *No. 4, p. 226–231.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Oil and grease, residual.*
Significant figures	*Two.*

Approved: 11/76

Class: *Hydrocarbons, halogenated aromatic* — *Aroclor 1016, 1221, 1232, 1242, 1248, 1254, 1260 (PCBs)*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter; also Ref. no. 1, D 3370–76. 100 mL to one liter of sample is required.*
Container	*Glass: narrow or wide mouth bottle with Teflon® -lined cap.*
Preliminary treatment ...	*None.*
Preservative	*Refrigeration is the only acceptable method.*
Storage	*Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Extraction with 15 percent methylene chloride in hexane and analysis by gas chromatography using electron capture, micro-coulometric or conductivity detector.*
Range	*1 μg/L and greater.*
Precision	*Single operator precision for Aroclor 1016 is 6.9 percent at 1 μg/L; Aroclor 1242 is 10.2 percent at 5 μg/L.*
References	*No. 1, D 3534–80.* *No. 22.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Aroclor mixture or total PCBs.*
Significant figures	*Two or three.*

Approved: 11/76

Class: *Herbicides, triazine*

Atraton (5), ametryn (27), atrazine (5,27), desmetryne (5), prometon (5), prometryn (6), propazine (6), simazine (6), simetryn (6), terbutryn (28)

I. SAMPLE

Applicability ..... *Fresh water.*

Collection ..... *See Section 5.B. of this Chapter.*

Container ..... *Glass.*

Preliminary treatment ... *None.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Gas chromatographic: liquid-liquid extraction with methylene chloride; no cleanup prior to analysis by GLC–alkali flame detector, or analysis by thin layer chromatography.*

Range ..... *98 to 107 μg/L (6), 1 to 100 μg/L (28).*

Precision ..... *98 ± 4.5 percent (28).*

References ..... *No. 5.*
No. 27.

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent compounds.*

Significant figures ..... *Two or three.*

Approved: 11/76

Class: *Herbicides, carbamate*

Barban, chlorpropham (CIPC), diuron, fenuron, linuron, monuron, neburon, propham (IPC)®, siduron, swep, Urab®, and Urox®.

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See Section 5.B. of this Chapter. One liter of water is required.*

Container ..... *Glass.*

Preliminary treatment ... *None.*

Preservative ..... *Refrigeration is the only acceptable means of preservation.*

Storage ..... *Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 2 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Thin layer chromatography; liquid-liquid extraction with methylene chloride; cleanup by column chromatography; detection by hydrolysis and diazonium salt formation.*

Range ..... *1 μg/L and greater.*

Precision .....

Reference ..... *No. 16.*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two or three.*

Approved: 11/76

Class: *Insecticides, carbamate* — *Baygon® (aprocarb), carbaryl(Sevin)®, Matacil® (aminocarb), Mesurol® (methiocarb) and Zectran®.*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter. One liter of water is required.*
Container	*Glass.*
Preliminary treatment	*None.*
Preservative	*Refrigeration is the only acceptable means of preservation.*
Storage	*Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 2 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Thin layer chromatography; liquid-liquid extraction with methylene chloride; cleanup by column chromatography; detection by hydrolysis and color formation on thin layer.*
Range	*1 μg/L and greater.*
Precision	
Reference	*No. 15.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Class: *Hydrocarbons, aromatic; and hydrocarbons, halogenated aromatic* — *Benzene, chlorobenzene, 1,2–dichlorobenzene, 1,3–dichlorobenzene, ethyl benzene, toluene.*

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. Collect 500 mL of sample. Fill a 40 mL bottle to overflowing.*

Container ..... *Glass bottle with teflon-lined septum.*

Preliminary treatment ... *If sample contains chlorine add 35 mg of sodium thiosulfate per part per million of free chlorine per liter of sample. Ice sample until ready for analysis.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator at 4°C until ready for use. Analyze within 14 days of collection.*

II. ANALYSIS

Method ..... *Inert gas purge followed by gas chromatography and photoionization detection.*

Range ..... *Not determined.*

Precision .....

Reference ..... *No. 29.*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 9/80

Class: *Hydrocarbons, aromatic; hydrocarbons, halogenated; and hydrocarbons, halogenated aromatic*	*Benzene, 1,1,2-trichloroethene, α,α,α-trifluorotoluene, toluene, 1,1,2,2-tetrachloroethene, ethylbenzene, 1-chlorocyclohexene, p-xylene, chlorobenzene, m-xylene, o-xylene, isopropylbenzene, styrene, 4-bromofluorobenzene, n-propylbenzene, t-butylbenzene, 2-chlorotoluene, 4-chlorotoluene, bromobenzene, s-butylbenzene, 1,3,5-trimethylbenzene, p-cymene, 1,2,4-trimethylbenzene, 1,2-dichlorobenzene, 1,3-dichlorobenzene, cyclopropylbenzene, n-butylbenzene, 2,3-benzofuran, 1,4-dichlorobenzene, hexachlorobutadiene, 1,2,4-trichlorobenzene, naphthalene, st 1,2,3-trichlorobenzene*

I. SAMPLE

Applicability	*General.*
Collection	*See ref. 30. Collect at least 40 mL sample. Fill to overflowing.*
Container	*Glass with teflon-lined septum.*
Preliminary treatment ...	*None.*
Preservative	*Adjust pH to <2 with 1:1 diluted hydrochloric acid or sodium thiosulfate plus hydrochloric acid, depending upon application.*
Storage	*Less than four hours unless acidified for preservation.*

II. ANALYSIS

Method	*Inert gas purge followed by gas chromatographic separation and detection with a photoionization detector.*
Range	*0.002 μg/L and higher, depending upon compound.*
Precision	*Single laboratory.*
Reference	*No. 30.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Class: *Hydrocarbons, halogenated aromatic amine* — *Benzidine,3,3'-dichlorobenzidine*

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. Do not prewash bottle with sample before collection.*

Container ..... *Glass bottle with Teflon-lined cap.*

Preliminary treatment ... *If chlorine is present immediately add 35 mg sodium thiosulfate per part per million of free chlorine per liter. If 1,2-diphenyl hydrazine is likely to be present adjust sample pH to $4_{\pm 0.2}$ units. If samples will not be extracted within 48 hours of collection adjust pH to 2 to 3 with sodium hydroxide or sulfuric acid. Ice sample until ready for analysis.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator until ready for use. All samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Chloroform extraction followed by concentration and high performance liquid chromatography with electrochemical detection.*

Range ..... *0.05 μg/L and higher.*

Precision .....

Reference ..... *No. 29.*

III. REPORTING

Units ..... *μg/L. without recovery correction.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Hydrocarbons, halogenated aromatic amine* — *Benzidine*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter. One liter of water is required.*
Container	*Glass: narrow or wide mouth bottle with Teflon® -lined cap.*
Preliminary treatment ...	*None required.*
Preservative	*Refrigerate at 4°C.*
Storage	*Extract immediately. If necessary to hold samples, store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Spectrophotometric: liquid-liquid extraction with ethyl acetate at pH 8.5 to 9.0; cleanup by extraction with HCl; oxidize by addition of chloramine T; detect and quantitate by scanning with a spectrophotometer from 510 to 370 nm.*
Range	*0.2 μg/L and greater.*
Precision	*= 0.09 at 1.2 μg/L. Single laboratory precision.*
Reference	*No. 23.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Approved: 9/80

Class: *Esters, phthalate*

Benzyl butyl phthalate, bis(2-ethylhexyl) phthalate, di-n-butyl phthalate, di-n-octyl phthalate, diethyl phthalate, dimethyl phthalate

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. Do not prewash bottle with sample before collection.*

Container ..... *Glass bottle with teflon-lined cap.*

Preliminary treatment ... *If samples will not be extracted within 48 hours of collection, adjust pH to 6.0 to 8.0 with sulfuric acid or sodium hydroxide. Ice samples until ready for extraction.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator until ready for use. All examples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Methylene chloride extraction followed by gas chromatography with flame ionization or electron capture detection.*

Range ..... *EC, 0.02 μg/L and higher.*
FID, 14 μg/L and higher.

Precision .....

Reference ..... *No. 29.*

III. REPORTING

Units ..... *μg/L without recovery data correction.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Insecticides, herbicides and fungicides, organochlorine*

BHC (lindane, benzene hexachloride), captan, chlordane, dicloran (DCNA), DDD, DDE, DDT, dieldrin, endosulfan, endrin, heptachlor epoxide, methoxychlor, mirex, PCNB (pentachloronitrobenzene), Strobane® , toxaphene, trifluralin

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See Section 5.B. of this Chapter.*

Container ..... *Glass.*

Preliminary treatment ... *None.*

Preservative ..... *Refrigeration is the only generally acceptable method.*

Storage ..... *Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Liquid-liquid extraction with methylene chloride/hexane; gas chromatography using electron capture, microcoulometric detectors.*

Range ..... *0.005 μg/L and greater.*

Precision ..... *See Ref. No. 1, Table 4.*

References ..... *No. 1, D 3086–79.*
No. 18.

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Class: *Hydrocarbons, halogenated; hydrocarbons, halogenated aromatic; and ethers, halogenated*

Bromoform, bromodichloromethane, bromomethane, carbon tetrachloride, chlorobenzene, chloroethane, 2-chloroethyl vinyl ether, chloroform, chloromethane, dibromochloromethane, 1,2-dichlorobenzene, 1,3-dichlorobenzene, 1,4-dichlorobenzene, dichlorodifluoromethane, 1,1-dichloroethane, 1,2-dichloroethane, 1,1-dichloroethene, trans-1,2-dichloroethene, 1,2-dichloropropane, cis-1,3-dichloropropene, trans-1,3-dichloropropene, methylene chloride, 1,1,1,2-tetrachloroethane, 1,1,2,2-tetrachloroethene, 1,1,1-trichloroethane, 1,1,2-trichloroethane, 1,1,2-trichloroethene, trichlorofluoromethane, vinyl chloride

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. More than 40 mL of water is required. Fill container to overflowing.*

Container ..... *Glass bottle with teflon-lined septum.*

Preliminary treatment ... *If chlorine is present add sodium thiosulfate (10 mg/40 mL). Ice sample until ready for analysis.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator until ready for analysis. Analyze within 14 days of collection.*

II. ANALYSIS

Method ..... *Inert gas purge, followed by gas chromatography with halide specific detection.*

Range ..... *0.004 μg/L and higher.*

Precision .....

Reference ..... *No. 29.*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two or three.*

Approved: 11/76

Class: *Insecticides, carbamate* — *Carbaryl, carbofuran, 3-ketocarbofuran, Mobam®, metmercapturon, propoxur*

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See section 5.B. of this Chapter. 100 ml to one liter of water is required.*

Container ..... *Glass; narrow or wide mouth bottle with Teflon® -lined cap.*

Preliminary treatment ... *None.*

Preservative ..... *Refrigerate or ice at 4°C.*

Storage ..... *Extract immediately. If necessary to hold samples, store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 2 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Gas chromatographic; extract acidified sample with methylene chloride; hydrolyze to the phenol; extract and derivatize to the pentafluorobenzyl ethers. Analyze by electron capture gas chromatography.*

Range ..... *Not given.*

Precision ..... *4.2 to 11.2 percent relative standard deviation for compounds listed.*

Reference ..... *No. 14.*

III. REPORTING

Units ..... *µg/L.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Carbon* — *Carbonate carbon, total organic carbon (TOC)*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter. One hundred ml of water is required.*
Container	*Glass bottle with Teflon® -lined cap.*
Preliminary treatment ...	*None.*
Preservative	*Refrigerate or ice at 4°C or below.*
Storage	*Analyze as soon as possible.*

II. ANALYSIS

Method	*Combustion infrared.*
Range	*2 to 200 mg/L.*
Precision	*No. 1. 0.019 + 1.88 or 5–10%.*
References	*No. 1, D 2579–78.* *No. 2, p. 532–534.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Carbon.*
Significant figures	*Two or three.*

Approved: 9/80

Class: *Ethers, halogenated* — *Bis(2-chloroethyl) ether, bis(2-chloroethoxy) methane, bis(2-chloroisopropyl) ether, 4-bromophenyl phenyl ether, 4-chlorophenyl phenyl ether*

I. SAMPLE

Applicability	*General.*
Collection	*See ref. 29. The sample bottle must not be prewashed with sample before collection.*
Container	*Glass bottle with teflon-lined cap.*
Preliminary treatment ...	*Ice samples from the time of collection until extraction. If samples will not be extracted within 48 hours of collection, adjust sample pH to 6.0 to 8.0 with sodium hydroxide or sulfuric acid.*
Preservative	*Refrigerate at 4°C.*
Storage	*Store in refrigerator until ready for extraction. All samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Methylene chloride extraction followed by gas chromatography with halogen-specific detector.*
Range	*0.4 μg/L and higher.*
Precision	
Reference	*No. 29.*

III. REPORTING

Units	*μg/L without recovery data correction.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Class: *Hydrocarbons, halogenated* — *Chloroform, bromodichloromethane, chlorodibromomethane, bromoform*

I. SAMPLE

Applicability	*General.*
Collection	*See sec. 5.B. of this Chapter.*
Container	*Glass bottle with teflon faced silicon septum.*
Preliminary treatment ...	*Arrest formation of trihalomethanes by adding sodium thiosulfate (3 mg/40 mL).*
Preservative	*Refrigerate at 4°C.*
Storage	*Refrigerate at 4°C. Analyze within 14 days of collection.*

II. ANALYSIS

Method	*Inert gas purge, followed by gas chromatography using a halogen specific detector.*
Range	*0.5 μg/L and higher.*
Precision	*Single lab precision data.*
Reference	*No. 32.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Approved: 9/80

Class: *Hydrocarbons, halogenated* — *Chloroform, bromodichloromethane, chlorodibromomethane, bromoform*

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See sec. 5.B. of this Chapter.*

Container ..... *Glass bottle with teflon faced silicone septum.*

Preliminary treatment ... *Arrest formation of trihalomethanes by adding sodium thiosulfate (3 mg/ 40 mL).*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Refrigerate at 4°C. Analyze within 14 days of collection.*

II. ANALYSIS

Method ..... *Pentane extraction followed by gas chromatography using linearized electron capture detector.*

Range ..... *0.5 μg/L and higher.*

Precision ..... *Single lab precision data.*

Reference ..... *No. 33.*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 9/80

Class: *Hydrocarbons, halogenated; hydrocarbons, halogenated aromatic; and ethers, halogenated*

Chloromethane, bromomethane, dichlorodifluoromethane, vinyl chloride, chloroethane, dichloromethane, fluorotrichloromethane, allyl chloride, 1,1-dichloroethene, bromochloromethane, 1,1-dichloroethane, cis-1,2-dichloroethene, dibromomethane, 1,1,1-trichloroethane, carbon tetrachloride, bromodichloromethane, 2,3-dichloropropene, 1,2-dichloropropane, 1,1-dichloropropene, trans-1,3-dichloropropene, 1,1,2-trichloroethlene, 1,3-dichloropropane, chlorodibromomethane, 1,1,2-trichloroethane, cis-1,3-dichloropropene, 1,2-dibromomethane, 2-chloroethyl ether, 2-chloroethyl vinyl ether, bromoform, 1,1,1,2-tetrachloroethane, 1,2,3-trichloropropane, chlorocyclohexane, 1,1,2,2-tetrachloroethane, 1,1,2,2-tetrachloroethene, pentachloroethane, 1-chlorocyclohexene, chlorobenzene, 2-chlorotoluene, bis-(2-chloroisopropyl) ether, 1,3-dichlorobenzene, 1,4-dichlorobenzene

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See sec. 5.B. of this Chapter.*

Container ..... *Glass bottle with silicone septum cap.*

Preliminary treatment ... *If chlorine present, add sodium thiosulfate (3 mg/40 mL).*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Refrigerate at 4°C. All samples must be analyzed within 14 days of collection.*

II. ANALYSIS

Method ..... *Inert gas purge, followed by gas chromatography with a halogen specific detector.*

Range ..... *0.003 μg/L (1,1,1,2-tetrachloroethane) to 0.07 μg/L (bromobenzene) and higher.*

Precision ..... *Single lab precision data.*

Reference ..... *No. 31.*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 9/80

Class: *Phenols* — *4-Choro-3-methylphenol, 2-chlorophenol, 2,3-dichlorophenol, 2,4-dimethylphenol, 2,4-dinitrophenol, 2-methyl-4,6-dinitrophenol, 2-nitro-phenol, phenol, 4-nitrophenol, pentachlorophenol, 2,4,6-trichlorophenol*

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. Do not prewash bottle with sample before collection.*

Container ..... *Glass bottle with teflon-lined cap.*

Preliminary treatment ... *If chlorine is present add 35mg of sodium thiosulfate per part per million free chlorine per liter. Adjust sample pH to 2 with sulfuric acid or sodium hydroxide. Ice samples until ready for extraction.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator until ready for use. Samples may be stored for seven days before extraction and 30 days after extraction.*

II. ANALYSIS

Method ..... *Methylene chloride extraction, followed by gas chromatography with flame ionization or electron capture detection.*

Range ..... *1.4 μg/L and higher.*

Precision .....

Reference ..... *No. 29.*

III. REPORTING

Units ..... *μg/L without correction for recovery data.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Herbicides, Chlorinated phenoxy acid* — *2,4-D, dicamba, silvex, 2,4,5-T, acid forms*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter, and Ref. 1, D3370-76. One liter of water is required.*
Container	*Glass.*
Preliminary treatment	*Chill samples after collection.*
Preservative	*2 ml H_2SO_4 and refrigerate.*
Storage	*Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Gas chromatographic; acid hydrolysis; liquid-liquid extraction; solvent wash; esterification; gas chromatography using electron capture, microcoulometric, or electrolytic conductivity detectors.*
Range	*Varies with compound: 0.002 to 0.005 μg/L and greater.*
Precision	*Single operator precision for 2,4-D is 5.0 percent at 0.3 to 0.5 μg/L; silvex is 6.5 percent at 0.07 to 0.29 μg/L; 2,4,5-T is 8.0 percent at 0.09 to 0.29 μg/L.*
References	*No. 3, p. 35-39.* *No. 17.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent acid form.*
Significant figures	*One or two.*

Approved: 11/76

Class: *Phenols* — *Phenols, cresols, monochlorophenols, and dichlorophenols.*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter.*
Container	*Glass: narrow or widemouth bottle with Teflon® -lined cap.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*Sample should be kept cool and protected from atmospheric oxygen; lapse of time before analysis should be kept to a minimum.*

II. ANALYSIS

Method	*Gas chromatographic (direct aqueous injection); flame ionization detection.*
Range	*1 mg/L and greater.*
Precision	*Phenol* $S_T = 0.048X + 0.6$, $S_o = 0.017X + 0.3$; *o-chlorophenol* $S_T = 0.083X + 1.2$, $S_o = 0.031X + 0.2$; *m-cresol* $S_T = 0.172X + 0.1$, $S_o = 0.036X + 1.2$; *shere* S_T *= overall precision, mg/L;* S_o *= single operator precision, mg/L;* X *= concentration of phenol determined, mg/L.*
References	*No. 1, D 2580–80* *No. 2, p. 584–592.*

III. REPORTING

Units	*mg/L.*
Form(s)	*Specific phenol.*
Significant figures	*Three.*

Approved: 11/76

Class: *Insecticides, organophosphorus* — *Demeton (Systox),® Di-Syston® (disulfoton), Diazinon,® Guthion® (azinphos-methyl), malathion, methyl parathion, parathion*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter.*
Container	*Glass.*
Preliminary treatment ...	*None.*
Preservative	*Refrigeration is the only acceptable means of preservation.*
Storage	*Store at 4°C in dark. Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 2 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Gas chromatographic; liquid-liquid extraction with methylene chloride/ hexane, optional partition, and column chromatography cleanup; electron capture, flame photometric detection.*
Range	*0.02 μg/L and greater.*
Precision	*Varies with compound – examples: methyl parathion: = 0.008 at 0.07 μg/L; parathion: = 0.004 at 0.030 μg/L.*
Reference	*No. 20.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Approved: 9/80

Class: *Insecticides, organophosphorus* — *Diazinon-oxon, Diazinon, Dimethoate, Ronnel,® B-phosphamidon, methyl parathion, malathion, chlorpyrifos, fenitrothion, ethyl parathion, Ruelene,® methidathion, ethion, EPN, phosmet, phosalone*

I. SAMPLE

Applicability ..... *Drinking water.*

Collection ..... *See sec. 5.B. of this chapter.*

Container ..... *Glass.*

Preliminary treatment ... *None.*

Preservative ..... *Refrigeration is the only acceptable means of preservation.*

Storage ..... *Store at 4°C in dark. Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 2 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Extract water sample with Amerlite XAD-2 resin; elute from resin with acetone-hexane (15 + 85) and determine with GLC with nitrogen-phosphorus selective detector and GLC-mass spectrometry.*

Range ..... *10 picograms (Diazinon) to 200 picograms (Phosmet) and greater.*

Precision ..... *No precision data, but recoveries greater than 90% except for dimethoate (37%) and phosphamidon (42%).*

Reference ..... *No. 34.*

III. REPORTING

Units ..... *μg/L.*

Forms ..... *Parent compounds.*

Significant figures ..... *Two.*

I. SAMPLE

Applicability	*Munitions wastewater.*
Collection	*See Section 5.B. of this Chapter and Ref. 1, D3370–76.*
Container	*Glass.*
Preliminary treatment ...	*None.*
Preservative	*Refrigerate at 4°C.*
Storage	*Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Extraction by methylene chloride and analysis by high pressure liquid chromatography using an internal standard.*
Range	*10 to 1,000 mg/L.*
Precision	*Coefficient of variation for chromatographic portion only is given as approx. 2.8 percent for NG and 2.6 percent for DNG.*
Reference	*No. 11.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compounds.*
Significant figures	*Two.*

Approved: 11/76

Class: *Hydrocarbons, halogenated; hydrocarbons, halogenated aromatic; and fungicides, organochlorine*

Hexachlorocylopentadiene, hexachlorobenzene, hexachlorobutadiene, hexachloroethane, 1,2–dichlorobenzene, 1,2,4–trichlorobenzene, 1,3–dichlorobenzene, 1,4–dichlorobenzene, 2–chloronaphthalene

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. Leave minimum headspace and do not prewash container with sample.*

Container ..... *Glass bottle with teflon-lined cap.*

Preliminary treatment ... *Ice samples from the time of collection until extraction. If samples will not be extracted within 48 hours of collection, adjust sample pH to 6.0 to 8.0 with sodium hydroxide or sulfuric acid.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *All samples should be extracted immediately and must be extracted within 3 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Methylene chloride extraction followed by concentration, gas chromatography with electron capture detection.*

Range ..... *0.001 μg/L and higher.*

Precision .....

Reference ..... *No. 29.*

III. REPORTING

Units ..... *μg/L without recovery data correction.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Phenols* — *Hexachlorophene (Ref. no. 10), pentachlorophenol (PCP) (Ref. nos. 10, 12, 28)*

I. SAMPLE

Applicability	*General (Ref. no. 10), fresh water (Ref. nos. 12 and 28).*
Collection	*See Section 5.B. of this Chapter.*
Container	*Glass.*
Preliminary treatment ...	*Acidification (Ref. no. 10); not given (Ref. nos. 12 and 28).*
Preservative	
Storage	

II. ANALYSIS

Method	*Gas chromatographic, liquid-liquid extraction with benzene (Ref. no. 12), toluene (Ref. no. 28) or chloroform (Ref. no. 10). Cleanup by acid-base partition with organic solvents (Ref. nos. 10, 12, 28). Following derivative formation, determination made by gas chromatography, electron capture detector.*
Range	*0.10 to 1.0 μg/L only (no. 28); 0.2 to 100 μg/L river, 1 to 10 μg/L in sewage (no. 10).*
Precision	*0.177 ± 0.004 μg/L std. dev. (no. 13); 0.05 μg/L ± 0.003 std. dev. (no. 28); ranges of ± 3.2 percent and ± 8.1 percent.*
References	*No. 10 No. 12. No.28.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two or three.*

Approved: 9/80

Class: *Hydrocarbons, nitroaromatic; and ketones, a,b-unsaturated* — *Isophorone, nitrobenzene, 2,4–dinitrotoluene, 2,6–dinitrotoluene*

I. SAMPLE

Applicability	*General.*
Collection	*See ref. 29. The sample bottle must not be prewashed with sample before collection.*
Container	*Glass bottle with teflon-lined cap.*
Preliminary treatment ...	*Ice samples from the time of collection until extraction. If samples will not be extracted within 48 hours of collection, adjust sample pH to 6.0 to 8.0 with sulfuric acid or sodium hydroxide.*
Preservative	*Refrigerate at 4°C.*
Storage	*Store in refrigerator until ready for extraction. All samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Methylene chloride extraction followed by exchange to toluene, gas chromatography with flame ionization detection.*
Range	*5 μg/L and higher.*
Precision	
Reference	*No. 29*

III. REPORTING

Units	*μg/L without recovery data correction.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Approved: 11/76

Class: *Surfactants (amionic)* *Methylene blue active substances (MBAS)*

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter and Ref. 1, D 1192 and D 3370, Methods for organic sampling.*
Container	*Glass bottle, with Teflon® -lined cap.*
Preliminary treatment ...	*None.*
Preservative	*Refrigeration, chloroform.*
Storage	*Analyze as soon as possible. If stored, sample requires some preservative. Refrigerate, or add chloroform if refrigeration is not available. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Direct methylene blue colorimetric for MBAS.*
Range	*0.025 to 100 mg/L.*
Precision	*For 110 labs: 0.48 mg/L 0.05 sd LAS in tap water; 2.94 ± 0.27 sd LAS in river water.*
References	*No. 1, D 2330–80.* *No. 2, p. 600–603.* *No. 4, p. 157–158.*

III. REPORTING

Units	*mg/L.*
Form(s)	*Methylene blue active substances as linear alkyl sulfonate. (LAS)*
Significant figures	*Two or three.*

Approved: 9/80

Class: *Nitrosamines* — *N-nitrosodimethylamine, N-nitrosodiphenylamine, N-nitrosodi-n-propylamine*

I. SAMPLE

Applicability	*General.*
Collection	*See ref. 29.*
Container	*Glass bottle with teflon-lined cap.*
Preliminary treatment ...	*If the samples will not be extracted within 48 hours of collection, they must be preserved as follows: add 35 mg of sodium thiosulfate per part per million of free chlorine per liter of sample. Adjust pH to 7 to 10 using sodium hydroxide or sulfuric acid. Ice sample until ready for analysis.*
Preservative	*Refrigerate at 4°C.*
Storage	*Store in refrigerator until ready for use. All samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Methylene chloride extraction followed by gas chromatography with nitrogen-phosphorous or reductive Hall detectors.*
Range	*0.3 μg/L and higher.*
Precision	
Reference	*No. 29.*

III. REPORTING

Units	*μg/L without recovery data correction.*
Form(s)	*Parent compound.*
Significant figures	*Two or three.*

Class: *Organic matter* — *Organic matter, solvent extractable*

I. SAMPLE

Applicability	*General.*
Collection	*Collect according to ASTM D 3370 methods for organic sampling. A grab or depth-integrated sample. The volume required will vary depending on concentration of organic matter; 800 to 3,000 mL is convenient.*
Container	*Glass bottle with Teflon® -lined cap.*
Preliminary treatment ...	*If practical, ice or refrigerate in the field as soon as possible.*
Preservative	*Refrigeration.*
Storage	*Samples should be extracted immediately; otherwise keep refrigerated. Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method	*Gravimetric: liquid-liquid extraction with solvent selected on the basis of the analyst's assessment of the type organic matter to be determined and the detection method to be employed. Serial extraction at neutral, acid, and alkaline pH. Tests for specific compounds may be applied.*
Range	*Widely variable.*
Precision	*Not applicable because of the variable nature of the materials determined.*
References	*No. 1, D 2778–70 (1974).*

III. REPORTING

Units	*mg/L.*
Form(s)	*Specify solvent and report quantity of extractables at neutral pH, acid pH, and alkaline pH.*
Significant figures	*Depends on the accuracy of the gravimetric measurement; usually two or three.*

Approved: 11/76

Class: *Phenols* *Phenols*

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See Section 5.B. of this Chapter.*

Container ..... *Glass.*

Preliminary treatment ... *None.*

Preservative ..... *Acidify to pH <4 with H_3PO_4; add 1g $CuSO_4 \cdot 5H_2O$/liter of sample.*

Storage ..... *Sample should be kept at 5 to 10°C; analyze within 24 hours after collection.*

II. ANALYSIS

Method ..... *Photometric: steam distillation and reaction with 4-aminoantipyrine followed by analysis. Sequence is carried out in a Technicon Auto-Analyzer.*

Range ..... *2 to 500 μg/L.*

Precision ..... *In a single laboratory (μg/L); 3.8±0.5; 15±0.6; 43±0.6; 89±1; 146±2; 299±4; 447±5.*

References ..... *No. 4, p. 243–248.*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Steam-distillable phenols reported as phenol.*

Significant figures ..... *Two or three.*

Approved: 11/76

Class: *Explosives, hydrocarbons, Nitroaromatics*

RDX (1,3,5-trinitro-1,3,5-triazacyclohexane), TNT (2,4,6-trinitrotoluene)

I. SAMPLE

Applicability	*General.*
Collection	*See Section 5.B. of this Chapter and Ref. 1, D 3370–76. One liter of water is required.*
Container	*Glass bottle with Teflon® -lined cap.*
Preliminary treatment ...	*Chill immediately after collection.*
Preservative	*Refrigeration is the only acceptable means of preservation.*
Storage	*None recommended. If short-term storage is essential, samples should be kept cool and in the dark.*

II. ANALYSIS

Method	*Liquid-liquid extraction with benzene; cleanup with alumina; gas chromatographic analysis using electron capture and electrolytic conductivity detectors.*
Range	*0.005 μg/L and greater.*
Precision	*Precision for gas chromatographic analysis is ± 3 percent.*
Reference	*No. 24.*

III. REPORTING

Units	*μg/L.*
Form(s)	*Parent compound.*
Significant figures	*Two.*

Approved: 11/76

Class: *Hydrocarbons, halogenated; and hydrocarbons, halogenated aromatic* *Solvents, halogenated*

I. SAMPLE

Applicability ..... *Fresh water and wastewater.*

Collection ..... *Carefully fill bottle 'to overflowing; stopper or cap so as to eliminate headspace.*

Container ..... *Glass: ground glass stoppered or serum with crimp cap and Teflon® -lined septum.*

Preliminary treatment ... *None.*

Preservative ..... *Ice or freeze.*

Storage ..... *Analyze immediately or store at 4°C for no longer than 14 days after collection.*

II. ANALYSIS

Method ..... *Samples are analyzed by direct aqueous injection gas chromatography with halogen-specific detector (microcoulometric or electrolytic conductivity) or with general flame ionization detector.*

Range ..... *1 mg/L and greater.*

Precision .....

Reference ..... *No. 19.*

III. REPORTING

Units ..... *mg/L.*

Form(s) ..... *Parent Compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Hydrocarbons, aromatic; and hydrocarbons, halogenated* *Solvents, volatile organic*

I. SAMPLE

Applicability ..... *Fresh water and wastewater.*

Collection ..... *Carefully fill bottle to overflowing, stopper or cap so as to eliminate headspace.*

Container ..... *Glass: ground stopper or serum bottle with crimp lid and Teflon® -lined septum.*

Preliminary treatment ... *None.*

Preservative ..... *Ice or freeze.*

Storage ..... *Analyze immediately; otherwise store at 4°C for no longer than 14 days after collection.*

II. ANALYSIS

Method ..... *Samples are purged with an inert gas. Volatilized constituents are adsorbed on an adsorbent trap then backflushed onto the head of a GC column and analyzed by programmed temperature gas chromatography using flame ionization or element-specific detectors (microcoulometric or electrolytic conductivity).*

Range ..... *Approx. 0.5 to 2,500 μg/L.*

Precision ..... *Relative standard deviation – chloroform: 6 percent at 2 μg/L; 1,2-dichloroethane: 5 percent at 1 μg/L; carbon tetrachloride: 14 percent at 2 μg/L; bromodichloromethane: 5 percent at 2 μg/L; dibromochloromethane: 10 percent at 2 μg/L.*

References ..... *No. 6. No. 8.*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Parent Compound.*

Significant figures ..... *One at 0.9 μg/L or less. Two at 1.0 μg/L and above.*

Approved: 9/80

Class: *Hydrocarbons, halogenated aromatic* — *2,3,7,8-Tetrachlorodibenzo-p-dioxin*

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See ref. 29. Do not prewash bottle with sample before collection.*

Container ..... *Glass bottle with teflon-lined cap.*

Preliminary treatment ... *Ice samples from time of collection until extraction. If sample will not be extracted within 48 hours of collection, the sample should be adjusted to a pH of 6.0 to 8.0 with sulfuric acid or sodium hydroxide.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator until ready for extraction. All samples should be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Methylene chloride extraction followed by transfer to hexane, and determine by capillary column gas chromatography/mass spectrometry with electron impact ionization.*

Range ..... *0.003 μg/L and higher.*

Precision .....

Reference ..... *No. 29.*

III. REPORTING

Units ..... *μg/L without recovery data correction.*

Form(s) ..... *Parent compound.*

Significant figures ..... *Two.*

Approved: 11/76

Class: *Hydrocarbons, aromatic alcohol* — *Tannin and lignin*

I. SAMPLE

Applicability ..... *General.*

Collection ..... *See Section 5.B. of this Chapter. 50ml or more of sample is required.*

Container ..... *Glass.*

Preliminary treatment ... *None.*

Preservative ..... *Refrigerate at 4°C.*

Storage ..... *Store in refrigerator at 4°C until ready for extraction. Samples must be extracted within 7 days and completely analyzed within 30 days of collection.*

II. ANALYSIS

Method ..... *Colorimetric: reacton with tungstophosphoric acid and molybdophosphoric acid; spectrophotometric or filter photometric equipment used.*

Range ..... *Approx. 0.1 mg/L for tannic acid and 0.3 mg/L for lignin; and greater.*

Precision ..... *Not given.*

References ..... *No. 2, p. 607–608.*

III. REPORTING

Units ..... *μg/L.*

Form(s) ..... *Unless tannin or lignin can be identified, report as "hydroxylated aromatic compounds."*

Significant figures .....

5.F. DETERMINATION OF RADIOACTIVE CONSTITUENTS

5.F.1. CONSTITUENTS SPECIFIED

Alpha activity, gross
Alpha, or alpha spectrometry
Americium
Americium, polonium, polutonium, uranium
Barium-140
Beta activity, gross
Carbon-14
Cerium-141 and -144
Cesium (radio) as cesium-137
Cesium (radio) isotopes
Cobalt-58
Cobalt-60
Gamma activity, gross
Iodine-131
Iron-55
Lead-210
Manganese-54
Neptunium
Plutonium
Polonium-210
Radium, as radium-226
Radium-226, by radon
Radium-228
Radon-222
Ruthenium-103 and -106
Strontium-89 and -90
Strontium-90
Thorium, natural
Tritium, H-3, in water molecules
Uranium, natural

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Approved: 3/82 *Alpha activity, gross*

I. SAMPLE

Applicability ..... *Water, fresh.*

Collection ..... *Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*

Container ..... *Plastic or glass.*

Size ..... *0.1 liter.*

Preliminary treatment ... *Filter through a 0.45-μm membrane filter, acidify to 0.5N with HNO_3.*

Preservative ..... *HNO_3.*

Storage ..... *1 year.*

II. ANALYSIS

Method ..... *Evaporation; counting with proportional or scintillation detector.*

Detection limit ..... *30 pCi for 60-min. count (3 pCi/L).*

Precision .....

Interferences ..... *Absorbing materials; recommend final plate be $<1 mg/cm^2$ (10 to 15 percent absorption loss). Method may be used up to 10 mg/cm^2 with substantially larger absorption correction.*

References ..... *No. 1, D 1943–66 (1977).*

III. REPORTING

Data ..... *Gross counting techniques are recommended only for survey purposes. Absolute isotopic concentrations should not be inferred or reported. If isotopic concentrations are required, refer to appropriate internal document.*

Unit ..... *pCi/L of calibration isotope, wt/L of natural uranium, or cpm/mL.*

Chemical yield .....

Significant figures ..... *Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Soils and sediments.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*10 gram dry solid material.*
Preliminary treatment ...	*Dry sample at < 85°C for 12 hours.*
Preservative	
Storage	*Indefinite.*

II. ANALYSIS

Method	*Decomposition of sample by pyrosulfate fusion; coprecipitation of alpha-emitting radionuclides by barium sulfate; alpha counting by proportional, scintillation counting, or alpha spectroscopy.*
Detection limit	*2 pCi.*
Precision	
Interferences	*Nitric acid, orthophosphates, uranium in excess of 0.5 mg, thorium, lanthanum, light lanthanides and bismuth in excess of 1 mg. Compensate by sample size or as otherwise described.*
Reference	*No. 15.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Single precipitation with barium sulfate removes 99.95 percent of alpha-emitting isotopes in samples ± 10 percent at 20 pCi/L.*
Significant figures	*Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, soils, sediments.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*0.1 liter.*
Preliminary treatment ...	*Water – filter through a 0.45-μm membrane filter and acidify to 0.5N HCl. Soil and sediment—dry at 65°C for 24 hours.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Sample prepared by pyrosulfate fusion, uranium and transuranium elements precipitated from boiling solution by dropwise addition of Ba^{++}; ppt dissolved; elements electroplated and counted by alpha spectrometry.*
Detection limit	*20 pCi for 1 hour count on 100-mL sample; (2 pCi/L).*
Precision	*Ten pure solutions taken through the entire procedure gave a relative standard deviation of 0.9 percent.*
Interferences	*Uranium (IV), thorium, lanthanum, light lanthanides and bismuth must not be present in quantities larger than about 0.5 mg for uranium (IV) and 1 mg for the others.*
Reference	*No. 15.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*>98 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability ..... *Water.*

Collection ..... *Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*

Container ..... *Plastic or glass.*

Size ..... *1 liter.*

Preliminary treatment ... *Filter through a 0.45-μm membrane filter.*

Preservative .....

Storage ..... *Analyze as soon as possible after collection.*

II. ANALYSIS

Method ..... *Partial precipitation of calcium carbonate and magnesium hydroxide by addition of 3 to 4 mmol NaOH/L of sea water with added tracers. Ion exchange, evaporation, or plating followed by alpha spectrometry.*

Detection limit ..... *Variable depending upon isotope. Approximately 0.001 pCi/L for Pu, 1 pCi/L for U.*

Precision ..... *Variable: from ±4 percent for U to ±25 percent for Pu, based on counting statistics.*

Interferences ..... *Iron interferes in the determination of U. Refractory particulate radionuclides collected with precipitate may require special treatment.*

Reference ..... *No. 8.*

III. REPORTING

Unit ..... *pCi/L.*

Chemical yield ..... *Variable according to element. (57 to 89 percent).*

Significant figures ..... *Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl.*
Storage	*Not critical except for decay of 12.8 day Ba-140. (1 month).*

II. ANALYSIS

Method	*Precipitation; gamma spectrometry or beta counting.*
Detection limit	*10 pCi/L, 100-min. count, 1 liter sample.*
Precision	*For random counting error < 1 percent, precision is within 2 percent.*
Interferences	*Large amounts of stable barium and sulfate ion.*
References	*No. 1, D 2038-74.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Approx. 80 percent.*
Significant figures	*Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter sample through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl. (Add 4 percent by volume of concentrated HCl).*
Storage	*Not critical except for decay of 12.8 day Ba-140.*

II. ANALYSIS

Method	*Evaporation, pyrosulfate fusion; separation of radioactive barium isotopes or barium sulfate and determination by gamma spectrometry (tentative).*
Detection limit	*About 3 pCi/L, 100-min. Ge(Li) gamma count, 1-liter sample.*
Precision	*±20 percent at about 40 pCi/L. Procedure has not been subjected to interlaboratory comparison.*
Interferences	*None with Ge(Li) spectrometry.*
Reference	*No. 19.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*98 percent.*
Significant figures	*Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*0.1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N with HNO_3.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Evaporation; counting within low background, thin window beta detector.*
Detection limit	*10 pCi/L, 100 mL sample, 60-min. count.*
Precision	
Interferences	*Absorbing materials.*
References	*No. 1, D 1890–66 (1977).*

III. REPORTING

Data	*Gross counting techniques are recommended for survey purposes. Absolute isotopic concentrations should not be inferred or reported. If isotopic concentrations are required, refer to appropriate internal document.*
Units	*Report data in units of pCi/L of calibrations isotope or in cpm/mL.*
Chemical yield	
Significant figures	*Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Groundwater*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 5, R-1100-76.*
Container	*15-gal. steel drum.*
Size	*Minimum 30 gallons, up to 90 gallons depending on bicarbonate content.*
Preliminary treatment	*None*
Preservative	*None*
Storage	*1 year.*

II. ANALYSIS

Method	*Collect dissolved carbonate species (adjust to pH 10.4) by precipitation as $BaCO_3$. The precipitate is treated with acid to liberate CO_2, which is then allowed to react with Li to produce Li_2C_2 and hydrolyzed to produce C_2H_2. Finally, C_2H_2 is passed over a vanadium-doped aluminum oxide catalyst to form benzene. The activity of benzene is assayed in a liquid scintillation counter.*
Detection limit	*40,000 years.*
Precision	*$\pm$ 100 years in the 10,000 year range and $\pm$ 800 years in the 30,000 year range.*
Interferences	*Prolonged contact with atmosphere during sampling and barium sulfate precipitation (high pH) may result in atmospheric CO_2 contamination.*
Reference	*No. 5.*

III. REPORTING

Unit	*In years Before Present (years B.P.).*
Chemical yield	*Ranges from 70 to 85 percent.*
Significant figures	*Report to nearest 50 years for age $<$1,000 and to nearest 100 years for ages $>$1,000.*

I. SAMPLE

Applicability	*Water, fresh*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter sample through a 0.45-μm membrane filter; acidify to 0.5N HNO_3.*
Preservative	*HNO_3 (Add 4 percent by volume of concentrated HNO_3).*
Storage	*Not critical except for radioactive decay.*

II. ANALYSIS

Method	*Evaporation; precipitation of CeF_3, $Ce(OH)_3$; oxidation to Ce (IV) and extraction with HDEHP; reduction to Ce (III) and back extraction; precipitation as $Ce_2(C_2O_4)_3$, beta counting, and/or high resolution gamma spectrometry.*
Detection limit	*2 pCi/L for Ce-144, 1-liter sample, 1 hour beta count.*
Precision	*±20 percent at about 15 pCi/L.*
Interferences	*Cerium in sample will give falsely high yields.*
References	*(a) No. 7, E-Ce-02, 10 p; (b) No. 7, E-Ce-04, 4 p.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*About 95 percent.*
Significant figures	*Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl. (Add 4 percent by volume of concentrated HCl).*
Storage	*Not critical except for radioactive decay.*

II. ANALYSIS

Method	*Evaporation, pyrosulfate fusion. Separation of cerium on barium sulfate. Dissolution in DPTA; precipitation as iodate; determination by high resolution gamma spectrometry or beta counting (tentative).*
Detection limit	*About 2 pCi/L for Ce-144, 1 h beta count, 1-liter sample.*
Precision	*± 20 percent at about 15 pCi/L. Procedure has not been subjected to interlaboratory comparison.*
Interferences	*> 1 mg of thorium, bismuth, lanthanum, or light rare earths including cerium; > 100 mg calcium.*
Reference	*No. 19.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*96 percent.*
Significant figures	*Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh and ocean*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*100 to 500 mL.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Carrier-free batch-type ion exchange using ammonium hexacyano cobalt ferrate; filter, mount, and beta count.*
Detection limit	*10 pCi using thin window flowing gas proportional counter with counts approximately equal to 2 cpm above background. (1 pCi/L).*
Precision	*Estimated ± 75 percent at 10 pCi/L.*
Interferences	*Any beta-emitting cesium isotopes (such as CS-134) which may be present will be reported as Cs-137. Gamma spectroscopy required if determination of each isotope is required.*
References	*No. 5, R-1111-76, p. 27-28.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*> 93 percent.*
Significant figures	*One significant figure in range from 0 to 10 pCi/L; two significant figures for values greater than 10 pCi/L.*

I. SAMPLE

Applicability	*Water, fresh and ocean*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Cesium carrier added to 1 liter of water, collected as phosphomolybdate, purified and counted as chloroplatinate.*
Detection limit	*Approximately 2 pCi/L.*
Precision	*± 50 percent at 10 pCi/L; ± 5 percent at 100 pCi/L.*
Interferences	*None indicated.*
Reference	*No. 12.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Not indicated.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*0.5 liter and 3.5 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl.*
Storage	*Not critical except for 71.3 day half-life of Co-58 (1 year).*

II. ANALYSIS

Method	*Gamma spectrometry, 3.5-liter sample counted with a NaI (Tl) detector, 500-mL sample with a Ge(Li) detector.*
Detection limit	*3 pCi/L, 100-minute count on NaI (Tl). 17 pCi/L, 300-minute count on Ge (Li).*
Precision	*Estimated to be ±20 percent at 20 pCi/L for NaI (Tl); ±20 percent at 130 pCi/L for Ge (Li).*
Interferences	*Gamma emitters with similar energies.*
References	*(a) No. 1, D 2459-72, 1977; (b) see also Section 5.F.4 of this Handbook.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Not applicable.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*0.1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl. Detection limit may be lowered by evaporating a larger sample after addition of stable cobalt carrier.*
Preservative	*HCl (Add 4 percent by volume of concentrated HCl).*
Storage	*Not critical except for 71.3 day half-life of Co-58 (1 year).*

II. ANALYSIS

Method	*Precipitation; gamma spectrometry with a NaI (Tl) detector.*
Detection limit	*500 pCi, 100-mL sample, 100-minute count, (50 pCi/L).*
Precision	*Estimated to be ± 20 percent at 230 pCi/L.*
Interferences	*None.*
References	*No. 11, p. 54-58.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*75 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*0.5 liter and 3.5 liter.*
Preliminary treatment ...	*Filter sample through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl (Add 4 percent by volume of concentrated HCl).*
Storage	*Indefinite.*

II. ANALYSIS

Method	*Gamma spectrometry, 3.5-liter sample counted with a NaI (Tl) detector, or a 500-mL sample counted with a Ge (Li).*
Detection limit	*4 pCi/L, 100-minute count on NaI (Tl); 18 pCi/L, 300-minute count on Ge (Li).*
Precision	*Estimated to be ±20 percent at 18 pCi/L for NaI (Tl), ±20 percent at 160 pCi/L for Ge (Li).*
Interferences	*Gamma emitters with similar energies.*
References	*(a) No. 1, D 2459-72, 1977; (b) see also Section 5.F.4 of this Handbook.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Not applicable.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*0.1 liter.*
Preliminary treatment ...	*Filter sample through a 0.45-μm membrane filter; acidify to 0.5N HCl. Detection limit may be lowered by evaporating a larger sample after the addition of carriers.*
Preservative	*HCl (Add 4 percent by volume of concentrated HCl).*
Storage	*1 year.*

II. ANALYSIS

Method	*Precipitation; gamma spectrometry with NaI (Tl) detector.*
Detection limit	*500 pCi, 100-mL sample, 100-minute count. (50 pCi/L).*
Precision	*Estimated to be ±20 percent at 260 pCi/L.*
Interferences	*None.*
References	*No. 11, p. 54-58.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*75 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N with HNO_3.*
Preservative	*HCl (Add 4 percent by volume of concentrated HCl).*
Storage	*1 year.*

II. ANALYSIS

Method	*Gross gamma counting of water sample.*
Detection limit	*1 nCi/L, 10–minute count on 3" x 3" NaI (Tl) well crystal.*
Precision	*±3 percent at 40 nCi/L.*
Interferences	*Energy range may be extended by lowering the discriminator setting.*
References	*See Section 5.F.4 of this Handbook.*

III. REPORTING

Units	*pCi/L as calibration isotope or in cpm/mL.*
Chemical yield	
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Glass only.*
Size	*1 liter.*
Preliminary treatment	*None.*
Preservative	*None, acidification will result in losses or radioiodine.*
Storage	*For maximum sensitivity analyze as soon as possible—(1 week).*

II. ANALYSIS

Method	*Precipitation or distillation; solvent extraction and precipitation followed by gamma or beta counting.*
Detection limit	*3 pCi/L, 1 liter sample, 100-minute count on NaI (Tl); 0.4 pCi/L, 1 beta sample, 100-minute beta count.*
Precision	*Estimated to be ±20 percent at 17 pCi/L for NaI (Tl) counting, ±20 percent at 4 pCi/L for beta counting.*
Interferences	*None.*
Reference	*No. 4.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Approximately 80 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Glass only.*
Size	*1 liter.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*For maximum sensitivity, sample should be analyzed within a few days.*

II. ANALYSIS

Method	*Method B, distillation, precipitation; Method C solvent extraction, precipitation. Gamma spectrometry or beta counting.*
Detection limit	*100 pCi/L, 100-mL sample, 100-minute count.*
Precision	*For random counting error less than 1 percent, precision is ±3 percent.*
Interferences	*Stable iodine can cause overestimation of yield, oxidizing agents.*
References	*No. 1, D 2334-73 1979, Methods B and C.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Approximately 80 percent. (Method B).*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

Approved: 11/76

Class: Hydrocarbons, petroleum *Hydrocarbons: aliphatic and aromatic, C1–C10*

I. SAMPLE

Applicability	*Fresh water and brackish water.*
Collection	*See Section 5.B. of this Chapter.*
Container	*50-mL glass hypodermic gas-tight syringe.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*None; analyze immediately.*

II. ANALYSIS

Method	*Gas chromatographic: helium equilibration of water sample and injecton of headspace; flame ionization detection.*
Range	*≤ 1 ng/L for aliphatic hydrocarbons; ≥ 4 ng/L for aromatic hydrocarbons.*
Precision	*1.8 percent, 0.8 percent and 0.7 percent relative standard deviations on water samples spiked with benzene, cyclohexane, and n-hexane, respectively.*
Reference	*No. 26.*

III. REPORTING

Units	*ng/L to μg/L.*
Form(s)	*Individual hydrocarbons.*
Significant figures	*Two or three.*

Approved: 11/76

Class: Hydrocarbons, petroleum — *Hydrocarbons: <2 percent soluble in water and boiling below 150°C.*

I. SAMPLE

Applicability	*General.*
Collection	*Carefully fill bottle to overflowing; stopper or cap so as to eliminate headspace.*
Container	*Glass: ground glass stoppered or serum bottle with crimp cap and Teflon® - lined septum.*
Preliminary treatment ...	*Due to the volatility of the organic molecules detected by this method, common sample preservation techniques are inadequate. The simplicity of the trap and purging device make it possible to prepare the sample at the site and to send the sealed trap back to the laboratory.*
Preservative	*Refrigerate at 4°C.*
Storage	*Store in refrigerator until ready for analysis. Analyze within 14 days of collection.*

II. ANALYSIS

Method	*GC/GC–MS: Sample is purged of volatile compounds with an inert gas and volatiles are trapped on a GC pre-column.*
Range	*1 to 2,500 μg/L.*
Precision	*5 percent relative standard deviation on water samples spiked with benzene or toluene.*
Reference	*No. 6.*

III. REPORTING

Unit	*μg/L.*
Form(s)	*Individual hydrocarbons.*
Significant figures	*Two.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl. Detection limit may be lowered by evaporating a larger sample after the addition of stable Fe carrier.*
Preservative	*HCl (Add 4 percent by volume of concentrated HCl) (no nitric acid).*
Storage	*1 year.*

II. ANALYSIS

Method	*Solvent extraction, precipitation, x-ray spectrometry, carrier added for chemical yield determination.*
Detection limit	*200 pCi (20 pCi/L), 100-minute count on x-ray proportional counter.*
Precision	*Estimated to be ± 20 percent at + 800 pCi.*
Interferences	*Highly stable iron species could interfere with chemical yield determination.*
References	*No. 7, E-Fe-01, 5 p.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*75 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*0.5 liter and 3.5 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl (Add 4 percent by volume of concentrated HCl).*
Storage	*Not critical except for 45.6 day half-life of Fe-59.*

II. ANALYSIS

Method	*Gamma spectrometry; 3.5-liter sample counted with NaI (Tl) detector; 500-mL sample counted with a Ge (Li) detector.*
Detection limit	*7 pCi/L, 100-minute count on NaI (Tl); 30 pCi/L, 300-minute count on Ge (Li).*
Precision	*Estimated to be ±20 percent at 40 pCi/L for NaI (Tl); ±20 percent at 260 pCi/L.*
Interferences	*Gamma emitters with similar energies.*
References	*(a) No. 1, D 2459-72 1977; (b) see also Section 5.F.4 of this Handbook.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Not applicable.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*0.1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl. Detection limit may be lowered by evaporating a larger sample after addition of stable Fe carrier.*
Preservative	*HCl (Add 4 percent by volume of concentrated HCl).*
Storage	*Not critical except for 44.6 day half-life of Fe–59.*

II. ANALYSIS

Method	*Solvent extraction; precipitation; gamma counting.*
Detection limit	*1,000 pCi (100 pCi/L), 100-minute count with NaI (Tl) detector.*
Precision	*Estimated to be 20 percent at 4,000 pCi.*
Interferences	*None.*
References	*No. 11, p. 77–80.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*75 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*0.1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Heavy metals removed by extracton of the thiocyanates with MIBK. Lead–210 and stable lead isolated by successive extractions as the iodide and dithizonate. Lead–210 determined by beta counting or combined alpha beta count from bismuth–210 and polonium–210.*
Detection limit	*30 pCi (3.0 pCi/L).*
Precision	*1.8 percent at 2,400 pCi level (30 percent at 30 pCi level on uranium mill effluents). Relative standard deviation of 5.1 percent on quadruplicate analysis of lead–210 standards.*
Interferences	*Excessive amounts of stable lead in sample will result in increased beta self absorption in counting planchets.*
Reference	*No. 21.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Mean recovery: 95.1 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter sample through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Lead and bismuth extracted from other metals in strong acid solution by diethylammonium diethyldithiocarbamate in chloroform. Lead and bismuth separated by dithizone prior to beta counting.*
Detection limit	*3 pCi/L using 500-mL sample and 30-minute count.*
Precision	*± 20 percent at a level of 40 pCi/L.*
Interferences	*Stable lead and bismuth to excess of 2 mg in sample. Presence of heavy metals may require preliminary extraction steps. Organic material or sulfur compounds may require oxidation. Lead-210 sorbed on sediments will be leached by acid if sediment not removed first.*
Reference	*No. 20.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*99 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HNO_3.*
Preservative	*HNO_3.*
Storage	*1 year.*

II. ANALYSIS

Method	*Lead and strontium carrier added to water sample are precipitated as sulfate, metathesized to carbonate, redissolved and separated from interferences with ion exchange column, precipitated and counted as lead chromate.*
Detection limit	*2 pCi/L.*
Precision	*± 100 percent at 2 pCi/L level; less than ± 10 percent at levels greater than 20 pCi/L.*
Interferences	*High concentrations of complexing agents resistant to oxidation will interfere. No interferences in most natural waters. Possible loss of Pb during filtration.*
References	*No. 5, R-1130-76, p. 33-37.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*> 90 percent.*
Significant figures	*One significant figure for values below 20 pCi/L; two significant figures above 10 pCi/L.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*0.5 liter and 3.5 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HNO_3.*
Preservative	*HNO_3.*
Storage	*1 year.*

II. ANALYSIS

Method	*Gamma spectrometry; 3.5-liter sample counted with a NaI (Tl) detector; 500-mL sample with a Ge (Li) detector.*
Detection limit	*3 pCi/L, 100-minute count on NaI (Tl); 15 pCi/L, 300-minute count on Ge (Li).*
Precision	*Estimated to be ±20 percent at 20 pCi/L for NaI (Tl), ±20 percent at 120 pCi/L for Ge (Li). Detection limits and precision may be adversely affected by complexity of gamma-spectrum.*
Interferences	*Gamma emitters with similar energies.*
References	*(a) No. 1, D 2459-72 1977; (b) see also Section 5.F.4 of this Handbook.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Not applicable.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HNO_3.*
Preservative	*HNO_3.*
Storage	*1 year.*

II. ANALYSIS

Method	*Exporation, precipitation, gamma spectrometry with NaI (Tl).*
Detection limit	*Approximately equal to 6 pCi/L; 1-liter sample, 100-minute count on NaI (Tl).*
Precision	*Estimated to be ±20 percent at 27 pCi/L.*
Interferences	*None.*
References	*No. 7, E-Mn-01, 5 p.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Not given.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter sample through a 0.45-μm membrane filter; acidify to 0.5N* HNO_3.
Preservative	HNO_3.
Storage	*1 year.*

II. ANALYSIS

Method	*Coprecipitation with all elements from radium through californium, except uranium, with barium sulfate. Alpha scintillation count precipitate uniformly deposited on membrane filter.*
Detection limit	*< 1 pCi.*
Precision	*Dependent on other alpha-emitters present.*
Interferences	*Lanthanum, bismuth, zirconium, and calcium.*
References	*(a) No. 14; (b) No. 15.*

III. REPORTING

Units	*pCi/L or pCi/g.*
Chemical yield	*> 99 percent.*
Significant figures	*Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh and ocean.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Polyethene or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HNO_3.*
Preservative	*Hydrochloric or nitric acid.*
Storage	*For best results, analyze as soon as possible.*

II. ANALYSIS

Method	*Evaporation, ion exchange, electrodeposition, alpha spectrometry; use of Pu–236 tracer recommended.*
Detection limit	*0.02 pCi per sample (2 sigma counting error = 100 percent) for a 1,000-minute count.*
Precision	*± 10 percent at 0.1 pCi/L, ± 0.01 pCi/L below (one sigma).*
Interferences	*Normally none. Protoactinium may interfere.*
References	*(a) No. 9, p. 102–124; (b) No. 20.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*90 percent.*
Significant figures	*Two significant figures.*

I. SAMPLE

Applicability ..... *Water fresh.*

Collection ..... *Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*

Container ..... *Plastic or glass.*

Size ..... *1 liter.*

Preliminary treatment ... *Filter sample through a 0.45-μm membrane filter as soon as possible after it is received: acidify to 0.5N HCl.*

Preservative ..... *HCl. (Add 4 percent by volume of concentrated HCl).*

Storage ..... *Start analysis as soon after receipt as possible to minimize Po-210 ingrowth from Pb-210 and Bi-210.*

II. ANALYSIS

Method ..... *Polonium-210 in water is coprecipitated with tellurium using stannous chloride as the precipitant.*

Detection limit ..... *Approximately .02 pCi/L (24-hour alpha count).*

Precision ..... *± 10 percent at 0.2 pCi/L.*

Interferences ..... *Decay products from randon-222 to lead-210 showed no detectable interference. Decontamination factors determined on uranium mill affluents; Ra-226-1,600; uranium-238-166,000; thorium-230-990,000. High calcium may present solubility problems.*

Reference ..... *No. 13.*

III. REPORTING

Unit ..... *pCi/L.*

Chemical yield ..... *98.8 percent.*

Significant figures ..... *Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Water fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*1 year.*

II. ANALYSIS

Method	*Radium radionuclides coprecipitated with barium sulfate—alpha counting with gas flow proportional counter.*
Detection limit	*Approximately 0.1 pCi/L.*
Precision	*Reproducibility at 95 percent confidence level is approximately ±0.1 pCi/L at levels <0.5 pCi/L and ±20 percent at higher concentrations.*
Interferences	*Other alpha-emitting radionuclides which coprecipitate with barium sulfate including thorium, polonium, transuranium elements, and others.*
References	*No. 5, R-1140-76, p. 39-41.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*>99 percent.*
Significant figures	*One significant figure for concentrations <1 pCi/L and two significant figures for values >1 pCi/L.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.1N HNO_3.*
Preservative	*HNO_3.*
Storage	*1 year.*

II. ANALYSIS

Method	*Radium coprecipitated with lead sulfate, then reprecipitated as carbonate which is dissolved in 3N nitric acid transferred to radon bubbler; radon is determined by alpha scintillation.*
Detection limit	*0.15 pCi (0.1 pCi/L for 1.5 liter sample counted for 30 minutes.)*
Precision	*0.15 pCi from 0.1 to 10 pCi/L, 15 percent above 1.0 pCi/L (one sigma).*
Interferences	*Radium-224 in uranium-mill effluents. This can be corrected for if known to be present.*
References	*No. 9, p. 42-43, 48-50.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*>95 percent.*
Significant figures	*Two.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*1 year.*

II. ANALYSIS

Method	*Radium is coprecipitated with barium sulfate, silica removed by HF; sulfate reprecipitated, dissolved in alkaline EDTA and radon determined by alpha scintillation.*
Detection limit	*0.01 pCi/L.*
Precision	*±20 percent at 0.1 pCi/L.*
Interferences	*Not indicated.*
References	*No. 7, E-Ra-05-01, 4 p.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*>99 percent.*
Significant figures	*Retain the number of significant figures justified by twice the relative standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*1 year.*

II. ANALYSIS

Method	*Radium is coprecipitated by barium sulfate, separated and then dissolved in alkaline DTPA; radon is ingrown and determined by alpha scintillation using radon emanation technique.*
Detection limit	*0.01 pCi/L.*
Precision	*Estimated ±20 percent at 0.10 pCi/L, ±10 percent for concentrations >0.10 pCi/L.*
Interferences	*None.*
References	*No. 5, R-1141-76, p. 43-49.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Estimated >99 percent.*
Significant figures	*Less than 0.10 pCi/L, one significant figure; >0.10 pCi/L, two significant figures.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify with HCl to pH < 1.5.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Radium isotopes coprecipitated with barium sulfate in presence of yttrium hold back carrier; precipitate purified by reprecipitation from EDTA solution; lead sulfide precipitated to remove interferences; and finally actinium coprecipitated with yttrium hydroxide mounted and counted.*
Detection limit	*Approximately 1 pCi/L using 1 liter sample.*
Precision	*Not indicated.*
Interferences	*Excessive radioactive contamination found in some yttrium and lanthanium compounds used as carrier; reagents should be checked to verify purity.*
References	*No. 5, R-1142-76, p. 51-54.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*>85 percent.*
Significant figures	*One significant figure for values <1.0 pCi/L, two significant figures for values >1.0 pCi/L.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter.*
Preservative	*None.*
Storage	*1 year.*

II. ANALYSIS

Method	*Radium isotopes coprecipitated with barium sulfate, converted to carbonate, then to nitrate after which actinium-228 daughter separated by dibutyl phosphate extraction, back extracted into 4N nitric; Pb, Po, and Bi removed by sulfide precipitation, solution containing actinium evaporated and counted.*
Detection limit	*Approximately 1 pCi/L using 1-liter sample.*
Precision	*Not indicated.*
Interferences	*Radium-224 (and daughter); minor.*
Reference	*No. 10.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Approximately 96 percent of Ac-228 when no barium sulfate precipitation and 80 percent when barium sulfate precipitation included.*
Significant figures	*Not indicated.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect appropriate volume of a representative sample directly into a radon bubbler by vacuum suction.*
Container	*Radon bubbler*
Size	*Depends on bubbler size; range is from 40–90 mL.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*1 year.*

II. ANALYSIS

Method	*Radium is de-emanated with helium gas into an evacuated alpha scintillation cell and activity measured.*
Detection limit	*4 pCi/L.*
Precision	*±100 percent at 4 pCi/L; ±30% between 10 and 100 pCi/L; and ±20% >1,000 pCi/L.*
Interferences	*None.*
References	*Available from: Methods Coordinator OWDC, U.S. Geological Survey, 417 National Center, Reston, VA 22092.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*Estimated >99 percent.*
Significant figures	*Less than 10 pCi/L, one significant figure; between 10 and 100 pCi/L, nearest 5 pCi/L; >100 pCi/L, two significant figures.*

I. SAMPLE

Applicability	*Water, urine, soil.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Water - filter through a 0.45-μm membrane filter; acidify to 0.5N HCl. Soil - dry at 65°C for 24 hours.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Sample is evaporated and residue containing Ru carrier is heated with H_2SO_4 and $KMnO_4$. Ruthenium as RuO_4 is distilled with carrier, precipitated and beta or gamma counted.*
Detection limit	*Approximately 1 pCi/L with 20 percent CE and 0.4 cpm background, (beta), GE (Li) detector, 3 ± 4 dpm for Ru-103 and 106 respectively on separated isotopes.*
Precision	
Interferences	*Ru-103 and -106 may be determined separately by beta counting, with and without a thin absorber. Other gamma emitting isotopes may interfere unless ruthenium isotopes are separated.*
References	*(a) No. 7, E-Ru-01, 4 p., and D-04, 24 p.; (b) No. 6.*

III. REPORTING

Units	*pCi/L, pCi/g.*
Chemical yield	*Approximately 80 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Polyethylene or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N with nitric acid.*
Preservative	*HNO_3.*
Storage	*1 year.*

II. ANALYSIS

Method	*Separation of calcium on cation exchange resin, selective elution, precipitation and counting immediately and again after 7 days. Sr-89 and Sr-90 are resolved mathematically.*
Detection limit	*2 pCi/L for Sr-90, 5 pCi/L for Sr-89, 50-minute counts.*
Precision	*Sr-90, 1.5 pCi/L from 2 to 30 pCi/L, 5 percent above 30 pCi/L (one sigma); Sr-89, 5t pCi/L from 5 pCi/L to 100 pCi/L, 5 percent above 100 pCi/L (one sigma).*
Interferences	*None.*
References	*No. 9, p. 25-29.*

III. REPORTING

Unit	*pCi/L.*
Chemical yield	*75 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability ..... *Water.*

Collection ..... *Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*

Container ..... *Polyethylene or glass.*

Size ..... *1 liter.*

Preliminary treatment ... *Filter through a 0.45-μm membrane filter; acidify to 0.5N HNO_3.*

Preservative ..... *HNO_3.*

Storage ..... *1 year.*

II. ANALYSIS

Method ..... *Ca is separated on nitrate ppt., Sr is finally pptd as $SrCO_3$. Y-90 ingrows 2 weeks, Y-90 is separated using TBP, back extracted, and planchetted as solution or ppt. Y-90 is beta counted.*

Detection limit ..... *Not given.*

Precision ..... *11% (2 sigma).*

Interferences ..... *None if procedure is adhered to.*

References ..... *(a) No. 2, p. 579-585; (b) No. 3.*

III. REPORTING

Unit ..... *pCi/L.*

Chemical yield ..... *98%.*

Significant figures ..... *Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water and wastewater (with effluents).*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76, grab sample.*
Container	*Plastic or glass.*
Size	*1.5 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter at time of analysis. A separate analysis of the suspended material allows the determination of "total" thorium.*
Preservative	*0.5N HCl.*
Storage	*One year.*

II. ANALYSIS

Method	*Colorimetric method; thorium is coprecipitated with calcium in the form of oxalate salts. The salts are filtered, dissolved in HCl and thorium is determined spectrophotometrically by use of thorin at 545 nm.*
Detection limit	*Less than 1 μg/L on a 1.5-liter sample; 0.7 μg (1 μg/L).*
Precision	*Single operator precision of ± 15 percent.*
Interferences	*Ferric iron, fluorides, oxalates, phosphates, and large amounts of sulfates. (Limitations: Inadequate sensitivity for most natural "unpolluted" water where concentrations will rarely exceed 0.01 μg/L).*
References	*No. 1, D 2333–80.*

III. REPORTING

Unit	*μg/L.*
Significant figures	*One significant figure below 1.0 μg/L level, two significant figures at 1.0 μg/L level and above.*

I. SAMPLE

Applicability	*Water, other liquids, and solid materials.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*None. Rinse sample container with 5 mL concentrated HCl and add to main solution to recover any thorium precipitated on walls. Filter–0.45-μm membrane filter.*
Preservative	*0.5N HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Sample prepared by pyrosulfate fusion, thorium concentrated by barium sulfate precipitation, redissolved and determined by fluorometry using morin at pH 11.5.*
Detection limit	*0.1 μg/L on 100-mL sample.*
Precision	*10 percent on 0.1 μg, 0.5 percent on 5 μg.*
Interferences	*Before separation: beryllium, titanium uranium, zirconium. After separation: rare earths and platinum.*
References	*(a) No. 16; (b) No. 17.*

III. REPORTING

Unit	*μg/L.*
Chemical yield	*>98 percent.*
Significant figures	*One significant figure for values <0.1 μg/L, two for values >0.1 μg/L.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370-76.*
Container	*Glass only, tritium-seal cap.*
Size	*1 liter.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*Indefinite.*

II. ANALYSIS

Method	*Distill sample using vacuum distillaton apparatus. Mix 8 mL of distillate with 14 mL scintillation cocktail and count in liquid scintillation counter.*
Detection limit	*Variable, according to background. Sea level: approximately 100 pCi/L. At 1,525 m elevation, approximately 500 pCi/L.*
Precision	*Approximately 20 percent at 1,600 pCi/L (500 T.U.).*
Interferences	*High salt concentrations, colored compounds, certain metal ions, and organic compounds that distill with water may cause quenching.*
References	*(a) No. 5, R-1171-76, p. 63-66; (b) No. 9, p. 63-65.*

III. REPORTING

Unit	*pCi/L (tritium units (T.U.) 1 TU = 3.22 pCi/L.)*
Chemical yield	*> 95 percent.*
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability	*Water.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Glass only, tritium-seal cap.*
Size	*1 liter.*
Preliminary treatment ...	*None.*
Preservative	*None.*
Storage	*Indefinite.*

II. ANALYSIS

Method	*Azeotropic distillation and liquid scintillation counting.*
Detection limit	*200 pCi/L for a 200-minute count (two sigma counting error = 100 percent).*
Precision	*± 10 percent at 2,000 pCi/L, ± 200 pCi/L below 2,000 pCi/L (one sigma).*
Interferences	*Radioiodine and other volatile radionuclides. If known to be present they can be eliminated or masked. Volatile organics can cause quenching.*
References	*No. 9, p. 66–67.*

III. REPORTING

Unit	*pCi/L (Tritium units (T.U.) 1 TU = 3.22 pCi/L.)*
Chemical yield	*> 95 percent.*
Significant figures	*Two.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Determine uranium by comparison of reflected fluroscence from spiked and unspiked residue fused with sodium-potassium carbonate-fluoride flux.*
Detection limit	*0.5 μg/L.*
Precision	*+20 percent at 0.5 μg/L level.*
Interferences	*Quenching by heavy metals and high concentrations (>300 mg/L) of dissolved solids. Nitric acid in original sample results in poor fusion buttons.*
References	*No. 5, R-1180=76, p. 83–88.*

III. REPORTING

Unit	*μg/L.*
Chemical yield	
Significant figures	*One significant figure for values <1 μg/L; two significant figures for values >1 μg/L.*

I. SAMPLE

Applicability	*Water, fresh.*
Collection	*Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*
Container	*Plastic or glass.*
Size	*1 liter.*
Preliminary treatment ...	*Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*
Preservative	*HCl.*
Storage	*1 year.*

II. ANALYSIS

Method	*Separate uranium by extraction with MIBK using acid-deficient aluminum nitrate solution containing TPAN. Fuse as in direct uranium fluorometric method.*
Detection limit	*0.05 to 50 mg/L.*
Precision	*Variable.*
Interferences	*Excess sulfate or acid concentrations.*
References	*No. 1, D 2907–75.*

III. REPORTING

Unit	*mg/L.*
Chemical yield	
Significant figures	*Retain the number of significant figures justified by twice the standard deviation of the determination.*

I. SAMPLE

Applicability ..... *Water, fresh and brackish.*

Collection ..... *Collect an appropriate volume of a representative sample in accordance with Ref. 1, D 3370–76.*

Container ..... *Plastic or glass.*

Size ..... *1 liter.*

Preliminary treatment ... *Filter through a 0.45-μm membrane filter; acidify to 0.5N HCl.*

Preservative ..... *HCl.*

Storage ..... *1 year.*

II. ANALYSIS

Method ..... *Coprecipitate uranium with aluminum phosphate. Dry precipitate and dissolve in magnesium-nitrate-nitric acid solution. Extract the uranium into ether, evaporate and fuse the residue with sodium-potassium carbonate-fluoride as in direct procedure.*

Detection limit ..... *0.01 μg/L.*

Precision ..... *100 percent at 0.01 μg/L minimum.*

Interferences ..... *Removed by precipitation. Highly saline water (ocean water) may contain excess calcium and magnesium that will interfere during precipitation of aluminum phosphate.*

References ..... *No. 5, R-1181-76, p. 89–92.*

III. REPORTING

Unit ..... *μg/L.*

Chemical yield ..... *80 to 95 percent, depending on ethyl ether aliquot evaporated for fusion button.*

Significant figures ..... *One significant figure < 0.1 μg/L. Two significant figures > 0.1 μg/L.*

5.F.4. GAMMA SPECTROMETRY

5.F.4.a. NaI (Tl) DETECTORS

5.F.4.a.1. DESCRIPTION OF STANDARD COUNTING SYSTEM

5.F.4.a.1.a. Detector.

Integral line standard 10.2-cm by 10.2-cm NaI (Tl) crystal. Low-potassium content, low-background base. Coupled to a 12.7-cm RCA8055 P.M.T. Typical resolution 8.0 to 8.2 percent. Similar to Harshaw Type 16MBS 16/5B.

5.F.4.a.1.b. Shield.

Low-background steel, 15.25-cm in all directions. Interior cavity volume of 61 cm^3 with graded shield lining of lead, cadmium, and copper.

5.F.4.a.1.c. Sample.

Volume of 3.5 liter contained in Marinelli beaker. Count time of 4,000 s at energy range of 0 to 2.56 MeV, at 10 KeV/channel.

Table 1.—*Typical gamma-ray efficiencies - 3.5 liter geometry - September 1973*

10.2 × 10.2-cm NaI (Tl) Detector

Nuclide	Energy KeV	Abundance γ's/dis	Peak Region channels	Efficiency for peak region	Peak channel	Efficiency for peak channel	Typical* MDA (pCi/L)
^{144}Ce	134	0.108	13–14	0.00832	14	0.00366	21.5
^{51}Cr	320	.099	31–35	.00582	33	.00157	33.4
^{131}I	364	.824	36–40	.0559	38	.0138	3.7
^{137}Cs	662	.846	63–69	.0380	66	.00762	4.3
^{54}Mn	835	1.000	79–85	.0301	82	.00581	4.4
^{65}Zn	1115	.506	105–111	.0255	108	.00456	4.5
^{40}K	1460	.107	135–143	.00195	139	.00281	57.2
^{140}La	1600	.956	146–154	.0142	150	.00199	6.1

*MDA is calculated for the photopeak region and is based strictly on counting statistics (2σ). It is further assumed that only the particular nuclide under consideration is present.

5.F.4.b. Ge (Li) DETECTOR

5.F.4.b.1. DESCRIPTION OF STANDARD COUNTING SYSTEM

5.F.4.b.1.a. Detector

Shape: right circular cylinder with 42-mm diam., drifted coaxially. p-Core 8.5-mm diam.
Length: 36-mm. Active area facing window: 13.2 cm^2.
Weight: 273g. Distance from window: 5mm.

Resolution and efficiency

Isotope	Energy (KeV)	FWHM (Kev)	FWTM (KeV)	Peak/ Compton	Efficiency percent
Co-57	122	1.41	2.65		
Co-137	662	1.82	3.36	39:1	
Co-60	1332	2.23	4.23	29:1	8.7
Th-228	2614	3.05	6.37	22:1	

5.F.4.b.1.b. Shield

Low background lead, 7.6 cm in all directions. Inside cavity measures 35.6 cm wide, 78.75 cm tall, 35.6 cm deep with graded shield lining of cadmium and copper.

5.F.4.b.1.c. Sample

Volume of 500 mL contained in a Marinelli beaker[1]. Count time of 4 h at energy range of 0 to 2 MeV, at 1 KeV/channel.

Table 2.—*Typical gamma-ray efficiencies — 500 milliliters geometry — August 1975*

8.7% Ge (Li) Detector

Nuclide	Energy KeV	Abundance γ's/dis	Peak region channels	Efficiency for peak region	Peak channel	Efficiency for peak channel	Typical* MDA (pCi/L)
^{144}Ce	133.39	0.108	133–139	0.02052	136	0.01073	9.74
^{131}I	364.57	.824	363–369	.00893	366	.00392	12.04
^{106}Ru	511.8	.205	509–515	.00671	512	.00262	17.19
^{137}Cs	661.64	.846	657–665	.00500	661	.00185	13.68
^{88}Y	898.03	.934	892–900	.00358	897	.00125	
^{60}Co	1173.2	.999	1164–1175	.00277	1170	.00090	19.73
^{60}Co	1332.43	1.000	1323–1333	.00237	1329	.00074	
^{88}Y	1835.86	.994	1820–1834	.00175	1829	.00047	

*MDA is based on 2σ counting statistics for the photopeak region and the assumption that only that particular nuclide is present.
[1]Control Molding, 84 Granite Avenue, Staten Island, NY 10303.

5.F.4.c. REFERENCES

Sanderson, Colin G., and Latner, Norman, 1974, Performance and cost comparison of a large Ge (Li) detector and smaller Ge (Li)–NaI (Tl) Compton suppression system: Institute of Electrical and Electronic Engineers, Transportation on Nuclear Science, NS-21, no. 1, p. 553–557.

5.G. ACQUISITION OF DATA USING FIELD-INSTRUMENTATION TECHNIQUES

5.G.1. INTRODUCTION

The purpose of this section is to set forth criteria for the use of field instrumentation, so that the data generated by the instrumentation techniques will meet acceptable levels of accuracy. This part deals only with systems in which chemical pretreatment of the sample is not required; only those parameters for which dependable sensors are available have been included.

The system-performance requirements outlined under this section are not to be considered engineering specifications. It should be recognized that, to meet specific needs of operation, enforcement, or management, data sometimes must be collected under more rigorous criteria for accuracy and transient response than those criteria prescribed in this document.

5.G.1.a. UNITS OF MEASUREMENT

Units of measurement used in this recommendation are degrees Celsius, microsiemens, millisiemens, milligrams per liter, pH units, and meters.

5.G.1.b. DEFINITIONS

The following definitions will be used throughout this subsection.

Calibrated Accuracy.—Difference between the indicated value and its accepted value (known value). This accuracy is determined by calibrating an uncontaminated sensor in the measuring system (as outlined under "System Calibration").

Response Time.—Time to which the system responds within the calibrated accuracy, after a step change of 50 percent of full scale.

Stability.—Measure of length of time a measuring system, once calibrated, continues to measure the actual value within the calibrated accuracy, without the need for adjustment or recalibration. Stability performance is based upon the measurement of standard calibrating solutions with an uncontaminated sensor.

Temperature Compensation.—Adjustment that corrects for the effect of temperature on the measuring system. In addition, it may also adjust the measured value of a selected temperature, based on a known parameter-temperature relationship. Temperature compensation may be incorporated into the measuring system, so that the value reported is the adjusted value. If this approach is not used, then manual or algebraic methods are necessary to obtain the adjusted value.

Contamination.—Any biological, chemical, or physical fouling that causes the calibrated accuracy to change.

Representative Sample.—Water sample whose measured values are characteristic of the body of water from which the sample has been taken, and the sample that achieves the basic objectives of the monitoring program.

Degradation.—Any biological, chemical, or physical process that causes the characteristics of the water sample at the sensor to differ from those at the sampling source. For the purpose of Section 5.G.1., any variations greater than those listed in the following table are considered excessive.

Characteristic	*Difference between measured value at the sensor and at the system intake.*
Water temperature	0.1°C.
Specific conductance	0.5% of calibrated full scale
Dissolved oxygen	0.2 mg/L
pH	0.05 pH unit
Chloride, fluoride, and sodium ions	1.0% of calibrated full scale

5.G.2. AUTOMATIC WATER-QUALITY MONITORS

Automatic water-quality monitors of electrochemical and electrophysical types provide the most economical means of obtaining continuous or time-series reporting of certain water-quality characteristics. Monitors of this type consist of three basic components: the sensing elements, the signal-conditioning elements, and the data logging or display section. The sensing elements may be immersed directly in the stream; however, the more common approach is to pump the sample to a sensor chamber in which the sensing elements are located. The signal-conditioning elements convert the signals from the sensors to an appropriate voltage level proportional to the measured variable. The data logging or display section presents the measured value, usually in engineering units.

5.G.2.a. INTAKE SYSTEMS

Obtaining a representative sample is one of the more difficult problems of automatic monitoring. This subsection reviews the various aspects of sampling that should receive careful study and consideration before the sampling process is begun.

5.G.2.a.1. LOCATION

The location of the intake, or sensors if they are of the *in situ* type, is dependent upon the objectives of the monitoring program. One must consider if the sample is to be representative of the entire stream or if some special need must be met, such as monitoring the localized effects on a stream of a waste discharge.

5.G.2.a.1.a. Preliminary Site Survey

In order to determine the appropriate coordinates of the intake or of the sensors, preliminary site survey should be made at intervals over the range of flow conditions. Usually, portable instruments are used and are the most satisfactory means for making preliminary site surveys; however, grab samples are sometimes used.

5.G.2.a.1.b. Site Location

Using the preliminary site surveys, the coordinates of the sampling site or sites are determined from an analysis of the data over the range of flow conditions.

The use of multiple intakes or sensor packages may be required in cases where non-homogeneous flow is encountered and for which no single location would give a representative sample.

a. Fixed elevation—One method of installation is to mount the intake or sensor package on a rigid support at a fixed elevation.

b. Fixed depth—A second method of installation is to suspend the intake or sensor package from a float so that it remains a fixed distance below the water surface.

c. Profiling—Another method is to vary the coordinates of the intake or sensor package.

The choice among these three methods depends on continuous monitoring objectives.

5.G.2.a.2. COMPONENTS

The typical intake system is comprised of the following components:

(1) Intake screen.
(2) Conduit from the intake to the pump.
(3) Pump-motor assembly.
(4) Required values.
(5) The conduit from the pump to the sensor chamber.

There are two general classifications of intake systems:

(1) Those deriving a sample from an existing intake facility, such as that at a power plant.

(2) Those having their own pumping facility, which is the most common intake system. Various arrangements can be used, such as:

a. A system employing a submersible pump located in the stream.
b. A system employing a surface-type pump lifting a sample and pumping it to the monitor.
c. A well version in which the water flows under gravitational force into the well, and the sample is pumped from that point to the monitor. (Caution: the volume of water in the well should not be large relative to the flow rate of the pump, so that residence time of a sample is kept to a minimum.)

5.G.2.a.2.a. Sample Volume

Regardless of the intake system used, the sample flow rate should be adequate to provide a complete sample change to the sensors at time intervals of one minute or less, to provide adequate flow for the dissolved oxygen sensors, and to cleanse the intake lines.

5.G.2.a.2.b. Pump

When a pump is required, it is important that it supply a sample to the sensor chamber with minimum degradation. Continuous pumping is recommended.

Intermittent pumping is not usually recommended because of several problems. Provisions must be made for keeping certain sensors continuously immersed for satisfactory operation; also, programming of the pump operation must be designed to provide for sensor response before data logging is begun. Additionally, pump interruption can result in sediment settling, sediment-slug introduction, and impeller binding.

Several types of pumps are suitable; local site conditions usually dictate the best choice. Submersible pumps are normally employed; however, surface-type pumps can be used when the suction head differential does not degrade the sample. If a surface-type pump is used, great care must be taken to see that there are no air leaks in the intake line.

5.G.2.a.2.c. Intake Screen

Filtering the sample is not recommended; however, screening around the intake to keep out debris is frequently necessary.

5.G.2.b. SYSTEM PERFORMANCE

The criteria set forth in this subsection pertain to the system from the sensor to the data logger; they apply to the system over environmental operating conditions ranging from −10° to 50°C, with humidity levels up to 99 percent. Any exceptions to the above are noted in the appropriate section. For details on calibration methods for each of the following characteristics, see the appropriate sections under System Calibraton. Full-scale ranges should be selected to cover ambient conditions, but chosen to obtain maximum resolution.

5.G.2.b.1. WATER TEMPERATURE

5.G.1.2.1.a. Calibrated Accuracy

The calibrated accuracy of the temperature-measuring system shall be within 1 percent of full scale or 0.3°C, whichever is less.

5.G.2.b.1.b. Response Time

The response time of the temperature measuring system shall not be greater than 2 minutes.

5.G.2.b.1.c. Stability

The temperature-measuring system shall retain its calibrated accuracy for a period of not less than 4 weeks with an uncontaminated sensor.

5.G.2.b.2. SPECIFIC CONDUCTANCE

5.G.2.b.2.a. Calibrated Accuracy

The calibrated accuracy of the specific-conductance measuring system shall be within 3 percent of full scale over the temperature range of −2° to 40°C.

5.G.2.b.2.b. Response Time

The response time of the specific conductance measuring system shall not be greater than 2 minutes.

5.G.2.b.2.c. Stability

The specific-conductance measuring system shall retain its calibrated accuracy for a period of not less than 4 weeks with an uncontaminated sensor.

5.G.2.b.2.d. Temperature Compensation

In freshwater application, the data from the specific-conductance measuring systems shall be temperature-compensated, according to the characteristics of potassium-chloride solution and normalized to 25°C.

5.G.2.b.3. DISSOLVED OXYGEN

5.G.2.b.3.a. Calibrated Accuracy

The calibrated accuracy of the dissolved-oxygen measuring system shall be within 0.2 mg/L over the water-temperature range of −2° to 40°C.

5.G.2.b.3.b. Response Time

The response time of the dissolved-oxygen measuring system shall not be greater than 2 minutes.

5.G.2.b.3.c. Stability

The dissolved-oxygen measuring system shall retain its calibrated accuracy for a period of not less than 4 weeks with an uncontaminated sensor.

5.G.2.b.3.d. Temperature Compensation

The dissolved-oxygen measuring system shall be temperature-compensated to meet the accuracy requirements as outlined in the section under CALIBRATED ACCURACY.

5.G.2.b.3.e. Chloride Compensation

When chloride concentrations exceed 3,000 mg/L (3 parts per thousand), corrections must be applied in accordance with the insructions given in *Standard Methods for the Examination of Water and Wastewater*, fifteenth edition, 1980, Part 421–B, page 392, Table 421:I.

5.G.2.b.4. PH

5.G.2.b.4.a. Calibrated Accuracy

The calibrated accuracy of the pH measuring system shall be within 0.1 pH unit, over the temperature range of −2° to 40°C.

5.G.2.b.4.b. Response Time

The response time of the pH measuring system shall not be greater than 2 minutes.

5.G.2.b.4.c. Stability

The pH measuring system shall retain its calibrated accuracy for a period of not less than 4 weeks with an uncontaminated sensor.

5.G.2.b.4.d. Temperature Compensation

The pH measuring system shall be temperature-compensated to meet the accuracy requirements as outlined under CALIBRATED ACCURACY.

5.G.2.b.5. CHLORIDE, FLUORIDE, AND SODIUM IONS*

5.G.2.b.5.a. Calibrated Accuracy

The calibrated accuracy of the measuring system shall be within 5 percent of full scale.

5.G.2.b.5.b. Response Time

The response time of the measuring system is a function of the application and cannot be specified.

5.G.2.b.5.c. Stability

The measuring system shall retain its calibrated accuracy for a period of not less than 4 weeks with an uncontaminated sensor.

*CAUTION: These sensors have restricted application and cannot be used for general-purpose monitors without qualifications.

5.G.2.b.5.d. Temperature Compensation

The measuring system shall be temperature-compensated to meet the accuracy requirements as outlined in the section under CALIBRATED ACCURACY.

5.G.2.b.6. Optical Properties

For many years it has been the common practice to measure turbidity; however, attempts to quantify turbidity have led to a proliferation of methods and units. The term "turbidity" is generally accepted as a non-technical qualitative descriptor of the optical properties of water. Therefore, it has been decided to replace attempts to measure turbidity with the optical measurements of transmittance and 90° scattering, employing white-light sources.

5.G.2.b.6.a. 90° Scattering

5.G.2.b.6.a.1. Calibrated Accuracy

The calibrated accuracy of the system shall be within 5 percent of the full scale over the water-temperature range of −2° to 40°C.

5.G.2.b.6.a.2. Response Time

The response time of the system shall not be greater than 2 minutes.

5.G.2.b.6.a.3. Stability

The system shall retain its calibrated accuracy with uncontaminated surfaces of a period of not less than 4 weeks.

5.G.2.b.6.b. Transmittance

5.G.2.b.6.b.1. Calibrated Accuracy

The calibrated accuracy of the system shall be within 5 percent of full scale over the water-temperature range of −2° to 40°C.

5.G.2.b.6.b.2. Response Time

The response time of the system shall not be greater than 2 minutes.

5.G.2.b.6.b.3. Stability

The system shall retain its calibrated accuracy with uncontaminated surfaces for a period of not less than 4 weeks.

5.G.2.c. SYSTEM CALIBRATION

Calibration data for measuring systems shall be provided in the manner described in the following paragraphs.

5.G.2.c.1. WATER TEMPERATURE

5.G.2.c.1.a. Method

The water-temperature measuring system shall be calibrated by comparing the output of the measuring system to that obtained by a high-quality thermometer, that has been checked against a precision thermometer certified by the National Bureau of Standards.

5.G.2.c.1.b. Calibration Points

The temperature-measuring system shall be calibrated at three points: one low, one medium, and one high scale of constant temperature.

5.G.2.c.2. SPECIFIC CONDUCTANCE

5.G.2.c.2.a. Freshwater Method

The specific-conductance measuring system shall be calibrated by immersing the sensor in a container of potassium-chloride standard solution and comparing the output of the measuring system with the known value of the standard solution. The potassium-chloride solution should be prepared in accordance with the instructions given in *Standard Methods for the Examination of Water and Wastewater, fifteenth edition, 1980, Part 205.*

5.G.2.c.2.b. Calibration Points

Each applicable range of the specific conductance measuring system shall be calibrated at three points by employing reference solutions at low, medium, and high scale. Each range shall be checked for temperature compensation using reference solutions having values of specific conductance near the midscale of each range.

5.G.2.c.3. DISSOLVED OXYGEN

5.G.2.c.3.a. Freshwater Method

The dissolved-oxygen measuring system shall be calibrated by immersing the sensor in a container of air-saturated distilled water and comparing the output of the measuring system to that obtained by an analysis of the water. The water shall be stirred or made to flow with sufficient velocity, so any increase in flow or stirring shall not cause a change in the sensor output. The analysis shall be made in accordance with the Alsterberg modification of the Winkler method of dissolved-oxygen determination. (Reference: *Standard Methods for the Examination of Water and Wastewater*, fifteenth edition, 1980; *Methods for Chemical Analysis of Water and Wastes*, 1979, Environmental Protection Agency; and *Techniques of Water-Resources Investigations of the United States Geological Survey*, Book 5, Chapter A1, "Methods for Determination of Inorganic Substances in Water and Fluvial Sediments") The water must be free of interfering substances; therefore, the use of distilled water is necessary.

Care must be taken to allow adequate time in each test for the sensor to reach equilibrium.

5.G.2.c.3.b. Calibration Points

The measuring system shall be calibrated at two points: one preferably at the zero level, and one in air-saturated water at ambient temperature. The zero level is obtained by adding a few crystals of cobalt chloride ($CoCl_2$) to a container of sodium-sulfite (Na_2SO_3) solution.

5.G.2.c.4. PH

5.G.2.c.4.a. Method

The pH measuring system shall be calibrated by immersing the sensor in a container of certified pH buffer solution traceable to NBS, and by comparing the output of the measuring system to the known value of the buffer solution, which is stirred.

5.G.2.c.4.b. Calibration Points

The pH measuring system shall be calibrated at low, medium, and high range.

5.G.2.c.5. CHLORIDE, FLUORIDE, AND SODIUM IONS

5.G.2.c.5.a. Method

The measuring system shall be calibrated by immersing the sensor in a standard solution and comparing the output of the measuring system to the known value of the standard solution, which is stirred. For chloride and sodium, the standard solution shall be prepared in accordance with the instructions given in *Techniques of Water-Resources Investigations of the United States Geological Survey*, Book 5, Chaper A1, "Methods for Determination of Inorganic Substances in Water and Fluvial Sediments." For fluoride, the standard solution shall be prepared in accordance with the instructions given in "*Standard Methods for the Examination of Water and Wastewater*," fifteenth edition, 1980.

5.G.2.c.5.b. Calibration Points

The chloride-ion measuring system shall be calibrated at low, medium, and high scale.

5.G.2.d. SYSTEM MAINTENANCE

These criteria and recommended methods set forth in this section are intended to ensure use of reliable monitoring instruments capable of generating water-quality data that will meet acceptable levels of accuracy. However, the accuracy of field data depends not only upon the representativeness of the sample, the system performance (calibrated accuracy, response time, stability, and temperature compensation), and the method of calibration, as outlined under subsections entitled INTAKE SYSTEMS, SYSTEM PERFORMANCE, and SYSTEM CALIBRATION, but also upon the maintenance of the system. Regularly scheduled preventative maintenance for the intake system and the measuring system and sensors is necessary, if a monitor is to operate within its system-performance capabilities.

5.G.2.d.1. INTAKE-SYSTEM MAINTENANCE

If an intake system is employed, routine cleaning of the intake system is essential, with frequency depending upon local conditions. Manual backflushing should be included on a scheduled maintenance program, if an automatic backflushing feature is not included in the system design. In cases where biological fouling is a problem, backflushing with a chlorinated solution is recommended. It is important that the intake screen be kept free of debris. The manufacturer's recommended maintenance procedure should be followed for the pump, and installation must be such that the pump can be easily removed for maintenance, repair, or replacement.

5.G.2.d.2. SENSOR AND MEASURING-SYSTEM MAINTENANCE

To ensure sensor and measuring-system accuracy, frequent servicing is required. It is important that sensor contamination be kept to a minimum, and that frequent calibration checks be made for all measuring systems. Systems having temperature-compensating elements should be checked periodically to see that these elements are functioning correctly. The calibration checks should be performed at a minimum of three widely spaced temperature points. Experience indicates that a reasonable interval between maintenance visits to monitor field installations is approximately 1 week. However, no set schedule can be specified because of varying local conditions. On such maintenance visits, the difference between reported and actual values of a parameter both before and after maintenance should be determined. This information will be invaluable in computing the finalized data. Under certain circumstances, it may be necessary to have preconditioned spare sensors available for immediate replacement.

It is recommended that a maintenance log be kept for every monitoring instrument. All maintenance performed on the monitor should be recorded on this log with date, time, and name of individual performing the maintenance. All calibrations of the system should be documented; indicating the parameter readings before calibration; the readings of the instruments used to make the calibration; and finally, the adjusted parameter

readings after calibrations. This is important, not only for data validation, but also to establish maintenance schedules and component replacement.

From time to time, during different seasons and under different flow conditions, checks should be made to determine that degradation of the sample between the system intake and the sensor sampling chamber does not exceed the limits outlined previously.

5.G.3. OCEANOGRAPHIC-MONITORING TECHNIQUES

Only *in-situ* systems will be considered for oceanographic monitoring. These systems include a sensor package, a signal transmitting or conditioning device, and a data-logging and display package. This sequence of events describes the *in-situ* measurement process: the sensor package is lowered over the side of a vessel, pier, or other suitable oceanographic platform; the characteristics are sensed instrumentally; and the signals are transmitting and conditioned to the data logger. A continuous profile of data versus depth is recorded.

Reliable oceanographic sensors available at this writing include only conductivity, temperature, pressure (depth), dissolved oxygen, and pH. Therefore, recommended methods are limited to these. Some systems offer an optional sensor for the direct measurement of sound speed; however, this parameter will not be discussed.

5.G.3.a. GENERAL DESCRIPTION OF THE SYSTEM

The system measures ocean properties by physically detecting conductivity, temperature, and pressure; electrochemically detecting dissolved oxygen and pH; and converting these properties into signal voltages. Temperature is detected with a platinum-resistance thermometer, pressure is detected with a bonded straingage transducer, and conductivity is derived by measuring the electrical conductivity of seawaters, usually with an inductive-coupling type sensor. These three properties can be converted into salinity. The dissolved-oxygen sensor is an electrochemical type covered with a membrane. The measurement of pH is by means of a combination electrode.

In addition to the sensors, the system is comprised of electronic-mixer modules, which are housed in, for example, glass-filled polycarbonate cases mounted on a rigid stainless-steel frame. Outputs of the sensors are frequency analogs of each measured parameter; these are transmitted as a composite signal through a single-conductor oceanographic cable to surface data-handling and (or) processing equipment. At the receiver end, a surface vessel or other suitable oceanographic platform, sensor, and cable are lowered and raised with a suitable powered winch and other necessary seaworthy hardware. Detailed operating instructons are found in the manufacturer's system manual.

5.G.3.a.1. SITE SELECTION

The location and spacing of the *in-situ* stations are dependent on the objectives of the program and the size of the geographical area under study. Vertical limits depend on the depth capability of the sensors, which is usually not greater than 300 meters. However, systems are available for depths to 6000 meters for conductivity, temperature and pressure.

5.G.3.a.1.a. Preliminary Site Survey

Selection of sampling locations should be made after examining historical data for the area. If little or no data are available, a look at bathymetric charts, a graph from a rapid expendable bathythermograph (XBT), or a temperature-profile survey of the area would be helpful. Analysis of surface samples for salinity would be a useful supplement to the temperature data. These latter data could establish whether the area is estuarine or open ocean.

5.G.3.a.1.b. Station Location

Station locations should consider the following: (1) the method of introduction of pollutant materials into the ocean (atmospheric fallout, coastal runoff, ocean dumping, or man's activities on the high seas); (2) the period of influx (continuously, as in industrial discharges; seasonally, as in spring runoff; occasionally, as in the case of ocean dumping); (3) water movement and dynamics (current systems, biological activity, vertical diffusion, and tidal effects). The actual number of stations and spacing will depend on complexity of the physical oceanographic features of the area (i.e., currents, tides, thermocline location, etc.).

Sampling depths should be of the continuous-profile type. It is often desirable, dependent on the objectives of the overall program, to take water samples for various other chemical analyses. Some of the oceanographic *in-situ* systems offer a unique sampling device called a rosette sampler, that allows sample bottles to be tripped electrically at selected depths. This device can be located near the *in-situ* package. Hanging bottles on the wire above the sensors is not desirable, since the internal conductors could be cut.

An excellent reference on marine monitoring and sampling can be found in: Goldberg, E.D., 1976, Strategies for Marine Pollution Monitoring, Scripps Institute of Oceanography, John Wiley and Sons, N.Y., N.Y.

5.G.3.a.2. Sampling Rate

Regardless of the system used, the rate of descent and (or) ascent of the sensor package shall be slow enough to allow for the response time of the sensor, and rapid enough to ensure proper water flow across the dissolved oxygen sensor. Typical rate of descent or ascent is about 10 meters per minute. If dissolved oxygen is not desired, this rate can be increased.

5.G.3.b. DEGRADATION

Degradation is any biological, chemical, or physical process, that causes the characteristics of the water sample at the sensor to differ from those at the sample source. These differences, if any, are checked by sampling with three Niskin sample bottles at surface, mid, and deep depths. For the purpose of Section 5.G.3., any variations greater than those listed below are considered excessive.

Characteristic	*Difference between measured value at the sensor and at the Niskin bottle*
Water Temperature	0.01°C
Conductivity	0.1%
Dissolved Oxygen	0.05 mg/l
pH	0.01 pH unit
Depth	0.25 m

5.G.3.c. SYSTEM SPECIFICATIONS

The criteria set forth in this subsection pertain to the system from the sensor to the data logger, and apply to the system over environmental operating temperatures ranging from −2°C to 35°C. Any exceptions to the above are noted in the appropriate sections. For details on calibration methods for each of the selected characteristics, see the appropriate sections under System Calibration. Full-scale ranges should be selected to cover ambient conditions, but chosen to obtain maximum resolution (see Table 1).

Table 1.—Summary of System Specifications

Capability	Conductivity	Temperature	Depth	pH	Dissolved Oxygen
Measurement Range	0 to 60 mS/Cm	−2°C to 35°C	0 to 600 m	6 to 9	0 to 20 mg/L
Max. Operating Depth	600 m (2) 300 m (3)	600 m (2) 300 m (3)	600 m (2) 300 m (3)	300 m	300 m
Precision (1)	0.03 mS/cm	0.02°C	0.25% (4)	0.02	2.0% (4)
Resolution	0.0001 mS/cm	0.0001	0.0002% (4)	0.0002 pH	0.0004 mg/L
Response Time	0.01 sec for 99%	0.35 sec for 67%	0.1 sec for 99% 0.02 sec for 67%	1 sec for 99%	6 sec for 95% 60 sec for 98%
Weight	30 lbs (appropriate for five measured unit)				
Power Requirements	150 to 250 mA constant current at a minimum of 33 vdc plus cable drop; i.e., Voltage = 33 v + (cable resistance × 0.25)				

(1) Precision is based upon a one sigma deviation about mean method of error analysis.
(2) Profiling.
(3) Moored.
(4) Full Scale.

5.G.3.c.1. SALINITY COMPENSATION FOR DISSOLVED OXYGEN

Since the salinity in ocean waters is usually high, oxygen solubility is appreciably affected; therefore, corrections must be applied. Salinity can be determined rapidly with the following nomogram in Figure 5.2. In most cases, oxygen meters are calibrated for freshwater use, and a correction factor must be applied when the instrument is used in the ocean environment. This correction factor is easily applied according to the method of Pijanowski[1]. Using the graph in Figure 5.2, the PIJ factor is applied to the observed oxygen concentration, knowing the temperature and salinity. If the dissolved-oxygen sensor is compensated for salinity internally, this correction is not necessary.

(1) Pijanowski, B., Environmental Science and Technology, 7 (10) 957–958, October 1973.

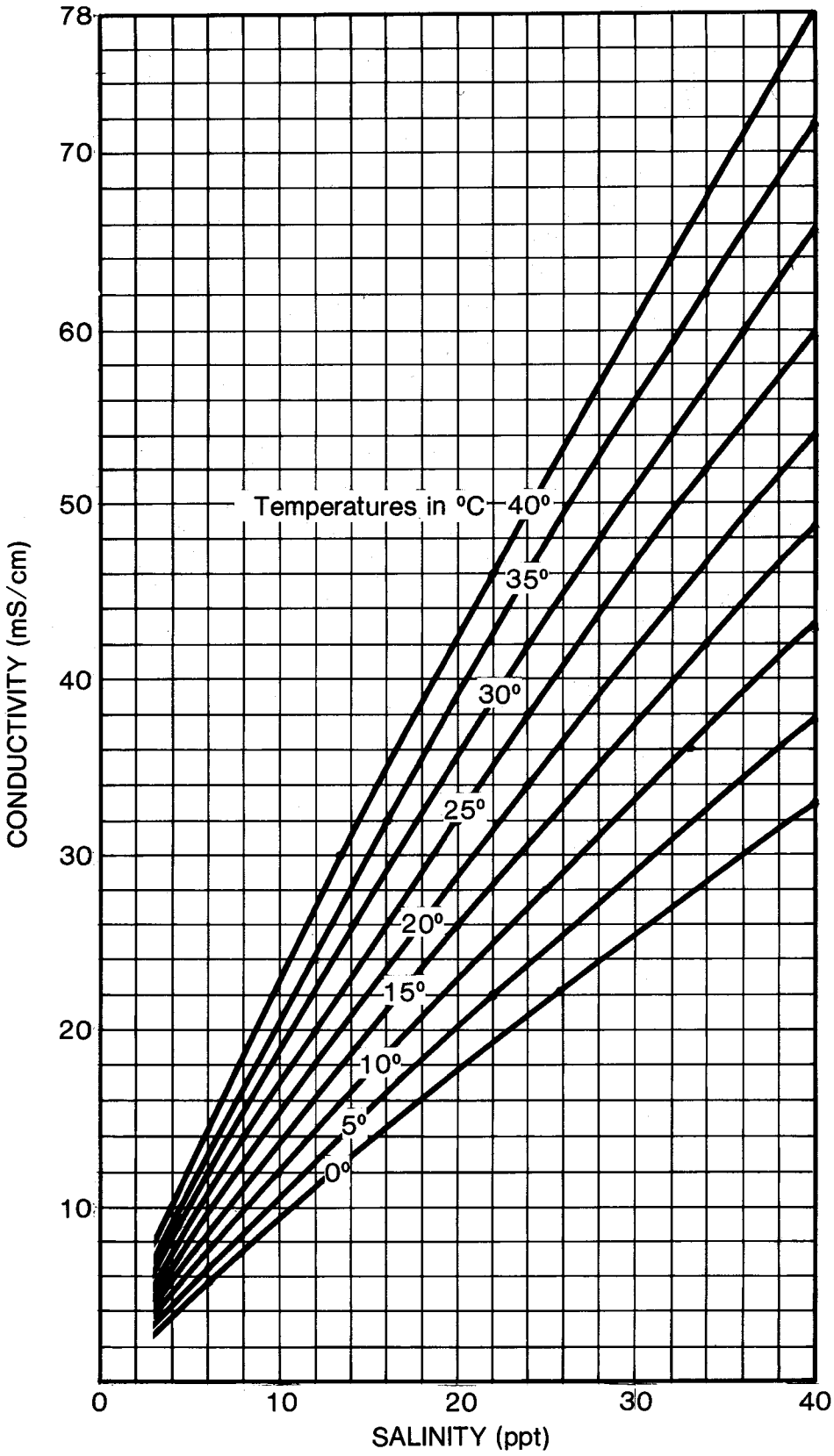

Figure 5.1. Nomogram to convert Electrical Conductivity to Salinity.

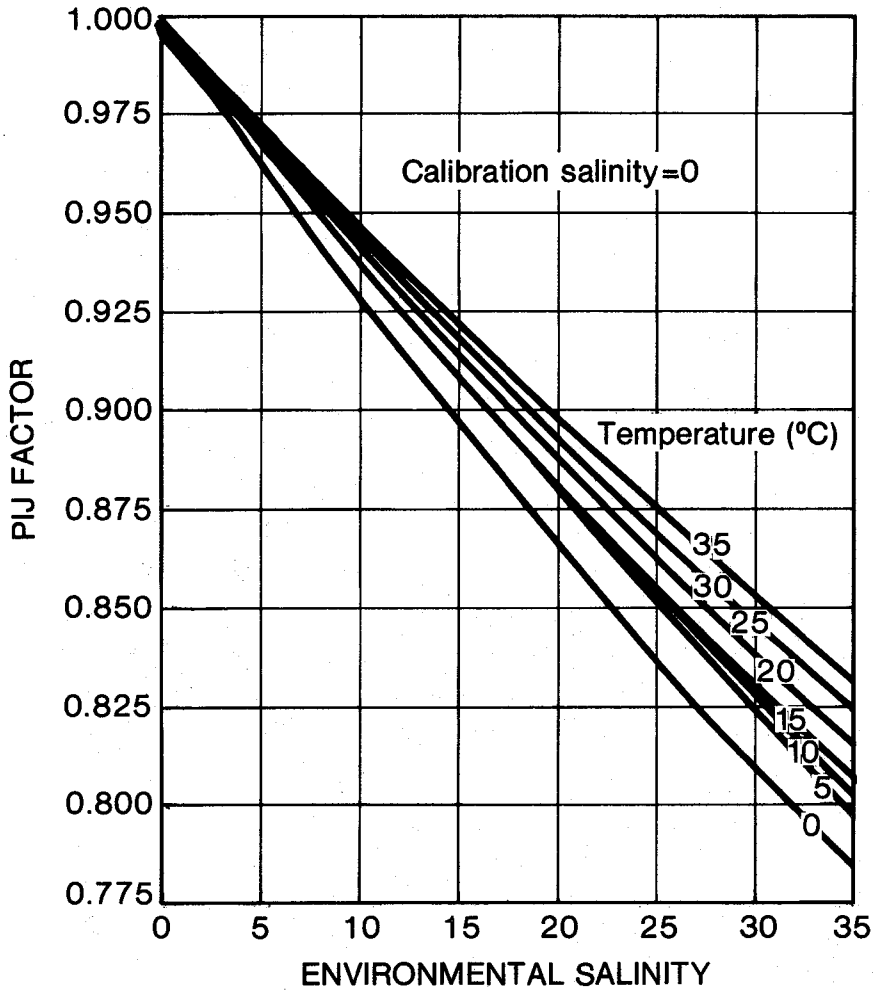

Figure 5.2. Correction factor as function of salinity and temperature.

5.G.3.d. SYSTEM CALIBRATION

Calibration data for all measuring systems shall be provided in the manner described in the following paragraphs. Initial calibrations should be made according to the manufacturer's instructions. Detailed instructions for calibrating conductivity, temperature, and depth sensors can be found in: Internal Document No. NOIC-CP-044A, June 1975, "Calibration procedure for CTD and STD Sensors," available from NOAA/OTES/ESO/TE32, Rockville, Maryland 20852.

Required calibration equipment includes: (1) a water bath capable of holding temperature stable and of a size required by the particular underwater sensor package (USP); and (2) appropriate standards.

The number of sensor calibration points is specified under each individual characteristic. The USP should remain at each calibration point to allow it to come to equilibrium. In absence of a specified time, thirty minutes is recommended.

5.G.3.d.1. WATER TEMPERATURE

5.G.2.d.1.a. Method

The water-temperature system shall be calibrated by comparing the output of the sensor in a water bath with a precision-quartz or platinum-resistance thermometer certified by the National Bureau of Standards.

5.G.3.d.1.b. Calibration Points

The temperature system shall be calibrated at a minimum of three points: one low, one medium, and one high point in the temperature range.

5.G.3.d.2. CONDUCTIVITY

5.G.3.d.2.a. Method

The conductivity system shall be calibrated by comparing the output of the sensor with the conductivity of the salt water in the calibrating bath. The water in the calibrating bath is sampled at the time of measurement, and the conductivity is measured with a precision-laboratory conductivity salinometer. The water in the calibration bath is either natural-filtered seawater, or that prepared from synthetic sea salt that meets the requirements of ASTM-D1141-75 (1980). The salinity determined with the laboratory-precision salinometer shall be converted to conductivity by the formula given in the UNESCO International Oceanographic Tables, Vol. 1, prepared by the UNESCO Joint Panel on Oceanographic Tables and Standards, 1966.

5.G.3.d.2.b. Calibration Points

The conductivity system shall be calibrated at three points: one low, one medium, and one high, using reference solutions of 10 parts per thousand (ppt) (low), 25 ppt (medium), and 35 ppt salinity (high). Each range shall be checked for temperature compensation by repeating the above measurements of temperatures of 5°, 20°, and 30°C.

5.G.3.d.3. DISSOLVED OXYGEN

5.G.3.d.3.a. Method

The dissolved-oxygen system shall be calibrated by immersing the sensor in the calibration bath containing air- or nitrogen-saturated water, and comparing the output to that obtained by the micro-modification of the Winkler method (Reference: Carpenter, J., 1965, Journal of Limnology and Oceanography, Vol. 10, No. 1) and UNESCO Oceanographic Tables, Vol. 2, prepared by the Joint Panel on Tables and Standards, 1973. The water

must be stirred with sufficient velocity to allow no change in the sensor output or introduction of temperature gradients within the bath. Care must be taken to allow adequate time for the water to be in equilibrium with the air and the sensor to become stable.

5.G.3.d.3.b. Calibration Points

The system shall have four calibration points: one with distilled water-air at 5°C, one with distilled water-air at 25°C, one with distilled water-nitrogen at 5°C, and one with distilled water-nitrogen at 25°C.

5.G.3.d.4. PH

5.G.3.d.4.a. Method

The pH system shall be calibrated by comparing the output of the sensor with the pH of the salt water in the calibration bath. The water in the calibrating bath shall be sampled at the time of measurement, and the pH shall be determined with a research grade laboratory pH meter. This pH meter shall be calibrated with NBS standard-reference material buffers.

5.G.3.d.4.b. Calibration Points

Since the pH of seawater usually is between 7.5 and 8.5, the research-grade laboratory pH meter shall be calibrated with NBS standard-reference material buffers having pH values of approximately 7, 8, and 9. The seawater in the calibration bath shall hve its pH determined at 5°, 20°, and 30°C, with the sensor of the *in-situ* system to determine temperature effects.

5.G.3.d.5. DEPTH

5.G.3.d.5.a. Method

The depth-measurement system shall be calibrated by comparing the output of the sensor to a NBS calibrated dead-weight tester, when the dead-weight tester is connected to the pressure transducer. The pressure transducer is then put into the calibrating bath.

5.G.3.d.5.b. Calibration Points

The depth-measurement system shall be calibrated at four points by applying pressure equivalent to: 0, 100, 200, and 300 meters. Temperature effects shall be measured by performing the above tests at 0°, 15° and 30°C.

5.G.4. RECOMMENDATIONS

Sensors now in use for measuring water-quality characteristics are being continually improved to meet the demands for increased reliability and precision in automatic-monitoring applications. In recognition of these improvements in the state-of-the-art and also in recognition of the frequently changing needs of water-quality management, any set of methods such as those in this report cannot be considered as final. Therefore, it is recommended that there be periodic review of new developments in acquisition of data, using field-instrumentation techniques, so that the present methods can be revised accordingly.

5.G.5. REFERENCES CITED

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5.H. QUALITY-CONTROL TECHNIQUES

5.H.1.SCOPE

The following criteria are provided to maintain and improve the quality of chemical and physical environmental measurement techniques and to ensure that accurate, precise, and reliable data issue from their implementation. These basic quality-control criteria will act as validation mechanisms to enable evaluation of the entire measurement process and with continued use will develop confidence in the measurement process by the ultimate user of the data. These criteria should be supplemented by more specific guides for each laboratory situation and sampling scheme.

5.H.2. QUALITY ASPECTS OF MEASUREMENT

Measurement, in general, can be regarded as a series of steps or modular functions. Sequentially, these functions are sampling, sample preparation, analysis, and data output. In some recent *in situ* measurement methods, these functions have been consolidated into a single instrumental method.

5.H.2.a. SAMPLING

Sampling is the collection of a representative portion of the environment for detailed investigation. Sampling may involve the collection of a discrete volume of water, soil, or biological material in containers, or it may involve partitioning the constituents directly from these media into a filtering or absorbing device or into another fluid (for example, the filtering of a fluid, such as wastewater through a 0.45-micrometer membrane filter to obtain a dissolved-metals sample). Additionally, it includes those procedures necessary to preserve the sample. In all of these sampling methods, the relationship between the fraction of the constituents and the sample source must be known as accurately as possible. Standardization of the sampling method helps to establish the reproductibility of this relationship. This relationship must be shown to be stable or to follow predictable changes from the time the sample is taken to the time the sample is prepared for analysis.

5.H.2.b. SAMPLE PREPARATION

Sample preparation consists of the concentration of constituents, or the removal of interfering substances, or the conversion of radioelements being sought to ionic monomeric forms, etc., to be compatible with analytical procedures used in measuring constituents of interest. It must be established that all constituent losses during sample preparation can be quantitatively accounted for and are reproducible within statistically acceptable limits.

5.H.2.c. ANALYTICAL METHODS

Analytical methods are designed to determine as accurately as possible, the true amount of the constituents remaining in the prepared sample. The standardization procedure helps to assure that these values are reproducible within statistically acceptable limits. Not only the values derived from the analytical method, but also predictiable losses in sampling and sample preparation must be considered in order to estimate the true concentrations of the constituents at the sample source.

Once the analytical method has been standardized, procedures for conversion, manipulation, and reporting of the data must also be standardized and audited to achieve acceptable quality.

The numerical values obtained should be specific, precise, and free of systematic error (or bias) within the practical limits required for final use (Cali and others, 1975). If these goals are met, the process should result in acceptable accuracy.

5.H.2.c.1.SPECIFICITY

During the measurement process, only the property under test must be measured. Nonspecificity is generally conceived as an inadequacy of the measurement principle in differentiating the desired property from other properties, which may give a false impression of singularity. For example, congener interference, such as the interference of bromide and iodide in the measurement of chloride, may affect the apparent concentration of the constituent being determined. Similarly, in many colorimetric determinations, the natural color in water samples may affect the measured absorbance.

The references associated with each analytical method should be consulted for information concerning specific interferences. Special emphasis is always warranted to avoid nonspecificity when discovered. There are a number of techniques which can be used; selection of a specific technique will usually depend on the type of interference and on the analytical method being used.

Color, for example, may be removed by bleaching or absorption or compensated by using a second sample to which the indicator reagent is not added, although no compensation may be needed for routine work if the absorbance of the constituent sought is more than 50 times the absorbance of the natural color, because the error introduced will be less than 2 percent. (Skougstad and others, 1979, p. 292). More generally, in situations where nonspecificity is suspected, the method of standard additions (Skougstad and others, 1979, p. 32, and U.S. Environmental Protection Agency, 1979b) can be used to compensate for certain types of interferences. The paper by Crump-Wiesner, Feltz, and Purdy (1971) presents an example of the use of this technique, while limitations of the method are discussed in Klein, Jr., and Hach (1977) and in the U.S. Environmental Protection Agency's "Methods of Chemical Analysis of Water and Wastes" (1979b).

5.H.2.c.2. PRECISION

A high degree of precision in a measurement process is demonstrated when essentially the same numerical value is obtained repeatedly. Sometimes the measurement of precision within the same laboratory is called "repeatability," and between different laboratories "reproductibility." The phenomenon of varying degrees of inaccuracy with varying degrees of imprecision in a measurement process is discussed in depth by Eisenhart (1963). In practice, as opposed to theoretical consideration, a high degree of accuracy is usually considered to be analogous to a high degree of precision, although highly precise systems are sometimes found to be inaccurate.

5.H.2.c.3.SYSTEMATIC ERROR AND ACCURACY

The end product of a sequence of operations in the measurement process is a numerical result with an inherent estimate of uncertainty. When systematic errors are present, the numerical result differs from the "true value." A careful assessment of the systematic errors, their identification, and elimination allows the resulting numerical value to be equated to the "true value."

Also, the use of a method may be limited to certain ranges where neither precision nor bias changes appreciably (Youden, 1975). It takes a careful study of a method to ascertain the range of circumstances over which the method will be applicable. Usually the collaborative test is applicable under most conditions. Guidelines for conducting collaborative testing are in ASTM publications (ASTM 1963, 1975c, 1980b) and Youden (1975).

The evaluation of the many analytical methods in use today may also be developed by collaborative study (McFarren and Lishka, 1971).

5.H.2.c.4.INTEGRITY OF THE MEASUREMENT PROCESS

Environmental testing procedures maintain their identified accuracy as long as quality control is maintained. Loss of precision is usually the first indication of a loss of accuracy. This problem is a constant concern and one that has been extensively studied. ASTM Publication 15–C (ASTM 1951) provides indepth coverage of the control chart method for detecting lack of statistical control. Lack of statistical control in data indicates that

observed variations in quality are too great to be attributed to chance. Long-term integrity of the measurement process has also been addressed by the National Bureau of Standards (Cali and others, 1975).

Several methods exist for using reference standard solutions. They may be used as "control" materials; analyzed simultaneously with the "unknown" sample materials, or be used to standardize instrumentation, or to develop new techniques of instrumentation. Bracketing a standardization curve or unknown with reference standards is a particular asset to the analyst. Storage of standardization materials or solutions presents the problem of decay or change depending upon their chemical nature (hygroscopic, volatile, and so forth) and their sensitivity to handling or storage conditions, including container effects. Thus, laboratory management must include a policy that deals with standards to prevent deterioration or contamination. The integrity of the data obtained depends as much on this consideration as on the applied techniqus and methods.

5.H.2.c.5. QUALITY-ASSURANCE RECORDS

Operating logs and records of quality-assurance activities should be maintained along with the records of corrective actions taken. Records should be properly marked for easy retrieval. Guidelines should be established concerning record retention, including duration, location, and assigned responsibility.

5.H.3. PRECISION AND ACCURACY

Each new analytical method or modification of a historical method should state the attainable precision, including the mean value at each level (potential concentration dependency), and bias observed under the conditions of a collaborative test, or at least single operator precision (ASTM 1975d). All selected methods should be identified (coded) to inform the prospective user of their conformance to the state-of-the-art at the time of development. The range of concentration accommodated by the method should be described. See also ASTM (1980a, 1975c).

5.H.3.a. PRECISION

The precision of a measurement process depends upon the selection of the correct method for the problem at hand. Four variables normally considered include: apparatus, laboratory, operator, and level because these items cannot be considered identical for all users of a method. Precision may also vary cyclically and seemingly randomly.

The number of replicates (ASTM 1980b) must satisfy the following inequality:

$$r > 1 + (30/P)$$

in which r is the number of replicates and P is the product of the number of the several variables.

In a statistical sense, the degree of random variability may be stated in terms of an index of precision of the form $\pm a$. The numerical value of a will get smaller the more closely bunched the individual measurements of a process are and may be different in separate processes because of different methods or systems of causes. In general, the larger the index, the less precise the process.

The format of precision statements should reflect the dependency of the magnitude of the index on the level of the material under test. Having plotted the precision values versus the level of concentration, a smooth curve should be drawn through the points. The precision will be found either to be constant and not vary with the level, to vary directly with the level linearly, or to vary with level in a curvilinear manner. The format should be expressed as shown in ASTM (1980b).

Suspected nonconformants may be tested by calculating their T-value, as shown in ASTM (1980b). No data should be discarded unless the cause is known or statistical criteria and subsequent analyses show them to be erroneous or aberrant.

One widely used method (U.S. Environmental Protection Agency, 1972) for the determination of precision is described as follows:

(1) Four separate concentration levels should be studied:

(a) at low concentration near the sensitivity level of the method;
(b) at two intermediate concentrations;
(c) at a concentration near the upper limit of application of the method.

(2) Seven replicate determinations should be made at each of the concentrations tested.

(3) The precision study should cover at least 2 hours of normal laboratory operations, to allow for changes in instrument conditions.

(4) In order to permit the maximum interferences in sequential operation, it is suggested that the samples be run in the following order: high, low, and intermediate. This series is then repeated 7 times to obtain the desired replication.

(5) The precision statement should include a range of standard deviations over the tested range of concentration. Thus, 4 standard deviations will be obtained over a range of 4 concentrations.

5.H.3.b. ACCURACY

Accuracy embraces the concept of deviations from the accepted level (best estimate of the true value). This consistent deviation may be considered as nonrandom or systematic error. A test method in statistical control is free of systematic error (bias) if the expected value of the result it yields agrees with the accepted level.

Precision and accuracy of a particular measuring process may depend on individual and perhaps changeable systematic errors inherent in lab management, test apparatus, operators, test specimens, level, and local conditions. Since bias is a common contributor to error in each sample measurement, it is possible that a certain amount will pass unnoticed until some change associated with a previously unidentified cause takes place.

Sources of bias lie often in the human element associated with the process, such as sample pretreatment, standardization of instruments. interpretation of instructions for making measurement, and local conditions. Incomplete reactions, precipitation, losses due to washing, and extraneous material carried down by a precipitate are some of the ways in which a method is vulnerable to bias. Also, it cannot be expected that the distribution of systematic errors will be the same for different amounts of material being tested. A graphical approach to depicting the random error and bias is presented by Youden (1960, 1975).

The form of the accuracy statement must consider the relative magnitude of the systematic error and the variability associated with the measure of precision. Also, it must be determined whether the numerical values presented in the statement remain fixed over the range of levels of material or the range of expected environmental conditions. Methods for expressing the standard corrections are given in ASTM (1980d).

An index of accuracy useful in general chemistry is expressed as percent recovery (U.S. Environmental Protection Agency, 1972, p. 6.3.).

$$\text{Percent Recovery} = 100\ \frac{\bar{c}}{\bar{a}_p + b}$$

where

$\bar{c}$ = mean of 7 aliquots of spiked environmental sample,
$\bar{a}_p$ = mean of 7 aliquots of the environmental sample,
b^p = reference value (spike).

Key steps for determining accuracy using environmental samples are also described therein.

The relative error gives the difference between the mean of a series of test results and the true value, expressed as a percentage of the true value. Thus, the relative error represents the measure of the accuracy of a method (American Public Health Association, 1981).

It is more important to detect and correct error, including systematic error, than merely to determine its magnitude for future reference (Eisenhart, 1963). It should be understood that after everything has been done to detect and correct errors, every final measured value may still have an uncertainty which may need to be evaluated and appended to the results.

A tabulation of standard reference materials and quality-control samples is given in Section 5.H.5, Reference Solutions and Standard Reference Materials.

5.H.3.c. COMPARISON OF TWO METHODS

As noted in the introduction of this chapter, the analytical methods selected for inclusion in this report have wide applicability and general acceptability. Occasionally, it may be desirable to compare data from a newly developed procedure with an accepted method or even to compare data from two methods which are accepted for the same determination. The most important factors to examine in deciding whether to accept, reject, or limit a procedure are the analytical concentration range, precision, bias, and the analytical interferences for each method. If these factors are essentially equivalent, consideration should be given to whether a new method would increase productivity and/or lower the cost of analyses, or whether a toxic reagent in the accepted method may be eliminated.

A *t*-test can be used to test the new procedures for significant bias (with respect to the old procedure) by comparing the determined mean concentration of a constituent in a sample with the "known" concentration of a reference material such as one obtained from the National Bureau of Standards or, alternatively, with the mean concentration of the constituent reported for the same sample when analyzed by an accepted procedure (Youden, 1975, p. 36–37). Somewhat similarly, a paried *t*-test can be used to look at the differences in data by using two analytical procedures to make analyses. An *F*-test can be used to test whether a newly developed method shows better precision than an accepted method (Youden, 1975, p. 38–39). More information on the use of *t*-tests and *F*-tests may be obtained in most standard statistical tests such as Dixon and Massey (1969).

An analysis of the bias and precision may readily indicate the preferred method. The analytical ranges and known analytical interferences may indicate that both methods are useful for different types of samples. In some cases, however, a new method may show much better precision but appear slightly more biased than the accepted method, or the new method may be slightly less biased but show worse precision than the accepted method. This type of situation requires careful examination of the data and Youden (1969) presents an excellent discussion relating to it.

No matter what decision is reached about the new procedure, it is necessary to realize that anyone dealing with or performing analyses for a regulatory agency will usually need permission to substitute a new method for an accepted procedure. The *Federal Register* for December 1, 1976, for example, describes how to apply to the U.S. Environmental Protection Agency for approval of alternative methods in testing for pollutants.

5.H.4. INTRALABORATORY QUALITY MANAGEMENT

Confidence in test results depends in part on the precision and accuracy developed for the analytical method and also upon the consistent manner in which it is carried out. A written plan of quality goals and objectives should specify what is to be accomplished in the measurement process and by whom. The written plan then becomes a simple device to measure and to evaluate the overall quality implemented in the laboratory. For those responsible for developing a specific quality assurance plan, the publication of the National Oceanic and Atmospheric Administration (Farland, 1980) provides excellent guidelines. A model plan is available from: Director, Quality Assurance Management Staff, Office of Monitoring and Quality Assurance, U.S. Environmental Protection Agency, Washington, D.C.

5.H.4.a. ORGANIZATIONAL RESPONSIBILITIES

Specified individuals should be given responsibility for each aspect of the program. Operational responsibilities in the measurement process should be assigned to key individuals responsible for the major monitoring and analytical activities.

5.H.4.b. SELECTION OF METHODS AND PROCEDURES

A laboratory policy should establish the selecton and use of test methods and procedures. Where generally accepted or approved procedures do not exist or require modification, the plan should state how this will be accomplished, covering in detail the technical and administrative procedures that are to be used in selecting and documenting the new methodology.

5.H.4.c. QUALITY-CONTROL PROGRAMS

A plan should require the development of very specific quality-control procedures. Although the quality-control elements will vary for different activities (laboratory testing versus data reporting), the composite of these elements should provide detailed coverage of at least the following items:

5.H.4.c.1. SAMPLING DESIGN

The sampling design may be simple or complex, depending on the objectives of the program, but it should be written down before sample collection is initiated. Standard texts on experimental design, such as those of Johnson and Leone (1977) or Montgomery (1976), may provide some help in developing the sampling scheme to be used. A discussion, which is directed to the collection of samples for biological analysis, but which also can be applied to the collection of samples for physical and chemical analyses, may be found in Greeson and others (1977).

The frequency of sample collection should be established as part of the sampling design. Evaluation of data from reconnaissance sampling may aid in determining the frequency. In general, it should be recognized that a single sample from a site may be adequate to define the water quality at the instant it was collected, but may be seriously inadequate if used as an indicator of the overall, long-term quality of the water at the site. Environment Canada's publications by Oguss and Erlebach (1976) and by Kleiber and Erlebach (1977) address the problem of applying the analyses from infrequently collected samples to mean water quality. Feltz (1980) notes that sampling and analyses of fresh bottom material deposits will give data representing seasonal or short-term trends, extension of the sampling period will yield data applicable to long-term trends, while examination of core sample data may yield significant historical information.

Factors to consider in selecting the sampling site are discussed in the section on sampling (see 5.B.2.). Although it may become necessary to change a site selected for sample collection, any change must be made carefully so that the objectives of the program are not adversely affected and must be thoroughly documented.

5.H.4.c.2. SAMPLE COLLECTION AND PRESERVATION

The importance of collecting a representative and properly preserved sample cannot be over emphasized. The quality-control program should specify in writing, the number and type of samples to be taken at a particular site and the procedures to be used. The section on sampling (5.B.) should be referred to for more information on this subject while the individual analytical procedures in this chapter should be referred to for specific information on sample preservation.

5.H.4.c.3. SAMPLE HANDLING

In order to associate the analysis with the sample, sample containers must be carefully labelled. As a minimum, the labels must include identification of the site, the date and time of sample collection, and a record of any preservative added. If the sample was filtered, this too should be noted.

Analyses made in the field, such as the measurement of pH, should be carefully recorded in a notebook. Since this information may help the laboratory analyst, it is recommended that this information also be sent to the laboratory.

If data from analyses are expected to be part of legal proceedings, a formal "chain-of-custody" scheme like the one described in McClelland and others (1978) may be necessary. Such a scheme usually will include complete documentation of all persons involved in handling the sample.

5.H.4.c.4. MEASUREMENT METHODS AND PROCEDURES

Documentation of a method should include an estimate of the precision, accuracy, and interferences. The analyst should be aware of the limitations of each method used. A record must be made if it becomes necessary to modify a method, no matter how slight the modification. In general, modifications should not be made unless a thorough study has been made of how the precision and accuracy of the procedure will be affected.

It is important that accurate records be kept of the analytical method used for each parameter. This knowledge is necessary for the comparison of data from two methods, and will be vital to the future data user in comparing his data to that produced by an historical method.

5.H.4.c.5. STANDARDS

The preparation of standards, including calculations, should be fully documented. Where possible, standards should be traceable* to recognized national reference standards, such as those of the National Bureau of Standards.

The quality-control plan should include information on the frequency with which standards and reagents should be made. A scheme for checking the concentration of newly prepared standards and rechecking older standards should be provided. The plan should also include information on any specialized storage of standards and reagents. For example, standards sensitive to light should be kept in a dark bottle while standards sensitive to heat should be stored in a refrigerator.

The number of standards necessary for each analytical method should be specified, as well as the use of analytical reagent blanks.

5.H.4.c.6. CALIBRATION AND INSTRUMENT MAINTENANCE

The proper use of analytical instruments is essential to the production of reliable analytical results. Instrument calibration and operation techniques for the same type of instrument may vary from manufacturer to manufacturer; therefore, the analyst must be famliar with the appropriate instrument manual as well as with the specified analytical methods.

One key factor in obtaining valid instrument response is to establish an instrument maintenance scheme; where such a scheme does not exist, it is not unusual to have 25 percent or more of the necessary equipment giving erroneous results (Juran and Gryna, 1976). Schedules to check and maintain instruments should be based on units of time (for example, check after every month) or on use (for example, check after every 200 samples) and records kept and reviewed. Juran (1974) and Juran and Gryna (1976) contain more information for establishing instrument maintenance schemes.

5.H.4.c.7. QUALITY-CONTROL TECHNIQUES

Specific quality-control procedures should be described for each parameter measured by the laboratory. McClelland and others (1978) and Friedman and Erdmann (1981) provide some guidelines which can be used for

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*For definition and discussion of the concept of "traceability," see the article by Belanger in ASTM Standardization News (1980).

the quality control of specific water-quality parameters. The U.S. Environmental Protection Agency's "Handbook for Analytical Quality Control in Water and Wastewater Laboratories" (1979a) describes some general quality-control procedures for water-quality analyses. In addition, "An EPA Manual for Organics Analyses using Gas Chromatography-Mass Spectrometry" (Budde and Eichelberger, 1979), "Manual of Analytical Quality Control for Pesticides in Human and Environmental Media" (Sherma, 1979) and the *Federal Register* for December 3, 1979, provides specific quality-control procedures for organic analyses of water samples, while the "Handbook for Analytical Quality Control in Radioanalytical Laboratories" (Kanipe, 1977) gives techniques applicable to radiochemical analyses.

5.H.4.c.8. QUALITY-CONTROL CHARTS

Maintenance of quality-control data is essential. Maintenance of records in the form of control charts should be encouraged since control charts will show trends and variability in analyses which may not be readily apparent from individual or tabulated results. Control charts can be efectively used to monitor analytical results in order to determine if bias is developing or if precision is less than expected. When used to monitor the quality of results produced by a particular analyst, control charts can be a helpful training and supervisory tool.

Most control charts consist of a plot of time (for example, date of analysis) versus mean or individual concentration values or versus mean or individual standard deviations or ranges. Usually, the use of more than one type of control chart will increase the probability of spotting problems soon after they occur. For instance, a value outside of the established control limits of a mean concentration control chart suggests that there may be an overall change in the method (such as might result from a shift in alignment of the light source in a spectrometer), while a value outside of a standard deviation or range control chart tends to indicate an increased variability in analysis (such as might result from dirty or limp tubing used in an automated colorimetric analysis).

Additional information on control charts may be found in many references, including Bicking and Gryna (1974), Grant and Leavenworth (1974), Knowler and others (1969), Youden (1975), the Environmental Protection Agency's "Handbook for Analytical Quality Control in Water and Wastewater Laboratories" (1979a), and ASTM Special Technical Publication 15D (1976).

5.H.4.c.9. PERFORMANCE TESTS

The quality-control plan should include a description of the number and type of reference samples, replicate samples, spiked samples, and so forth, to be used for each constituent. McClelland and others (1978) gives recommendations for the number of replicate analyses which are needed for specific water-quality parameters. The subsection Reference Solutions and Standard Reference Materials (5.H.5.) lists sources for obtaining reference materials.

Criteria for repeating and/or rejecting an analysis should be detailed. Data should be tabulated and/or plotted as soon as an analysis is completed. Periodically, at time intervals specified in the plan, data from performance tests should be summarized and reviewed.

5.H.4.c.10. DATA DOCUMENTATION AND REVIEW

All information pertaining to the identification of a sample should be recorded, at time of collection, in a "field notebook." Such information should include, but is not limited to, the date and time of collection, complete site identification information (such as latitude, longitude, and depth of a well), the name of the person or persons collecting the sample, and important environmental facts and observations (such as weather conditions or apparent turbidity). Data from field measurements (such as temperature, pH, specific conductance and alkalinity) also must be recorded in the field notebook, along with information pertinent to instrument calibration.

If an automated monitor is in use at a sampling site, a comparison should be made between *in situ* observed values and those recorded by the monitor. Discrepancies, such as differences in temperature, dissolved oxygen, or gage height, should be carefully noted in the field notebook and on the monitor's recorded output. If debris (such as leaves) appears to have caused a problem with the monitor intake system, this fact should be recorded.

As noted in 5.H.4.c.4., analytical methods must be carefully documented and available for review. The analyst should record every deviation from routine procedure. Instrument calibration procedures should be documented, and data for all checks on instrument calibration recorded.

Records should be kept on the preparation of all standards. They should include not only data related to stock preparation, but also data on all intermediate and working standards. The date of preparation and name of the analyst should be noted. The dates of opening reagents and standards should be recorded on the bottle labels and, if critical, also in a notebook.

The quality-control plan should ensure that raw analytical data is reviewed immediately following analyses by the analyst and/or his supervisor. In addition, periodic reviews of all laboratory data, including standard solution preparation, instrument analysis, and reference material analysis must be scheduled. Data review programs should provide for continual review and evaluation of laboratory performance.

5.H.4.c.11. REPORTS

The quality-control plan should describe how often the quality-control data should be summarized, what information is to be included in the summary reports, and to whom the data should be reported. Provisions should be made for using these reports to evaluate sampling and analytical procedures. All data pertaining to any necessary remedial action should be fully documented.

5.H.4.d. PARTICIPATION IN INTERLABORATORY TESTS

Efforts should be made to participate in as many studies as can be accommodated. The plan should discuss how the results will be treated and interpreted. The papers in the American Society for Quality Control publication, "Interlaboratory Testing Techniques" (1978) and the Youden and Steiner papers in the Association of Official Analytical Chemists publication "Statistical Manual of the AOAC" (1975) describe techniques for conducting and interpreting the data from such tests.

5.H.4.e. DATA HANDLING

Precise procedures should be established for the review and approval of data prior to release. The plan should specify the format to be used, the records to be kept, and the identity of the individuals responsible for checking validity and release of the data.

A careful review of the analytical report should be made after all analyses have been completed. If samples are being collected repeatedly at the same site, it may be possible to calculate specific relatonships for that site. For example, the concentration of a major ion may show a definite relationship with specific conductance. Once established, such a relationship can be used to check for anomalies in the analysis. General relationships are also useful for the review. For example, a comparison of measured and calculated specific conductance provides a guide to the quality of the chemical analyses of waters of low specific conductance (such as precipitation samples). The observed relationship between percent moisture content at 15 bars and percent clay can be used as an indication of satisfactory physical analyses for similar-type soils. A comparison between the sum of the milliequivalents of anions and the sum of the milliequivalents of cations can be used to check the analyses of major constituents, if the concentration of all major anions and the cations of the water sample is believed to have been determined. Descriptions of many of the relationships which can be used in a review of the analytical report can be found in Hem (1970), Howard (1933), and Skougstad and others (1979, p. 7-9).

While data reviews may be useful in spotting possible errors, the reviewer should keep in mind that anomalies in the data do not necessarily indicate analytical error. For example, the loss of chloride from waters high in magnesium chloride or the loss of nitrate from waters high in nitrate may make the dissolved solids value determined by the concentration of residue after evaporation appear low when compared to a value for dissolved solids, which has been calculated by adding the concentration of individual constituents. The reviewer must be aware that the presence of anomalies may be extremely important in the overall interpretation of the data.

The reviewer should use his knowledge of the precision of the analytical method in reviewing the analytical report. Data should reflect at least the precision of the method. Although the data reviewer may request the analyst to repeat an analysis of a sample, only in rare cases should reanalysis be made for constituents which are known to be unstable.

5.H.4.f. TRAINING

Successful implementation of a quality-control program depends upon the competence of the analytical and monitoring personnel. The quality-control plan should provide for a periodic assessment of training needs and should describe the scope and manner in which training is to be accomplished. New employees should not be allowed to work alone until the quality of their work is at least equivalent to existing employees. Meetings and workshops should be scheduled to exchange information and maintain high levels of skill.

5.H.5. REFERENCE SOLUTIONS AND STANDARD REFERENCE MATERIALS

5.H.5.a. NATIONAL BUREAU OF STANDARDS

Standard reference materials (SRM's) are described in NBS Special Publication 260 (1979–1980 Edition), Catalog of NBS Standard Reference Materials. A complete list may be obtained by writing to the Office of Standard Reference Materials, Room B311, Chemistry Building, National Bureau of Standards, Washington, D.C. 20234; Telephone: (301) 921-2045

5.H.5.b. U.S. ENVIRONMENTAL PROTECTION AGENCY

As more fully described in the January 1981 edition of the EPA Quality Assessment Newsletter, the following types of quality-control samples are available, primarily as ampouled concentrates, for use to interested water analyses laboratories:

Antimony, thallium, and silver
Chlorine
Chlorophyll
Cyanide
Demand analyses
Haloethers
Herbicides
Linear alkylate sulfonate
Mercury
Mineral/physical analyses
Municipal digested sludge
Nitrate/fluoride
Nitrilotriacetic acid
Nutrients
Oil and grease
Pesticides
Pesticides, organochlorine
Pesticides, organophosphorus
Pesticides, urea-based
Petroleum hydrocarbons
Phenol
Phthalate esters
Polychlorinated biphenyls
Polychlorinated biphenyls in fish
Polychlorinated biphenyls in oils
Polychlorinated biphenyls in sediments
Purgeables, halogenated
Purgeables, nonhalogenated
Residues, nonfilterable, volatile, and total filterable
Sludge, municipal
Trace metals
Trihalomethanes
Turbidity
Volatile organics

Samples may be obtained from:

Quality Assurance Branch
Environmental Monitoring and Support Laboratory
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

In addition, laboratories involved in environmental monitoring of radioactivity may participate in intercomparison studies and obtain specific radionuclide standards. Details on requesting samples may be obtained from:

Quality Assurance Division
Environmental Monitoring Systems Laboratory
P.O. Box 15027
Las Vegas, Nevada 89114
Telephone: (702) 798-2100
(FTS) 595-2100

5.H.5.c. U.S. GEOLOGICAL SURVEY

The Standard Reference Water Sample (SRWS) series is prepared in conjunction with a long-term USGS research activity in interlaboratory comparison. Types of samples include: major conservative ions, trace metals, nutrients, insecticides, and herbicides. In general, the SRWS series is available only to USGS, cooperating State, and contractor laboratories for quality-control purposes.

Samples are prepared in a natural water matrix and need no dilution prior to analysis. Information on the series has been published by Skougstad and Fishman (1975) and Schroder and others (1980). Additional information may be obtained from:

Project Chief for Standard Reference Water Sample Program
U.S. Geological Survey, Water Resources Division
Mail Stop 407, Box 25046
Denver Federal Center
Denver, Colorado 80225

5.H.5.d. STANDARD SEA WATER

A standard sea water, certified in chlorinity, is available and may be used to calibrate both *in situ* and laboratory salinometers (see 5.G.6.b.2.). Further information and the actual standard sea water may be obtained from:

Dr. F. Culkin
Institute of Oceanographic Sciences
Brook Road
Wormley, Surrey GU8 5UB
England
Telephone: Wormley 2122 (STD 0428-79-2122)

5.H.5.e. MARINE STANDARD REFERENCE SOLUTIONS

Standard chemical solutions of phosphate, silicate, and nitrate prepared in 30.5 percent NaCl solution for use in marine nutrient analysis, and mercury in 30.5 percent NaCl solution are available as standards for laboratory methods (see 5.G.6.b.2.). They may be obtained from:

Mitsuko Ambe
Sagami Chemical Research Center
Nishi-Ohnuma 4-4-1
Sagamihara, Kagawa 229
Japan

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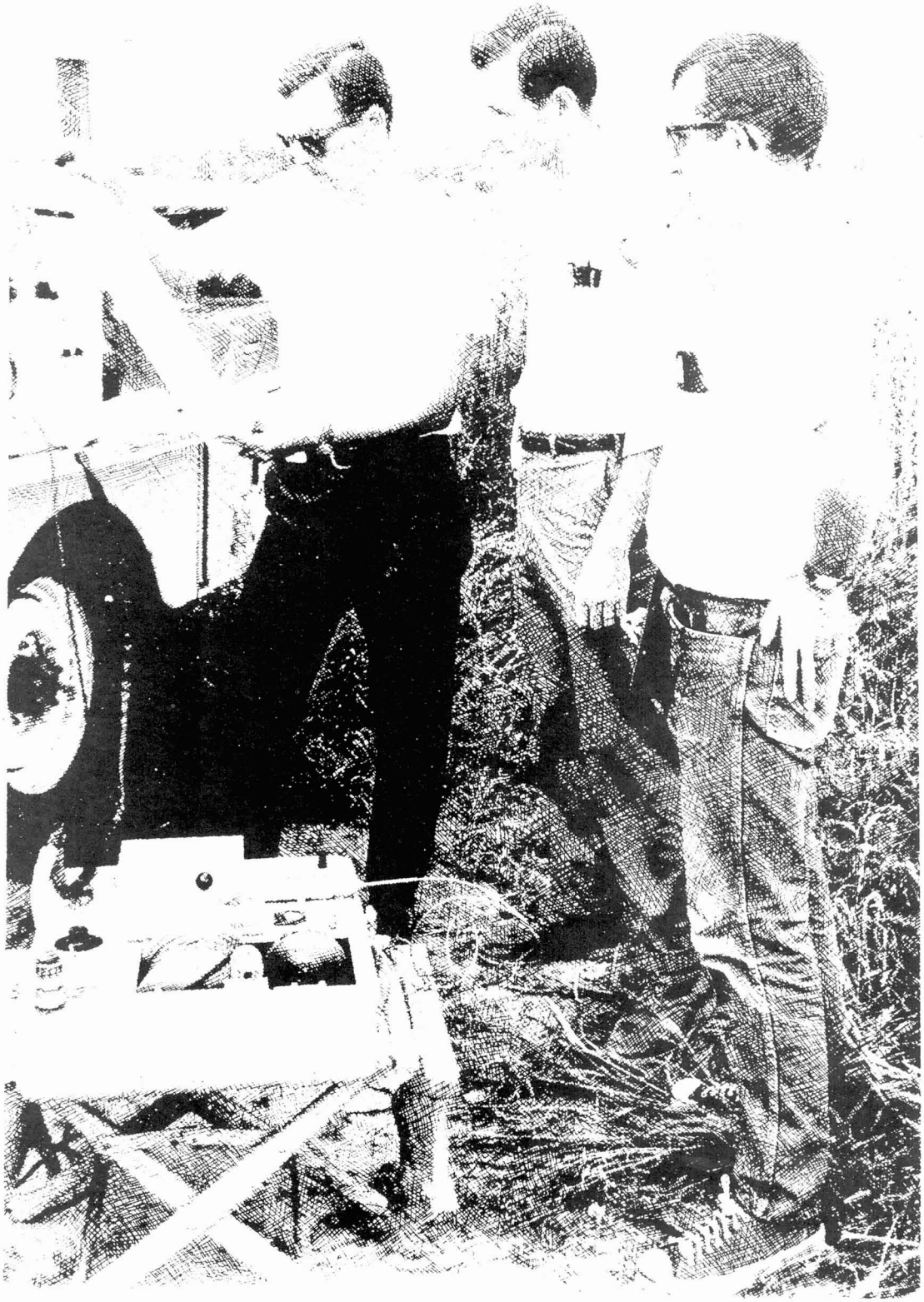
Chapter 6

Soil Water



CHAPTER 6 – SOIL WATER

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CHAPTER 6—SOIL WATER

6.A. INTRODUCTION

This chapter identifies recommended methods for measuring soil water and lists sources that describe these methods in detail. The recommended methods for characterizing soil water apply to the upper 1 to 2 meters of the soil, which generally are above the permanent water table. This chapter does not consider methods for analyzing the chemistry of soil water. The units used in the cited methods vary, but the Work Group recommends using the SI system in the future.

Soil water exists in the zone of aeration in three different conditions. Gravity water is water in the large soil pores that moves under the influence of gravity. Capillary water is water in small pores that is held by capillarity against gravitational forces. Hygroscopic water is water retained about individual soil particles by molecular attraction. The gravity water, which represents a transient state, drains freely from the soil. The capillary water can be removed from the soil only by overcoming the capillary forces, whereas hygroscopic water can be removed only by heating.

Measurements of soil water involve three aspects: the volume of water, the movement of water, and the energy with which water is held in the soil. The water content of soils and the suction or tension with which the water is held generally are inversely related. In unsaturated soils, the water potential is negative and is sometimes called the *matric suction*. The terms *soil-water tension* and *capillary pressure* also refer to negative water potential. The rate of water movement is determined by the energy gradient and a water-conductivity coefficient. In saturated soils, this coefficient is called the *permeability* or the *hydraulic conductivity*, and in unsaturated soils, it is called the *capillary conductivity* or the *unsaturated hydraulic conductivity*.

Representative measurements of soil water require that enough soil samples be taken to ensure confidence in the values reported. The reliability of the measurements obtained at a particular site and the conclusions drawn about the water characteristics of a broader expanse of soil depend upon the quality of the data, the representativeness of the sample site, and the accuracy of the individual measurements.

6.B. SOIL-WATER CONTENT

Water content is expressed as the ratio of the mass of water in a sample to the mass of the oven-dry sample, or as the ratio of the volume of water in a sample to the total volume of the sample. For a ratio computed on the basis of mass, disturbed samples suffice. Such samples can be obtained by relatively simple sampling techniques. For a ratio computed on the basis of volume, the volume of the sample must be known or a measurement of bulk density must be made. Bulk density can be measured using core samples or other techniques as described by Blake (1965), the U.S. Soil Conservation Service (1967), or the American Society for Testing and Materials (ASTM), (1975a; 1975b).

The water content of soil can be measured by direct or indirect methods. Direct methods require a separate sample for each measurement, which precludes repeated measurements at the same point. Direct methods are preferred only when one-time data are needed. Indirect methods require calibration to relate measurement to water content. Once the relationship is established, however, frequent or continuous measurements are possible. These measurements are nondestructive and usually require little time.

6.B.1. DIRECT METHODS

Direct measurements of water content remove water from a soil sample. Two recommended direct methods are oven drying and drying with burning alcohol.

6.B.1.a. OVEN DRYING METHOD

Oven drying is the oldest and most widely used direct method of measuring water content. The procedure involves weighing the sample before and after drying it at 105°C and then calculating its original water content per unit mass of oven-dry soil. Recommended sources for this method are Gardner (1965, p. 92-96) and American Society for Testing and Materials (1975a, p. 275-276).

6.B.1.b. DRYING BY BURNING ALCOHOL METHOD

Drying by burning alcohol is recommended as a rapid field method requiring minimal equipment. Soil drying may be speeded up considerably by removing part of the water from soil samples using ethyl, methyl, or propyl alcohol, then by evaporating the water by burning the alcohol. This method can remove as much water as can oven drying if the burning process is repeated several times. A complete determination of the water content can be made in about 20 minutes. The recommended source for this method is Gardner (1965, p. 96-98).

6.B.2. INDIRECT METHODS

Indirect methods for measuring water content include neutron scattering, gamma-ray attenuation, gas pressure, soil-water retention curves, electrical and thermal conductivity, and velocity of sound. The neutron scattering, gamma-ray attenuation, and gas-pressure methods are recommended in this section, and the water-retention method is discussed in section 6.D. Measurements based on electrical and thermal conductivity (Shaw and Baver, 1940; Bloodworth and Page, 1957) and on velocity of sound (Brutsaert and Luthin, 1964) have not resulted in unique correlations with water content and thus have not come into common use.

6.B.2.a. NEUTRON SCATTERING METHOD

Neutron scattering is a single-probe, bore-hole logging technique in which fast-moving neutrons are emitted from a radioactive source. The neutrons collide with hydrogen atoms in the surrounding soil, are slowed down, and are counted by a slow neutron detector. Neutron scattering is a reliable field method for measuring water content. However, a drawback of this method is the difficulty to install access tubes in stony soil. Recently Rawitz (1969) and Cline and Jeffers (1975) have reported on installing tubes under such conditions. Recommended sources for this method are Gardner (1965, p. 104-114), Smith and others (1968), and American Society for Testing and Materials (1975b, p. 394-398).

6.B.2.b. GAMMA-RAY ATTENUATION METHOD

The gamma-ray attenuation method is essentially a core-logging technique in which gamma rays are emitted from a radioactive source. The rays that are not attenuated when they pass through the soil core are counted by a detector. Gamma-ray attenuation has been a very effective laboratory method, and Ligon (1969), Smith and others (1967), and Reginato (1974) have reported on significant progress in adapting the method to field studies. If problems such as the parallel placement of tubing and the sensitivity of electronic equipment can be resolved, the technique could have wide applications for field use. The recommended source for this method is Gardner (1965, p. 114-125).

6.B.2.c. GAS PRESSURE METHOD

In the gas pressure method, water content is determined by measuring the pressure-temperature increase of the acetylene gas that is produced when calcium carbide is mixed with soil in a small, closed container. It is a rapid field method for estimating the water content of soil. The recommended source for this method is Blystone and others (1961).

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6.C. SOIL-WATER POTENTIAL

The total water potential in the soil-water system equals the sum of the gravitational potential, the matric potential (also called the capillary, pneumatic, or hydrostatic potential), and the osmotic potential. For a good review of soil-water potential, see Remson and Randolph (1962) and Rose (1966). For definitions and recommended symbols concerning soil-water potential, see the recent glossary of the Terminology Subcommittee (1975). Table 6-1 gives the most common units used for expressing measurements of soil-water potential.

Three instruments that can be used to measure soil-water potential are tensiometers, electrical resistance blocks, and psychrometers.

TABLE 6-1.—Units for expressing soil-water potential and equivalents

kilopascal (kPa)	millibar (mb or 10^3 g $cm^{-1}s^{-2}$)	atmosphere (atm)	centimeters of water (cm H_2O)	erg per gram (erg g^{-1} or cm^2 sec^2)	calorie per gram[1] (cal g^{-1})	joules per kg[1] (J kg^{-1})
1.0	10	9.87×10^{-3}	10.17	1×10^4	2.39×10^{-4}	1.0
0.1	1.0	9.87×10^{-4}	1.017	1×10^3	2.39×10^{-5}	0.1
101.3	1013	1.0	1.03×10^3	1.013×10^6	2.42×10^{-2}	101.3
9.83×10^{-2}	0.9833	9.7×10^{-4}	1.0	983.3	2.35×10^{-5}	9.83×10^{-2}
1×10^{-4}	1×10^{-3}	9.87×10^{-7}	1.017×10^{-3}	1.0	2.39×10^{-8}	1×10^{-4}
4.18×10^{-3}	4.18×10^4	41.28	4.25×10^4	4.18×10^7	1.0	4.18×10^3
1.0	10	9.87×10^{-3}	10.17	1×10^4	2.39×10^{-4}	1.0

[1] These are thermodynamic units.

6.C.1. TENSIOMETERS

The tensiometer is a device to measure matric potential in the field. Tensiometers do not perform at tensions greater than 0.85 bar because the water column breaks. The instrument consists of a porous ceramic cup buried in the ground and connected by water-filled plastic or metal tubing to a mercury manometer or vacuum gauge. Tensiometers are commercially available in a great variety of sizes and models or can be assembled in the workshop from tubing and porcelain cups. The recommended source for this method is Richards, S. J. (1965, p. 153-163).

6.C.2. ELECTRICAL RESISTANCE BLOCKS

Electrical resistance blocks may be used to measure soil-water potential greater than 0.85 bar. These blocks are easily constructed, and electrical conductivity is easily measured. The most serious limitations of this method are its low precision and the elaborate and time-consuming calibration it requires (Gardner, 1965). The recommended source for this method is Gardner (1965, p. 99-104).

6.C.3. PSYCHROMETERS

Psychrometers have advantages over tensiometers because psychrometers measure potentials greater than 0.85 bar and because they measure total potential. Originally, the main drawback of psychrometers was their requirement for a precisely controlled, constant-temperature bath. Although this drawback has been overcome by using appropriate heat sinks (Spanner, 1951) and psychrometers are now suited for field measurements, their use is still largely a research technique. A fuller discussion is given by Brown and van Haveren (1972). Recommended sources for this method are Richards, L. A. (1965, p. 140-151) and Brown and van Haveren (1972, p. 322-342).

6.C.4. SOIL-WATER CONTENT AT GIVEN MATRIC POTENTIAL

Determining the soil-water potential (tension or suction) depends on attaining equilibrium between the water in the soil and a force applied to that water. Laboratory determinations of soil-water potential are routinely made using the following equipment: suction table, pressure-plate and pressure-membrane apparatus, and filter paper. When such determinations are coupled with measurements of gravimetric or volumetric water content, the water held at specific values of soil-water potential may be used to estimate water-retention differences among different tensions. With measurements over a series of potentials, a soil-water retention curve (moisture-characteristic curve) may be constructed. (See section 6.D.1.)

6.C.4.a. SUCTION TABLE

A suction table can measure soil-water potential only at low suctions (0 to 0.1 bar). Soil samples are placed on a porous plate that is in contact with water underneath that is at less than atmospheric pressure. At least 24 hours are required to approach equilibrium. The suction table is simple and inexpensive, but this apparatus is not widely used. The recommended source for this method is Holmes and others (1967, p. 280-281).

6.C.4.b. PRESSURE PLATE AND PRESSURE MEMBRANE

Pressure-plate and pressure-membrane apparatus are used all over the world for making laboratory determinations of soil-water potential. Advantages of pressure-plate and pressure-membrane methods are their broad operational range and reproducibility of measurements. Although somewhat specialized equipment is required, several excellent designs in different sizes are commercially available.

Pressure-plate and pressure-membrane methods work by applying differential air pressure across a membrane or ceramic plate that holds pre-wetted soil samples. Water flows from the soil until the matric potential of the soil and the air pressure in the chamber are in equilibrium.

Pressure plates are equipped to withstand pressures up to 15 bars without permitting air to pass through the plates. Stronger pressure chambers and membranes containing smaller pore openings are used to extend the operating range of the pressure-membrane apparatus to pressures as high as 150 bars.

Recommended sources for these methods are Richards, L. A. (1965, p. 131-137) and American Society for Testing and Materials (1975a, p. 280-286; 1975b, p. 410-417).

6.C.4.c. FILTER PAPER

The filter-paper method can measure soil-water potentials between 0.001 and 1500 bars. A filter-paper disc holding a gravimetric soil sample is placed in a container and is allowed to equilibrate in the laboratory. The paper is then weighed, dried, and reweighed. Calibration curves give the moisture content of the filter paper versus the soil-moisture potential. The recommended source for this method is McQueen and Miller (1968, p. 225-231).

Comment: The filter-paper method is accurate and economical. However, one must not shake the moist samples when transporting them from the field to the laboratory because stress values may change (without a change in moisture content) if the size and shape of the soil pores are altered.

6.C.5. PIEZOMETER

The piezometer is used in ground-water studies to measure the elevation of the water table and the direction of flow under saturated conditions. A full discussion of the method can be found in chapter 2 (Ground Water) of this Handbook. The method is mentioned here as it relates to shallow water tables and to entrapped air studies (Garner and others, 1969). The piezometer consists of a tube that is open at both ends. The piezometer is driven into the soil so that the bottom of the tube extends into the zone of free water to the depth at which the hydraulic head is to be measured. The recommended source for this method is Reeve (1965, p. 180-196).

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6.D. SOIL-WATER RETENTION

The amount of water in a soil horizon at any given time following saturation is determined by the volume of water present at saturation and the rate at which water leaves the horizon. The quantity of water held at any given matric potential depends on the surface area of the soil material, which is a function of particle size and clay mineralogy, and on the geometry of the soil pores. Typical soil-water retention curves (moisture-characteristic curves) showing water content as a function of matric potential are given in figure 6-1. Characteristic curves for water sorption and desorption provide an index of water content if a matric potential is known and vice versa.

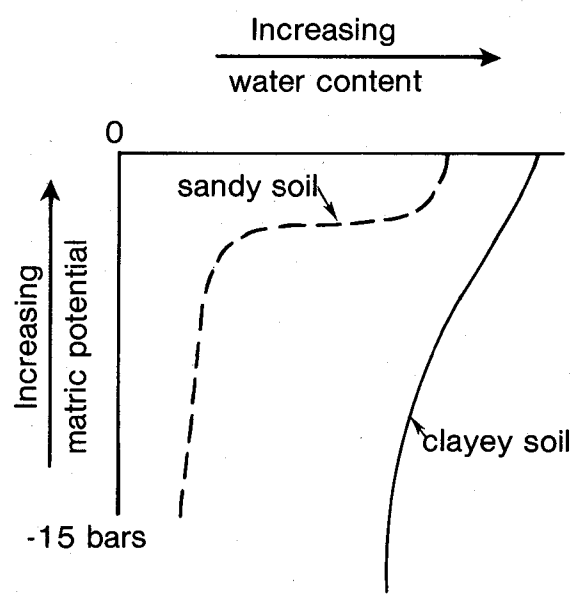

Figure 6-1.—The effect of texture on soil-water retention.

Laboratory measurements of water retentivity at moderate and low tensions (less than about 2 bars) should be made on undisturbed ("natural") soil samples. Measurements on materials that have been disturbed to the extent that they pass through a 2-mm sieve cause overestimates of water retained at moderate and low tensions, unless the soil is coarse textured (Young and Dixon, 1966). Water retentivity at high tension (low potential) can be measured on materials in which the natural soil fabric has been altered, as by seiving.

6.D.1. FIELD CAPACITY

Field capacity is defined as the amount of water in a soil 2 days after it has been saturated, if the soil is covered to prevent evaporation. Veihmeyer and Hendrickson (1931) have defined field capacity as "the amount of water held in the soil after the excess gravitational water has materially decreased." In most soils, however, the rate of water loss following saturation decreases gradually and no point can be identified where the rate of loss changes abruptly (Peters, 1965, p. 279-281).

Comment: The original intent of defining field capacity was to devise a procedure to determine the upper limit of water available to plants in soils as they exist out-of-doors. In the ideal situation of deep permeable soils, the values obtained do approximate the upper limit of available water. However, soil conditions which impede drainage, cause perched water tables, or markedly impede plant roots would cause misleading results. Therefore, it is necessary to study each soil and determination to ensure that the results obtained are realistic for the use to which the data will be put.

Efforts have been made to relate field capacity to water-retention values that can be determined in the laboratory. Certain retention values do have a useful correlation with the upper limit of water contents for certain soils in the field. Generalizations are hazardous, however, because, as is indicated above, field capacity depends on the rate of drainage of the soil profile as well as on the water-retention properties of the particular horizon. Consequently, the method recommended here is specific for field determination. For additional comments see section 6.D.3.

6.D.2. PERMANENT WILTING POINT

The permanent wilting point is defined as the water content of the soil at which a plant can no longer extract sufficient water from the soil to live. The permanent wilting point can be determined only in a controlled environment. After a dwarf sunflower plant (*Helianthus annuus*, large seeded variety) has reached a specified size, watering is discontinued. The water content of the soil is determined when the plant fails to recover in a specified time in a vapor saturated chamber. In some soils, the permanent wilting point is closely related to the -15 bar water-retention percentage as determined by the pressure-plate or pressure-membrane procedure. However, growth of most plants may stop long before the permanent wilting point is reached. The recommended source for this method is Peters (1965, p. 282-285).

6.D.3. AVAILABLE WATER CONTENT

Peters (1965, p. 285) describes the available water content as follows: "The available water in a soil is the amount of water that can be used or removed from the soil in the support of the life of higher plants. The available water content is estimated by the difference between the water content at field capacity and the water content at the permanent wilting point. The accuracy of the available water content is therefore dependent upon the reliability of the field capacity and permanent wilting point to estimate, respectively, the upper and lower limits of available water."

Comment: Water retention difference (WRD) is the volume of water held by soil specimens between a specified low tension (usually 0.06, 0.1, or ⅓ bar) and a higher tension (generally 15 bars) as determined in the laboratory. The WRD is an index number that may be used with soil morphology and plant rooting habit to estimate available water capacity when field capacity measurements are not feasible.

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6.E. SOIL-WATER MOVEMENT

The entry of water into soil, movement to plant roots, flow to drains, seepage, and evaporation are a few of the processes in which the rate of water movement plays an important role. Soil water responds to differences in potential and moves from areas of high potential into areas of low potential. Movement due to temperature and osmotic gradients does occur, but it is often minor. The rate of water movement is determined by the potential gradient and the hydraulic conductivity.

With all studies of infiltration and permeability (hydraulic conductivity), at least three rules are important: (1) Carefully select representative sites or soils; (2) use exacting and well-designed techniques; and (3) repeat the tests as required by the significance level of your design. Variations are normal and the results should be averaged and the variance should be determined. Land use (grassland, forestland, pastureland, plowed ground, and so forth) may affect water movement in upper soil horizons much more than does soil type.

6.E.1. INFILTRATION

Infiltration refers to the movement of water *into* a soil as contrasted to the movement of water *through* a soil. Because the infiltration rate is influenced by the water content and surface condition of the soil, correct use of these factors is important when interpreting the results. To date, no single measuring technique that will work under all conditions has been developed. However, two general methods, flooding and rainfall simulators, are widely used.

6.E.1.a. FLOODING

The double-ring infiltrometer is probably the most widely used instrument for measuring infiltration. Infiltration can also be determined by flooding the soil and measuring the rate of water intake. A large plot bounded by a wall of soil or some impermeable material to contain the water may be used. Recommended sources for this method are Bertrand (1965, p. 202-207) and Johnson (1970, p. 187-191).

6.E.1.b. RAINFALL SIMULATORS

Obtaining a satisfactory measurement of infiltration with this method requires that the artificial rain closely simulate natural rainfall and that the plot areas be large enough to represent the given soil. Infiltration equals the difference between the amount of water applied and the amount of runoff. The recommended source for this method is Bertrand (1965, p. 198-201).

6.E.2. HYDRAULIC CONDUCTIVITY

This section presents recommended methods for measuring hydraulic conductivity in both the laboratory and in the field.

6.E.2.a. SATURATED, LABORATORY

Either constant-head or falling-head methods can be used in the laboratory to measure hydraulic conductivity under saturated conditions. The constant-head system is best suited to samples with conductivities greater than approximately 0.01 cm per minute (relatively pervious soils), whereas the falling-head system is best suited to samples with conductivities lower than 0.01 cm per minute (relatively impervious soils). Laboratory measurements of saturated hydraulic conductivity are carried out using either disturbed or undisturbed soil samples that are held in metal or plastic cylinders. Recommended sources for these methods are Klute (1965a, p. 210-221) and American Society for Testing and Materials (1975, p. 298-304).

Comment: For undisturbed cores, the major disadvantages of these methods are the small sample size (which necessitates the use of a large number of samples) and the possibility of leakage along the interface of the soil core and the sample retainer.

6.E.2.b. SATURATED, FIELD

Five techniques can be used in the field to measure hydraulic conductivity under saturated conditions. Two of the techniques (auger-hole and piezometer methods) measure hydraulic conductivity below the water table, and three (double-tube, air-entry, and shallow-well pump-in methods) measure hydraulic conductivity above the water table.

6.E.2.b.1. AUGER-HOLE METHOD

The auger-hole method is based on the measurement of flow into an uncased cavity. The hydraulic conductivity calculated from the results of this test is an average value of the horizontal conductivity of primarily the layers below the water table penetrated by the hole. In stratified soil the results are dominated by more permeable horizons; hence, the method is of most value in unstratified soil. The recommended source for this method is Boersma (1965a, p. 223-229).

Comment: The auger-hole method is difficult to use in rocky soil or in coarse gravel, in soils with very high permeability rates, and under conditions in which the water table is at or above the ground surface.

6.E.2.b.2. PIEZOMETER METHOD

The piezometer method is based on the measurement of flow into an uncased cavity at the lower end of a cased hole. Because the vertical dimension of the unlined cavity is small, the method is well-suited for measuring the hydraulic conductivity of individual layers of soil. In this method the length of the cavity is generally several times its diameter, and the horizontal component of conductivity is measured. The wider the hole and the shorter the length of the cavity left unlined, the more nearly the measurement becomes the vertical conductivity. The tube method developed by Frevert and Kirkham (1948), a modification of the piezometer method, is designed to measure vertical conductivity. The recommended source for the piezometer method is Boersma (1965a, p. 229-233).

Comment: The piezometer method is difficult to use in rocky soils. Even when the tube can be installed in these soils, it is difficult to do so without leaving channels along the outside of the tube. Also, it is difficult to establish cavities of the correct dimensions. The diameter of the cavity is very important when calculating the hydraulic conductivity, making a stable cavity mandatory for reproducible results.

6.E.2.b.3. DOUBLE-TUBE METHOD

The double-tube method uses an auger hole above the water table. The hole is excavated to the depth at which a measurement of hydraulic conductivity is desired. This method can measure hydraulic conductivity of a well-defined sample area in the absence of a water table. Results from the double-tube method in the field compare favorably with hydraulic conductivity values obtained in the laboratory from soil samples taken at the bottom of the auger hole after completion of the field tests. The recommended source for this method is Boersma (1965b, p. 234-242).

Comment: The double-tube method measures hydraulic conductivity in an orientation between vertical and horizontal. It is time-consuming, requiring a day to characterize a volume about the size of a 4-inch core.

6.E.2.b.4. AIR-ENTRY METHOD

With the air-entry method, hydraulic conductivity is calculated from Darcy's equation using infiltration rates measured under high-speed conditions. The recommended source for this method is Bouwer and Jackson (1974, p. 631-633).

Comment: This method essentially gives the value of hydraulic conductivity at the air-entry value of matric suction. This value is approximately equal to half of the saturated conductivity (Bouwer, 1966).

6.E.2.b.5. SHALLOW-WELL PUMP-IN METHOD

Hydraulic conductivity of soil in which no water table is present can be determined in place by measuring the rate of flow of water from a cased or uncased auger hole when a constant height of water is maintained in the hole. This method is known as the shallow-well pump-in method or the dry-auger-hole method. The shallow-well pump-in method permits the measurement of an average hydraulic conductivity for the full depth of the hole being tested. The final value, however, reflects primarily the conductivity of the more permeable layers. The recommended source for this method is Boersma (1965b, p. 242-248).

Comment: Limitations of the shallow-well pump-in method are that large quantities of water are needed, considerable equipment is required, and the procedure is time consuming. Values of hydraulic conductivity obtained with the shallow-well pump-in method are usually lower than values obtained with the auger-hole test.

6.E.2.c. UNSATURATED HYDRAULIC CONDUCTIVITY

Hydraulic conductivity declines many fold for most soil materials as tension increases from saturation to 0.1 bar. Measuring unsaturated hydraulic conductivity requires information on both the tension and the rate of water movement. The relationships and some methods are described by Klute (1965b), Bouwer and Jackson (1974), and Bouma and others (1974). The crust method for measuring unsaturated hydraulic conductivity in the field, described by Bouma and others (1974), is less time consuming and is less difficult than measuring saturated hydraulic conductivity in the field.

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6.F. QUALITY CONTROL

6.F.1. DISCUSSION

Quality control in water-data acquisition may be accomplished in three ways: (1) improving techniques and procedures to minimize potential sources of experimental errors; (2) sampling adequate representatives of a system; and (3) making a sober and realistic appraisal as to what constitutes normal field variability and, thus, what range of data values may be considered acceptable.

TABLE 6-2.—Coefficient of variation (C_v), description of data, and source for specified values of water content (θ)

Water Content, θ (cm^3/cm^3)	Coefficient of variation, C_v (percent)	Description of data	Source for specified values of water content
At saturation[1]	5- 6	between cores	Mason and others, 1957
	4-11	within series	Rogowski, 1972
	7-11	within series	Mason and others, 1957
	3-11	within series	Cassel and Bauer, 1975
	20	between soils	Rogowski, 1972
Field soil[2]	5-23	by weight	Reynolds, 1970
	3-17	by volume	Reynolds, 1970
	9-21	bare soil	Reynolds, 1970
	10-33	vegetated	Reynolds, 1970
Moisture characteristic	10-23	150-hectare field	Nielson and others, 1973
At one-third bar	10	within plots	Ike and Clutter, 1968
	16-19	within series	Ike and Clutter, 1968
At 15 bars	14-16	within plots	Ike and Clutter, 1968
	20-28	within series	Ike and Clutter, 1968
	7-35	within series	Rogowski, 1972
	25-63	between soils	Rogowski, 1972
	11-16	within series	Cassel and Bauer, 1975
	13-55	with depth	Cassel and Bauer, 1975

[1] Calculated from values given for bulk density assuming 2.65 as particle density.
[2] Calculated from values given in tables 3 and 4 of Reynolds (1970).

Procedures designed to improve techniques and to aid representative sampling are described in Allmaras (1965, p. 24-42), David and Cady (1965, p. 73-81), Dixon (1965, p. 43-53), Kempthorne and Allmaras (1965, p. 1-23), and Peterson and Calvin (1965, p. 54-71).

To assess the relative degree of variability, some coefficients of variation (100 × (Standard Deviation/Mean)) extracted from literature are listed for comparison in tables 6-2, 6-3, and 6-4. While in general several discrete or continuous distributions may be associated with physical field measurements (Krumbein and Graybill, 1965, p. 110), the distributions we need to be concerned with here are the normal distribution of soil-water contents and log-normal distributions of matric potential and hydraulic conductivity at a given water content. In assessing the potential variability of soil in the field, it is well to remember that on the average, only 50 percent of the sites chosen at random within a mapped soil series are likely to be occupied by profiles matching the definition of the profile for which the unit is named (Beckett and Webster, 1971). Consequently, large spatial variability is to be expected.

TABLE 6-3.—Coefficient of variation (C_v) and description of data for specified values of matric suction (ψ), after Webster (1966)[1]

Matric suction, ψ (cm)	Coefficient of variation, C_v (percent)	Description of data
13-540	11-26	at 40 cm—within site, grass
43-224	8-11	at 13 cm—impeded drainage
93-427	7-10	free drainage
16-250	10-19	at 38 cm—impeded drainage
52-229	3-9	free drainage
32-56	10-22	high ground water

[1] Matric suction values exhibit log-normal distribution, consequently C_v values are computed on the basis of logarithmic mean and standard deviation.

TABLE 6-4.—Coefficient of variation (C_v), description of data, and source for hydraulic conductivities of soils[1]

Coefficient of variation, C_v (percent)	Description of data	Source for hydraulic conductivities of soils
8-21	clay loam	Willardson and Hurst, 1965
16-35	silty clay	Mason and others, 1957
32	loamy sand	
7-18	different textures	Mason and others, 1957
14	between cores	Mason and others, 1957
25	between sites	Mason and others, 1957
38	between soils	Rogowski, 1972
5-36	within series	Rogowski, 1972

[1] Hydraulic conductivity values exhibit log-normal distribution, consequently C_v values are computed on the basis of logarithmic mean and logarithmic standard deviation.

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Chapter 7

Physical Basin Characteristics for Hydrologic Analyses

CHAPTER 7—PHYSICAL BASIN CHARACTERISTICS FOR HYDROLOGIC ANALYSES

Prepared by
Work Group 7 on Physical Basin Characteristics for Hydrologic Analyses

June 1978

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COMMENTS ON CHAPTER 7

National Handbook of Recommended Methods for Water-Data Acquisition

I found this "National Handbook" chapter to be useful. Comments:

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Reference _____

The method is unsatisfactory for the following reason(s): _____

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CHAPTER 7—PHYSICAL BASIN CHARACTERISTICS FOR HYDROLOGIC ANALYSES

7.A. INTRODUCTION

7.A.1. CHARACTERISTICS INCLUDED

The characteristics covered by this chapter are the physical attributes of drainage basins that have been found to be or are believed to be important in hydrologic analyses. Basin characteristics are used by many disciplines for a variety of reasons. Geomorphologists in particular have defined many of the characteristics in their land-form/hydrologic-process studies. Basin characteristics are also used by land use planners, engineers, agriculturists, geologists, foresters, and others. To consider all the characteristics used by all groups is beyond the scope of a handbook concerned with water data; hence, the focus is on those characteristics used in hydrologic analyses.

One class of basin attributes is associated with hydrologic analyses and as such might have been included in this chapter. These attributes include various measures of precipitation, evapotranspiration, streamflow, ground water, soil moisture, and water quality. These are dynamic measures even though some, such as mean annual streamflow, appear to be a characteristic for a given area. Dynamic measures are not described in this chapter because standard methods for most of these measures will be found in other chapters.

The basin characteristics, except for land use, included in this chapter are relatively static measures that do not change appreciably over a planning period time frame. These are the characteristics that become important when, for example, the effects on streamflow of changes in such attributes as land use or channel meanders are to be predicted or when it becomes necessary to make these predictions at ungaged locations. Mathematical models or other quantification techniques developed for such purposes must account for the influence of some of the physical characteristics of watersheds. These models can be better used by others and more easily extended to other locations if standard methods are used for determining the basin characteristics.

7.A.2. BASIN CHARACTERISTICS AND THEIR USES

The focus on hydrologic analyses in this chapter is a result of the increasing use of models, equations, and graphical relationships to transfer hydrologic information from basins or locations where data are available to locations where data are unavailable. These methods are also used to appraise the impact of changes in basin characteristics on the hydrologic regime. To be used in hydrologic analyses, basin characteristics usually must be quantified and their importance in the process involved must be evaluated. Because the importance of these characteristics is related to many factors and the evaluation process is quite subjective, a proliferation of measures has resulted.

The various applications of basin characteristics may be grouped into two broad categories: (1) planning and (2) process-response studies. The planning applications range from mineralogical evaluations using geologic maps to urban impact assessments that may use land use, topographic, soils, geologic, and other maps. Typically planning applications involve only the use of maps, although when mathematical models are used, even these mapped characteristics must be

quantified. Process-response studies usually necessitate quantitative measurement of the basin characteristics. Whether the objective is to explain form from process (geomorphologic studies) or process from form (hydrologic studies), mathematical modeling is a basic tool. Models can vary from graphic, two- or three-dimensional portrayals to multivariable statistical models to mathematical nonlinear parametric models to mathematical deterministic systems models. Regardless of the type of model used, numeric representation of each characteristic is required.

The art of modeling is in its infancy. Also, because of the complexity of most natural hydrologic systems, a number of simplifications must be made. Even in the more complete (so-called deterministic) watershed hydrologic models, many processes cannot be included or well represented: (1) because of the complexities they introduce; (2) because many of the necessary measures are not easily determined or readily available; and (3) because many of the processes and their interactions are not well understood. All too often the development of a model is conditioned by those basin characteristics that are readily available; many of these are only indices or surrogate measures of the basin characteristics actually involved. Thus, the appearance of a particular characteristic in a model does not necessarily indicate its intrinsic value in the actual process-response relationship.

Other reasons for the proliferation of basin characteristic measures involve the scale and type of application. Many of the detailed measures of characteristics necessary, for example, for a model of the hydrology of hill slopes would be difficult to justify including in a watershed model, and probably would be meaningless in a continental hydrology model. As the scale of model application varies, so does the degree of detail in the hydrologic processes included, and consequently, the type and number of basin characteristics included. Also, the goal of the application, to a degree, governs the basin characteristics used. For a reconnaissance model, only readily available, easily determined basin characteristics can be included, while for a complex process model, much more detailed measures can be justified.

Despite the problems that exist in modeling fluvial-response/basin-characteristics relationships, such models offer great potential. On the one hand, they offer a means for increasing understanding of the process-response relationships that will in turn lead to improved models. On the other hand, they greatly increase the utility of water-resources data when they are employed to simulate fluvial processes at other locations or under conditions where data are unavailable.

7.A.3. PURPOSE AND ORGANIZATION OF CHAPTER

The purpose of this chapter is to recommend methods for determining basin characteristics to be used in hydrologic analyses. The focus is on numeric quantification of the characteristics, although classification and mapping are also considered. The lack of adequate map coverage of soils, geology, and land use/land cover in the past has retarded development of techniques for quantification; therefore, emphasis is more on mapping.

Scale must be considered in determining and applying basin characteristics. From a modeling viewpoint three scales can be visualized: (1) microscale, in the range of acres (square meters); (2) mesoscale, in the range from about one to hundreds of square miles (2 to over 1,000 square kilometers); and (3) macroscale, major river basins to continental scale. Generally, the basin characteristics considered in this chapter are measured at the mesoscale because it is at this scale that most modeling is done. At the microscale, processes are complex relative to existing mapped measures which are generally too broad to be applicable, while at the macroscale, it is difficult to

correlate the data since the relationships are poorly understood. At the mesoscale there are usually adequate maps from which to obtain characteristics, and they can be relatively easily determined.

It is beyond the purpose of this chapter to evaluate the utility of various characteristics for a given study or to evaluate how they might be used in specific analyses. The particular characteristics in the chapter are included because of their general use in past studies or models. However, the popularity of a particular characteristic may be a result of the ease of obtaining that measure rather than its intrinsic importance in a process. Thus, evaluating the importance of various characteristics and evaluating how they are to be used remains the responsibility of the analyst. Nor does it follow that the absence of a particular characteristic from this chapter reflects that it is not useful in hydrologic analyses. Some past measures that may be important have not found general application, and new characteristics are continually being tried by investigators. Since the importance of characteristics is relative and involves subjective decisions, hopefully future editions will rectify any problems resulting from omissions.

This chapter is organized according to general methods for describing drainage basins proposed by R. E. Horton (1932). Horton included morphologic, soil, geologic or structural, and vegetative factors. Many of his ideas were later developed into a hydrologic context (Horton, 1945) and later supplemented by W. B. Langbein's (1947) contribution on topographic characteristics of basins. Because the subdivision proposed by Horton remains a meaningful one, this chapter essentially includes his three groupings of characteristics: (1) topographic, (2) soils and geology, and (3) land cover and land use.

References are provided for recommended methods for determining the basin characteristics described. The measurement accuracy to be expected is explained where applicable. In the case of mapped characteristics data sources are documented.

There is no attempt to include a bibliography relevant to this chapter. To do so would result in an unwieldy document. However, a wealth of information regarding basin characteristics and their use can be obtained from geomorphologic sources, such as the text by Gregory and Walling (1973), the encyclopedia by Fairbridge (1968), or the handbook edited by Chow (1964).

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7.B. TOPOGRAPHIC CHARACTERISTICS

7.B.1. INTRODUCTION

A drainage basin is an area which contributes water, sediment, and impurities to a stream. Measurement of a basin, and the processes through which it evolves, usually begins with the concept of the basin as a geomorphic unit. Meteorological forces over the basin and geological forces under the basin are the principal sources of energy. Losses occur through evaporation, transpiration, and outflow of water and sediment. Landforms in the basin are modified and transformed throughout the system. In time, the network of channels and valleys becomes adjusted to the quantity of water and sediment produced in the controlling environment. The resultant morphometry of the drainage network is a set of geometric relationships described by Horton's laws of stream areas, lengths, orders, and numbers (Horton, 1945). As greater or lesser amounts of energy flow, the basin goes through new adjustments continuously forming and altering the network.

This section covers the topographic variables of drainage basins which have been found useful in hydrologic analyses. The size of the basin influences the water yield; the length, shape, and relief affect water and sediment yield; and the extent and character of the channels affect sediment availability and water yield. Topographic characteristics need to be visualized in the context of the ways in which they influence drainage-basin processes. The relations which exist among the characteristics are also important. Therefore, topographic characteristics of drainage basins may be visualized for the basin as a whole, basin subareas, the total channel system or network, and individual parts of channels or reaches. For each of these categories, indices of area, length, shape, and relief are required. Some variables such as area and length are singular measures of basin geometry, whereas others are combinations of two or more measures of geometry, such as slope (height and length). Most require operational definitions and prescribed methods for their computations.

The methods recommended for determining the given topographic characteristics have been selected on the basis of their wide applicability and their general acceptability. Usually only one method is listed, but where several methods are generally acceptable, all are given. No attempt is made to state which characteristic should be used in a particular type of study. User requirements will determine which characteristics are important.

In this section, the characteristic is first defined and methods are simply described and referenced. Units of measurement are given in both the common and metric systems.

7.B.1.a. MEASUREMENT OF CHARACTERISTICS

Basin characteristics are usually determined from maps or aerial photographs by measuring areas, lengths, elevations, and directions, and by counting identifiable features such as the intersections of contours and grid lines or the junctions of streams.

The U.S. Geological Survey 1:24,000-scale map is the standard map for determining topographic basin characteristics because the scale provides adequate representation of most drainage basins, and these maps conform to National Map Accuracy Standards. (*See* section 7.B.1.b. for a discussion of map scale.) In most instances, the area of a large drainage basin can be defined from the cumulative sums of subareas determined from several 1:24,000-scale maps encompassing the basin. Because

map scales and standards for soils, geologic, and land use characteristics vary, a standard map for these characteristics has not been proposed.

For some characteristics and for small drainage areas (less than approximately 0.5 square mile), the 1:24,000-scale topographic maps may show insufficient detail to define basin characteristics accurately. Therefore, larger scale maps, aerial photographs, or field surveys are sometimes necessary. For example, pond areas on a 1:24,000-scale map may be too small to measure reliably by planimeter. In addition, stream cross-sectional areas cannot be represented adequately and may require a field survey. Consequently, standards are not given for measuring characteristics such as these.

The Federal Interagency River basin Committee (1951, appendix B) has developed standards for measuring basin areas, and the U.S. Water Resources Council (1968, p. 9–10) has developed standards for measuring river lengths. Unless otherwise noted, these standards should be used to determine any area or length required to compute a basin characteristic.

On topographic maps, contours are delineated at intervals ranging generally from 5 feet to 200 feet depending on the steepness of the terrain and the scale of the map. Point elevations should be determined by linear interpolation between the contour intervals on the map. Direction should be measured to the nearest degree by determining the tangent of the angle with true north and converting this to azimuth using trigonometric tables.

Recommended sampling techniques for evaluating some characteristics require the use of a grid to establish the sampling points. Although interpolating between contour intervals and measuring direction are straightforward procedures, counting identifiable features requires careful evaluation of the grid size used to insure an accurate count. The grid size must be selected so that a sufficient number of features, such as line-contour intersections, fall within the grid. Therefore, several grid sizes should be tested to determine the best size. Select a grid size to provide a minimum of 50 points within a drainage-basin boundary.

7.B.1.b. MEASUREMENT ACCURACY

The accuracy required for determining topographic characteristics depends on the purpose for which the characteristics will be used. Often, survey and reconnaissance studies may require less accurate descriptions of a basin than do project-design studies of the same basin. The size of the area under consideration also affects the degree of accuracy required for determining topographic characteristics; smaller areas generally require more precision than do larger areas. The following recommended methods for measuring should be used whenever possible because they provide accurate results and others can then use these results with confidence.

The amount of detail that can be extracted from a topographic map depends largely on the scale of the map. Map scale is the relationship between a distance on the map and the corresponding distance on the ground. Scale is usually expressed as a ratio or fraction, such as 1:24,000 or 1/24,000. The numerator (usually 1) represents the distance on the map, and the denominator represents the distance on the ground. Changing the denominator changes the scale, so that as the denominator gets larger, the fraction and the scale get smaller. For example, 1/24,000 is larger than 1/100,000; thus, a map of the former scale is a larger scale map than the latter. The terms "large scale" and "small scale" are relative and have no limiting definitions. Scales may be as large as 1:5,000 for detailed urban areas, or as small as 1:17,000,000 for some maps of the United States.

Measurement accuracy is often related to the standard error of estimate. The accuracy of a characteristic determination should be stated in terms of its standard error of estimate, which usually can be computed. The smaller the standard error of estimate, the more accurate the measurement (Bryant, 1966, p. 135, and most statistical texts). However, because of the many variables involved in measuring basin characteristics, rigorous standard errors of estimate cannot be determined for the various measurements. Hence, only relative standard errors of estimate are provided.

In making maps, or in compiling data on drainage-basin characteristics from these maps, both bias and random error can occur. Bias may be inherent in the map as a result of distortion in the aerial photographs or as a result of ground features being obscured by foliage. In addition, instrument or operator error can cause bias. Random errors, on the other hand, originate from transferring three-dimensional information to a two-dimensional map, from errors in making the map, from enlarging or reducing the map, from defining the basic variable to be measured (i.e., drawing drainage divides), from measuring instrument and operator error, and from the scale of the map. A small-scale map, such as 1:250,000 does not permit accurate location and depiction of many features; therefore, larger errors may occur in measuring characteristics on these maps.

Reasonable effort should be made to eliminate controllable bias in measuring characteristics on maps. Both instruments and operators should be as unbiased as possible. By repeated measurements, the compiler can estimate and alleviate random errors in determining area, length, azimuth, and count. Errors caused by defining an area, length, azimuth, or count can be checked by having several individuals independently define the same feature or by having one individual describe the likely variation in the feature, e.g., by drawing the full range of possible positions of a drainage divide.

The compiler of basin characteristic data should use the best topographic map available, measure and delineate the characteristic carefully, and use recommended methods to make basic measurements. Both bias and random error will be minimized, and user can then use these topographic-characteristic data with confidence.

When it becomes impractical to directly measure the basin characteristics of a watershed, the compiler can estimate certain characteristics using gridding techniques. If gridding techniques are used to determine characteristics such as azimuth, mean elevation, or land slope, the compiler should estimate the characteristic at each grid intersection falling within a watershed boundary and average their values. For those characteristics that involve an areal determination, such as drainage area or land cover, the compiler should count the characteristic at the grid line intersections and determine the areal extent of the basin characteristic by multiplying the intersection count total by the drainage area represented by a grid cell, under the general assumption that:

$$C_T = \int c\, dA \simeq \sum_{i=1}^{n} c_i \Delta A$$

where C_T = value (integral) of the characteristic,

c = the magnitude of the characteristic on a differential area, dA, and

c_i = the magnitude of the characteristic on a small area, ΔA.

When gridding techniques are used rather than direct measurements, the magnitude of the error will be somewhat greater and will depend on the number of grid cells that fall within the boundaries of the watershed. Errors will also vary with map scale and contour interval. Thus, if a large number

of maps are to be analyzed using the gridding technique, the compiler should first sample a few maps using grids to determine the error due to scale and contour interval. Once a suitable grid has been found, the compiler should use this grid in a consistent manner on all the maps.

7.B.1.c. SOURCES OF BASIN DATA

Many topographic characteristics have been measured for the multitude of basin studies completed to date, and the data obtained are available through Federal, State, and local agencies as well as professional organizations. The U.S. Geological Survey is the major source of basin data and publications containing basin data, as well as being the prime agency responsible for preparing topographic maps of the United States. U.S. topographic maps are available in several scales, and may be ordered by writing to:

Branch of Distribution U.S. Geological Survey 1200 South Eads Street Arlington, Va. 22202	Maps east of the Mississippi River, including Minnesota, Puerto Rico, and the Virgin Islands.
Branch of Distribution U.S. Geological Survey Federal Center Denver, Colo. 80225	Maps west of the Mississippi River, including Alaska, Hawaii, Louisiana, Guam, and American Samoa.

Maps may also be obtained over the counter at U.S. Geological Survey offices where books are sold and at:

Room 1C 402 National Center 12201 Sunrise Valley Drive Reston, Va. 22092	Room 1C4S 1100 Commerce Street Dallas, Tex. 75202
900 Pine Street Rolla, Mo. 65401	678 U.S. Court House West 920 Riverside Avenue Spokane, Wash. 99201
Building 41 Federal Center Denver, Colo. 80225	8102 Federal Building 125 South State Street Salt Lake City, Utah 84138
345 Middlefield Road Menlo Park, Calif. 94025	504 Custom House 555 Battery Street San Francisco, Calif. 94111
Room 441 Federal Building 710 West Ninth Street Juneau, Alaska 99801	1012 Federal Building 1961 Stout Street Denver, Colo. 80202
7638 Federal Building 300 North Los Angeles Street Los Angeles, Calif. 90012	108 Skyline Building 508 2nd Avenue Anchorage, Alaska 99501

Survey maps are also sold by some 1,500 commercial dealers throughout the United States.

The U.S. Geological Survey also publishes Professional Papers, Water-Supply Papers, Open-File Reports, and various bulletins and circulars. Many of these contain useful topographic characteristic data on river basins. Also, some of these publications define and describe some of the methods recommended in this section. Books may be obtained through:

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

or:

Branch of Distribution
U.S. Geological Survey
1200 South Eads Street
Arlington, Virginia 22202

Many of the data collected by the Geological Survey are stored on computers at the national headquarters in Reston, Virginia. The data are in the WATSTORE data file (National Water Data Storage and Retrieval System) or the NAWDEX file (National Water Data Exchange). Some of these data are available through computer links to other Government agencies. Other data may be obtained by writing to the U.S. Geological Survey, Reston, Virginia, or the local State office of the U.S. Geological Survey, or where applicable, the State geological surveys.

Additional reports may be purchased only through the National Technical Information Service (NTIS) by writing to:

NTIS
U.S. Department of Commerce
Springfield, Virginia 22161

The Defense Mapping Agency also prepares detailed maps of the United States and these may be obtained by writing to:

Defense Mapping Agency
U.S. Naval Observatory
Building 56
Washington, D.C. 20305

Additional basin-characteristic and map data may be obtained through other Federal agencies, such as the Tennessee Valley Authority and the National Weather Service. The Soil Conservation Service maintains aerial photo files and soil maps that are often located within county offices to provide an easy-access data source. Section 7.C.2.b.2. lists some of the sources for these data.

7.B.2. TOPOGRAPHIC MEASURES

7.B.2.a. BASIN MEASURES

7.B.2.a.1. BASIN DRAINAGE AREA

(Recommended symbol, A for total area, A_C for contributing area)

The area of a river basin, measured in a horizontal plane, that is enclosed by a topographic divide, such that direct surface runoff from precipitation normally would drain by gravity into the river basin. The area on a map enclosed by the basin boundary is measured with a planimeter, calibrated for the map being used, by comparing the planimeter reading for a quadrilateral of latitude and

longitude on the map with the area for that quadrilateral obtained from tables, such as shown in U.S. Federal Inter-Agency River Basin Committee, Appendix E (1951). Drainage areas are usually available for basins where streamflow records have been published.

The boundary of the basin is defined by an irregular line that traces the perimeter of the basin drainage area and is perpendicular to each surface contour line that it crosses. Areas within the basin that do not contribute to direct surface runoff are measured separately and subtracted from the total area to obtain the contributing area. Both the total area, A, and the contributing area, A_C, should be listed even though they are the same. Units are square miles (square kilometers) (U.S. Federal Inter-Agency River Basin Committee, 1951). Relative standard error of estimate is 5 percent.

7.B.2.a.2. BASIN LENGTH
(Recommended symbol, L_B)

Air-line distance from outlet to the point on the basin divide used to determine main channel length, L_C (section 7.B.2.c.1.). Units are miles (kilometers) (Wisler and Brater, 1949, p. 45). Standard error of estimate is 5 percent.

7.B.2.a.3. BASIN WIDTH
(Recommended symbol W_B)

Average width of the basin determined by dividing the area, A, by the basin length, L_B. Units are miles (kilometers).

7.B.2.a.4. BASIN PERIMETER
(Recommended symbol, P_B)

The length of the curve that defines the surface divide of the drainage basin. It is measured from a map by using a map-measuring wheel (stadiometer) or by accumulating chord segments using dividers. Units are miles (kilometers). Relative standard error of estimate is 5 percent.

7.B.2.a.5. BASIN PERIMETER SLOPE
(Recommended symbol, S_P)

An index of general basin slope based on net east-west slope, S_{EW}, and net north-south slope, S_{NS}. East-west slope, S_{EW}, is computed from about 20 equally spaced east-west lines on a map of the basin, by subtracting the sum of the elevations at the intersection of each line with the westerly boundary from the sum of the elevations at the intersections of the lines with the easterly boundary, and dividing by the total length of the east-west lines. S_{NS} is similarly computed from about the same number of north-south lines, by subtracting the sum of the elevations at the southerly boundary intersections from the sum of those at northerly boundary intersections, and dividing by the total length of the north-south lines. Computed as follows:

$$S_P = (S_{EW}{}^2 + S_{NS}{}^2)^{1/2}$$

S_P will be in the same units as S_{NS} and S_{EW} but should be reported in dimensionless units (Horton, 1932; Wallis, 1965). Relative standard error of estimate is 5 percent.

7.B.2.a.6. BASIN PERIMETER ASPECT
(Recommended symbol, AZ_P)

Compass direction of a line normal to basin-perimeter-slope lines and pointing down slope. Azimuth in degrees measured clockwise from the north is computed as follows:

$$AZ_P = 180 + \cot^{-1} (S_{NS}/S_{EW}) \text{ when } S_{NS} \text{ is positive,}$$

$$AZ_P = \cot^{-1} (S_{NS}/S_{EW}) \qquad \text{when } S_{NS} \text{ is negative,}$$

in which S_{NS} and S_{EW} are the north-south and east-west components, respectively, of basin perimeter slope S_P (Horton, 1932; Wallis, 1965).

7.B.2.a.7. BASIN LAND SLOPE

7.B.2.a.7.a. Method one (recommended symbol, S_{B1})—Average land slope calculated at points uniformly distributed over the basin. Slopes normal to the contours at each of 50 and preferably 100 grid intersection points are averaged to obtain S_{B1}. The difference in elevation for the two contour lines nearest a grid point is determined and the normal distance between these lines is measured. Reported in dimensionless units (Linsley, Kohler, and Paulhus, 1949, p. 250). Relative standard error of estimate is 5 percent.

7.B.2.a.7.b. Method two (recommended symbol, S_{B2})—Average land slope from count of contour crossings. Computed as follows:

$$S_{B2} = 1.571 \frac{hN}{L}$$

in which N is the number of times the contours cross evenly spaced grid lines, L is total length of the grid lines, and h is the contour interval. A minimum of four grid lines in each direction is recommended for drainage areas less than 100 square miles (250 square kilometers), with this number increasing to 8 at 1,000 square miles (2,500 square kilometers), and to 16 at 10,000 square miles (25,000 square kilometers). Reported in dimensionless units (Linsley, Kohler, and Paulhus, 1949, p. 250). Relative standard error of estimate is 5 percent.

7.B.2.a.7.c. Method three (recommended symbol, S_{B3})—Average land slope from length of contours. Computed as follows:

$$S_{B3} = \frac{hL}{A},$$

in which L is the total length of all the contours in the basin, A is the drainage area, and h is the contour interval. Results are affected by detail shown in the contours. Reported in dimensionless units (Horton, 1932). Relative standard error of estimate is 10 percent.

7.B.2.a.7.d. Method four (recommended symbol, S_{B4})—Average land slope by weighted-average version of method used for S_{B3}. A weighted average of the average slope between successive contours computed by the equations:

$$s = \frac{hL}{A} \text{ and } S_{B4} = \frac{\Sigma (as)}{A}$$

in which h is the contour interval, a is the area bounded by two successive contours, L is the sum of the lengths of the two boundary contours, and A is the total area of the basin. Reported in dimensionless units (Horton, 1926, 1932). Relative standard error of estimate is 10 percent.

7.B.2.a.8. BASIN ELEVATION

7.B.2.a.8.a. Method one (recommended symbol, E_{B1})—Average distance above mean sea level computed by summing the products of planimetered subareas (a) and their mid-range elevations (e) and dividing by the total area (A). Units are feet (meters). Relative standard error of estimate is 2 percent.

$$E_{B1} = \frac{\Sigma(ae)}{A}$$

7.B.2.a.8.b. Method two (recommended symbol, E_{B2})—Average distance above mean sea level of representative points in the basin. Computed as the arithmetic average of the elevation of 50 to 100 points at the intersections of equally spaced grid lines superposed on a map of the basin. Units are feet (meters) (Linsley, Kohler, and Paulhus, 1949; Carter and Green, 1963). Relative standard error of estimate is 5 percent.

7.B.2.a.9. BASIN DIAMETER
(Recommended symbol, B_D)

Diameter of the smallest circle that will encompass the entire watershed. Units are miles (kilometers) (Schumm, 1963). Relative standard error of estimate is 5 percent.

7.B.2.a.10. BASIN SHAPE

7.B.2.a.10.a. Basin shape (recommended symbol, SH_{B1})—A measure of the shape of the basin computed as the ratio of the length of the basin to its average width (U.S. Corps of Engineers, 1963). Computed from L_B and A (page 8–14) as follows:

$$SH_{B1} = \frac{(L_B)^2}{A}$$

Reported in dimensionless units. Relative standard error of estimate is 5 percent.

7.B.2.a.10.b. Elongation ratio (recommended symbol, SH_{B2})—The ratio of the diameter of a circle of area equal to that of the basin, to the length of the basin (Schumm, 1956). Computed from L_B and A as follows:

$$SH_{B2} = \left[\frac{4A}{\pi(L_B)^2}\right]^{1/2} = 1.13\left[\frac{1}{SH_{B1}}\right]^{1/2}$$

Reported in dimensionless units. Relative standard error of estimate is 5 percent.

7.B.2.a.10.c. Rotundity (recommended symbol, SH_{B3})—Computed from L_B and A as follows:

$$SH_{B3} = \frac{\pi (L_B)^2}{4A} = 0.785(SH_{B1})$$

Reported in dimensionless units. Relative standard error of estimate is 5 percent.

7.B.2.a.10.d. Compactness ratio (recommended symbol, SH_{B4})—The ratio of the perimeter of the basin to the circumference of a circle of equal area. Computed from A and P_B as follows:

$$SH_{B4} = \frac{P_B}{2(\pi A)^{1/2}}$$

(Wisler and Brater, 1949, p. 45) Reported in dimensionless units. Relative standard error of estimate is 10 percent.

7.B.2.a.10.e. Lemniscate ratio (recommended symbol, SH_{B5})—A measure of shape that is the ratio of the perimeter of a lemniscate loop for the watershed SH_{B3} to the measured perimeter of the basin, P_B (Chorley, Malm, and Pogorzelski, 1957, p. 138–141; Chow, 1964, p. 4–51). Reported in dimensionless units.

7.B.2.a.11. BASIN SURFACE STORAGE

7.B.2.a.11.a. Total storage (recommended symbol, ST_{B1})—An index of surface storage in the basin computed as the percent of contributing area occupied by the surface of lakes, ponds, and swamps. Measured from a map by using a planimeter or by using a grid to count the number of squares occupied by the water or swamp surface. Index may depend on the date of determination. (Surface area depends on the proportion of storage capacity occupied) (Benson, 1962). Relative standard error of estimate is 10 percent.

7.B.2.a.11.b. Lakes and ponds (recommended symbol, ST_{B2})—Same as by the above method except that only the surface of lakes and ponds is included; the area of swamps is excluded. Index may depend on the date of determination.

7.B.2.a.12. LATITUDE OF BASIN CENTROID
(Recommended symbol, B_{LAT})

Latitude, in degrees and hundredths of a degree of the centroid of the drainage basin. Determined by finding the centroid of a cardboard image of the drainage basin by locating its center of gravity using pins, threads, etc. The cardboard image is suspended by a pin thrust through the cardboard close to the perimeter. A weighted thread is suspended from this pin, and the position of the thread on the outline is marked. The process is repeated one or more times by suspending the cardboard image from different points on the perimeter, the centroid being the common point of intersection of these pendulum-determined lines. Error increases or decreases depending on map scale (Snyder, 1938). Relative standard error of estimate is 0.05 degree.

7.B.2.a.13. LONGITUDE OF BASIN CENTROID
(Recommended symbol, B_{LONG})

Longitude, in degrees and hundredths of a degree of the centroid of the basin determined for basin latitude in the preceding definition. Error increases or decreases depending on map scale (Snyder, 1938). Relative standard error of estimate is 0.05 degree.

7.B.2.a.14. HYPSOMETRIC (AREA-ALTITUDE) CURVE
(Recommended symbol H_{CU})

The relation of horizontal cross-sectional drainage-basin area to elevation, or relative area a/A to relative height h/H. The hypsometric intergral (the area under the curve), sinuosity, and slope of the curve at its inflection are all used for intrabasin comparisons. The hypsometric curve is constructed by measuring the area between successive contours with planimeter, and plotting cumulated area against the elevation of the lower contour (Langbein, 1947; Strahler, 1952).

7.B.2.b. DRAINAGE NETWORK

7.B.2.b.1. STREAM ORDER
(Recommended symbol, R)

A dimensionless measure of the position of a stream in the hierarchy of tributaries. First-order streams are defined as having no tributaries. Second-order streams have first-order streams as tributaries. The higher order stream extends headward to the tip of the longest tributary it drains. Where differences in length are questionable, the tributary with the largest drainage area is chosen (Horton, 1945, p. 281, 1932, p. 356). First-order streams may not always be depicted (partially or fully) on standard topographic maps. The investigator should consult aerial photographs and make field surveys to insure that they are adequately represented. Where two n-order streams join, a segment of $n+1$ order is formed (Strahler, 1957).

7.B.2.b.2. STREAM NUMBER
(Recommended symbol, N_R)

The number of streams of a given order. The number of streams (or segments) in a given order will be fewer than in the next lower order, and more numerous in the next higher order (Horton, 1945).

7.B.2.b.3. BIFURCATION RATIO
(Recommended symbol, R_B)

Average ratio of number of streams in a given order to number in next higher order $R/(R+1)$ (Horton, 1945).

7.B.2.b.4. LENGTH RATIO
(Recommended symbol, L)

Ratio of average length of streams in a given order to average length of streams in the next lower order $R/(R-1)$ (Horton, 1945).

7.B.2.b.5. DRAINAGE DENSITY

7.B.2.b.5.a. Method one (recommended symbol, DD_1)—The total length of all streams per unit of area. Drainage density applies broadly to total landscape as well as to drainage basins $DD_1 = \frac{\Sigma L}{A}$. Units are miles/mile^2 (kilometers/kilometer^2) (Horton, 1932). This measure is affected by

the scale of map used, the contour interval, and the extent to which stream lines are mapped. Stream channels should be extended up contour crenulations. First-order streams may not always be depicted (partially or fully) on standard topographic maps.

7.B.2.b.5.b. Method two (recommended symbol, DD_2)—Rapid approximation calculation by the line-intersection method.

$$DD_2 = 1.571 \frac{\Sigma N}{\Sigma L},$$

in which ΣN is the total intersections all streams and extended channels make with the grid system, and ΣL is the total length of all grid lines in the watershed. Units are miles/mile^2 (kilometers/kilometer^2) (Carlston and Langbein, 1960). Relative standard error of estimate is 5 percent.

7.B.2.b.6. CONSTANT OF CHANNEL MAINTENANCE
(Recommended symbol, C)

The number of units of drainage area required to sustain one linear unit of channel. This is the reciprocal of drainage density $C = A/\Sigma L$. Units are square feet/foot (square meters/meter) (Schumm, 1956).

7.B.2.c. CHANNEL (STREAM) MEASURES

7.B.2.c.1. MAIN CHANNEL LENGTH

7.B.2.c.1.a. Method one (recommended symbol, L_{C1})—Length is measured in 0.1-mile chords (.2 kilometer) or by stadiometer along a map representation of the main channel from the outlet to the basin divide. The main channel is chosen at each bifurcation by following the fork that has the largest drainage area. The upstream end of the system is determined by extending the main channel from the end of the mapped representation of the stream (blue line) to the basin divide. For map scales of 1:250,000 or smaller, substituting a chord length of 0.25 mile (.4 kilometer) is recommended, and for map scales larger than 1:24,000, a chord length of less than 0.1 mile (.2 kilometer) is permissible. Units are miles (kilometers) (Benson, 1964). Relative standard error of estimate is 5 percent.

7.B.2.c.1.b. Method two (recommended symbol, L_{C2})—Main channel length can be measured by an alternate method that follows up the forks that have the longest watercourses. This is an acceptable substitute. Units are miles (kilometers) (Langbein, 1947). Relative standard error of estimate is 5 percent.

7.B.2.c.2. MAIN CHANNEL SLOPE

7.B.2.c.2.a. Method one (recommended symbol, S_{C1})—An index of the slope of the main channel computed from the difference in streambed elevation at points 10 percent and 85 percent of the distance along the main channel from the outlet to the basin divide. Computed by the equation:

$$S_{C1} = \frac{(E_{85} - E_{10})}{0.75\, L_C},$$

in which E_{85} and E_{10} are the elevations in feet at the 85 and 10 percent points. Reported in dimensionless units (Benson, 1959). Relative standard error of estimate is 5 percent.

7.B.2.c.2.b. Method two (recommended symbol, S_{C2})—An index of main channel slope that represents the slope in a uniform channel having the same length, L_C, as the main channel and an equivalent time of travel. Computed as:

$$S_{C2} = \left[\frac{n}{\Sigma \frac{1}{\sqrt{S}}}\right]^2$$

in which S is the average slope in each of n (usually 10) equal length increments of the main channel length, L_C, from the basin divide to the outlet. Reported in dimensionless units (Taylor and Schwarz, 1952). Relative standard error of estimate is 5 percent.

7.B.2.c.3. CHANNEL ELEVATION PROFILE
(Recommended symbol, E_{CI})

Elevation above mean sea level of the streambed at various percentages (indicated by I) of the distance along the main channel from the outlet, E_{C0}, to the basin divide, E_{C100}, by 10 percent increments such as E_{C10}, E_{C20}, through E_{C90}, with E_{C85}, for the elevation at the 85 percent point. Units are feet (meters).

7.B.2.c.4. CHANNEL STORAGE
(Recommended symbol, V)

Main channel storage volume for a particular streamflow discharge can be approximated by:

$$V = \frac{a_c L_c}{3}$$, where a_c = average cross-sectional area of stream, and

L_C = main channel length

Units are cubic feet (cubic meters) (Benson, 1964, p. 27). Relative standard error of estimate is in excess of 10 percent.

7.B.2.c.5. MEAN FLOW LENGTH

7.B.2.c.5.a. Index (recommended symbol L_{cai})—The average distance a particle of water must travel to the outlet of the channel. An index of the mean flow length is defined as the distance from the outlet along the main channel to the centroid of the basin. The centroid is determined by the method described in 7.B.2.a.12. Units are miles (kilometers) (Snyder, 1938).

7.B.2.c.5.b. Method one (recommended symbol, L_{cal})—A mean flow index is defined as:

$$L_{cal} = \frac{\Sigma al}{A}$$

Σal is the sum of the product of many subbasin areas (a) and the channel distance (l) from the midpoint of the mainstream serving it, downstream to the basin outlet. A is the total basin area, l is measured in 0.1 mile chords. Units are miles (kilometers) (Langbein, 1947).

7.B.2.c.5.c. Method two (recommended symbol, L_{ca2})—This method consists of constructing a rectangular grid over the basin map, and from each grid intersection, measuring in miles the surface flow distance a particle of water must follow to reach the basin outlet. The mean of the measured flow lengths is the desired index. Units are miles (kilometers) (Busby and Benson, 1960).

7.B.2.c.6. SINUOSITY RATIO
(Recommended symbol, P)

Ratio of main channel length to the basin length:

$$P = \frac{L_C}{L_B}$$

(Leopold and Wolman, 1960; Schumm, 1963; Gregory and Walling, 1973, p. 50).

7.B.2.c.7. SYMMETRY
(Recommended symbol, S_g)

Measured by the deviation of the main channel from a position along the central axis of the basin. The perpendicular distance to the northern and southern basin boundaries is measured at uniformly spaced points along the main channel. Symmetry is computed as the ratio of the average of the larger measurements to the average of the smaller measurements. An index of 1.0 denotes perfect symmetry, and all indexes of nonperfect symmetry are greater than 1.0 (Hadley, 1961).

7.B.2.c.8. CHANNEL PATTERN

The configuration of a river as it would appear from an airplane. Recognized qualitative channel patterns are straight, meandering, and braided. Descriptions are given in most geomorphology texts (Leopold and Wolman, 1957; Brice, 1964; Schumm, 1963).

7.B.2.c.9. SPECIFIC REACH

A length of channel uniform with respect to discharge, depth, area, and slope. At different discharges the observed depth and width reflect the hydraulic characteristics of the channel reach. (Leopold, Wolman, and Miller, 1964, p. 215–270). For characterization purposes, it is recommended that width and depth measurements for the specific reach be taken at bank-full level (stage at which a stream first overflows its natural banks). See 7.B.2.c.9.b. and c.

7.B.2.c.9.a. Depth (recommended symbol, d)—Maximum vertical distance from the lowest riverbank to the bottom of the streambed in a straight reach of channel. Units are feet (meters) (Gregory and Walling, 1973).

7.B.2.c.9.b. Mean depth (recommended symbol, d_m)—The mean of several depth measurements across channel. This measure is also obtained by dividing cross-sectional area by width, which is sometimes referred to as hydraulic depth. Method of measurement described in texts (Gregory and Walling, 1973; Leopold and Maddock, 1953, p. 5). Units are feet (meters).

7.B.2.c.9.c. Top width (recommended symbol, B)—Horizontal distance across channel at top of banks. Measurement method described in text by Gregory and Walling (1973). Units are feet (meters).

7.B.2.c.9.d. Channel cross-sectional area (recommended symbol, a_c)—The product of width and mean depth.

$$a_c = Bd_m$$

Measurement methods are described in the references: Gregory and Walling (1973); Leopold and Maddock (1953); Leopold and Miller (1965).

7.B.2.c.9.e. Channel shape—width/depth ratio (recommended symbol, F)—Ratio of the channel top width to mean depth.

$$F = \frac{B}{d_m} = \frac{B^2}{a_c}$$

(Gregory and Walling, 1973; Leopold, Wolman, and Miller, 1964).

7.B.2.c.10. ROUGHNESS MEASURE

Manning Coefficient (Recommended symbol, n). An empirical coefficient used in the equation proposed in 1889 by Manning to determine velocity as:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} \qquad \text{(English units)}$$

or

$$V = \frac{R^{2/3} S^{1/2}}{n} \qquad \text{(metric units)}$$

in which V is the velocity, R is the hydraulic radius, and S is the slope of the channel in a given reach. In natural channels, without discharge measurements, the determination of n is quite subjective such that errors of measure may exceed 15 percent. Unit is feet$^{1/6}$ (meter$^{1/6}$) (Chow, 1959, p. 98–123; Barnes, 1967).

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7.C. SOILS AND GEOLOGY

7.C.1. INTRODUCTION

Soils act as growing media for plants and as a control for the surface behavior of water and its entry into the terrestrial system. Geologic structure and lithology provide the basic makeup of earth materials and influence the amount, composition, and movement of ground water.

This section deals with the attributes of soils and the lithology and structure of rocks that have been found to be or are believed to be useful in hydrologic analysis of drainage basins. Those characteristics of soils and rocks that are not thought to be directly relevant to hydrologic analyses are not considered here.

7.C.2. SOILS

7.C.2.a. DEFINITION

It is useful to recognize that the meaning of the term "soil" is not necessarily the same to geologists, engineers, and soil scientists. To all of these, the term refers to the upper part or the whole of the regolith. Geologists commonly use the term "soil" to refer to the surficial layer altered by weathering. Thus, for geologists soil might include all or part of the regolith. Civil engineers use the term to refer to that part of the regolith removed in excavation, used for fill materials, or to provide foundations for structures. Thus, to engineers soil generally includes the whole of the regolith. To soil scientists (pedologists), "soil" refers to earth material, commonly one to two meters thick, that supports or is capable of supporting plants, and that has been formed through the interaction of climate, biological activity, and the rock fragments and mineral grains in the upper part of the regolith.

For the purposes of this chapter, "soil" refers to the organized natural bodies as they exist in drainage basins and as they affect the behavior of water. The methods recommended and sources of information cited in this section pertain mainly to the uppermost one or two meters of soil.

7.C.2.b. SOURCES OF INFORMATION

7.C.2.b.1. SOIL SURVEYS

Modern soil surveys published by the U.S. Department of Agriculture contain much information that is useful for hydrologic analysis of drainage basins. Soil surveys having recent publication dates generally contain more quantitative information on soil characteristics than those published earlier. All include soil maps that show the location of different kinds of soils, texts that contain descriptions of the soils, and tables of selected soil properties or qualities. Classification of each kind of soil in a nationwide system of soil classification is also given. Map scales commonly are 1:15,840, 1:20,000, 1:24,000, and 1:31,680.

Modern soil surveys provide information on most or all of the following soil properties and qualities: soil slope, soil drainage class, particle size distribution (and textural class), soil structure, bulk density, permeability (hydraulic conductivity), available water capacity, salinity, alkalinity, acidity, carbonate content, depth to bedrock, depth to seasonally high water table, depth to a layer restrictive to water movement or to roots, shrink-swell potential, soil-erosion factors K and T, and hydrologic soil groups (infiltration rate).

Soil surveys published by the U.S. Department of Agriculture that are still in print can be obtained from the local office of the Soil Conservation Service, from the county agent, or from the Congressman who represents the area. Some State agricultural experiment stations, other State agencies, and private companies also publish soil maps. Many libraries keep published soil surveys on file for reference. Also, soil conservation district offices, agricultural extension offices, and State land grant colleges or universities have copies of local soil surveys that can be used for reference.

7.C.2.b.2. OTHER SOURCES

Information on the availability of soil surveys of particular areas and on properties of particular kinds of soils may be obtained from the soils departments or agronomy departments of land grant colleges or universities, from county extension agents, from local offices of the Soil Conservation Service, the Bureau of Reclamation, Bureau of Land Management, and from national forest headquarters offices.

Standards for the description of soil morphological features, such as soil structure and porosity, are given in the Soil Survey Manual (Soil Survey Staff, 1951) and in Soil Taxonomy (Soil Survey Staff, 1975).

7.C.2.c. METHODS OF SOIL DATA ACQUISITION

Descriptions of many widely used methods for analyzing soils and for measuring soil properties and qualities are in: (1) Methods of Soil Analysis, Agronomy Monograph no. 9 (C. A. Black, ed., 1965), (2) Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples (SCS, 1972b), and (3) Annual Book of ASTM Standards (ASTM, 1978).

Recommended methods for soil water measurements, including soil water content, soil water potential, soil water retention, infiltration of water, and hydraulic conductivity of soil, are identified in Chapter 6 of the handbook (Black, 1965). They are not repeated here.

Recommended methods for determinations other than those for soil water follow.

7.C.2.c.1. PARTICLE SIZE DISTRIBUTION

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U.S. Soil Conservation Service, 1972b, Soil survey laboratory methods and procedures for collecting soil samples: p. 10–13.

7.C.2.c.2. BULK DENSITY

Am. Soc. for Testing and Materials, 1978, Annual book of ASTM standards: part 19. Method D1556-64 (1974), p. 219–222; and Method D2167-66 (1977), p. 279–282.

Blake, G. R., 1965, Bulk density, *in* Methods of soil analysis, part 1, ed. by C. A. Black: Agronomy Monograph no. 9, p. 374–382.
U.S. Soil Conservation Service, 1972b, Soil survey laboratory methods and procedures for collecting soil samples: p. 14–16.

7.C.2.c.3. LINEAR EXTENSIBILITY

Grossman, R. B., and others, 1968, Linear extensibility as calculated from natural-clod bulk density measurements.
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7.C.2.c.4. MINERALOGY

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U.S. Soil Conservation Service, 1972b, Soil survey laboratory methods and procedures for collecting soil samples: p. 51–56.

7.C.2.c.5. ION-EXCHANGE ANALYSIS AND CHEMICAL ANALYSES

Black, C. A., ed., 1965, Methods of soil analysis, part 2: Agronomy Monograph no. 9, p. 771–1572.
U.S. Soil Conservation Service, 1972b, Soil survey laboratory methods and procedures for collecting soil samples.

7.C.2.d. QUANTIFICATION FOR HYDROLOGIC ANALYSES

Because soil surveys were late in becoming available for many areas, the use of soils information in hydrologic analyses has lagged. Modern soil surveys with their wealth of information on soil properties are presently limited in areal extent. This has further inhibited use of soils data in hydrologic studies. So few soil measures have been used in basin studies that there is little point in attempting to standardize methods for quantification. Typically, when properties such as permeability, available water capacity, and depth to bedrock that are quantified in soil survey manuals are used in hydrologic analyses, the values for individual soils are weighted in proportion to the amount of each soil in the watershed.

Hydrologic soil groups, which classify soils according to infiltration characteristics, are used extensively in hydrologic studies. Musgrave (1955) gives infiltration rates (in inches per hour) after prolonged wetting for the four hydrologic groups of soils as follows: A = 0.45 to 0.30; B = 0.30 to 0.15; C = 0.15 to 0.05; and D = 0.05 to 0.00. The hydrologic soil group classification for about 9,500 soil series is given in the SCS National Engineering Handbook, Section 4, Hydrology (SCS, 1972a). Where land cover data are available, the hydrologic soil group and the cover data can be combined to determine a hydrologic curve number (CN). This curve number has been used by the Soil Conservation Service in hydrologic studies (SCS, 1972a) and by others. Standardized methods for determining CN are presented by the Soil Conservation Service (SCS, 1972a and 1975). Additional information on computation of the curve number is presented in Section 7.D.6.

7.C.3. GEOLOGY

7.C.3.a. DEFINITION

Geology emcompases all phases of earth science. However, for purposes of this report the discussion is confined to the relations of lithology and structure to basin hydrology. Other sections of this handbook are directed specifically toward surface water, ground water, and fluvial sediment.

7.C.3.a.1. LITHOLOGY

The description of rocks, including the mineralogic composition and texture, from observing hand specimens or outcrops. For the purpose of this chapter, lithology will be considered as a characteristic that affects the movement and chemical composition of water in the lithosphere or the Earth's crust.

7.C.3.a.2. STRUCTURE

Very few areas are underlain by rocks that have not been affected by deformation, such as folding, faulting, and fracturing, to some degree. Therefore, the movement and storage of ground water is influenced by the rock structure as well as the rock type.

7.C.3.a.3. DEPOSITIONAL FEATURES

In addition to structural deformation, there are features such as unconformities, bedding planes, and facies changes that influence the movement of ground water.

7.C.3.b. ROCK CHARACTERISTICS

In order to describe drainage-basin characteristics as they affect hydrologic processes and relate to the acquisition of water data, a description of the rock underlying the basin must be included. The type of rocks and their physical characteristics will determine the occurrence, storage, and rate and direction of ground-water movement. Geologists have developed several methods for describing rock characteristics; those not relevant to hydrologists will not be considered here.

Rocks are commonly divided into three classes—igneous, sedimentary, and metamorphic. (These classes do not, in themselves, define any hydrologic characteristics.) In addition, there are unconsolidated deposits such as alluvium, colluvium, and aeolian sand that mantle the consolidated rocks over much of the Earth. Their hydrologic characteristics are important in water-resources investigations. Quantitative expression of the hydrologic character of consolidated rocks and unconsolidated sediment is in terms of porosity, permeability, hydraulic conductivity, and other aquifer properties. Hydrologic characteristics related to rock and sediment type are described in detail by Morris and Johnson (1967).

7.C.3.b.1. POROSITY

Porosity of soil or rock material may be defined as follows:

$$\text{Porosity} = \frac{\text{volume of voids in the material}}{\text{total volume of the material}}$$

Porosity is usually expressed as a decimal fraction or as a percentage. For example, a sandstone with a porosity of 25 percent will contain pore spaces or openings equal to one-fourth of the total volume of the rock. The porosity of a sedimentary rock depends largely on: (1) the shape and arrangement of particles, (2) the degree of sorting of particles, (3) the cementation and compaction since deposition, (4) the removal by solution of mineral matter, and (5) the fracturing of the rock that results in joints and other openings (Meinzer, 1923, p. 3). With respect to the movement of water, only systems of interconnected voids are significant (Lohman and others, 1972, p. 10). Laboratory methods for determining porosity are discussed in Chapter 2 in this handbook.

Representative values for porosity of some major rock types and unconsolidated earth materials are summarized in the following table:

Table 1.—*Some average ranges of porosity (compiled from various sources including Meinzer, 1923; Todd, 1959; Waltz, 1971)*

Geologic material	Porosity (percent)		
Unconsolidated:			
clay	45	to	55
silt	40	to	50
alluvial sand	30	to	40
alluvial gravel	25	to	40
Sedimentary rocks:			
shale	3	to	12
siltstone	5	to	20
sandstone	5	to	25
conglomerate	5	to	25
limestone	0.1	to	10
Igneous and metamorphic rocks:			
granite (weathered)	0.001	to	10
granite (fresh)	.00001	to	1
basalt	.001	to	50
slate	.001	to	1
schist	.001	to	1
gneiss	.00001	to	1
tuff	10	to	80

7.C.3.b.2. INTRINSIC PERMEABILITY

Intrinsic permeability is a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is the property of the medium alone and is independent of the nature of the liquid and of the force field causing movement. The property of the medium is dependent upon the shape and size of the pores (Lohman and others, 1972).

7.C.3.c. GEOLOGIC STRUCTURE

7.C.3.c.1. INTRODUCTION

A rock formation is a more-or-less distinct unit that can be mapped. Formations consist of igneous, sedimentary, or metamorphic rocks and unconsolidated deposits of alluvium and

colluvium. Rock formations may be essentially flat lying and undeformed or they may be folded, faulted, and fractured by structural deformation subsequent to deposition and lithification (Billings, 1956). Some of the structural features of rocks that affect the occurrence and movement of water will be discussed briefly.

7.C.3.c.2. STRATIFICATION

Stratification is the result of changes in the physical conditions under which deposition occurred. Successive layers may differ in composition and compaction within formations as well as among formations. Stratification is important in the occurrence and movement of ground water because of variations in porosity and permeability.

7.C.3.c.3. STRUCTURAL DIP OF STRATA

Rock strata are seldom horizontal. Slight dips may be caused by depositional environment or by deformation subsequent to deposition. The movement of ground water is influenced by structural dip, and the measurement of formational dips is an integral part of ground-water investigations. Dips can be measured at rock outcrops or by correlation of well logs.

7.C.3.c.4. FOLDS

Folds are local warping of rocks into structural flexures. These folds may be regular in configuration, irregular and asymmetrical, or dome-like with rocks dipping in all directions from a central, topographic high point.

7.C.3.c.5. FAULTS

A fault is a fracture accompanied by movement between the two segments of a rock formation separated by the fracture. Faults affect the movement of ground water and can either impede or conduct ground-water flow.

7.C.3.c.6. JOINTS AND FRACTURES

A joint is a natural fracture in a rock commonly found in hard, nonplastic rocks, either igneous or sedimentary. Joints and fractures are some of the most important water-bearing and transmitting openings in rock formations.

7.C.3.d. SOURCES OF INFORMATION

7.C.3.d.1. INTRODUCTION

Surface and subsurface geologic and hydrogeologic maps are essential to understanding the processes involved in a basin's hydrologic response. Geologic maps show the location and extent of

mappable rock units and surficial deposits. In addition to this information, hydrogeologic maps describe the occurrence of ground water and show surface-water/ground-water interrelationships. These maps include: (1) location and stratigraphy of major aquifers, (2) areas of recharge, direction of movement, and areas of discharge of ground water, (3) location of water table or potentiometric surface for individual aquifers, and (4) physical characteristics of the unsaturated zone, including thickness and stratigraphy.

7.C.3.d.2. GEOLOGIC MAPS

Geologic maps published by the U.S. Geological Survey and many State geological surveys are useful in planning and conducting hydrologic investigations. The degree of detail and subdivision of rock units is generally controlled by the map scale. Map scales are commonly 1:24,000, 1:31,680, 1:62,500, 1:100,000, and 1:250,000.

Geologic maps published by the U.S. Geological Survey are available from several sources. For maps of areas east of the Mississippi River, including Minnesota, Puerto Rico, and Virgin Islands, order from Branch of Distribution, U.S. Geological Survey, 1200 South Eads Street, Arlington, Va. 22202. For maps of areas west of the Mississippi River including Alaska, Hawaii, Louisiana, Guam, and American Samoa, order from Branch of Distribution, U.S. Geological Survey, Box 25286, Federal Center, Denver, Colo. 80225. (*See* section 7.B.1.c. for additional U.S. Geological Survey addresses.)

Maps published by State geological surveys may usually be obtained from the State Geologist or departments of natural resources.

7.C.3.d.3. HYDROGEOLOGIC MAPS

Hydrogeologic maps are also published by the U.S. Geological Survey and many State geological surveys. However, many maps and other hydrogeologic information are included in Water-Supply Papers and other book reports and are not published as map series. For information on hydrogeologic investigations refer to the catalog, "Publications of the Geological Survey, 1879–1961," its supplement for 1962–1970, and annual supplements since 1970, or contact the appropriate State Geologist or department of natural resources.

7.C.3.e. QUANTIFICATION FOR HYDROLOGIC ANALYSES

As in the case of soil data, lack of geologic maps for enough drainage basins has inhibited the development of quantitative measures for use in hydrologic analyses. There are too few methods available to consider standardization. Typically, when the geology is quantified for use in hydrologic studies, the measures include: porosity as described in section 7.C.3.b.; the percent of a watershed in each of several major categories; indicial measures related to porosity; or surrogate measures, such as the percent of area in sinkholes or rock outcrop areas.

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7.D. LAND USE

7.D.1. INTRODUCTION

The term "land use" as used in this section includes categories of both land use and land cover. Land use refers to "Man's activities on land which are directly related to the land" (Clawson and Stewart, 1965). Land cover describes "the vegetational and artificial constructions covering the land surface" (Burley, 1961).

As a river basin or watershed characteristic, land use generally has received less attention than topography, soils, and geology in modeling and analysis. Lack of readily available land use data of satisfactory precision and reliability has often restricted the use of such data in hydrologic models. Until recently, few hydrologic models included land use as a variable.

Recognition of the important relationship of land use to water quality has recently increased use of such data. Methods for collecting land use data have also improved recently, and it is now possible to compile these data rapidly and efficiently even for relatively large areas.

In this section recommendations are made concerning a land use classification system, general sources of existing data are noted, and methods for acquiring land use data are described. As stated in the chapter's introduction, the emphasis is on recommended methods for collecting data at the meso scale, a range from one to hundreds of square miles. Because the techniques used to compile land use data depend to a large degree upon the data source and the purposes for which these data are to be used, no standards for land use compilation are presented. We believe that adopting the recommended classification system will help standardize compilation techniques for land use data in hydrologic analyses.

7.D.2. A CLASSIFICATION SYSTEM

It is recommended that the Land Use and Land Cover Classification System For Use With Remote Sensor Data, which has been developed by the U.S. Geological Survey (Anderson, and others, 1976), be used as the framework for classifying land use for river-basin planning, research, and management activities (*see* table 2). This classification system is a modification of earlier systems (Anderson, 1971; Anderson and others, 1972). Additional levels of detail may be added to this framework if so desired; however, no attempt is made at this time to recommend category breakdowns for third- or fourth-level mapping.

The United States has already achieved reasonably effective standardization in soil surveys, topographic mapping, weather-information collecting and forest resources inventories. Recent developments in data-processing and remote-sensing technology necessitate coordinating land use inventories for river-basin planning, research, and management, also.

Often, remote sensing is the most efficient and economical means of obtaining land use data. Conventional aerial photographs have been used extensively in basin surveys. Further developments in remote sensing will improve utility of data obtained by this means because remote sensors can record major land use characteristics in correct spatial relationships, thus providing a convenient base for additional inventory and classification on the ground. However, remote sensing may not necessarily provide all the information needed in a typical, small-area survey. Consequently, the design of a classification system should be governed by remote-sensing capabilities, but provision should be made for adding data from other sources.

Table 2.—*U.S. Geological Survey land use and land cover classification system for use with remote sensor data*[1]

Level I	*Level II*	
1 Urban or built-up land	11	Residential
	12	Commercial and services
	13	Industrial
	14	Transportation, communications, and utilities
	15	Industrial and commercial complexes
	16	Mixed urban or built-up land
	17	Other urban or built-up land
2 Agricultural land	21	Cropland and pasture
	22	Orchards, groves, vineyards, nurseries, and ornamental horticultural areas
	23	Confined feeding operations
	24	Other agricultural land
3 Rangeland	31	Herbaceous rangeland
	32	Shrub-brushland rangeland
	33	Mixed rangeland
4 Forest land	41	Deciduous forest land
	42	Evergreen forest land
	43	Mixed forest land
5 Water	51	Streams and canals
	52	Lakes
	53	Reservoirs
	54	Bays and estuaries
6 Wetland	61	Forested wetland
	62	Nonforested wetland
7 Barren land	71	Dry salt flats
	72	Beaches
	73	Sandy areas other than beaches
	74	Bare exposed rock
	75	Strip mines, quarries, and gravel pits
	76	Transitional areas
	77	Mixed barren land
8 Tundra	81	Shrub and brush tundra
	82	Herbaceous tundra
	83	Bare-ground tundra
	84	Wet tundra
	85	Mixed tundra
9 Perennial snow or ice	91	Perennial snowfields
	92	Glaciers

[1] Anderson and others, 1976.

A framework for a national, land use classification system was developed by the U.S. Geological Survey, in consultation with many Federal, State, and local agencies, to meet the needs for an up-to-date overview of land use throughout the country. The framework is uniformly categorized at the more generalized first and second levels, and is receptive to data from satellite- and aircraft-borne remote sensors (Anderson, and others, 1976). The proposed system utilizes features of existing classification systems that are amenable to data derived from remote-sensing sources. The system is open-ended so that Federal, regional, State, and local agencies can develop more detailed land use categorization at the third and fourth levels to meet their particular needs, and at the same time remain compatible with the national system. Also, while it is generally appropriate for level III and IV mapping to be at 1:24,000 scale or larger, it might also be appropriate to use level II detail for large-scale mapping.

7.D.3. MAJOR SOURCES OF EXISTING DATA

Until recently land use data for extensive areas of the United States were available only in tabular form on a county-wide basis. Data sources include the agricultural censuses conducted every 5 years (1969, 1974, etc.) by the U.S. Bureau of the Census, and the conservation-needs inventories and forest surveys by the U.S. Department of Agriculture. The agricultural census data are collected by enumeration surveys; the conservation-needs and forest inventories use sampling procedures. Maps for land use generally have not been available. The most recent *Census of Agriculture* is available from the:

Superintendent of Documents
U.S. Government Printing Office
Washington, D.C. 20402

or

any U.S. Department of Commerce
district office.

Preceding censuses as well as the most recent are usually on file at Government depositories, such as State university libraries, throughout the country.

The conservation-needs inventory data are stored for computer retrieval at:

Statistical Laboratory
Iowa State University
Ames, Iowa 50010.

Tape copies of the data can be purchased from the laboratory. Forest inventory data are available from regional experiment stations of the U.S. Forest Service.

Topographic maps have been used to obtain land use information. Such information is usually limited to the extent of an area in forest, open, and urban land use. Measurements of these areas can be obtained using methods discussed in section 7.D.4.

Because land use maps and derived statistical data did not exist for the Nation, the U.S. Geological Survey began a program of land use and land cover mapping for the entire country in 1975. The Geological Survey is mapping land use from remotely sensed sources using high-altitude,

color-infrared photography wherever possible. Current plans call for the initial mapping phase to be completed by 1982, with updates starting in 1979 to show changes in land use. The first areas being mapped are coastal areas, areas with energy resources available for development, areas that are undergoing urbanization, and States which have entered into cooperative, cost-sharing agreements with U.S. Geological Survey for land use mapping. Approximately 30 percent (1 million square miles) of the United States has been mapped as of October 1977. The maps are available for purchase from the U.S. Geological Survey.

Land use categories that are being used are those set forth in "A Land Use and Land Cover Classification System for Use with Remote Sensor Data," U.S. Geological Survey Professional Paper 964, 1976 (*see* table 2, 7.D.2.).

A minimum mapping unit of 10 acres is being used for the following categories: all urban or built-up areas; all water areas except where linearity is a characteristic feature such as canals and streams; confined feeding operations; other agricultural land; strip mines, quarries, and gravel pits; and urban or built-up occurrences of transitional land. For all other categories the minimum mapping unit is 40 acres. Individual polygons of land use categories are delineated on 1:250,000-scale topographic maps. In order to make the land use maps more useful, associated maps showing political units, hydrologic units, areas of Federal land ownership, and census county subdivisions are also being prepared. The new 1:100,000-scale base maps will be used instead of the 1:250,000-scale maps as they become available. Updates also will be made on the 1:100,000 base. Information on ordering all U.S. Geological Survey map products may be obtained from the:

National Cartographic Information Center
U.S. Geological Survey, Mail Stop 507
12201 Sunrise Valley Drive
Reston, Va. 22092.

Technical information concerning land use mapping may be obtained from the:

Chief, Geography Program
U.S. Geological Survey, Mail Stop 710
12201 Sunrise Valley Drive
Reston, Va. 22092.

7.D.4. METHODS OF DATA ACQUISITION

When no suitable land use maps and data exist for an area, it is recommended that careful evaluation of the problem precede acquisition. Procedures for preparing land use maps from which statistical data can be obtained will depend on the detail desired and the accuracy of categorization, the size of the area to be mapped, map scale, time available for data gathering, and the manpower and finances available. Again, it is recommend that the U.S. Geological Survey land use and land cover classification be used as a framework even if more detail is needed at the third and fourth levels. For watersheds of less than 10 square miles, field mapping may also be necessary to determine such factors as sewered areas, curbs, gutters, and lot sizes; however, using aerial photographs will greatly expedite such mapping. For more extensive areas, a combination of remote sensing and field mapping is appropriate depending on the detail desired, time, personnel, and funds. Sampling procedures may also be acceptable for data collection.

7.D.4.a. SAMPLING

If resources are not adequate for obtaining land use data on a 100-percent basis, then sampling techniques may be helpful. Sampling techniques will not be discussed here because many statistics textbooks cover this topic adequately. Once the sample areas are selected, land use data can be obtained by field studies or by remotely sensed data.

7.D.4.b. FIELD MAPPING

Prior to beginning field mapping, a plotting base should be selected. This base can be a planimetric map, a topographic map, or aerial photographs. Aerial photographs are commonly used as bases because the photograph itself contains much information about the condition of the Earth's surface. On this base, areas with the same land use are outlined and labeled. Some land use boundary lines are quite simple to delineate; others are more difficult. Experience in reading maps and in photointerpretation is necessary for accurate delineation. Labeling cover types also requires some experience in agronomy or forestry.

Field mapping performed on good base maps by highly skilled personnel is the most accurate method for organizing and showing land use data. Mapping can be scheduled to be kept as up-to-date as the field work. Time, money, and other limitations may make it necessary to accept a combination of acquisition methods, including sampling.

7.D.4.c. DATA COLLECTION AND COMPILATION USING REMOTE SENSORS

Many researchers have long realized the advantages of obtaining land use data by remote sensing. Some of these advantages include rapid data collection, detection of phenomena not readily visible in field surveys, synoptic observation of large areas, and relatively low costs of data collection as compared to costs for ground observation. Remotely sensed data used to determine land use include conventional large-scale black-and-white aerial photographs (1:10,000, 1:20,000, 1:40,000 have been commonly used scales), high-altitude (1:60,000 to 1:120,000) color-infrared photographs, and Landsat multispectral imagery.

Because of its good resolution, one of the most useful remotely sensed images is the high-altitude color-infrared photograph. Some land use differences are enhanced in the infrared portion of the spectrum. Unfortunately, such photographs are not available for the entire United States. The more conventional large-scale, black-and-white photographs are widely available.

Significant advances are also being made in land use compilation using Landsat multispectral images. Until recently, interpretation had to be done from the image itself. However, research indicates that computer-compatible tapes (CCT) from Landsat I and/or II, which are digital records of the spectral response for each pixel (picture element, approximately 1.1 acre in size), can be used for automatic interpretation with an interactive computer system. In other words, computers can be programed to make interpretations based on classifications of various spectral responses and thus to produce a land use map.

Remotely sensed data are available from numerous sources. The National Cartographic Information Center (NCIC) is a focal point for collecting and distributing cartographic data and

information. NCIC's primary role is to supply information on what cartographic and photographic data are available. NCIC maintains records of aerial photographs and satellite imagery of the United States and its territories based on reports from Federal, State, and local agencies and from commerical companies. Prospective purchasers of remotely sensed data should designate the extent of coverage desired, either by supplying a map or by supplying latitude and longitude coordinates. Type of film, size, and other pertinent data should be specified if possible. For further information contact:

National Cartographic Information Center
U.S. Geological Survey
Mail Stop 507, National Center
Reston, Va. 22092
Telephone: (703) 860–6187.

The EROS Data Center (EDC) in Sioux Falls, S. Dak., maintains an extensive archive of aerial and space photographs, processes and distributes photographic and digital products, and provides extensive user training and technical assistance in using remotely sensed data. EDC's archive is a major component of NCIC.

To place an order, to inquire about the availability of data, or to establish a standing order with EDC contact:

User Services Unit
EROS Data Center
Sioux Falls, S. Dak. 57198
Telephone: (605) 594–6511, ext. 151.

For Agricultural Stabilization and Conservation Service (ASCS) aerial photographs (large-scale, black-and-white aerial photographs), write:

Aerial Photography Division
SEA/CS, USDA
2505 Parleys's Way
Salt Lake City, Utah 84109.

Several manuals are available to assist in acquiring land-use information from remotely sensed data (Weidel and Kleckner, 1974; Reeves, 1975; Avery, 1977). Some general recommended guidelines are given here:

1. For interpreted land use, a plotting base can be a map, a rectified aerial photograph, or a photomosaic. These can all be used as positional guides for compiling land use. The plotting base should be highly accurate. Some of the better plotting bases for large-scale work include 1:24,000-scale topographic quadrangles and orthophotoquads. The new series of U.S. Geological Survey 1:100,000-scale topographic maps (as they are completed) and the 1:250,000-scale maps sold by U.S. Geological Survey can be used for intermediate- and small-scale mapping.

2. Because of the size of the area and the plotting base it is usually not possible to map every discrete land use complex. Selecting a suitable minimum area or size of area to be mapped

will alleviate problems caused by resolution loss. A minimum-area measure is the dimension of any land use category that can be appropriately mapped at a specified scale. A land use category occupying a smaller unit area of the map would not be mapped as a distinct land use category, but would be merged with an adjacent category in the most logical manner possible. Thus the time-consuming problem of interpreting small areas is eased considerably.

Continuity must be maintained in using a minimum-area recording unit. The most important factor in determining minimum size is the size of the polygon that can be mapped and coded. Anything smaller than a 2- x 2-mm square is difficult to outline and code on a map.

3. Supplemental data can be used if interpretation of a particular land use complex is impossible using remotely sensed data alone. This material may include large-scale aerial photographs, multispectral imagery, and topographic, county highway, or other maps. Landsat imagery, both in film and computer-compatible tape (CCT) format, can also be used as a supplemental source for land use mapping. There are some potential uses of Landsat CCT capabilities for identifying particular land cover types where interactive computer capability is available for analyzing the CCTs. Specially trained computer operators are required to interact with sophisticated programs and equipment used to interpret the CCT. Access to this system, however, is now limited for most users because of scarcity of equipment and trained operators.

   Recent research indicates at least three aspects of Landsat CCT capabilities that may contribute to land use mapping and data compilation. Landsat data can augment mapping and data compiled from higher resolution source material by providing data at frequent intervals during the year, thus complementing data sources that are only available at one time of the year. Landsat imagery differentiates between deciduous, coniferous, and mixed forest types. Consequently, forested wetlands can be distinguished from other forested areas, and areas of perennial snow and ice can also be detected.

   Landsat can also be used to monitor transitional land uses (disturbed land). For example, construction activity and strip mining may be sources of high sediment yield or have other hydrologic impacts. These activities have been identified fairly easily from Landsat data.

   Additionally, Landsat can be used to identify areas where land use is changing in order to select areas that need to be updated using higher resolution source materials. For example, areas of urban expansion, mining activity or frequent flooding can be identified and scheduled for map revision based on the rate of change.

4. All maps prepared from remotely sensed source material should be field checked to assure accuracy and reliability. Those areas where the land use could not be identified must be examined and a sample of all land use categories that have been interpreted must be verified. The maps should be field checked only after they have been thoroughly edited.

5. No matter what scale or resolution is used to map land use with remotely sensed source materials, there is always a question of accuracy. At this time there has been no research on the accuracy of land use data needed for hydrologic models. Accuracy in areal delineation, interpretation of land use, and position must be considered, however, when mapping land use with remotely sensed data.

   The compilation scale will have some effect. When photographic source materials are used, the delineation should be as precise as the scale will allow.

   Field checking or field validation techniques and processes establish interpretation accuracy. When qualified interpreters are used, an accuracy of 85 percent or better can be achieved at reasonable cost.

The larger the scale, generally, the better the positional accuracy. Recitified photomosaics and large-scale topographic quadrangles have very good positional accuracy.

Two manual techniques that have proved most successful and accurate for determining the area in various land use categories are planimeters, including electronic models, and the dot grid. The planimeter is best for measuring larger areas such as drainage basins. The dot grid is easier to use when measuring smaller areas such as land use polygons.

Area measurements can also be obtained by more sophisticated and expensive semiautomated or fully automated computer techniques. Unless a computerized information system is to be used for extensive data manipulation, it is generally not worthwhile to use automated techniques to generate area measurements.

7.D.5. PROBLEMS IN USING LAND USE MAPS

Errors are often made when map and statistical data are inadvertently used for purposes other than those for which the data were compiled. It is important for users to understand the purposes for collecting the data, the compilation procedures used, and the analytical methods used for a particular set of data. The limitations of the data must be identified in order that they be used properly.

Several common errors occur when using land use maps. For example, there can be a problem of defining land use according to the classifications. Confusion may exist about what types of uses are included in certain categories; land use categories may be incompatible. Small-scale, land use maps, particularly those at scales about 1:500,000, often look more accurate than they are. Positional accuracy of features could be for less than the user assumes. One of the biggest problems is combining or comparing maps that are compiled under different procedures and from different sources. For example, land use maps prepared at the same scale will not have the same accuracy if different minimum mapping units were used for each map. And finally, these maps represent land use only at the time the map data were collected. Measures taken from current land use maps may be inappropriate; for example, if used in hydrologic analyses involving historic data.

It is difficult to explain how to use a land-use map correctly. Certain characteristics must be understood before using these maps: the classification system used; the types of uses that are included in each category; the degree of detail in each classification; the minimum mapping unit used; how the map was compiled; the source materials used; the age of the source materials; and the compilation scale. If remotely sensed data are used, it is necessary to determine if the map was field checked. Don't use data that is not suited to the particular needs and design of your project.

7.D.6. QUANTIFICATION FOR HYDROLOGIC ANALYSES

At this time, no specific recommendations can be made about quantifying land use data for hydrologic studies. Relatively little refined use of quantified data has yet been included in hydrologic models. The percentage of total area occupied by generalized land use categories is about all that has been incorporated into models.

The Soil Conservation Service has developed curve numbers (CN) representing the relationships between land use and soil permeability. The curve number is an index of the runoff that will occur from a storm rainfall event. Detailed information on the use of this basin characteristic and how it is

Table 3.—*Runoff curve numbers for selected agricultural, suburban, and urban land use. (Antecedent moisture condition II, and $I_a = 0.2S$)*

Land use description		Hydrologic soil group			
		A	B	C	D
Cultivated land[1]:					
without conservation treatment		72	81	88	91
with conservation treatment		62	71	78	81
Pasture or range land:					
poor condition		68	79	86	89
good condition		39	61	74	80
Meadow:					
good condition		30	58	71	78
Wood or forest land:					
thin stand, poor cover, no mulch		45	66	77	83
good cover[2]		25	55	70	77
Open spaces, lawns, parks, golf courses, etc.					
good condition: grass cover on 75% or more of the area		39	61	74	80
fair condition: grass cover on 50% to 75% of the area		49	69	79	84
Commercial and business area (85% impervious)		89	92	94	95
Industrial districts (72% impervious)		81	88	91	93
Residential:[3]					
Average lot size	Average percent impervious[4]				
1/8 acre or less	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
Paved parking lots, roofs, driveways, etc.[5]		98	98	98	98
Streets and roads:					
paved with curbs and storm sewers[5]		98	98	98	98
gravel		76	85	89	91
dirt		72	82	87	89

[1] For a more detailed description of agricultural land use curve numbers refer to National Engineering Handbook, Section 4, Hydrology, Chapter 9, Aug. 1972.

[2] Good cover is protected from grazing and litter and brush cover soil.

[3] Curve numbers are computed assuming the runoff from the house and driveway is directed towards the street with a minimum of roof water directed to lawns where additional infiltration could occur.

[4] The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

[5] In some warmer climates of the country a curve number of 95 may be used.

determined for a watershed can be found in U.S. Soil Conservation Service (1972). Table 3 (taken from SCS, 1975) shows the CN values associated with a range of land use hydrologic soil-group conditions. Because CN quantifies the land use/soil complex in a single number, it has been used by others in a variety of hydrologic studies.

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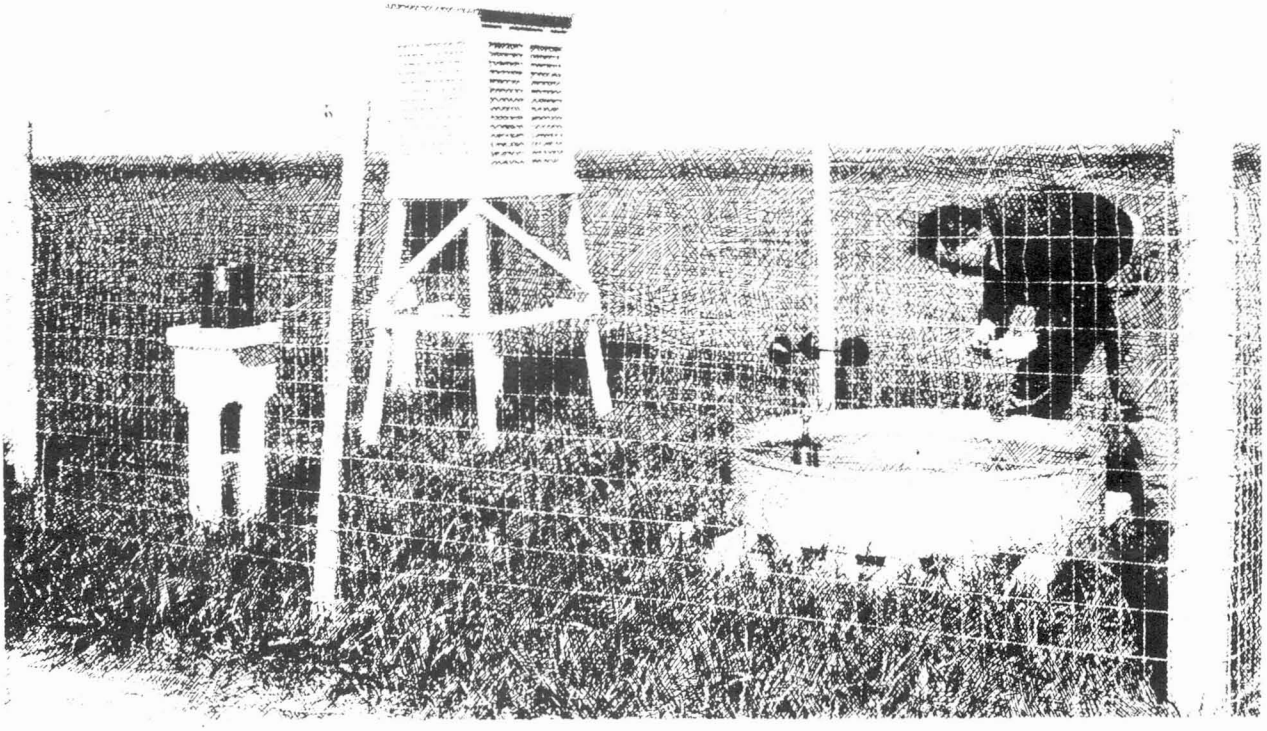
Chapter 8

Evaporation and Transpiration



CHAPTER 8—EVAPORATION AND TRANSPIRATION

Prepared by
Work Group 8 on Evaporation and Transpiration
June 1982

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COMMENTS ON CHAPTER 8

National Handbook of Recommended Methods for Water-Data Acquisition

I found this "National Handbook" chapter to be useful. Comments:

_____

_____

_____

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Method _____

Reference _____

The method is unsatisfactory for the following reason(s): _____

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Thank you for submitting your views on Chapter 8 of the "National Handbook." Your comments will be considered in revising the "National Handbook" to benefit all users. Please mail this form to:

Office of Water Data Coordination
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CHAPTER 8—EVAPORATION AND TRANSPIRATION

8.A. INTRODUCTION

8.A.1. RELATION OF CHAPTER 8 TO OVERALL MISSION OF THE NATIONAL HANDBOOK OF RECOMMENDED METHODS

Methods of measuring evaporation vary widely, and in keeping with the purpose and goal of the *National Handbook of Recommended Methods for Water Data Acquisition,* this chapter is a collection and documentation of various methods of measuring and collecting evaporation data.

8.A.2. SCOPE OF CHAPTER 8

As stated by Tanner (1968), the term evaporation is concerned primarily with the transport of water vapor from the source of vaporization into the atmosphere and not with the state of water and flow of water to the source. Within the scope of water data acquisition, the term evaporation means many things to many different people. From this diversity arise many different techniques of measurement. The diversity is largely due to differences in the "source of vaporization" as stated above. For example, the hydrologist may be concerned with evaporation from a large lake or with evaporation values that can be applied to a river basin. In contrast, the agronomist or irrigation engineer may be concerned with the evaporation from a field crop, while a plant physiologist may be concerned with the evaporation of water from a single plant leaf or pine needle. In preparing a document to describe methods of measuring evaporation, an attempt was made to cover methods for this wide range in application. In many cases there are several techniques even within a narrow discipline, and the attempt has been to document the various approaches and give the reader enough information and references to enable him to choose the method most suitable for his particular application. In cases where comparability of data from different locations is desired, standardized techniques, approaches, and instrumentation are specified. Because of the wide diversity of methods and applications, the designation of a *best* method cannot be made. Underlying this spectrum of application, however, the basic principle is that evaporation is a physical process of gaseous exchange that requires an energy input and a means of effecting the exchange, or removal of the vapor from the surface. Since the variation in methods of measurement arises largely from the source of vaporization or the surface from which gaseous exchange occurs, the chapter is divided into sections that describe methods and variations of methods for measuring evaporation from various types of surfaces within the scope of land, water, and vegetation.

8.A.3. TERMINOLOGY

The vaporization of water from different sources has led to some confusion in terminology. The term **evaporation** is used as a collective term to describe the process without specifying the surface involved. **Transpiration** is used to designate the vaporization of water from plant surfaces and is also used in designating a quantity of water moving through the plant and being vaporized and exchanged from plant tissue. Where the land surface is composed of both vegetative cover and bare soil the two terms are lumped and treated singularly as **evapotranspiration.** In some disciplines the term evaporation is used to designate vapor loss from bare soil surfaces. Some caution in reviewing the literature is warranted because often the terms evaporation, transpiration, and evapotranspiration are used interchangeably and the surface of vaporization should be determined and specified for clarity.

8.A.4. CHAPTER OUTLINE

In this chapter, the differences in methodology are subdivided according to the type of surface. Evaporation from free water surfaces is discussed first, followed by a special application to bare soil

surfaces. Water vapor loss from a combination of soil and vegetation—evapotranspiration—is discussed next, followed by brief discussions of techniques specifically for measuring transpiration and for measuring soil surface evaporation under vegetative canopies. Within each section there are some discussions as to scale, that is, a range, for example, from single leaf to single plant, to field, to watershed, to river basin, to region, and so on, with documentation that should enable the reader to find information on techniques that might be used for his specific application. References appear after each section rather than in a single listing at the end of the chapter.

8.A.5. REFERENCE

Tanner, C. B., 1968, Evaporation of water from plants and soil, *in* Kozlowski, T. T., ed., Water deficits and plant growth, v. 1: New York, Academic Press, p. 73–106.

8.B. EVAPORATION MEASUREMENT METHODS

8.B.1. INTRODUCTION

8.B.1.a. STATE OF THE ART

This section presents a summary of current and proposed methods for measuring evaporation from bodies of water, including important references in the area of evaporation measurement.

8.B.1.b. DIRECT MEASUREMENT OF EVAPORATION

Direct measurement of evaporation, that is, measurement of the flow of moisture-laden air away from a lake or reservoir, is not sufficiently accurate with the equipment currently available to be of much practical value. The next most direct method is the **water-budget method,** in which evaporation is computed as the difference between inflow and outflow, allowing for changes in the amount of water stored in the lake. Unfortunately, this method can be applied only rarely because data are seldom available, and, even when they are, normal errors in measuring inflow and outflow (including ground-water flow) cast doubt on the accuracy of measurement of the residual, which is the evaporation figure sought.

8.B.1.c. THE ENERGY-BUDGET METHOD

The **energy-budget method** is similar to the water-budget method, except that all incoming and outgoing radiant energy, both long- and short-wave, is accounted for. The difference between the incoming and outgoing energy, allowing for changes in the amount of energy stored in the lake, is the amount of energy contributing to evaporation, which is then computed from the known latent heat of evaporation of water. The equipment required for this method is expensive and processing the data is time-consuming, so the method is ordinarily not used unless the need for the information is deemed to warrant the cost.

8.B.1.d. PAN METHODS

In more common use in the United States than the foregoing methods is the **class A pan,** which has been operated by the National Weather Service (NWS) for many years. Records are available for many stations.

A new international standard pan is being tested in the United States, the U.S.S.R., India, Hungary, and Uganda against a 20 m^2 tank. If universally adopted, this pan would make possible direct comparison of data from all over the world. This pan, however, may be too expensive for widespread use.

8.B.1.e. REMOTE-SENSING METHODS

Remote sensing, the newest method for estimating evaporation, uses data collected by earth-scanning satellites. Although it is especially promising for surveillance of large areas where frequent readings are required, the application methods are not yet fully developed.

8.B.1.f. THE IFYGL STUDY

Important new information on lake hydrology, and on evaporation in particular, was collected during the International Field Year for the Great Lakes (IFYGL), a joint study by Canada and the United States. Many government agencies in each country participated in the enormous project, which covered evaporation as well as many other aspects of lake hydrology, limnology, and meteorology.

Data acquisition equipment and methods were the most modern available, as were data processing and analytical methods. References to some of the reports published in both countries are given in IFYGL Bulletin No. 12 (October 1974).

Nearly all the field observations were completed in March 1973. Most large libraries have the published reports of IFYGL. For information in the United States, write

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Great Lakes Environmental Research Laboratory
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8.B.2. BUDGET METHODS

8.B.2.a. WATER-BUDGET METHOD

The water-budget method may be used to measure evaporation indirectly in drainage basins, reservoirs, and lakes. According to Horton (1943), the water-budget continuity equation may be written in the general form

$$E = I - O - S$$

where E = evaporation
I = inflow
O = outflow
S = change in storage

In practice, the residual from the algebraic summation of all significant hydrologic components measured during a given time interval gives a direct measure of the evaporation for that time interval. Expanding the equation,

$$E = I + P - O_g - O - (S_0 - S_1)$$

where P = precipitation
O_g = net seepage outflow
S_0 = storage at beginning of period
S_1 = storage at end of period.

The significance of each component depends on the hydrologic characteristics of the reservoir and the interval of time for which the evaporation is evaluated. For some reservoirs, some of the components are nonexistent or insignificant in size. In most instances, however, the precision required in the measurement of each component is difficult to attain. An excellent summary of the water-budget components, and an example of their relative importance, has been given by Harbeck and Kennon (1954).

8.B.2.a.1. ADVANTAGES

1. Evaporation can be determined without knowing such meteorological variables as windspeed, atmospheric pressure, water temperature, solar and atmospheric radiation, vapor pressure, and air temperature.
2. The method works well in cases where large amounts of accurate data on stream gaging, reservoir stage, precipitation, and seepage have been assembled. Seepage, the most difficult parameter to measure, can be ignored in reservoirs or lakes with relatively impermeable confining beds.

8.B.2.a.2. DISADVANTAGES

1. All sources of inflow and outflow, including ground-water inflow and agricultural and municipal withdrawals, must be considered when using the water-budget method. Large errors in the evaporation computation may result if the flows are large in relation to the amount of evaporation. Stream-gaging records with an accuracy of 95 percent or better are usually necessary for use with this method. Even this accuracy in stream-gaging records may not be sufficient if the inflow to the reservoir is large in comparison with the amount of evaporation.
2. Determination of seepage requires a study of the confining bed to relate stage to hydraulic conductivity. The water-budget method can be used on a continuous basis if a stage-seepage relationship can be established. However, it is often impossible to define the stage-seepage relationship accurately enough to compute accurate evaporation rates.
3. An adequate gaging network is needed to determine precipitation. Rainfall at a point can be readily measured, but it is difficult to determine the areal distribution or average. The actual water content of snow added to a lake or reservoir is also difficult to determine.
4. Computation of storage change requires stage records and an accurate area-capacity curve for the lake or reservoir. Several measurement stations may be required to provide a suitable average stage for the area. Large errors caused by wind-generated waves may affect the stage computation. If precise results are needed thermal expansion of the water in the reservoir must be considered (Harbeck and Kennon, 1954; Linsley and others, 1975). The amount of water stored in ice is difficult to evaluate, causing further complications. The bank storage component may contribute additional errors if the water-budget method is used over short time periods (less than one month). The bank storage effect can be excluded when computing on an annual basis unless large annual changes in stage occur.

8.B.2.b. ENERGY-BUDGET METHOD

The energy-budget method is rigorously correct in theory, and has been used at many of the larger reservoirs in the United States. Energy-budget field observations have usually been made for a period of 12 to 18 months, using a total hemispherical radiometer to measure net incoming radiation; psychrometric equipment to measure temperature and humidity; an instrument to record water-surface temperature; and an anemometer to measure windspeed, usually at the 2-m level. At predetermined intervals (often of 1 month), a thermal survey of the lake is made to measure the variation of water temperature with depth at 25 or more selected points, in both deep and shallow water. These data are used to compute the amount of energy stored in the lake, so that the change in amounts of energy stored from one thermal survey to another can be determined. The energy-budget method of estimating evaporation is based on a balance of incoming, outgoing, and storage energy terms. Energy budget studies are discussed at length by Anderson (1954). This balance is expressed by

$$Q_s - Q_r - Q_b - Q_h - Q_e + Q_v = Q_{ST} \qquad (1)$$

in which Q_s = energy in solar radiation incident on the water surface
Q_r = energy of the solar radiation that is reflected at the water surface
Q_b = the net energy exchange in long-wave transfer
Q_h = the energy exchanged from the water to the atmosphere as sensible heat
Q_e = the energy lost from the water by evaporation
Q_v = the net energy advected onto the reservoir by water flow into or out of the system
Q_{ST} = the change in energy stored in the water body

Q_b can further be written

$$Q_b = Q_{lw} - Q_{lwr} - Q_{br}$$

in which Q_{lw} = the incident energy in long-wave or atmospheric radiation
Q_{lwr} = the long-wave energy reflected at the water surface
Q_{br} = the energy radiated from the water surface.

8.B.2.b.1. USUAL ASSUMPTIONS

$$Q_{lwr} = 0.03\ Q_{lw} \qquad (2)$$
$$Q_r = 0.06\ Q_s$$

The value of Q_r may be quite different than assumed for short time periods. Water radiates as a gray body with an emissivity of 0.97.

We assume that sensible heat processes are similar to evaporation processes and that the ratio Q_h / Q_e (known as the Bowen ratio, B) can be computed from measurements of air and water-surface temperature and the humidity of the air. Thus, if $Q_h / Q_e = B$, then $Q_h = BQ_e$.

8.B.2.b.2. ESTIMATING EVAPORATION

Using the definitions and assumptions previously stated, evaporation is estimated by

$$E = \frac{0.94Q_s + 0.97Q_{lw} - Q_{br} + Q_v - Q_{ST}}{LH\ (1 + B)} \qquad (3)$$

where LH is the latent heat of evaporation in energy per unit depth.

8.B.2.b.3. REQUIRED MEASUREMENTS

Measurements must be made of incoming radiation (both long- and short-wave), air temperature, dewpoint or similar humidity measurement, and change in heat storage. Solar radiation measurements are treated in chapter 10 of this handbook.

Long-wave radiation can be measured, and also, in many cases, can be almost as accurately estimated from other measurements. One method for such an estimation is described by Anderson and Baker (1967); another is the method proposed by Koberg (1964).

Measurement devices for long-wave radiation are limited to all-wave radiometers covered by short-wave filters, such as the Eppley Long-Wave Radiometer. The filters tend to weather with time and are made of a toxic material that requires special care in cleaning.

Many investigators estimate long-wave radiation by measuring all-wave and short-wave radiation and taking the difference between them. The major drawback of this method is that it incorporates errors from both radiometers. The difficulty in handling these errors gave impetus to the development of estimation techniques such as those of Anderson and Baker.

Water-surface temperatures, air temperatures, and dewpoints for the observation period are required input to the energy budget.

Water-surface temperature in lakes can be measured with a thermocouple encased in a thin, waterproof cover supported by a float so the thermocouple samples water within 1 to 2 inches of the water surface (Anderson, 1954).

Mean air temperature is most simply estimated by measuring the maximum and minimum temperatures in a standard shelter and using the arithmetic mean as the representative temperature for the period. For more details see National Weather Service (NWS, 1972, p. 1-16).

Dewpoints can be conveniently measured with dew cell recorders, or can be computed from hygrothermograph records or sling psychrometer data. These measurements are discussed in chapter 10 of this handbook.

Determining the change in heat storage requires bathymetric measurement, which is beyond the scope of this manual, but descriptions can be found in standard textbooks on this subject.

8.B.2.b.4. LIMITATIONS

Errors in measurement of the energy storage term cause high fluctuations in evaporation estimates for short periods. For an energy-budget period of a week or longer, the accuracy of this method begins to compare favorably with other methods (Anderson, 1954).

Radiation instruments are subject to shifts which require frequent calibrations to avoid bias or random error in the measurements.

8.B.2.b.5. VARIATIONS

The method of estimating free water evaporation preferred by the Hydrologic Research Laboratory of the National Weather Service is a modified energy budget, which uses the insulated pan to determine incident minus reflected radiation. This method was originally developed by Cummings (1940) and later modified by Kohler and Parmele (1967).

This incident-minus-reflected radiation (Q_{iR}) is given in terms of equation (1) by

$$Q_{iR} = Q_e + Q_h - Q_\nu + Q_{ST} + Q_b$$

where Q_ν is now heat exchange through the side of the pan, which, in an insulated pan, is ~0. With the assumption that $Q_h = BQ_e$, Q_{iR} can be written

$$Q_{iR} = Q_e\,(1 + B) + Q_{ST} + Q_{br}\,. \tag{4}$$

In terms of Q_{iR}, evaporation is estimated by

$$E_{fw} = \frac{[Q_{iR} - \varepsilon\sigma T_a^4]\Delta + E_a[\gamma + 4\varepsilon\sigma T_a^3/f(u)]}{\Delta + [\gamma + 4\delta\sigma T_a^3/f(u)]} \tag{5}$$

in which E_{fw} = the free water evaporation or the evaporation which would occur in a very shallow water body

ε = the emissivity of the water

σ = the Stefan-Boltzmann constant

T_a = the pan water surface temperature in °K

E_a = the evaporation estimated from the mass-transfer equation $E_a = f(u)\,(e_o - e_s)$, assuming that the water surface temperature T_s is represented by the air temperature T_a

$f(u) = a + bu$ or regression constants for wind movement 2 m above the ground

Δ = the slope of the saturation vapor pressure-versus-temperature curve at the air temperature

γ = the psychrometric constant appearing in Bowen's ratio equation $B = (T_o - T_a)/(e_o - e_a)$, where e_o is the water vapor pressure at T_o and e_a is the atmospheric water vapor pressure.

Eq 5 requires the following daily measurements from the insulated evaporation pan:

Maximum pan water surface temperature (TWMX)
Minimum water surface temperature (TWMN)
Daily evaporation from pan (see pan evaporation section) (EO)
Pan water temperature at observation time (after stirring pan) (TWOB).

The reading of observation-time temperature is taken to determine the change in heat storage. This reading is taken after the readings for maximum and minimum surface water temperature have been taken. Because energy exchange at the surface depends on these temperatures, it is important that they be taken before the pan is stirred.

After the maximum and minimum temperatures are read, the pan can be stirred with a rod with a disk on the bottom end to bring the water to a uniform temperature. Three or four up and down strokes have been found to be sufficient. They should be slow enough that no splashing occurs.

After stirring, the observed temperature can be read either from a thermometer hanging down into the pan or from the maximum temperature thermometer. Change in heat storage requires that the observed water temperature be measured both at the beginning and ending of the period; that is, the temperature must be measured on the day that the pan is filled and operations begin.

8.B.2.b.6. OTHER MEASUREMENTS

In addition to the evaporation pan measurements, several environmental measurements are required:

Maximum air temperature (TAMX)
Minimum air temperature (TAMN)
Dewpoints—preferably at least four (TDP(J)J = 1,4) per day spaced at equal time intervals.

NOTE:
Dewpoints can be derived from wet-bulb/dry-bulb measurements or relative humidity and temperatures using standard tables such as Smithsonian meteorological tables. These data are averaged to get the daily mean dewpoint (TDPAV).

Wind movement at 1 m (WND), or
Wind movement at 2 m (WND2) or 4 m above the ground (WND4)
Station pressure corresponding to station altitude (PA).

Daily precipitation must be known to determine daily evaporation from the pan (EO). Practical use of the modified energy budget can be most easily presented in terms of lines of FORTRAN coding.

```
C   AVERAGE AIR TEMP
    TAA=(TAMX+TAMN) /2.0
C    AVERAGE WATER TEMP
    TWA+(TWMX+TWMN) /2.0
C   CONVERT TEMP TO DEGREES CELSIUS
    TAC=0.5555*(TAA-32.0)
    TWC=0.555*(TAA-32.0)
    TWOC=0.5555*(TWOB-32.0)
    TDPC=0.555*(TDPAW-32.0)
C   COMPUTE VAPOR PRESSURE AT WATER SURFACE
    EWT=8.1175E6*DEXP(-7701.544/(TAA+405.0265))
C   COMPUTE VAPOR PRESSURE IN AIR
    EDP=8.1175E6*DEXP(-7701.544/(TDA405.0265))
C   COMPUTE GAMMA
    GAMMA=0.000367*PA
    B=GAMMA*(TWA-TAA)/(EWT-EDP)
C   COMPUTE LATENT HEAT
C   ALH=579.3-(0.56*TWC)
C   COMPUTE FIRST TERM IN EQUATION (4)
C   EO MUST BE CONVERTED TO CM. IT IS OBSERVED
C   ON INSULATED PAN IN MM.
    QEH=0.1*EO*ALH*(1+B)
C   COMPUTE BACK RADIATION
    QB=0.97*11.71E-8*(TWC+273.16)**4
C   COMPUTE CHANGE IN HEAT STORAGE
C   CHECK FOR FIRST DAY. IF THIS IS THE FIRST
C   DAY GO TO 900 AND SET
C   TWOCY=TWOC (OBSERVED
C   WATER TEMP YESTERDAY)
    QST=55.88*(TWOC-TWOCY)
C   COMPUTE QIR
    QIR=QEH+QB+QST
C   COMPUTE 4 METER WIND
    WND4=1.25*WND2
    WND4=1.51*WND1
C   COMPUTE WIND FUNCTION
    FU=0.181+0.00236*WND4
C   COMPUTE SATURATION VAPOR PRESSURE AT TAA
    EAT=8.1175E6*DEXP(-7701.544/(TAA+405.0265))
C   COMPUTE EA IN EQUATION 5
    EA=FU*(EAT-EDP)
C   COMPUTE GAMMA
    GAMMA=0.000367*PA
C   COMPUTE AIR TEMP IN DEGREES KELVIN
    TAK=TAC+273.16*0.01
C   NOTE: 0.01 AVOIDS LARGE EXPONENT
C   ON SIGMA IN QB
C   COMPUTE DELTA
    DELTA=(7701.544/((TAA+105.0265(*(TAA+405.0265)))*EAT
```

```
C   COMPUTE TAK TO 3RD AND 4TH POWER
    TAK4 = TAK**4
    TAK3 = TAK**3
C   COMPUTE FREE WATER EVAP BY KOHLER AND PARMELE
C   1ST TERM
    FSTTRM = (QIR-0.97*11.71*TAK4)*DELTA
C   COMPUTE TERM COMMON TO 2ND TERM AND DENOMINATOR
    COMTRM = GAMMA + (4.*0.97*11.71*TAK3/FU)
C   COMPUTE DENOMINATOR
    DENOM = DELTA + COMTRM
C   FINAL KOHLER-PARMELE COMPUTATION
    EKP = (FSTTRM + EA*COMTRM)/DENOM
900 TWOCY = TWOC
C   GO TO BEGINNING FOR A NEW DAY
```

This method of estimating free water evaporation is preferred by the Hydrologic Research Laboratory of the National Weather Service. The equation must be converted by eqs 11 and 12 in Kohler and Parmele (1967) to represent lake evaporation, but can be used as is to calculate potential evaporation for agricultural use.

8.B.3. COMPARATIVE METHODS

8.B.3.a. PAN EVAPORATION

Measurement of evaporation from pans is considered one of the easiest and most accurate ways of estimating evaporation from a "free water surface." Placement of the pan and methods of observation can be controlled and factors influencing the pan can be measured at the pan site with a minimum of effort.

The following definitions apply to terms used in the discussion which follows.

Free water surface—a thin film of water having no heat storage.

Shallow lake—a lake closely approximated by a free water surface.

Pan coefficient—a factor used to adjust pan evaporation to shallow lake evaporation.

In 1973 the Commission for Instruments and Methods of Observation (CIMO) of the World Meteorological Organization recommended adoption of the Russian 20 m^2 tank as an international standard to represent evaporation from shallow lakes (CIMO, 1973). This large tank, however, has been judged too expensive to be brought into common use.

Alternate pans in wide use are the GGI-3000, which looks somewhat like a sunken 50-gal drum, and the National Weather Service class A pan. In the United States and most of the Western World, existing evaporation data have been collected largely with the class A pan.

The class A pan has been the standard in this country for many years. For planning purposes, the report "Evaporation Maps for the United States" (Kohler and others, 1959) contains excellent maps showing the areal variations in lake and pan evaporation over the 48 contiguous States. The method described by Kohler and Parmele (1967) is recommended for estimating evaporation at a designated site.

A new international standard pan has been undergoing tests at nine sites worldwide since 1975. It is an insulated pan similar to the Russian GGI-3000, white outside and black inside, with a surface area of 3,000 cm^2. Recommended standard installation requires the pan base to be set below ground level in such a way that its rim is 15 cm above ground. It is hoped that this standard pan will be generally accepted and used worldwide, so that directly comparable data may be collected and used to advance knowledge of the worldwide areal variability in lake and reservoir evaporation.

Among available methods of pan measurement, the Hydrologic Research Laboratory of the National Weather Service currently proposes the following order of preference:

1. Use of a newly developed insulated pan as a radiation integrator with a modified energy-budget equation (Kohler and Parmele, 1967). This method was discussed in section 8.B.2.b.5 because, although a pan is used, the method is based on an energy budget.
2. Class A pan measurements adjusted for heat transfer through the sides of the pan.
3. Simple observations from the insulated pan using a constant pan coefficient.
4. Simple observations from the class A pan with a local pan coefficient.

The recommended order of priority is based on a comparison of different methods with the 20 m^2 tank, corrected for heat storage under several different climatic regimes.

8.B.3.a.1. PAN COEFFICIENT

Pan coefficients for the class A pan have been found to average about 0.7 on an annual basis, but will generally vary from 0.8 to 0.6. In some climates or during certain seasons, much larger variations can be expected. For example, seven reservoirs in central Colorado, operated by the Denver Board of Water Commissioners, were studied from 1967 to 1973 to determine evaporation losses. Comparing seasonal pan evaporation to lake evaporation, as estimated by the calibrated mass-transfer method, the pan coefficient for the 33 seasons averaged 0.64, but varied from 0.29 to 0.94, with a standard deviation of 0.17 (Ficke and others, 1977, p. 169). Use and determination of pan coefficients are discussed fairly completely by Kohler (1954) and also by Hounam (1973).

This variability in pan coefficients is attributed to heat exchange through the sides of the pan. Methods of correction for variation in pan coefficients will be discussed in later sections.

8.B.3.a.2. METHOD OF OBSERVATION

The method of making observations on the class A pan (fig. 1) required in items 2 and 4 of the preferred observation list is explained in detail in National Weather Service (1972).

There are two methods of measuring evaporation with the class A pan. One method uses a hook gage and an associated stilling well. This method is fast becoming obsolete. New equipment is becoming difficult to obtain. There are, however, pans equipped with hook gages still in use, so the method will be covered. The following is extracted from National Weather Service (1972, p. 41-42).

> The gage consists of a hook in the end of a stem that is graduated to tenths of inches over a range of several inches. The stem is constructed with double threads throughout its range of adjustment. The threads have a pitch on one-tenth of an inch.
>
> A three-legged spider and adjusting-nut assembly supports the hook and provides for adjustment of the height of the hook when the gage is installed on the stilling well. The adjusting nut is threaded to screw on the stem of the hook. After assembly, the gage is placed on the stilling well with the three legs of the spider resting on the top rim of the well. The stem should be vertical. The adjusting nut is free to turn within the spider so that it may be used conveniently to adjust the height of the hook. The relative height of the hook in the well is indicated by the scales of the gage.
>
> The stilling well is a cylinder mounted on a plate equipped with leveling screws. At the center of the base is a small tube to allow the passage of water. The purpose of the well is to damp out oscillations in the water surface and provide a base for the hook gage during water level measurements.

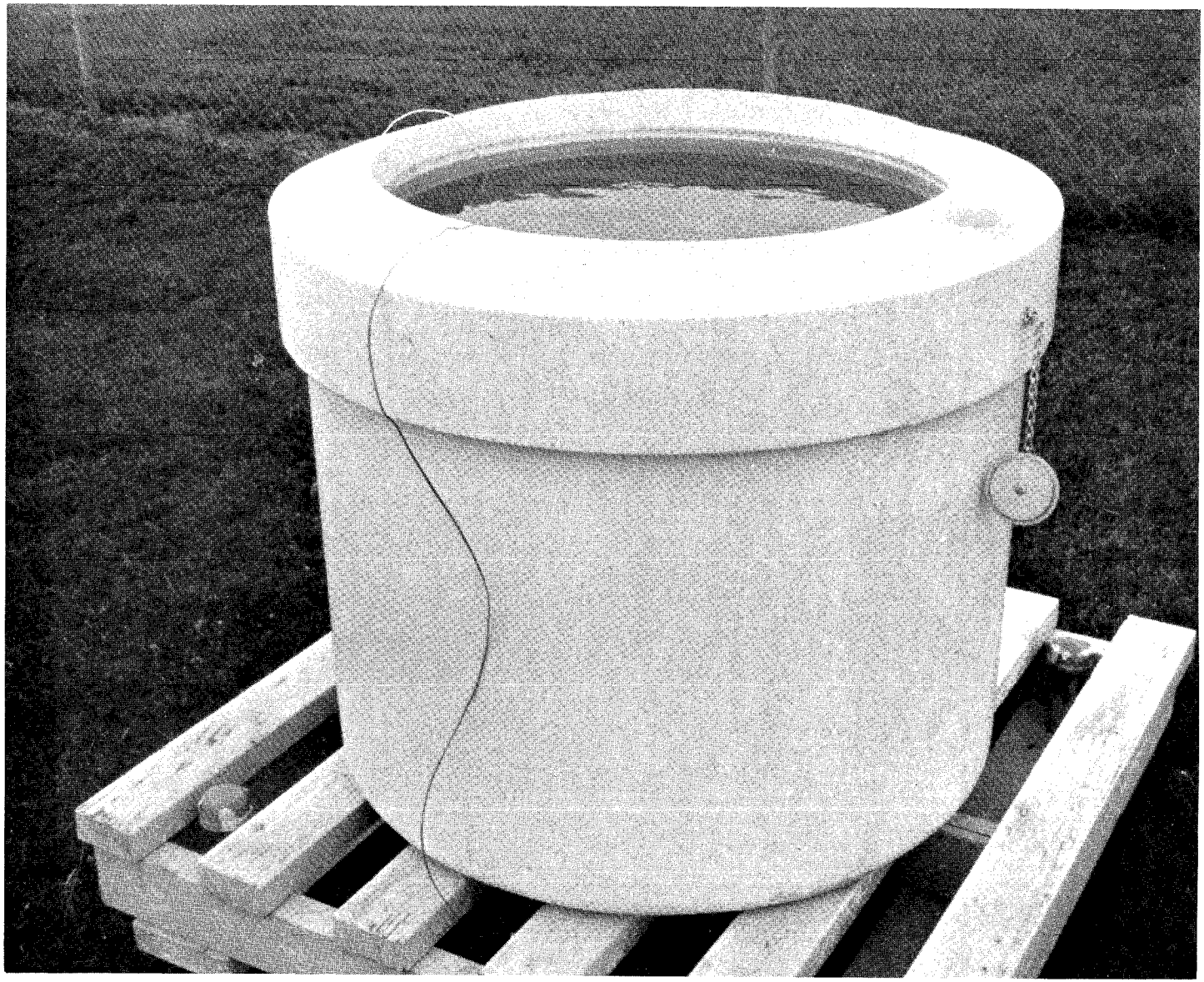


Figure 8-1.—Class A evaporation pan with anemometer for measuring air movement.

Measurement of evaporation consists of taking the difference in water level before and after the evaporation interval.

NOTE:

As the water level drops away from the lip of the pan, the evaporation rate is significantly affected. For this reason, the water level should be maintained between 2 and 3 inches below the lip of the pan.

8.B.3.a.3. ADDITIONS AND WITHDRAWALS OF WATER FROM THE PAN

When evaporation has proceeded far enough that water must be added to the pan, the hook gage is read both before and after the water is added. The difference between the reading made before adding water and the reading from the previous day is the evaporation for the period ending at this observation. The new value on the hook gage is the value from which the following day's hook reading will be subtracted.

Rainfall may cause the pan to overflow or bring the water level close enough to the lip for water to blow out or splash out as rain falls into the pan. When this happens, water must be removed from the pan. Readings should be taken both before and after withdrawals are made. If the pan has overflowed, no evaporation estimate can be made. If the pan has not overflowed, evaporation is the difference between the previous day's reading and the reading before water is withdrawn, after the rainfall is subtracted. Readings on days with any significant rain generally have much larger errors than readings on nonrainy days. Part of this error is due to differences in the amount of rain caught in the rain gage and in the pan. Most of the remainder can be attributed to splashout or blowout. Readings from days with apparent high evaporation and significant rain should be viewed with suspicion and, if possible, evaporation should be computed using a mass-transfer or a Penman equation. Where this is not feasible, substitution of one of the lowest nonrainy-day values measured in the same season of the year will likely reduce the error between the recorded value and the true evaporation.

8.B.3.a.4. FIXED-POINT GAGE

The other method of reading the class A pan uses a fixed point mounted in a stilling well and a graduated cylinder that measures water added to or withdrawn from the pan.

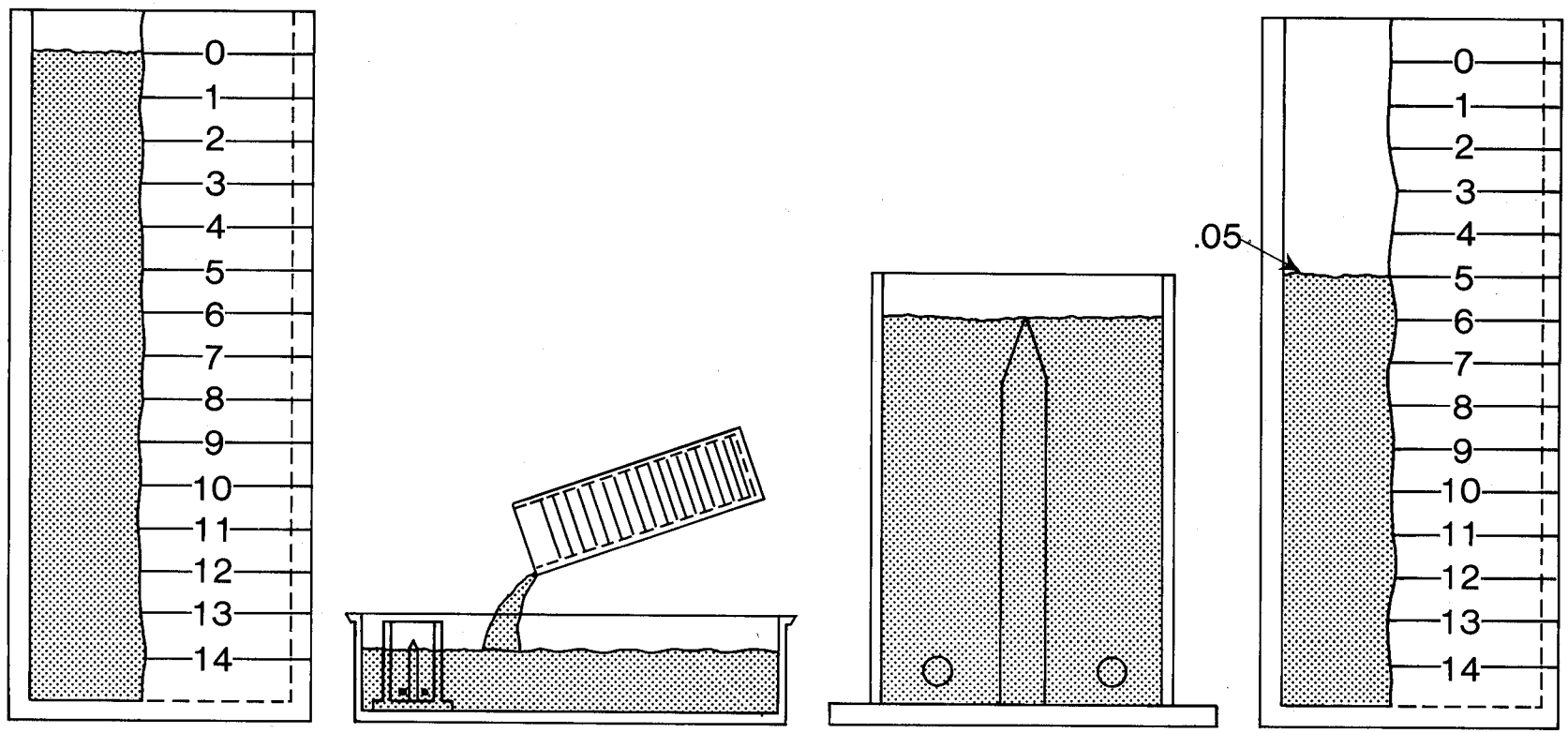
At the beginning of each evaporation period the water level is adjusted so the tip of the point is even with the water surface.

NOTE:

Surface tension causes the water surface to bend toward the point. Observers should be consistent in their method of making readings. Because of reflection and surface tension, it is better to take the water level down to the point than to bring it up from below.

At the end of the evaporation period, water is added using a graduated cylinder (or, in the case of precipitation, removed) to bring the water surface back to the point of the gage. The National Weather Service standard cylinder (fig. 2) is plastic, measures 16 inches deep, and is of such diameter that a 1-inch-deep layer of water in the cylinder is equivalent to a layer 0.01 inch deep in the class A pan. The cylinder is numbered from 0 to 15, starting 1 inch below the lip.

A reading is made by filling the cylinder so that the water level reaches the zero line. Water is



Note that the measuring tube is filled to zero.

Water is poured into the evaporation pan until the surface of the water in the fixed-point gage corresponds with the tip of the fixed point.

The change in the depth of the water in the evaporation pan is determined by reading the water level in the plastic tube. Each marking is the equivalent of .01 inch in the evaporation pan.

Figure 8-2.–Technique for determining water volume change in pan.

then poured from the cylinder into the pan until the water surface is above the point. Then water is drained from the pan into the cylinder until the level just touches the tip of the gage.

The cylinder is then held vertically and the water level read to the nearest inch. The reading is equal to the evaporation, in hundredths of inches. When more than 0.15 inch has evaporated, more than a full cylinder (filled to the zero line) must be added to the pan.

When required, remove water with the cylinder until the water level just breaks to the point so the level for all readings approaches the point from the same direction. The amount of water removed is determined by counting up from the bottom of the cylinder.

8.B.3.a.5. SPECIAL CONSIDERATION

Pans must be maintained to a uniform standard if measurements are to be comparable with data collected in national networks.

Methods for cleaning pans and retarding the growth of algae are discussed in National Weather Service (1972). The reflectivity of the pan should not be intentionally altered. Some observers have painted pans with aluminum paint, causing significant changes in their characteristics.

Site conditions and protection from animals that might drink the water are covered in detail in National Weather Service (1972).

8.B.3.a.6. ADDITIONAL MEASUREMENTS

Correction of measurements for precipitation requires that a measurement be made near the pan for any precipitation occurring during the evaporation period (usually 24 hours). Daily observation of evaporation makes the standard 8-inch rain gage a logical choice for measuring the precipitation for the period. Standard methods for measuring rain are discussed in National Weather Service (1972).

Measurements of air temperature, dewpoint, pan wind, and pan water temperature are required to correct the class A pan for heat exchange through the walls. While the mean air temperature, dewpoint, and water temperature are the desired variables, it is assumed that the arithmetic means of the maximum and minimum air and water temperatures adequately represent these values. Humidity is assumed to change more slowly and can be represented by four instantaneous readings spaced 6 hours apart. Wind at the pan can be measured in miles per day with an F104 totalizing anemometer, mounted over a corner of the pan with the center of the cups 6 to 8 inches above the pan. Wind movement for each day is determined by taking the difference between readings on successive days.

8.B.3.a.7. LAKE EVAPORATION ESTIMATED FROM THE CLASS A PAN ADJUSTED FOR HEAT STORAGE

Kohler, Nordenson, and Fox (1955) derived a method for adjusting class A pan data for heat exchange through the pan. Free water evaporation in inches per day is given by

$$E_{FW} = 0.70[E_p + 0.00051P\alpha_p(0.37 + 41U_p)(T_o - T_a)^{0.88}] \qquad (6)$$

where

E_{FW} = free water evaporation
E_p = observed pan evaporation for the day
P = atmospheric pressure
α_p = the portion of advected energy (class A pan) used for evaporation
U_p = pan wind in miles per day

T_o = pan-water surface temperature in °F. It is assumed that the class A pan water is nearly isothermal at all times.
T_a = air temperature in °F
α = computed in equation 9 of Kohler and others (1955)

The following brief program is included so that the method may be used without reference to the derivation (Lamoreaux, 1962).

Definitions:

TAA = mean daily air temperature
UP = pan wind in miles per day
TAW = mean pan water temperature
WINDTERM = $0.37 + 0.0041U_p$
DELT = TAW-TAA
DEL88 = $(DELT)^{.88}$
ADELT = DELT + 1.0
ADE88 = $(ADELT)^{.88}$
TAW1 = 398.363
TAW2 = $(TAW1)^2$

$$DEDTW = \frac{4.7988X10^{10}}{TAW2 \exp(7482.6/TAW1)}$$

EINC = (DEDTW) (WINDTERM)

$$BRINC = 2.28854x10^{-11}TAW^3 + 3.9835x10^{-8}TAW^2 + 11.8332x10^{-5}TAW + 2.8121x10^{-3}$$

SHINC = 0.01098(ADE88-DEL88)WINDTERM

$$\alpha = \frac{EINC}{EINC + BRINC + SHINC}$$

EVAP = $0.7*(E_p*5.1E\text{-}4*P*\alpha*(0.37 + 4.1E\text{-}3*U_p)DEL88)$

8.B.3.a.8. INSULATED PAN MEASUREMENTS

A primary purpose for developing the insulated pan was to establish a stable coefficient showing little variation with location, climate, or season.

The annual coefficient for the pan, when mounted on a platform (fig. 3) with the lip 1 m (39.4 in.) higher than the surrounding land surface, is 0.74. If the pan base is set into the ground so that the lip is 15 cm (6 in.) above ground level, the annual pan coefficient is 0.81.

The insulated pan (fig. 4) is 62 cm (24 in.) in diameter, 61 cm (24 in.) deep, and insulated with 8 cm of Freon-blown polyethylene. The inner and outer shells are fiberglass. The pan is entirely white both on the outside and above the water level on the inside; below the water level, it is black to absorb radiation. It is designed with a stilling well, including a fixed-point gage built into the rim of the pan. The water surface at the gage tip is 5 cm (2 in.) below the lip of the pan (see fig. 4).

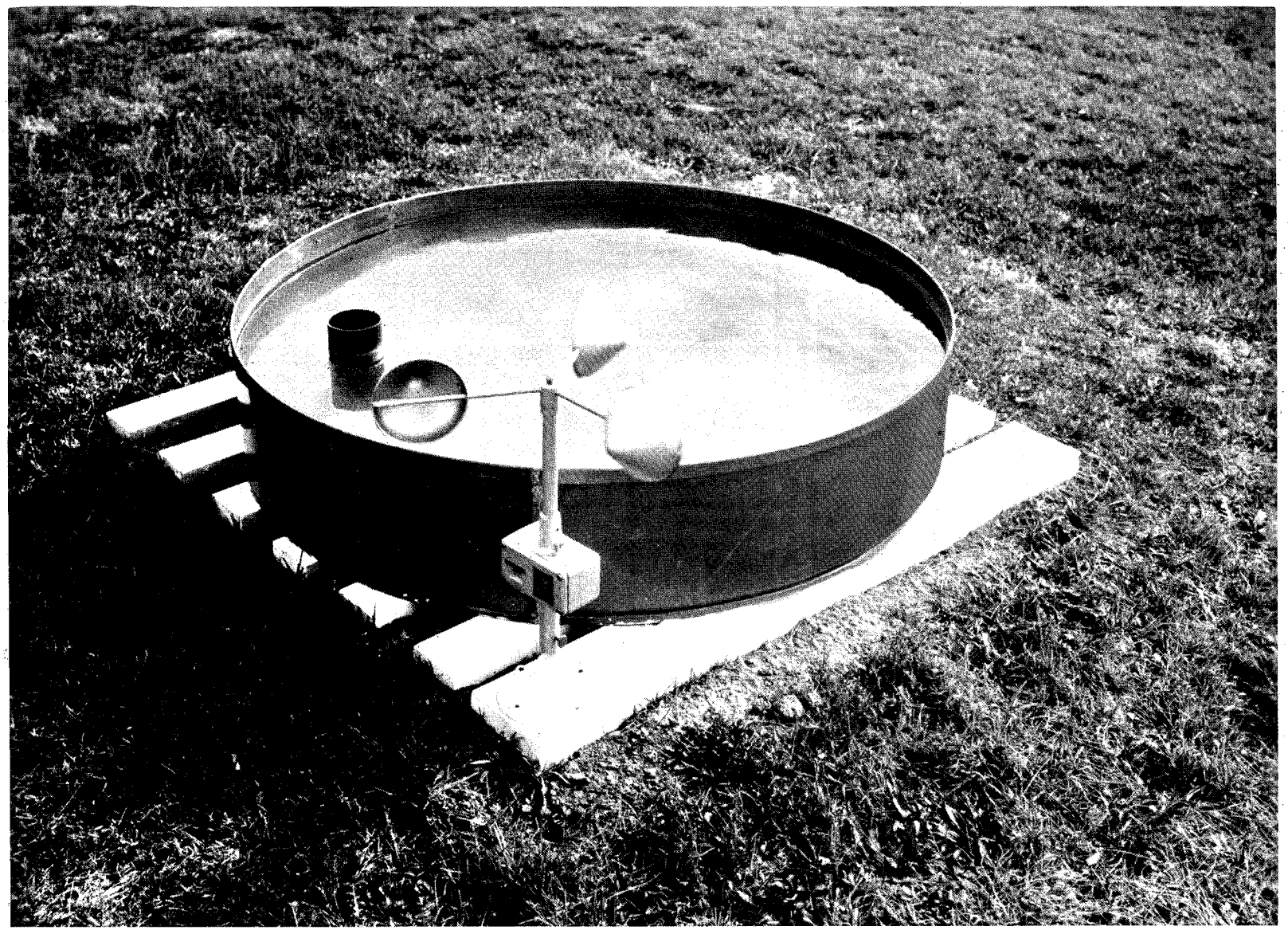


Figure 8-3.—National Weather Service insulated pan, mounted on platform.

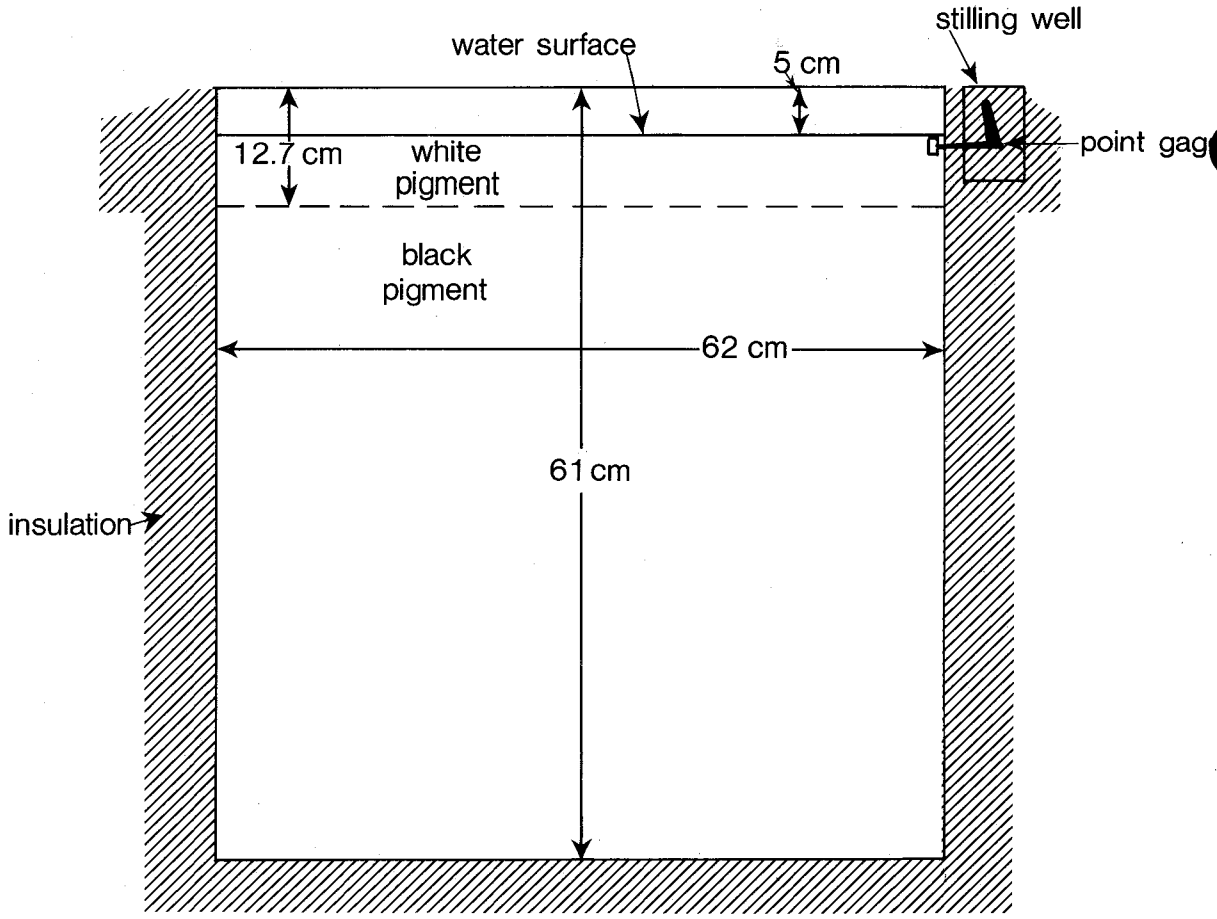


Figure 8-4.–Cross section of National Weather Service insulated evaporation pan.

The readings are taken in the same way as those for the class A pan with a fixed-point gage. The graduated cylinder is the same as that used with the class A pan; however, each graduation on the cylinder now represents 1 mm of pan depth.

8.B.3.a.9. TAKING READINGS

Remove stilling well cover.

8.B.3.a.9.a. No Rain

Fill cylinder with water to top mark. Pour water into pan until water surface is above the point. Then remove water from the pan to the cylinder until surface breaks to tip of point gage. For consistency, the water surface should always be brought to the point from the same direction. If more than one cylinder of water is needed to bring water surface up to the tip of point gage, add the amounts to determine the total amount evaporated. Remember to replace the stilling well cover.

8.B.3.a.9.b. Rain, No Overflow from Pan

Water surface is below tip of point gage. Follow steps in previous paragraph for no rain. Then multiply the precipitation reading (if in inches) by 25.4 to convert to millimeters, and add to amount added to pan to compute total evaporation.

8.B.3.a.9.c. Water Surface Above Tip of Point Gage

Remove water from pan until water surface breaks at the gage tip (be sure that water surface is always brought to the tip from the same direction). Measure removed water in cylinder, by counting up from the bottom. Subtract this amount from the amount of precipitation (converted to millimeters) to compute total evaporation.

When the water level nears the top of the pan, the inaccuracy in the reading becomes so large as to make it useless.

Whenever precipitation is greater than 8 mm, splashout and blowout begin to bias the pan readings. A correction for this bias is computed by

$$E_c = E_o + 3.0 - 0.33(\text{MPMM})$$

where E_c is the corrected evaporation, E_o the observed evaporation, and MPMM the measured precipitation in millimeters.

8.B.3.a.9.d. Rain, Overflow

Evaporation cannot be determined from a pan which has overflowed. It is unlikely that significant evaporation occurs on a day with sufficient rain to overflow the pan. Remove water to bring the level down to the point gage.

8.B.3.a.9.e. Special Consideration

Silt and other foreign material falling into the pan may change energy-absorbing characteristics. Because the pan is black below the water line, it may be difficult to determine when cleaning is indicated. The pan should, therefore, be cleaned regularly to assure that significant characteristics remain constant.

8.B.3.a.10. ADDITIONAL MEASUREMENTS

The primary additional measurement required for direct observation of evaporation is measurement of precipitation. The requirement differs from that described for the class A pan only in that precipitation readings must be converted from inches to millimeters.

Additional measurements are required when this pan is used as a radiation integrator. These have been described in the section on energy-budget methods.

8.B.3.a.11. CONVERSION OF FREE WATER EVAPORATION TO LAKE EVAPORATION

In estimating evaporation from a natural water body using a free water estimate (obtained by either pan measurement or by any other method), it is necessary to take into consideration significant heat storage or energy advected by water flowing in or out. Equations 11 and 12 in Kohler and Parmele (1967) provide a method for this conversion.

8.B.3.a.12. NETWORK DESIGN

Peck and Monro (1976) found that measurements from pans in unobstructed sites in Kansas would correlate well with data from pans as much as 400 km away, if periods as long as 10 days were considered and rainy days were excluded. For single days, pans over 100 km away had correlation coefficients of over 0.8.

In mountainous areas, the degree of correlation between sites is dependent upon the exposure of the pan sites.

8.B.3.a.13. SUMMARY

Some World Meteorological Organization and National Weather Service methods for estimating free water evaporation using pans were presented. The method of choice is the Kohler-Parmele modified-energy-budget equation, using the insulated evaporation pan as a radiation integrator.

The second method in order of preference uses the National Weather Service class A pans, with additional measurement of pan water temperature and air temperature to adjust the pan coefficient for heat exchange through the pan.

The most consistent of the simple pan observations is obtained using the insulated pan, which has fairly stable annual coefficients of 0.74 and 0.81, depending on whether it is mounted on a platform or set into the ground.

The most commonly used method in the Western World is the class A pan, with pan coefficient assumed to be 0.70. Users must realize that this coefficient will, however, vary significantly with climate and season.

8.B.3.b. ATMOMETERS AND EVAPORIMETERS

An atmometer is a water-filled glass tube having an open end through which water evaporates from a filter paper (Piche type) or porous plate (Bellami type). The tube supplying water is graduated to read evaporation in millimeters, but the evaporation (termed latent evaporation) can only be compared with readings from another such instrument in a similar exposure. The latent evaporation is mainly a measure of the drying power of the air. The instrument is apparently more responsive to windspeed than to radiant energy.

The atmometer is commonly used for estimating evaporation losses, particularly in agricultural work. Use of these devices has increased in recent years because they are inexpensive, portable, and easily maintained and installed. They require very small amounts of water and are easily standardized. Atmometers are useful in evaporation studies because they have small surfaces, unlike large water bodies, and therefore are more representative of conditions affecting moisture loss from plants. However, the value of using these types of devices for measuring evaporation from free water surfaces is subject to considerable dispute. Mukammal (1961) reports that atmometer observations are difficult to interpret, and it is necessary to know the conditions created by the particular instrument before relying on its results. Different conversion factors may be necessary with atmometers for different evaporation ranges, as well as for different areas. Class A or larger pans are preferable for estimating evaporation from large bodies of water.

The variety of atmometers available is so great that a complete listing would not be feasible; however, some of the more common types, such as the Piche, Livingston, and Bellani, will be discussed in detail.

8.B.3.b.1. PICHE ATMOMETER

According to Abbe (1935) this instrument consists of a glass tube, about 23 cm in length, with an inside diameter of 11 mm, with one end closed and the other end open. The tube is filled with distilled water and inverted on a circular piece of blotting paper 3 cm in diameter that has been affixed to the open end with a disc. The tube is graduated to facilitate direct reading of evaporated water. This atmometer is very sensitive to wind. The size of the blotting paper is also important. If the paper is too large, the evaporation measurement will not be representative of a constant evaporating surface.

8.B.3.b.2. LIVINGSTON ATMOMETER

This instrument (Livingston, 1935) consists of a hollow porous porcelain sphere, with a diameter of 5 cm and wall thickness of about 3 mm, connected by tubing to a distilled-water reservoir. Evaporation is measured by refilling the supply reservoir to the reference mark. The reading must be compared with a standard and multiplied by the sphere manufacturer's calibration coefficient.

A black and a white coated sphere can be used to estimate solar radiation because evaporation differences have been found to be highly correlative with the intensity of solar radiation. O'Connor (1955) determined that black and white atmometers are suitable for measuring global radiation for meteorological studies. Halkias and others (1955) determined that the average monthly difference between black and white atmometers, in cubic centimeters, is equal to 0.028 times the average monthly radiation measured in gram-calories per square centimeter by an Epply pyrheliometer. A correlation coefficient of 0.94 was established for the relationship. According to Livingston and Haasis (1929), use of this type of atmometer is limited in cold weather because the bulb will burst upon freezing. Plant physiologists commonly use this type of instrument to study plant moisture loss.

8.B.3.b.3. BELLANI ATMOMETER

This instrument consists of a thin, porous, black ceramic disc 7.5 cm in diameter, fused to the large end of a glazed ceramic funnel; it is similar in operation to the Livingston atmometer. A burette containing distilled water is used as the supply reservoir. Mukammal and Bruce (1960) report that this instrument is very sensitive to wind, but less sensitive to net radiation, the main factor affecting evaporation. They compared the three major parameters involved in evaporation (net radiation, humidity, and wind) and found that the ratio of the effects of these factors for the class A evaporation pan was 80:6:14, and for the Bellani atmometer 41:7:52. In an intensive study in Western Canada, involving the use of evaporimeters for estimating consumptive use requirements for different crops, Sonmor (1963) determined the conversion coefficients listed in table 8-1.

8.B.4. AERODYNAMIC METHODS

8.B.4.a. EDDY CORRELATION

Of all the techniques used to estimate evaporation, none is as direct as the eddy-correlation method. Water molecules escaping from the water surface are carried upward into the air by turbulent diffusion; that is, they are carried vertically by turbulent air currents. If observations are made near the surface of the water, all horizontal gradients in vapor contents are zero, so the vertical flux of water vapor must be equal to the time-average value of the product

$$E = \rho \overline{vq} \tag{7}$$

in which E = rate of evaporation, ρ = density of water, v = vertical component of the instantaneous velocity, and q = instantaneous value of the absolute humidity.

The eddy-correlation method has been used to determine the vertical flux of water vapor over both land (Swinbank, 1951; Goltz and others, 1970; Hicks, 1973) and water (Easterbrook, 1968; Hicks and others, 1973). The method requires expensive and delicate instrumentation and has been used only for short-term research applications, but it is very useful in measuring evaporation rates applicable to local areas for short time periods.

Table 8-1.—*Coefficients to be applied to various evaporimeter readings to estimate seasonal consumptive use of different crops in Western Canada*

Crop	Black Bellani Plate [1]	Class A Pan [2]
Perennials		
Alfalfa	0.0030	0.66
Grass, Pasture	0.0031	0.68
Annuals		
Soft Wheat	0.0030	0.66
Hard Wheat	0.0029	0.66
Oats	0.0028	0.59
Barley	0.0028	0.64
Flax	0.0026	—
Peas	0.0031	—
Row Crops		
Sugar Beets	0.0025	0.54
Potatoes	0.0025	0.56
Corn	0.0022	0.50
Tomatoes	0.0024	—

[1] Inches of consumptive use per cubic centimeter of evaporation measured.
[2] Inches of consumptive use per inch of evaporation measured.

Note.—Coefficients are to be applied over the length of the growing season.

8.B.4.b. AERODYNAMIC OR GRADIENT METHOD

The aerodynamic or gradient method relates the vertical gradients of humidity and horizontal velocity to the rate of evaporation from the underlying surface. A turbulent-diffusion or mixing coefficient is determined from the velocity gradient and an assumed functional relationship between windspeed and elevation. The vertical flux of water is then determined from the humidity gradient, the mixing coefficient, and an assumed functional relationship between humidity and elevation. The evaporation rate is considered equal to the vertical flux of water vapor. The aerodynamic or gradient method requires very accurate measurements of velocity and humidity gradients that are difficult to obtain, particularly near the center of a body of water. The method also suffers because the form of the functional relation between windspeed or humidity and elevation has defied accurate definition.

The best known and most widely tested (Marciano and Harbeck, 1954) evaporation formula of the aerodynamic type was derived by Thornthwaite and Holtzman (1939). The formula, which is based on logarithmic profiles of wind and humidity, is

$$E = \frac{\rho\kappa^2 (q_1 - q_2)(U_2 - U_1)}{(\ln z_2/z_1)^2} \tag{8}$$

in which E = rate of evaporation; ρ = density of air; κ = Karman coefficient; and q_1, q_2 and U_1, U_2 are specific humidities and mean wind velocities, respectively, at heights z_1 and z_2. It is generally agreed that the Thornthwaite-Holtzman equation is only valid for neutrally stable

atmospheric conditions. Even under these conditions, however, small errors in the measurement of either q or U are greatly amplified. For example, Jobson (1973) has shown that a 1-percent error in specific humidity is amplified about 40 times when working between the 2- and 4-m levels under conditions typical for Lake Hefner, Okla., in the month of July.

The error amplification in the Thornthwaite-Holtzman equation can be reduced by increasing the distance between measurement levels. On the other hand, for the equation to be valid, all measurements must be obtained well within the boundary layer formed by the evaporating surface. As a general rule, an upwind fetch of not less than 100 times the height of the highest instrument is required to insure that the measurements are representative of the evaporating surface (de Vries, 1958).

Under non-neutrally-stable conditions, either lapse or inversion, use of the Thornthwaite-Holtzman equation will give erroneous results because of the breakdown of the logarithmic profile laws. These non-neutrally-stable conditions, particularly the lapse condition, are often periods of intense evaporation.

For atmospheric conditions reasonably near to being neutrally stable, the profiles are sometimes fitted using the Monin and Obukhov (1959) log + linear law, which was evaluated by Jobson (1973) using a massive set of data collected at Lake Hefner, Okla. It was found that, while this law gave better results than the Thornthwaite-Holtzman equation, the computed evaporation rates contained many large errors.

The aerodynamic or gradient method can be used for short-term, intensive studies but cannot be recommended as a routine method.

8.B.4.c. MASS-TRANSFER METHODS

An excellent summary of mass-transfer methods at the time it was prepared is given in Marciano and Harbeck (1954). Many good papers published since then are also listed in the bibliography. A good empirical method is described by Harbeck (1962).

8.B.4.c.1. DESCRIPTION

The semiempirical mass-transfer method of evaporation computation (hereafter called the mass-transfer method) is widely used. Equations for estimating evaporation by the mass-transfer method take the form

$$E = f(u)\,(e_o - e_a) \tag{9}$$

in which E = evaporation rate; f(u) = some function of windspeed, often called the wind function; e_o = saturation vapor pressure calculated from the temperature of the water surface; and e_a = vapor pressure of the air. This expression is usually attributed to the work of Dalton (1802) and is often called Dalton's law. Many have concluded that the mass-transfer method represented by equation 9 is the most practical method of computing evaporation rates, at least over long periods of time (Braslavskii and Vikulina, 1954; Harbeck, 1962; Turner, 1966; Hughes, 1967; Richards and Irbe, 1969; and Ficke, 1972).

The wind function, f(u), represents the combined effect of many variables; however, almost all functional relationships which have been proposed are of the form

$$f(u) = a + NU^n \tag{10}$$

in which a and n are constants, N is the mass-transfer coefficient, and U is the windspeed representative of conditions over the lake. Excellent summaries of many of the proposed relationships have been presented by Ryan and Stolzenback (1972) and the Tennessee Valley Authority (1972), among others. Generally, the value of n is assumed equal to unity when computing evaporation from

lakes. The value of a is often assumed to be zero, particularly if windspeed is measured over the open water near the center of the lake. The value of the mass-transfer coefficient, N, accounts for the manner of the variation of wind with height, the size of the lake, the roughness of the water surface and the upwind land surface, atmospheric stability, and barometric pressure, as well as the density and viscosity of the air. All the factors combine somehow so that the value of the mass-transfer coefficient remains reasonably constant for a given reservoir and a given configuration of measurement locations.

Equation 9 generally gives the most accurate results when all data are collected at a point near the center of the lake and the method is calibrated (that is, the value of the mass-transfer coefficient determined) by comparison with independently determined evaporation estimates. A calibration period of at least 15 months, including 2 summers, is recommended. When calibrated in this way against the water budget, the method was capable of estimating monthly evaporation rates at Lake Hefner, Okla., to within approximately ± 10 percent (Jobson, 1973), although the errors did tend toward a slight seasonal bias. In comparison with the water budget, the mass-transfer formula tended to predict lower-than-observed evaporation rates during the fall (September through December). During the winter and spring (January through July) the mass-transfer method tended to overpredict the water-budget evaporation.

The vapor pressure of air is somewhat difficult to monitor, particularly at remote locations such as the center of the lake. Although a more accurate calibration can be made when the vapor pressure is measured at the center of the lake, the mass-transfer formula is often calibrated using the vapor pressure of air obtained over land because of the difficulty of obtaining measurements over the water. If the vapor pressure is obtained over land, the observations should be made far enough away from the lake so that the values are not affected by passage of the air over the lake. If the land station is too near the lake, the value of the vapor pressure will be highly dependent on wind direction and calibration will not be reliable. The goal is to determine the humidity of the air as it approaches the lake. Of course the humidity of the unaffected air will be different from the humidity at the center of the lake; therefore, the mass-transfer coefficient will be different in the two cases.

After a study of the evaporation from 20 reservoirs, ranging in size from 0.4 to 12,000 hectares, Harbeck (1962) concluded that

$$\begin{aligned} a &= 0.0 \\ n &= 1.0 \\ N &= \left(\frac{1.84}{A_s^{0.05}}\right) \end{aligned} \tag{11}$$

in which the evaporation is given in millimeters per day when the windspeed is in m/s, the vapor pressures are given in kilopascals, and A_s equals surface area of the reservoir in hectares. For eqs 9, 10, and 11 to be valid, the water temperature and windspeed should be observed at the center of the reservoir, with the anemometer 2 m above the water surface. The vapor pressure of the air should be measured at a site, usually several miles away from the lake, where it is representative of the natural humidity unmodified by passage of the air over the body of water. If these conditions are met, Harbeck (1962) estimates that the standard error in the computed yearly evaporation rate will be about 16 percent.

If windspeed must also be obtained over land, it is questionable how representative it will be of conditions over the reservoir, and larger errors can be expected. If evaporation rates must be estimated before the construction of a reservoir, mean monthly or annual ratios of windspeed over land to those at the center of the reservoir are sometimes estimated so that eq 11 can be assumed valid. These ratios have been computed for the Great Lakes by Richards and Irbe (1969) and for lakes in general by Braslavskii and Vikulina (1954).

If the water-surface temperature cannot be measured near the center of the reservoir, additional errors can be expected because horizontal temperature gradients are likely to be present in the surface waters. In general, these gradients are dependent on windspeed and wind direction and the warmest surface water will generally occur at the downwind edge of the reservoir. Ficke (1972) found surface temperatures to vary over a range of more than 2° C. The effect of an error in surface temperature on the computed evaporation varies with conditions. As an example, however, a 2° C error in surface water temperature during May could give an error in computed evaporation of over 40 percent for a lake in northeastern Indiana.

8.B.4.c.2. MEASUREMENT CONSIDERATIONS

The temperature of the water at the lake surface should be recorded by a thermograph mounted on a raft anchored near the center of the lake. The instrument's sensing unit should be shaded from direct solar radiation and be mounted in such a manner that it remains 1 or 2 cm below the water surface. The calibration of the thermograph should be checked periodically by use of a mercury-in-glass thermometer.

On windy days, the warm, less dense water will tend to pile up on the downwind side of the reservoir while the cold water will remain on the upwind side. Nevertheless, the water temperature at the center of the reservoir should be approximately equal to the mean surface temperature. On calm days greater warming will occur in shallow areas and the temperature measured at the center of the reservoir may be about 0.5° C less than the mean (Ficke, 1972, p. 8). On calm days, however, the evaporation should be low and these errors should have a minimal effect on the monthly evaporation estimates.

The windspeed should, ideally, be measured at a spot near the center of the reservoir. Generally, the height of the anemometer should be 2 m above the water surface. At higher elevations, the anemometer could be out of the boundary layer for small reservoirs or be affected by atmospheric stability for large reservoirs. At elevations below 2 m, the anemometer is subjected to a large amount of spray during high winds. The anemometer should be mounted on the same end of the raft as the anchor, so that as the wind direction shifts, the anemometer will always be on the upwind edge of the raft.

A recording system which gives at least daily totals of wind movement should be employed. A totalizing dial that can be checked at the time of service visits is also highly desirable.

If the vapor pressure of the air is obtained at the raft site, it is desirable that these measurements also be obtained at the 2-m level. Again, at least daily average values should be recorded.

The mass-transfer formula can be derived from aerodynamic considerations so its accuracy should increase as smaller and smaller time intervals are used to compute the evaporation rate. In other words, the monthly evaporation, computed as the average of the hourly rates, each determined from eq 9, should be more accurate than the monthly evaporation computed by using the monthly average values of windspeed, water temperature, and vapor pressure in eq 9. Since all recorded data must be considered as the average over some time interval, the following question arises: How large can the average interval for the data be before the results obtained from eq 9 are likely to be significantly in error? Common practice has been to use daily averaged values of the basic data in eq 9 and to average the resulting daily evaporation rates to determine the monthly or annual evaporation rates. The validity of this practice has been demonstrated statistically by Jobson (1972).

8.B.4.c.3. DETERMINATION OF THE WIND FUNCTION

When all mass-transfer data are obtained near the center of a reservoir and the mass-transfer coefficient has been inferred by comparison with an accurate and independently determined evaporation estimate obtained over a 15-month period (including 2 summers), the mass-transfer method should

provide monthly evaporation estimates accurate to within about ± 10 percent. The errors probably will not be completely random but will contain some seasonal bias. The energy-budget method has been found to be a reliable method for independently determining the monthly evaporation from lakes and reservoirs. The level of effort required to make energy-budget determinations of evaporation is large, but after the mass-transfer method has been calibrated for a particular reservoir, evaporation measurements can be continued indefinitely with a minimum of effort using the mass-transfer method.

Although, for best accuracy, all mass-transfer data should be collected near the center of the reservoir, the method can also be calibrated by use of data obtained at other locations. Errors that result from data collected elsewhere are probably severe for water temperature, moderate for windspeed, and fairly small for vapor pressure. At any rate, the mass-transfer method should be calibrated using the measurement locations that will be used in continued monitoring. If the windspeed is obtained over land, it is probable that better results will be obtained if a value other than zero is selected for the coefficient a in eq 10.

For lakes and reservoirs with small inflow and outflow, it is sometimes possible to calibrate the mass-transfer equation by use of a water budget. This is sometimes accomplished by plotting the daily change of stage (adjusted for inflow and outflow) versus the daily mean product of $U(e_o - e_a)$. If these data are carefully screened to eliminate periods of rainfall or large inflow and outflow, the plot often defines a reasonably good straight line. The slope of the line is assumed to be the mass-transfer coefficient. If the windspeed is measured at the center of the lake, the intercept of the line is assumed to be the net daily seepage (Turner, 1966). Concurrent ground-water studies are of course highly desirable as very small errors in total inflow or outflow can cause a large error in the evaporation residual.

If neither of the above approaches is practical, the mean annual lake evaporation may be estimated from the data presented by Kohler and others (1959). If the mean annual lake evaporation and the mean value $U(e_o - e_a)$ averaged over 15 months are known, the value of a mass-transfer coefficient can be estimated. This calibration procedure is based on the observation that the annual variability in lake evaporation is small (Harbeck, 1966) and that while monthly values of pan-to-lake evaporation ratios vary widely, the annual ratios are fairly constant. The annual evaporation rate estimate obtained from the mass-transfer method calibrated in this way is, of course, no more accurate than the evaporation maps presented by Kohler and others, but monthly estimates can be obtained which should be almost as accurate as the yearly total. This method can be used to estimate evaporation rates even before reservoirs are built if the water-surface temperature can be predicted from air temperature records or comparisons with reservoirs of similar size in the same region. If the 2-m windspeed and the water temperature are obtained over the lake, and if the humidity of the unaffected air is available, Harbeck's eq 11 can be used without calibration to estimate the mass-transfer coefficient. The standard error of estimate of the computed annual evaporation should be about 16 percent. Ficke and others (1977) found this standard error to be reasonable for the reservoirs of the Denver Water Supply System.

8.B.5. REMOTE SENSING

The relatively new remote-sensing techniques, which are still being developed, use satellite-acquired data for indirect estimation of evaporation or evapotranspiration. A procedure is discussed by Idso and others (1975) for calculating 24-hour totals of evaporation from wet and dry soils. Application requires a knowledge of daily solar radiation, maximum and minimum temperatures, moist-surface albedos, and maximum surface temperature. Solar radiation and maximum, minimum temperatures are obtained from standard weather-service measurements. Moist-surface albedos are estimated from one-time surface measurements. The maximum surface temperature is estimated from surface or airborne thermal sensors.

Chadwick (1973) suggested that an integrated value of soil moisture could be obtained by measuring attenuation of polarized surface radio waves that are propagated over the ground surface between transmitting and receiving stations.

The most promising potential application of remote sensing appears to be the use of enhanced infrared images to extend point measurements to provide areal coverage.

Investigations into the applications of remote sensing have also been made by McCoy (1967), Poe and others (1971), Sers (1971), and Burgy and Algaz (1974).

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8.C. EVAPORATION FROM BARE-SOIL SURFACE

8.C.1. PHYSICAL CONDITION—SOIL SURFACE, A SPECIAL CASE

Before describing some methods for determining the evaporation of water from soil surfaces, a brief discussion of why evaporation from soils is being treated as a special case is necessary. Hillel (1971) has summarized some of the physical conditions basic to the evaporation process and also to bare-soil surfaces. He describes three conditions necessary for the evaporation process regardless of the surface. First, there must be a continual supply of energy or, in other terms, a supply of heat to meet the latent-heat requirement. Second, a vapor-pressure gradient must exist (that is, the vapor pressure in the atmosphere over the evaporating surface must remain lower than the vapor pressure at the surface of that body). Coupled with the vapor-pressure gradient must be a means of transporting the vapor away from the surface—a diffusion or convection process or a combination of both. These conditions (an energy supply and a means of vapor removal) are not peculiar to any particular surface type but must be present anywhere for evaporation to take place. These two factors are influenced to a large degree by external meteorological factors of temperature, humidity, wind, and radiation.

As described by Hillel (1971), the third major condition necessary for the evaporation process to occur is that there be a continual supply of water from or through the body to the site of evaporation. A continual supply of water to the evaporation site depends on the water content, the water-potential gradient within the body, and the conductive properties of the body. The uniqueness of the soil as an evaporating surface is largely due to these latter properties. In a strict sense the soil surface does influence the external properties of the atmosphere by the way that its reflectivity, emissivity, and thermal conductivity affect the net supply of energy, but, in large part, it is the specific features of the soil influencing the movement of water to the evaporating sites that cause soil to be classified as a special case in measuring evaporation.

8.C.2. SOIL CONDITIONS INFLUENCING EVAPORATION

Just as soil is being considered as a unique surface for the evaporation process, there are also sets of conditions within the soil itself that may influence the method used to determine bare-soil evaporation. Two major considerations are the presence or the absence of a shallow ground-water table. With a shallow ground-water table at a constant or variable depth, steady-state flow from the saturated zone through the unsaturated zone to the sites of evaporation will occur. Evaporation can thus occur without changing the water content of the soil. Measuring evaporation using water-balance methods (see sections 8.C.3.a and 8.D.2.c) may be difficult unless some measure of the upward flux of water from the ground-water table is made. This steady-state flow will result in evaporation being determined largely by external meteorological factors, and some meteorological techniques for measuring evaporation could be used.

In the absence of a shallow ground-water table (or where the water table is too deep to influence evaporation), the evaporation of water at the surface resulting from upward flow within the soil profile or an increasing depth to the site of evaporation in the soil profile results in soil drying. This interruption of the supply of water at the evaporating sites causes the evaporation rate to be controlled by the amount of water in the soil and the conductive properties of the soil rather than by external meteorological factors. In this case, measuring evaporation by the water-balance method is more feasible. However, the deep-drainage component may be the most difficult to measure for accurate application of the water-balance method.

Measuring soil evaporation in the case of drying soil may involve application of two or more techniques depending on whether (a) soil water is not limiting and evaporation is controlled by the energy supply, that is, **energy-limiting phase**; or (b) evaporation is limited by the amount of water

moving to the sites of evaporation, that is, **soil-limiting phase**. Specific methods of measuring evaporation from bare soils will consider the conditions outlined above.

8.C.3. METHODS OF MEASURING BARE-SOIL EVAPORATION

8.C.3.a. WATER-BALANCE METHODS

Probably the most common approach to measuring bare soil evaporation is the simple "checkbook" balance approach, that is, keeping track of all incoming and outgoing water and of the net change in soil-water content to a specified depth, or considering this change in a specified volume of soil in a specified length of time. Several authors have written guidelines for using the water-balance method (Rose, 1966; Slatyer, 1967; Tanner, 1967, 1968; Hillel, 1971), and only a brief discussion of some of the precautions involved in the measurements will be given here.

In simple terms, the water-balance equation for a given volume of soil is the difference between the amount of water added, W_i, and the amount of water leaving, W_o, during a specified time which would then be equal to the change in water content of the soil, ΔW.

$$W_i - W_o = \Delta W. \tag{12}$$

To evaluate completely all inputs and outputs of water for a field situation, the water-balance equation would be

$$\Delta W = P + I - R - D - (E+T) \tag{13}$$

where P= precipitation, I = irrigation, R = runoff, D = deep drainage, E = soil evaporation, and T = transpiration. Note that D and R can have both positive and negative components. R would be "runon" as well as runoff, and D can be either upward or downward flow at the lower boundary of the specified soil volume. Of course, T would be zero with bare-soil situations.

Application of eq 13 to the problem of measuring bare-soil evaporation involves the case where no vegetation is present, and all other unknowns in the equation except E must be evaluated. While measurements of P and I are rather straightforward, evaluation of R and D is more complicated. For an agricultural field, R can be prevented by choosing a level site for evaluation, but in cases of natural contour sites, such as watersheds and the like, this becomes a major problem. Probably the greatest difficulty arises in the evaluation of D. This may be complicated even more by the presence of a water table. If these two components can be evaluated or, at least, if conditions can be chosen where they can satisfactorily be assumed to be negligible, evaluation of E from eq 13 reduces to the problem of accurately measuring the change in soil-water content, ΔW. Various techniques for measuring soil-water content are discussed in chapter 6 of this handbook and also in the references cited earlier.

8.C.3.b. DIRECT MEASUREMENTS

Weighable lysimeters offer the most direct measurement of bare soil evaporation. Various types of lysimeters are discussed in section 8.D.2.a, Evapotranspirometers, so a detailed discussion will not be included here. Bare-soil lysimeters are simply a special case of those discussed in section 8.D.2.a where the lysimeters are free from vegetation. The same problems will occur with bare-soil lysimeters that occur with lysimeters with growing vegetation, and the same precautions will apply. Numerous references to specific types of lysimeters are given by Tanner (1967), Hillel (1971), and in section 8.D.2.a of this chapter.

Arkin and others (1974) describe a device for direct measurement of soil-water evaporation using an evaporation plate covered with a thin layer of soil. The evaporation plate is connected to a water

supply that can be measured. The authors state that this device is as accurate as a weighing lysimeter, but because a constant, wet surface is maintained, the measurement of soil evaporation is limited to the *first stage*, or the energy-limiting phase, of drying only.

8.C.3.c. METEOROLOGICAL MEASUREMENTS

Because the evaporation of water from bare soil is an energy-driven process, the field-water balance is intimately connected to the energy balance. Where direct measurement of the soil water is difficult or time scale and the like are factors, bare-soil evaporation can be evaluated using the meteorological instrumentation necessary for evaluating the energy balance of an evaporating surface. It is beyond the scope of this handbook to review the details of energy-balance techniques. Numerous publications develop the theory, explain the limitations, and describe the instrumentation necessary for use of these techniques (Lemon, 1967; Penman and others, 1967; Tanner, 1967, 1968; Szeicz, 1975; Thom, 1975). Fuchs and others (1969) and Black and others (1969) showed some applications of meteorological techniques to evaporation from bare soils and compared their results to bare-soil evaporation from lysimeters.

8.C.3.d. EMPIRICAL METHODS

Many empirical equations have been developed to calculate evaporation. These equations are usually developed for a specific site, relating evaporation to climatic measurements or, in the case of bare soil, to some function of time once the soil-water content has reached certain boundary conditions. As Tanner (1967) emphasizes, empirical relationships have the greatest usefulness when correlated with "potential" evapotranspiration (ET) and are best suited for estimates of potential ET.

The problem in applying empirical equations to bare soils is evident from the earlier discussions of energy-limiting versus soil-limiting phases of drying soil. Tanner (1967) reviews a wide range of empirical equations for calculating evaporation. These should be studied as to how they apply to the special case of bare-soil evaporation. Hillel (1971) summarizes the calculation of soil evaporation as an empirical relationship with time for the soil-limiting phase and cites many references that deal with numerical procedures and the interaction of heat and moisture flow in a drying soil. Tanner and Jury (1976) show how evaporation from the soil can be calculated using various semiempirical models for both the energy-limited and the soil-limited phases.

8.C.3.e. REMOTE SENSING

The measurement of bare-soil evaporation using remote-sensing technology is still in the developmental stages. Several recent reports indicate that there are techniques available which use thermal scanners to obtain surface temperature measurements. Idso and others (1975a) describe a procedure for calculating 24-hour evaporation totals from both wet and drying soils. Its application requires knowledge of daily solar radiation and maximum and minimum air temperatures, moist-surface albedo, and the maximum and minimum surface temperatures obtainable from surface, aircraft, or satellite sensors. Most of these inputs are standard weather-service measurements and the technology for scanning large areas for surface temperature measurements is rapidly increasing. Researchers at the U. S. Water Conservation Laboratory, Phoenix, Ariz., have extended their remote-sensing techniques to include measuring the soil-water status in the root zone in growing vegetation and determining stress conditions that influence crop yields (see Idso, Jackson, and Reginato, 1975b, 1977; Idso and Ehrler, 1976; Idso, Reginato, and Jackson, and others, 1977).

Other references dealing with bare-soil evaporation measurements using remote-sensing technology are Conaway and van Bavel (1967), Schmer and Werner (1974), Stone and Horton (1974), and Moore and others (1975).

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8.D. EVAPOTRANSPIRATION METHODS

8.D.1. INTRODUCTION

Evaporation is the transformation of water to its gaseous state. Transpiration is evaporation from water in plants. This section considers evapotranspiration (ET) as evaporation from natural surfaces whether the water source is in soil, in plants, or in a combination of both.

Evaporation from soil and plants is a combined, interactive process. When natural surfaces are wet, the evapotranspiration rate is usually limited by the heat energy available at the surface to supply the latent heat demand. Approximately 600 times more energy is required to evaporate water than to increase its temperature 1° C. The two main sources of energy for evapotranspiration are solar radiation and sensible heat. Sensible heat is mainly transferred from adjacent areas by the air, but, when large decreases in surface temperature occur, significant sensible heat may at times be obtained from the soil. The air, soil, clouds, and sky are energy sinks which influence the net energy available for evaporation. The rate of evaporation is also influenced by the vapor-pressure gradient between the water at the evaporating surface and the bulk air, and the resistance in the watervapor pathways. Under steady-state conditions, a change in either available energy, vapor gradient, or resistance may not produce a proportional change in evapotranspiration, but rather will result in changes in the other factors until a new rate is established (Christian and others, 1970).

Measurement of evapotranspiration from natural surfaces requires determination of either the evaporation component for water balance, the latent heat term for energy balance, or the net upward flow of water vapor in the air above the evaporating surfaces.

Numerous reliable water-balance measurements of evapotranspiration from uniform agricultural crops that are well-watered have been made using tanks or lysimeters. In contrast, fewer measurements of evapotranspiration from natural watersheds with a combination of tall and short vegetation have been made because they are much more difficult to make. The same basic equipment is needed, but the rate of evapotranspiration, even if measured with several lysimeters or tanks, may not represent that of the entire watershed.

The most common water-balance measurements of evapotranspiration have involved soil sampling to approximate the evaporation component. This method is limited to time periods when drainage from the soil is negligible.

More recently, energy-balance and vapor-transfer techniques are being used for instantaneous or short-term determinations of localized evapotranspiration. Aerial techniques have been used to a very limited extent where there is a mixture of vegetation, bare soil, or both (Holmes, 1972). These measurements are very expensive and require a high degree of technical skill and complex instrumentation.

Numerous procedures have been developed to estimate evapotranspiration. Most of these procedures are based on commonly available climatological data or commonly measured meteorological parameters. Most empirical estimating procedures assume that soil water is not limiting, but some also take into account the level of available soil moisture. Major improvements in techniques are still needed to determine evapotranspiration from areas of natural terrain which may be undulating with various exposures and may contain several types of native vegetation or farm crops growing under variable soil-moisture conditions.

8.D.2. WATER-BALANCE METHODS

8.D.2.a. EVAPOTRANSPIROMETERS

If properly constructed, located, and operated, evapotranspirometers can provide the most accurate information on actual or potential evapotranspiration and are the only means to calibrate other methods

of measuring or estimating ET (Gangopadhyaya and others, 1966; Harrold, 1966; Tanner, 1967; Blad and Rosenberg, 1974).

An evapotranspirometer is an instrument consisting of a block of soil, usually planted with some vegetation, enclosed in a container which isolates it hydrologically from its surroundings. If there is provision for drainage of the soil water, either by gravity or with porous tubes or plates under a vacuum, one speaks of lysimeters (literally "leach meters," from the Greek "lusein," to leach). Both the drainable and the closed-bottom types can, by various means, be made weighable and a distinction should be made between those that are refilled with disturbed soil and those that contain undisturbed soil; in the latter case, one speaks of monolith lysimeters or evapotranspirometers (Hudson, 1965). In the literature one finds "weighed," "weighing," and even "weighted" lysimeters spoken of. Technically and grammatically all three terms are definitely wrong, but the first two seem to be firmly entrenched.

For detailed discussions of "conditions to be met by a lysimeter installation for accurate and representative measurement of the evapotranspiration rate," see van Bavel (1961) and Gangopadhyaya and others (1966).

8.D.2.a.1. NONWEIGHABLE LYSIMETERS

These instruments have limited usefulness because they are not suited for short-term (daily or hourly) measurements, but their ease of installation and comparatively low cost make them attractive. For descriptions of small types (less than about 7 m^2, or 75 ft^2) see Gilbert and van Bavel (1954), Mather (1954), and Evans (1971).

Instruments without drainage outlets are not to be recommended. Especially if the water table is maintained at a constant level, an increase in salinity can be expected (Williamson, 1963; van Hylckama, 1966; Robinson, 1970) and water-level fluctuations due to change in atmospheric pressure may obscure the true losses due to ET (Stevenson and van Schaik, 1967; van Hylckama, 1968).

Near Castricum, the Netherlands, large nonweighable lysimeters are successfully used to measure water regimes under forested areas. They have a 625 m^2 (6,700 ft^2) surface, are 2.5 m (8 ft) deep, and are made of reinforced concrete, coated inside to prevent seepage. Daily readings of drainage are made (Wind Hzn, 1958).

8.D.2.a.2. WEIGHABLE LYSIMETERS

To follow daily, hourly, or even more frequent changes in ET rates, weighable lysimeters are indispensable, but they are expensive, especially when they are of the monolith type. Three of the nine lysimeters in Coshocton, Ohio, belong in this group (the others are nonweighable). Monolith blocks of soil 1.90 m by 4.26 m (6.2 ft by 14 ft) in area and 2.44 m (8 ft) deep, cased in concrete, rest on mechanical balances (Harrold and Dreibelbis, 1951). Mustonen and McGuinness (1968) evaluate these lysimeters and describe certain improvements. The rim area was made much narrower and the seal of the air gap was changed. This greatly changed the estimates of dew formation as reported by Harrold and Dreibelbis in 1963.

Pruitt and Angus (1960) describe the construction of a large, circular lysimeter 6.1 m (20 ft) in diameter and 0.9 m (3 ft) deep near Davis, Calif. The rim area is only 3 percent of the container area and the recording sensitivity is 0.03 mm ET. Of course, the shallow depth limits its usefulness to shallow-rooted plants, although determination of potential maximum evapotranspiration even for normally very deeply rooted crops appears to be no problem as long as both field soils and lysimeter soils remain in the upper ranges of soil moisture.

The construction of weighable lysimeters is greatly simplified by using load cells or strain-gage transducers. A system such as this installed near Tempe, Ariz., is described in van Bavel and Myers (1962) and van Bavel and Reginato (1965). These lysimeters are 1 m^2 (10.8 ft^2) in area and 1.5 m

(5 ft) deep. Similar instruments were installed near Mead, Neb., as described by Rosenberg and others (1967). They are made of steel and the rim area is only 5 percent of the soil area. The sensitivity is 0.01 to 0.02 mm ET. Libby and Nixon (1963) also propose to use a load cell for "a portable lysimeter," 1.44 m^2 (10.8 ft^2) in surface and 1.2 m (4 ft) deep, weighing 2,200 kg (4,800 lb). Because of its simplicity and low cost, the lysimeter described by Ritchie and Burnett (1968) is of interest. The instrument has a surface of about 3.35 m^2 (36 ft^2) and is 1.22 m (4 ft) deep. The sensitivity is equivalent to $\pm$ 0.025 mm ET.

8.D.2.a.3. HYDRAULIC LYSIMETERS

The hydraulic method consists of putting the container on rubber bags or other water-filled tubing or bolsters and recording the change in pressure due to the change in weight of the container. Hanks and Shawcroft (1965) and DeBoodt and others (1966) describe such instruments. Ekern (1967) reports on their use in Hawaii.

Dagg's (1970) paper deals with the use of fairly large (9 m^2 x 1.8 m; 97 ft^2 x 6 ft) lysimeters resting on a series of water-filled bolsters, as described by Forsgate and others (1965), for use in tea research in Kenya. Rather than using a manometer to register the change in weight, Black and others (1968) describe using two hydraulic load cells to sense pressure change. One of the two measures 5.5 m by 2.1 m (18 ft by 7 ft) in area and is 1.5 m (5 ft) deep; the other one is round with a 4 m (13 ft) diameter and is 1.5 m (5 ft) deep. The system seems capable of handling even larger containers with sufficient accuracy.

Useful instructions for placing large, undisturbed monoliths in lysimeters are given by Brown and others (1974). There should be at least one of these in every climatic and agricultural region. If well instrumented for microclimatological data gathering, they can be of tremendous value for increasing our understanding of the physics of the plant-soil-water relationship.

8.D.2.b. LARGE-AREA WATER-BUDGET METHOD

Evapotranspiration estimates obtained by the hydrologic-budget method—also referred to as the water-budget or inflow-outflow method—are frequently applied to large areas such as irrigated cropland, watershed, or floodplain. The hydrologic components may include precipitation, surface runoff, ground-water movement, water stored on the land and in the soil profile, and water imported for irrigation. The residual from the algebraic summation of all significant components quantified during a given time interval gives an estimate of ET for that time interval. For certain sites, some of these components do not exist or are insignificant and can be eliminated in the budget.

8.D.2.b.1. ESTIMATION OF ET FROM CROPLANDS

Estimates of ET from croplands are generally used to determine irrigation water requirements. Usually, average consumptive use rates for daily, weekly, or monthly periods during the growing season are desired. Lysimeters have been used in many instances to obtain estimates of ET for various crops (see section 8.D.2.a on evapotranspirometers). Extrapolation of the results of lysimeter studies to large areas of irrigated land is questionable, unless actual field conditions are simulated in the lysimeter.

Lowry and Johnson (1942) applied the hydrologic-budget method to several different types of cropland to obtain estimates of average annual ET. The components quantified by sampling and other measurement techniques were precipitation, surface inflow to and from the area, and changes in surface and ground-water storage.

In areas of homogeneous soil with uniform distribution of roots and no water table to influence the ET, sampling to quantify the change in soil-moisture content after irrigation may provide reliable

estimates of ET. Moisture content is measured at representative sites by the gravimetric method (Beckett and others, 1930) or with a neutron probe (Nixon and Lawless, 1960), 2 to 3 days after irrigation and again before the next irrigation (see also chapter 6 of this handbook, which concerns soil-moisture measurements). This method is well adapted to areas where precipitation is low and the irrigation water is applied uniformly over the cropland. However, significant errors in estimating ET may occur if, between sampling periods, water is lost by deep percolation or gained by upward movement of water into the sampling zone (Wilcox, 1960, and Jenson, 1967).

8.D.2.b.2. ESTIMATION OF ET FROM WATERSHEDS

The hydrologic budget is generally applied to a watershed in determining changes in surface-water yield following removal or alteration of the vegetative cover of the watershed. Inflow as precipitation is sampled and outflow as streamflow is measured for a number of years to establish average annual inflow and outflow rates. The difference between the average annual inflow and outflow rates is used as an estimate of the annual ET for the area (Hewlett and others, 1969). Ideally, streamflow should be measured on a bedrock control at the outflow point to assure that all upstream subsurface flow is accounted for. The number, type, and placement of precipitation gages are important factors to be considered in instrumenting the area (see chapter 10 of this handbook, which concerns hydrometeorological observations). Surface and subsurface storage are usually ignored, because these factors generally become insignificant when many years of data are used to obtain the average inflow and outflow rates (Williams, 1940). Significant deep percolation, however, will result in an overestimate of the actual ET. Lee (1970), in discussing the discrepancies and uncertainties in estimating the water-budget components of a watershed, showed that annual vaporization losses computed as the difference between precipitation and runoff may be in error by as much as ± 30 percent. Reliable estimates of seasonal trends in ET for a watershed generally require that changes in moisture content also be measured (Row and Reimann, 1961).

8.D.2.b.3. ESTIMATION OF ET FROM FLOODPLAINS

Application of the hydrologic budget to a reach of floodplain requires that all significant surface and subsurface inflow be quantified along with the precipitation and surface-water outflow components. For narrow riparian reaches where the stream channel is graded to bedrock and the floodplain is of only limited extent, estimates of ET may be obtained by evaluating only precipitation and the surface-water inflow and outflow components (Taylor and Nickle, 1933; Bowie and Kam, 1968). However, most riparian areas require that changes in storage of the ground-water reservoir be evaluated, as this component may provide a significant contribution to ET.

For large floodplain areas, downvalley ground-water movement and moisture content in the unsaturated zone generally are significant components of the hydrologic budget. Budget studies for large floodplain areas are described by Gatewood and others (1950) and Hanson and others (1972). Culler (1970) gives a detailed description of the instrumentation, methods of data collection, and problems to be considered when designing a comprehensive hydrologic-budget study for a large floodplain of phreatophyte cover.

Estimates of ET for riparian areas based solely on analysis of the streamflow hydrograph have been successful in some instances. Reigner (1966) used diurnal fluctuations of the streamflow hydrograph to calculate daily ET rates and Langbein (1942) used base flow recession curves to obtain an estimate of monthly ET.

Daily fluctuations in the ground-water table were used by White (1932) and Troxell (1936) to compute the total quantity of ground-water withdrawn by ET during a day. In a more recent study, Weeks and Sorey (1973) used an array of five observation wells in a floodplain to measure monthly ET rates.

Generally, methods utilizing only the streamflow hydrograph or ground-water level fluctuations have limited application and, in most instances, are not recommended for estimating ET.

A comprehensive abstract bibliography of the studies performed to date (1976) on evaluation of ET from watersheds and floodplain areas is presented by Horton (1973). An extensive bibliography on phreatophytes, listing studies which have applied various approaches in the hydrologic budget, is available in Paylor (1974).

8.D.2.c. SOIL-MOISTURE DEPLETION METHOD

Probably the oldest and most commonly used method of determining evapotranspiration is measurement of the change in soil-moisture content at representative sites over a time period of a few days to several weeks. Soil-moisture depletion approximates evapotranspiration under ideal conditions, where rainfall is estimated from gage data, the water table is considerably below the root zone, and there is no significant drainage from the root zone. Attempts to measure the flux of soil water upward or downward below the root zone at representative sites using flux meters have not been successful because of the difficulty of installing these meters without disturbing the vegetation and soil at the site. Similarly, attempts to estimate the upward or downward movement of soil water by measuring the hydraulic gradient and calculating the hydraulic conductivity have not been very successful because very small hydraulic gradients are involved and hydraulic conductivity is a highly nonlinear function of the soil-water content. However, measurement of the hydraulic gradient may indicate when upward or downward flow can be ignored. Also, soil moisture may move upward or downward due to thermal and salt gradients which can introduce significant error under some circumstances. When precipitation is involved, it also must be measured accurately to determine evapotranspiration indirectly by soil-moisture depletion. Additional information can be found in a recent American Society of Civil Engineers (ASCE) report (Jenson, 1974).

8.D.3. ENERGY-BALANCE METHOD

The energy-balance method of determining evapotranspiration is based on the conservation of heat energy. Only a few studies have been conducted continously for more than several days because of complex instrumentation requirements, maintenance problems, and voluminous amounts of data that must be processed and interpreted (Denmead and McIlroy, 1970). Automatic recording devices and field systems equipped with digital computers or microprocessors can greatly simplify data processing.

Accurate daytime determinations of evapotranspiration using energy-balance techniques are relatively easy to obtain for well-watered, actively growing vegetation because the water-vapor gradients are large compared to temperature gradients. Accurate nighttime measurements are difficult to obtain because the net radiation flux is nearly equal to the net soil-heat flux and vapor gradients usually are very small. The energy-balance method is not as reliable for desert areas where the soil surface is dry or in areas where there is very little transpiration because of sparse vegetation or where vegetation is matured or dormant. Thorough discussions of this method and instrumentation requirements are presented by Tanner (1960), Fritschen (1965), Denmead and McIlroy (1970), and Blad and Rosenberg (1975).

8.D.4. MASS-TRANSFER METHODS

Mass-transfer methods for determining evapotranspiration generally require very complex instrumentation and well-trained personnel. Very few determinations of evapotranspiration with this technique have been made over long time periods because very accurate measurements of windspeed and specific humidity (mass of water vapor per unit mass of moist air) are required.

8.D.4.a. DIRECT MEASUREMENTS

The eddy-flux approach is the most direct means of determining evapotranspiration if the vertical vapor flux over the surface can be measured, which requires the integration of the instantaneous product of vertical airflow and water-vapor content. Under natural conditions, both of these quantities fluctuate rapidly and significantly because turbulent diffusion dominates the transfer process in the boundary layer above the land, water, or vegetated surfaces. Basically, this method is still in the development stage (Swinbank, 1951; Dyer, 1961, 1968; Gangopadhyaya and others, 1966; Goddard and Pruitt, 1966; Tanner, 1966; Swinbank and Dyer, 1967; and Christian and others, 1970).

8.D.4.b. INDIRECT MEASUREMENTS

Several methods have been developed to determine vertical vapor flux indirectly. Generally, these are less accurate than the eddy-flux method. For instance, the profile method requires the determination of the mean horizontal wind velocities and specific humidities at two or more heights above a uniform surface within the equilibrium boundary layer. Under nonneutral conditions, the temperature gradient is also needed (Thornthwaite and Holzman, 1942; Priestly, 1959; Dyer, 1963, 1965; King, 1966; Pruitt and others, 1973; and Pierson and Jackman, 1975).

Probably the most common mass-transfer method is based on the Dalton equation, which involves the product of a windspeed function based on windspeed measured at some height above the surface, and the difference between the water-vapor pressure at that height and at the evaporating surfaces. Penman (1948) developed an expression for estimating ET from well-watered grass which is similar to that developed for water surfaces by Rohwer (1931). Pruitt (1963) developed a similar expression for well-watered grass at Davis, Calif. Estimates of the foliage temperature are needed when the surface temperature is not the same as the air temperature in order to obtain the surface vapor pressure.

8.D.4.c. USE OF ENCLOSURES

Evaporation can also be measured by determining the changes in water vapor content of measured airflow through an enclosure over the natural surface under study. However, evaporation inside such an enclosure may not be the same as that occurring outside the enclosure. Windspeed, wind distribution, and net radiation must be identical to those occurring under natural conditions. Accurate measurements of humidity and airflow rate are required, but these are not too difficult to achieve (Decker, 1960; Lee, 1966; and Mace and Thompson, 1969).

8.D.5. COMBINATION METHODS

The combination equation can be used to determine evapotranspiration if, along with the temperature and vapor pressure of the evaporating surfaces, the air stability is known. This allows one to compensate for buoyancy when the surface is warmer than the air mass; for natural stability due to cooler, dense air near the evaporating surface; and for the aerodynamic roughness of surface. The combination equation can be used in a form similar to that described by either Monteith (1965) or Tanner (1968). The aerodynamic components of the combination equation described by Monteith and Tanner are very similar to those described by Businger (1956, 1966) and van Bavel (1966). They basically relate to hour-by-hour predictions of ET. The combination equation was first presented by Penman (1948) using weekly mean climatic data in empirically derived expressions for the energy and the aerodynamic components. Later revisions included an additional parameter to account for leaf resistance (Penman, 1956, and Monteith, 1963). Pruitt and Doorenbos (1977) suggest an empirical correction to estimates from the Penman equation to account for differences in day-night wind patterns and an interaction with maximum relative humidity (RH) and solar radiation level.

8.D.6. PREDICTION METHODS

8.D.6.a. POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration is defined as the rate of water loss from a wet soil or well-watered, actively growing vegetation, or as the rate of evaporation from a water surface. These may not be the same. Investigators should not report potential evapotranspiration without describing the surface involved in the measurements or for which the estimates are provided, nor should one compare reported values of potential evapotranspiration without first considering the character of the surface to which the values apply. In addition, measurements of potential evapotranspiration may not be representative of a large area if the instrumented site is not representative of that area or does not have adequate fetch. A well-watered short crop like alfalfa with 30 to 50 cm (12 to 20 in.) of top growth and a well-watered, actively growing grass clipped to 10 to 15 cm (4 to 6 in.) are the most common reference surfaces. A similar crop surface for at least 100 m (330 ft) upwind is needed. Some values reported in the literature, measured under unrealistic site conditions even though measured accurately with a lysimeter, can be as much as three times higher than the evapotranspiration that can actually occur from fields or large areas of native vegetation under natural conditions.

8.D.6.a.1. EMPIRICAL EQUATIONS

Numerous empirical equations based on climatological data have been developed during the past three decades for estimating potential evapotranspiration. The earlier procedures were based mainly on air temperature, with some adjustment for solar radiation that usually used latitude or percentage of possible daytime hours. For example, studies in the 1920's related evapotranspiration to air temperature. Probably the most commonly known and widely used air temperature method is that proposed by Blaney and others (1952), Blaney and Criddle (1962), and Thornthwaite (1948). The basic assumption in the Blaney-Criddle equation is that monthly evapotranspiration from an actively growing, well-watered crop varies directly with the product of mean monthly air temperature and the percentage of total annual daytime hours for that month. Originally, coefficents (K) were developed for the total seasonal evapotranspiration for crops like alfalfa or a grass. Later, these coefficients were modified for monthly periods (k), and they have been developed for various types and densities of vegetated cover. However, most published monthly crop coefficients are not independent of climatic conditions (Quackenbush and Phelan, 1965; Jensen, 1966a, 1966b). Monthly coefficients for each type of vegetation should be determined within a given area or under very similar climatic conditions. There have been modifications of this approach by the Soil Conservation Service (SCS) and by the Food and Agricultural Organization (FAO) that have improved accuracy (Pruitt and Doorenbos, 1977).

Thornthwaite also developed an empirical equation utilizing mean monthly air temperature and an adjustment for latitude to compensate for differences in solar radiation (Thornthwaite, 1948; Thornwaite and Mather, 1955). Because the Thornthwaite equation was derived under humid conditions typical of those in the southeastern United States utilizing measured evapotranspiration and mean monthly temperature in the region, its utility for semiarid and arid areas is limited if accurate values are desired. The Thornthwaite procedure basically has not been changed since 1948 and is probably the most abused equation when used for semiarid and arid areas. Many investigators have made estimates of evapotranspiration using the Thornthwaite equation that are in error by as much as 50 to 100 percent. The main justification for using the Thornthwaite equation in many situations is that air temperatures are the only climatic data available. This is hardly a valid justification for generating estimates of potential evapotranspiration if their accuracy is questionable. The original authors of the procedure also severely limited its application, but this has often been ignored. Thornthwaite and Mather stated in 1955, "First, the albedo of the evaporating surface must be a standard. Second, the rate of

evapotranspiration must not be influenced by advection of moist or dry air. And, finally the ratio of energy utilized in evaporation to that of heating the air must remain essentially constant." Since these conditions essentially do not exist for long periods of time even in subhumid areas, and generally do not exist at all in arid and semiarid areas, the equation cannot be expected to provide reliable estimates of potential evapotranspiration in such areas.

The most reliable empirical equations for estimating potential evapotranspiration are those based on solar or net radiation including the combination equation. Under nonadvective conditions, estimates of potential evapotranspiration based on measured or estimated net radiation are very conservative and accurate. The equation proposed by Priestly and Taylor (1972) has recently been critically evaluated in subhumid areas of the United States and found to be less erratic than the combination equation (Ritchie, 1982). Pruitt and Doorenbos (1977), however, found ET to be estimated closely by the Priestly-Taylor equation at only 2 sites out of 10, even though 5 of the 10 sites were in subhumid-to-humid areas of the world.

Makkink (1957) developed an empirical equation for estimating potential evapotranspiration which uses solar radiation and air temperature. This equation is applicable to the cool, marine climatic conditions of the Netherlands and is reasonably accurate for 10-day estimates of potential evapotranspiration for short, well-watered grass in coastal climates. Pruitt and Doorenbos (1977) present a more generally applicable adaptation of Makkink's equation, although estimates of mean humidity and wind are required for the climate involved.

Turc (1961) simplified an earlier version of an equation for estimating potential evapotranspiration for 10-day periods under the general conditions of western Europe. Turc's equation requires solar radiation and air-temperature estimates if relative humidity is greater than 50 percent, and relative humidity as well if the relative humidity is less than 50 percent. The Turc equation is most reliable for cool climatic conditions similar to those in western Europe or in coastal areas.

Jensen and Haise (1963) reported on an evaluation of 3,000 observations of evapotranspiration determined by soil sampling by numerous scientists over a 35-year period. From a selection of about 100 values of reported evapotranspiration from well-watered crops with full cover in the western United States, a relationship between evapotranspiration and solar radiation and air temperature was developed. This was later modified (Jenson, 1966b; Jensen and others, 1970) to adjust the coefficients for elevation and humidity by considering mean maximum and mean minimum air temperatures during the warmest month of the year.

Christiansen (1968) and Christiansen and Hargreaves (1969) developed equations for estimating potential evapotranspiration based on a stepwise regression of measured evapotranspiration from short grass and solar radiation, with modification, if available, for temperature, windspeed, relative humidity, and elevation. The main equation is a product of solar radiation and a series of coefficients. The modifying coefficients are selected so that each is equal to 1.0 at a temperature of 20° C, an average daily windspeed of 6.7 km/h (100 mi/d), and a mean relative humidity of 60 percent, respectively. If solar radiation is estimated using extraterrestrial radiation, the formula includes similar coefficients for mean percentage of sunshine, with the coefficient equal to 1.0 at 80 percent sunshine and an elevation coefficient equal to 1.0 at 305 m (1,000 ft). Tables of coefficients and their logarithms are provided by the authors. The Christiansen method has been shown to provide reliable estimates for coastal areas (Jensen, 1974).

Estimates of potential evapotranspiration can also be made from pan-evaporation data. Pan evaporation can provide very reliable estimates of potential evapotranspiration provided the site and the immediate fetch surrounding the pan are standardized. The type of pan involved also affects the coefficients to be used with pan-evaporation data—especially in dry climates where pans are surrounded by a dry surface. Pan evaporation appears to be more sensitive to wind conditions than evapotranspiration from well-watered, short grass, especially when radiation levels are lower, as they

are in the spring and fall months. Comprehensive discussions of pan evaporation are included in a recent FAO publication (Doorenbos and Pruitt, 1977), in a report of the ASCE Irrigation Water Requirements Committee (Jensen, 1974), and in a World Meteorological Organization (WMO) report (Gangopadhyaya and others, 1966). The State of California Department of Water Resources (1973) has also made a comprehensive analysis of evaporation measured throughout the State with pans sited in irrigated pastures. This report contains pan coefficients based on field studies for a large number of crops. The importance of proper siting and providing a standard fetch for the evaporation pan cannot be overemphasized. The California Department of Water Resources data showed that the annual evaporation from a pan located at a dryland site in California was about 60 percent greater than evaporation from the same type of pan located in a nearby irrigated pasture. Similar results have been shown by many other investigators. Additional details on evaporation pans can be found in numerous publications (Rohwer, 1931, 1934; Young, 1947; Kohler, 1955; Hounam, 1958; Pruitt, 1960; Stanhill, 1962; and Gangopadhyaya and others, 1966). With a proper pan environment, mean monthly potential evapotranspiration can be predicted within ± 10 percent or better for most climatic conditions, except perhaps where dry winds predominate for a part of the season, or where small upwind fetches of dry or wet-dry conditions prevail.

A comprehensive summary of linear relationships among observed monthly evaporation data from well-watered grass and four climatic indices also is presented for California by the California State Department of Water Resources (1973). The four climatic indices are pan evaporation (National Weather Service class A pan), net atmometer evaporation, solar radiation, and the Blaney-Criddle "f" factor.

8.D.6.b. EVAPOTRANSPIRATION

Estimating evapotranspiration for various crop surfaces usually involves first estimating the potential evapotranspiration and then applying coefficients to account for partial plant cover during the period of crop development, the characteristics of the crop with full cover, and the effects of maturity of crops. A comprehensive summary of coefficients for various types of crops has been presented by Doorenbos and Pruitt (1977) in a recent FAO publication. The California State Department of Water Resources (1973) also has presented a comprehensive summary of the ratios of monthly evapotranspiration to pan evaporation for the principal irrigated crops in California, along with growing seasons and root depths.

New approaches to estimating evapotranspiration by crops at various stages of growth involve the leaf area index (LAI), or area of leaves per unit of land area (Hanks, 1974; Kristensen, 1974; and Ritchie, 1974). As LAI approaches and exceeds 3, climatic conditions control evapotranspiration for most well-watered farm crops. Similarly, various functions are used to estimate the decrease in evapotranspiration as soil moisture is depleted (Jensen and others, 1970; Hanks, 1974; and Ritchie, 1974).

8.D.7. REFERENCES

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8.E. TRANSPIRATION MEASUREMENT METHODS

8.E.1. INTRODUCTION

A method has yet to be devised that provides an actual measurement of transpiration from any significant area of plant-covered land. Mentioned in the literature are techniques that can provide accurate measurement of transpiration, but only for single plants or parts of plants and usually under atypical environmental conditions. Several methods can provide credible estimates of transpiration loss from areas of plant-covered land; a few references from the recent literature illustrate their theory, instrumentation, and applicability. All of these methods are discussed in other sections of this chapter; discussion in this section is restricted to their adaptation for estimating transpiration from plant-covered land.

8.E.2. STATE OF THE ART

Scientists have sought to measure transpiration for more than 300 years, but despite continuing effort, transpiration from any significant expanse of plant-covered land has never been measured directly. Many techniques have been devised to provide accurate measurements of transpiration for a given leaf or even for whole plants under laboratory conditions. The process, however, is subject to enormous variation, temporal as well as spatial, over most plant-covered landscapes, so that measurements must be extrapolated to areal estimates very cautiously. Furthermore, many reports obscure our understanding of published measurements by failing to define the transpiration through leaf stomata of water taken from the soil by living plants. Transpiration accounts for about 95 percent of plant-water use (Kramer, 1969), most of it lost through stomata simply because they provide an evaporative path of low resistance. Minor amounts of water also evaporate through the leaf cuticle and stem lenticels, and by guttation. The unevaporated 5 percent of water used by plants is consumed in growth, respiration, and photosynthesis. For present purposes, these consumptive processes will be lumped with transpiration; not only are they relatively small but they are indistinguishable by most measurement methods.

Transpiration must be carefully distinguished from evapotranspiration, which includes, in addition to transpiration, the evaporation of water intercepted on plant surfaces and from moist land surfaces (see section 8.D). The importance of separating transpiration and soil evaporation losses is illustrated in studies of crop-water use by Black, Tanner, and Gardner (1970). Other estimates of transpiration loss are inflated by failure to account for water draining deep into the soil, beneath the reach of plant roots (Black, Gardner, and Tanner, 1970). But despite these almost unaccountable water losses that confound some estimates of transpiration, there are times when transpiration does equal evapotranspiration. For example, consider a situation where unwetted green plants fully shade the dry surface of a moist soil from which deep drainage is minimal. Our point is that equality can occur but it is not common.

One of two primary factors determining the rate of transpiration is heat energy available at the leaf surface or, more exactly, at the stomatal aperture. Without heat energy, there is no transpiration. Wind velocity and vapor pressure act to modify evaporative demand as determined by available heat energy. Thus, interacting atmospheric influences establish the potential or upper limit of evaporative loss. Some of the physical principles controlling evaporation (that is, the physical principles that control the capacity of air as a water-absorbing medium) are reviewed by Gates (1966).

The second of these primary factors is water available for evaporation. Even though transpiration is essentially an evaporative process, it differs significantly from evaporation in the physical sense because transpiration losses are modified by soil properties, plant morphology, and stomatal behavior.

Knowledge of the physics and physiology of transpiration is essential for full understanding of the process but not for its measurement, so there will be no further discussion here of fundamental studies.

These limited capabilities in transpiration measurement are corroborated by Pereira (1973, p. 55, 59), one of the world's leading hydrologists.

> Under natural outdoor conditions it is not yet possible to claim that evaporation from lakes, rivers, marshes, fields, and forests can be measured, but we can make some good estimates. . . .
>
> Water loss from crops, pastures, or forest is even more difficult to measure than is evaporation from open water. Observations--for some 300 years--have gained much information about plants but remarkably little about their transpiration. . . .

8.E.3. DIRECT MEASUREMENT OF TRANSPIRATION

The plant physiology literature describes many methods for measuring transpiration accurately but under conditions often far removed from the natural plant environment. They range in complexity from simple (cobalt chloride paper) to space-age (beta ray gaging) technology. Methods falling between these extremes of technical complexity include weighing plants or parts of plants; thermocouple psychrometry; corona analysis; the pressure bomb; and variously designed porometers, potometers, and phytometers. Stocker's description (1956) of direct transpiration measurement methods is perhaps the most complete single source of information concerning them.

All such approaches share the common uncertainty of employing small plants or even parts of plants, often with their transpiring surfaces exposed to evaporation under conditions atypical of the plant's usual surroundings. The temporal and spatial limitations inherent in these techniques (Brun and others, 1973) are readily apparent. The representativeness of transpiration so measured is open to question because of the modifications to the plant or its environment required (Slatyer, 1967). To take an extreme example, it seems inconceivable that an excised leaf disc will transpire in a darkened, controlled-climate chamber at the same rate as the canopy of leaves remaining on the parent plant.

Measurements of transpiration based on direct methods can be of great value to scientists who seek to understand the physiology and physics of the process. These measurements must, however, be extrapolated to field conditions with great caution. Even though considerable conformity is possible among such measurements (Kochenderfer and Lee, 1973), the uncertainty inherent in extrapolating from accurate measurement on tissue samples in atypical surroundings is readily apparent.

These problems, troublesome enough in the relatively uniform fields and crops of agriculture, loom overwhelmingly in the forest where trees of many species and sizes compete for enormously variable supplies of water and energy. When transpiration must be quantified from any considerable expanse of plant-covered land, methods other than direct measurement usually provide estimates more acceptable to the scientific community. In other words, even the most accurate microscale measurement of transpiration is suspect as a basis for quantifying the macroscale transpiration loss from square miles of variously vegetated land.

8.E.4. INDIRECT ESTIMATES OF TRANSPIRATION LOSS

Transpiration, like other evaporation processes, is invisible and unsuited to the kind of absolute measurement one would use, for example, to quantify the use of gasoline from an automobile tank. For plant-covered surfaces larger than a few square feet, transpiration losses must be based on carefully derived estimates. The distinction between a measurement and an estimate must be made clear. The measurement of transpiration specifies an observed water loss within a given time and space, as, for example, the weight loss from properly prepared potted plants or the volume of water conducted

through a plant stem. Transpiration from plant-covered land is estimated by extrapolating from one or more samples of measured loss to the presumed loss from entire plant populations. Thus, one might estimate transpiration from an acre of grassland when pounds of water lost from one square foot of potted sod are multiplied by 43,560, or when gallons of water conducted through one tree stem are multiplied by the number of trees of similar size per acre in a forest stand. Clearly, the accuracy of transpiration measurement is critical to the validity of areal estimates, but so is assurance that samples do in fact represent the entire plant population accurately. These are matters of well-founded technical and statistical procedure that will not be discussed here.

Each of the following brief statements on methods for estimating transpiration includes one or more studies reporting a credible quantification of that loss. No attempt was made to review the considerable literature on each method. Nor are procedural details included here; they are available in the cited literature. Furthermore, each of these methods is touched upon in sections 8.B and 8.D of this chapter. Only those features relevant to estimating transpiration are added here. These methods follow in the order presented in sections 8.B and 8.D.

8.E.4.a. WATER-BALANCE METHODS

This approach requires measurement of precipitation and a means to quantify all but one of its losses from the wetted land. Each of the quantified losses (interception, soil moisture storage, deep percolation, and streamflow) is deducted from precipitation; the remainder is assumed to be transpiration. All of these losses are subject to measurement error, thus building some uncertainty into the resulting estimate of transpiration. Ward (1971) nevertheless suggests that if the water-balance equation can be solved, then it is likely that its components have been satisfactorily estimated. The water-balance approach is best suited for long-term estimates of transpiration in humid climates where ample soil moisture permits transpiration to proceed at rates controlled by available heat energy. Gaged watersheds are, of course, essential. Annual transpiration loss was computed by this means as 17 inches for a forested watershed in West Virginia (Patric, 1973).

The water-balance approach is most feasible with forests because there is little or no direct evaporation from soil heavily covered by litter. It is less feasible on agricultural land where evaporation from bare soil is the only water loss from fresh-tilled fields. Evaporation decreases in importance as crops grow. Transpiration gradually becomes the major water loss as crops reach full growth, but it temporarily ceases when hay is cut (Harrold and Dreibelbis, 1967). The near impossibility of separating evaporation from transpiration and deep percolation under farm conditions precludes most use of the water balance to estimate transpiration losses from cropland.

In some of the older literature, diurnal fluctuation of streamflow on gaged watersheds is interpreted as an effect of transpiration. These fluctuations probably are more accurately accounted for as evapotranspiration.

Given complete vegetative cover, it may prove possible to estimate transpiration from measurements of lowered water tables, an opportunity most often found in arid regions. Water losses under these conditions are more likely to be from evapotranspiration than from transpiration as here defined.

8.E.4.a.1. LYSIMETERS

Some authorities (Australian Water Resources Council, 1970) believe that well-designed lysimeters offer one of the best approaches to quantifying evaporative losses from land surfaces. Precipitation, overland flow, deep percolation, and changes in soil-moisture content can be quantified accurately, with the transpiration loss calculated by water balance.

Reliable lysimetric estimates of transpiration loss have been reported for crops (Harrold and Dreibelbis, 1967), grass (Pruitt, 1964), phreatophytes (van Hylckama, 1970), and shrubs (Patric,

1974). Valid daily and even hourly estimates of transpiration are possible with sensitive weighing lysimeters. Reliable lysimetric estimates of transpiration require meeting two poorly defined criteria. First, lysimeter-grown vegetation should be surrounded by sufficient expanses of like vegetation to insure representative exposure of plants to changing heat, vapor pressure, and wind. What constitutes "sufficient expanses" has never been clearly defined. Second, the confined soil block should be large enough to insure root proliferation and soil-water distribution uninfluenced by lysimeter walls and bottoms. The latter condition is especially difficult to attain when forest trees are grown in lysimeters (Patric, 1961).

8.E.4.a.2. SOIL-MOISTURE DEPLETION METHODS

Chapter 6 of this handbook deals in detail with soil moisture and its measurement, yet another approach to quantifying transpiration. Here, too, the water balance must be relied upon to provide an estimate. Given quantification of precipitation, interception loss, deep percolation, and evaporation from the soil surface, losses of soil moisture over time can be attributed to transpiration. It is crucial for obtaining valid estimates of transpiration that the network of stations for sampling soil moisture be designed to provide results accurate to a predetermined level.

This approach remains a mainstay of agriculturists and foresters seeking to quantify transpiration from crops and trees. Some soil-moisture depletion studies are designed to disregard rainfall interception losses, knowing that they merely depress transpiration rates until plants dry after rains (Nicholson and others, 1968). Covering the soil with plastic or some other impervious material minimizes evaporative loss from moist soil surfaces. Some investigators account for water percolating deep beneath the reach of plant roots. With each of the preceding water uses duly accounted for, decreases in soil-water content are equatable to transpiration loss. Transpiration from plastic-covered corn plots increased with plant growth, peaking when corn foliage completely shaded the soil (Peters and Russell, 1959). Trees on fully wetted, deep, plastic-covered soils transpired at near-potential rates as soon as leaves were fully grown (Patric and others, 1965). The former study was based on results of gravimetric soil sampling, still relied upon heavily in agricultural studies; the latter used the neutron-moderation technique, especially well adapted to forest soil-moisture measurement.

8.E.4.b. ENERGY-BALANCE METHOD

The usefulness of this method for estimating transpiration is limited. Transpiration from a single leaf can be calculated if leaf temperature, air temperature, absorbed radiation, and windspeed are known (Gates, 1964). The calculation requires knowledge or measurement of total solar spectrum absorptivities for individual leaves. Transpiration rates for 22 tree species were measured by Birkebak and Birkebak (1964) and for 18 species by Gates and others (1965).

Heat-transfer coefficients are also required and have been calculated from horizontal plate theory and verified for oak, magnolia, and cherry leaves (Knoerr and Gay, 1965). The basic procedure has been further modified with values of leaf resistance to water loss (van Bavel, and others, 1967; Miller and Gates, 1967).

The energy-balance technique is impractical for most transpiration- measurement needs because of the extensive instrumentation required. However, criteria for sampling mean leaf temperature by canopy levels are proposed by Miller (1971). To date, there has been no direct measurement of transpiration for an entire plant canopy using the energy budget.

8.E.4.c. MASS-TRANSFER METHODS

These methods for estimating transpiration are derived from measurements of vapor pressure and windspeed (Rosenberg and others, 1968). Indirect evaluations of transpiration can be made using

combinations of mass-transfer, energy-budget, and plant-parameter components. The difference between potential evapotranspiration and soil evaporation has been used to calculate the transpiration of snap beans, with modifications for stomatal resistance, leaf area index, wind velocity, and wind-profile parameters (Black, Tanner, and Gardner, 1970). The combination model SPAM (soil-plant-atmosphere model) is also available for calculating transpiration and photosynthesis rates (Sinclair and others, 1974). Models by Penning de Vries (1972), Reed and Waring (1974), and Shirazzi and others (1976) may be useful.

These models are limited in usefulness, however, because of the extensive measurements required and because they have been verified under a small number of conditions.

8.E.4.d. USE OF ENCLOSURES

Water is added to unsaturated air whenever the air moves across transpiring leaves. Thus, the increased humidity of air forced through chambers enclosing all or parts of plants provides a direct measure of transpiration loss. Chambers may range in size from a few cubic centimeters (Chatterton and Lee, 1973) to many cubic meters (Sebenik and Thames, 1967). Some of these devices use ambient air while some of the more sophisticated require air under rigid quality control (Pallas, 1973). Transpiration losses are accurately measured by these means, but questions always arise concerning the unavoidable difference between the climate within the chambers and a plant's natural environment. This equipment, too, is not readily portable.

8.E.4.e. COMBINATION METHODS

Physicists and engineers often interpret transpiration not as a vital process controlled by the plant but as the plant's unavoidable response to its physical environment. They regard transpiration as a leakage process controlled by the heat energy available for evaporation, an interpretation long championed by Penman (1963). Biologists, however, often find this viewpoint unacceptable (Lee, 1967). A model by Monteith (1965) blends both viewpoints into a method for estimating transpiration losses based on physical as well as biological parameters. The physical approach has long been used to quantify evapotranspiration and, with adequate biological refinement, seems to be the best now available for estimating transpiration losses under field and forest conditions.

8.E.4.f. HEAT-PULSE METHOD

This method seems best adapted for use on trees, where long and rigid stems conduct relatively large transpiration streams. A spot on the stem is heated quickly and the rate of ascent (R) of the heated sap is timed. Given the cross-sectional area (A) of the sap-conducting column, the transpiration rate (T) is calculated by $T = R \times A$. Conventional electric heating devices as well as short-wave radio energy (Ladefoged, 1960) may provide the heat pulse. By this method, Duam (1967), Swanson (1972), and Lassoie and others (1977) have made estimates of transpiration losses from forest trees which agree well with checks by other means. The heat-pulse method suffers from several disadvantages. It seems to work best on smaller trees, and the equipment is not readily portable or well adapted for use with agronomic plants.

8.E.4.g. RADIOISOTOPES

Many radioactive materials can be injected into trees (or soils) and their subsequent movement in the transpiration flow traced. Flow rate and cross-sectional area measurements then are calculated to estimate volumes of water movement through tree stems, that is, transpiration loss. Such estimates of water use have ranged from 0.16 cm/d in western conifers (Owston and others, 1972) to a maximum of 0.8 cm/d in eastern hardwood forest (Kline and others, 1971). This method requires sophisticated

equipment and a high degree of training in its use. The public health implications of using radioisotopes must not be overlooked. The method nevertheless seems one of the most promising for estimating transpiration losses from forest land.

8.E.4.h. REMOTE-SENSING METHODS

Transpiration rates have not been directly measured with remote-sensing techniques. However, thermal scanners from SKYLAB have been used to detect moisture stress in various soil-plant conditions.

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8.F. EVAPORATION FROM SOIL SURFACES UNDER PLANT CANOPIES

8.F.1. INTRODUCTION

One method of obtaining independent measurements of the components of evapotranspiration (ET) is to measure the soil surface evaporation (E) under plant canopies independently and subtract it from some measure of the total ET in order to obtain the transpiration component (T). Denmead (1973) has shown that these two components are essentially independent and therefore additive. Stanhill (1973) discusses this separation of E and T as being an important step in further developing various water conservation controls and practices. He further states, however, that there are some mutual relationships between E and T. For example, as the soil surface dries and rates of E decline, more of the energy reaching the soil surface will be partitioned into sensible heat, which may be used to increase T from leaves lower in the canopy. The measurement of E under plant canopies has considerable bearing on the treatment of the soil surface in irrigation scheduling programs (Jensen and others, 1971). An independent measure of T is needed for modeling water uptake by root systems where T is directly related to the amount of water absorbed by roots. Measuring E under plant canopies can be of interest in many applications—for example, an agricultural row-crop, an orchard with bare soil underneath trees, or a forest floor.

Measuring evaporation from soil under canopies at first appears to be a special application of measuring bare-soil evaporation. There are some restrictions and complications that make this more difficult than simply applying the techniques explained in section 8.C. The bare-soil surface under plant canopies is different from that of an open field in that (1) the microclimate is changed by the presence of vegetation and (2) plant roots permeate the lower soil layers and uptake by plant roots establishes soil-water potential gradients that may alter the rate and direction of water flow to the evaporating sites.

The presence of vegetation alters the microclimate and in many cases makes meteorological techniques for measuring evaporation inapplicable. Certain basic assumptions as to fetch, homogeneous distribution of evaporating surfaces, and the like, cannot be made. In this discussion we will briefly review some approaches to measuring E under canopies, classified as direct measurements, modeling or empirical approaches, and meteorological approaches.

8.F.2. DIRECT MEASUREMENT

Direct measurement has been made of E under canopies, using lysimeters placed under the canopy. Stanhill (1973) reviews some of the problems involved in using this method. The limitations of "containers," "monoliths," "lysimeters," and the like placed under the canopy are: (1) the volume of soil involved is isolated from plant roots and the effect of water uptake by plant roots is eliminated, (2) drainage of the soil layer enclosed by the lysimeter may be restricted, and (3) upward movement of water may be restricted. Stanhill suggests that some of these problems can be overcome by replacing bare-soil monoliths at frequent intervals with replicates taken from the unmeasured soil surface. Al-Khafaf and others (1978) have reported measurements of E under a cotton crop canopy using containers 30 cm in diameter and 30 cm deep embedded in the soil under the canopy. They did not state how they adjusted for the limitations described above, but did show reasonable agreement between cumulative loss from containers and cumulative water-content changes for the 0-to-10-cm and 0-to-100-cm soil layers. Shawcroft and Gardner (1982) measured E under a corn crop canopy using small lysimeters (20, 10, and 5 cm deep) embedded in the surface soil and also conducted detailed soil sampling at comparable depths outside the lysimeters. They found the 20- and 10-cm-deep lysimeters gave good estimates of E under the canopy, as compared to net, cumulative change in water content of the soil, as long as the average water content of the soil in the lysimeter was maintained slightly above that of the comparable soil layer outside of the

lysimeters. They followed E over a drying cycle of about 16 days and showed how both the energy-limiting and soil-limiting phases of evaporation could be measured.

Water-balance methods for shallow layers may give reasonable estimates of E under canopies, but Jackson (1973) showed that the shallow layer typically is a dynamic zone of both upward and downward redistribution of soil water. This factor plus the need to evaluate the effect of plant water uptake makes simple water-content changes as a measure of E somewhat misleading.

The device described by Arkin and others (1974) has application for measuring E under canopies and is beneficial in that it can be automated and data logged continuously. This device maintains a wet surface at evaporation plates placed immediately under the surface. For this reason it is only useful for measuring energy-limited E.

8.F.3. MODELING AND EMPIRICAL APPROACHES

Several authors have presented modeling and empirical approaches to estimating E under canopies. Ritchie (1972) used the relationship of energy-limited E to net solar radiation at the soil surface as an estimate, and then used an empirical relationship with time to evaluate soil-limited E. Tanner and Jury (1976) used a similar approach, with slight modification, and estimated E under the canopy in both phases. Both of these approaches showed good agreement between ET measured by large lysimeters and the ET measured by the sum of the independent estimates of E and T. They had no direct measurements of E to compare with their calculated values.

8.F.4. METEOROLOGICAL APPROACHES

As Stanhill (1973) pointed out, horizontal homogeneity in a crop canopy is a necessary but limiting condition for use of both the energy-balance and aerodynamic methods underneath the canopy. This makes meteorological approaches more difficult. Some successful applications of this technique have been reported. Stanhill cites work of Kalma (1970), who applied the Bowen-ratio technique below a mature orange-tree plantation. Hanks and others (1971) used a Bowen-ratio technique to evaluate E under a sorghum canopy. Allen and others (1974) used a "profile" Bowen-ratio analogy to calculate carbon dioxide flux from the soil surface and showed how the profile Bowen-ratio technique could be used to calculate E directly by means of the energy-balance technique.

8.F.5. SUMMARY

Several techniques for the special application of measuring E have been described. The literature cited should be studied for various levels of application. Some methods are suited for short-term estimates of E under canopies; others may be suited for continual measurements. The precision of these methods will vary, and the literature should be reviewed to determine the degree of precision required for a particular application.

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Chapter 9

Snow and Ice

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COMMENTS ON CHAPTER 9

National Handbook of Recommended Methods for Water-Data Acquisition

I found this "National Handbook" chapter to be useful. Comments:

_____

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_____

I found the following method to be unsatisfactory: _____

Method _____

Reference _____

The method is unsatisfactory for the following reason(s): _____

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CHAPTER 9—SNOW AND ICE

9.A. INTRODUCTION

Only about 2.8 percent of the world's water is fresh; the remainder is in the oceans. Of the world's fresh water, 75 percent is frozen, mostly in ice caps and glaciers. Even though the ice caps and glaciers contain by far the largest percentage of the world's fresh water, they are one of the least-used sources.

Precipitation is the world's main source of fresh water. Because it is not ideally distributed in space or time for many of man's needs, seasonal forecasting of water supply on a local and regional basis is of crucial importance to water users. Precipitation deposited as snow or ice in northern drainage basins during winter sustains a major part of those basins' water supply during the months that follow. Therefore, knowledge of the rates and amounts of melt water released seasonally is necessary for accurate prediction of water availability.

Glaciers and other perennial ice masses play an important role in climatic variation; thus, our knowledge of the history and causes of climatic variation can be increased through the study of glacial fluctuations.

This chapter presents recommended methods for measuring the extent, depth, water equivalent, and other features of both seasonal and perennial snow and ice. Not all of the methods presented include detailed instructions; rather, the more accepted techniques are emphasized, and the advantages and limitations of each are discussed. Several meteorologic factors essential to snow studies have been omitted because they are discussed in Chapter 10 of the *National Handbook*. The most important of these factors are wind speed and direction, air temperature, dew point, rainfall, and solar radiation.

9.A.1. DEFINITION OF ELEMENTS [1]

Ablation.—(a) All processes by which snow or ice are lost from a snow or ice mass. These processes include melting, evaporation, sublimation, wind erosion, and calving. Sometimes calving is excluded, or the term may be restricted to surface phenomena. (b) The amount of snow or ice removed by the processes given in (a). Syn. *wastage*. Ant. *accumulation*. The term *net ablation* is ambiguous and no longer recommended. See *summer balance*.

Accumulation.—(a) All processes that add snow or ice to a snow or ice mass. These include snowfall, condensation, avalanching, snow transport by wind, and freezing of liquid water. (b) The quantity of snow or ice added by these processes. Syn. *nourishment*. Ant. *ablation*. The term *net accumulation* is ambiguous and no longer recommended. See *winter balance*.

Alter shield (see *wind shield*).—A type of wind shield.

Annual balance.—The change in mass (balance) of a glacier from beginning to end of a hydrologic year (usually October 1 to September 30), or other measurement year as defined by fixed calendar dates, determined at a point, as an average for an area, or as a total mass change for the glacier. Units of millimeters, meters, or cubic meters of water equivalent are normally used. See *mass balance, net balance*.

Avalanche.—A mass of snow moving rapidly downslope that sometimes contains rocks, soil, and ice.

---

[1] See also Huschke, 1959

Balance (see *mass balance*)

Calorimeter.—An instrument that measures heat quantities. Two types of calorimeters have been used to measure liquid water content of snow samples. In the melting type, hot water is added to melt the snow sample; in the freezing type, a freezing agent is used to freeze the liquid water in the sample.

Density (see *snow density*)

Depth hoar.—Snow crystals with stepped surfaces and occasionally a cup shape formed by temperature-gradient metamorphism within the snowpack.

Equitemperature (ET) metamorphism (formerly called destructive metamorphism).—One of several processes that cause changes in snow grains within a cold (subfreezing) snowpack. The transport of water vapor from regions of high surface energy (sharply convex portion of grains and smaller grains) to regions of lower surface energy (concave portions of grains and larger grains) leads to the production of uniform-sized, fairly well-rounded grains.

Einsinktiefe.—Depth to which the bottom section (and guide rod) of a 1-kg ramsonde with a 60° apex and 4-cm diameter penetrates into the snow under its own weight, expressed in cm.

Electromagnetic radiation.—Energy propagated through space or material in the form of an advancing disturbance in electric and magnetic fields in space or in the medium. The term "radiation" is used commonly for this type of energy, although it actually has a broader meaning. (See Huschke, 1959, p. 196).

Flood icing (see *naled*)

Firn.—A transitional phase between snow and glacier ice. Snow becomes firn after one summer; firn becomes glacier ice when its permeability to liquid water drops to zero. Occasionally, the boundary between snow and firn is based on density instead of time. Some authors consider firn a subspecies of snow, but nonfirn snow is not separately defined. Distinction may be drawn between *Alpine* or *melt firn* (formed in the presence of melting and refreezing) and *polar* or *dry firn* (formed without melting). Syn: *neve.*

Free water content (of snow) (see *liquid-water content)*

Frost.—(a) Ice crystals formed on the subfreezing surface of objects by the direct sublimation of atmospheric water vapor. (Also called hoarfrost, white frost, crystalline frost). (b) (In meteorological usage) the condition formed when the temperature of the Earth's surface and earth-bound objects falls below freezing. It is better to refer to this as periods of subfreezing temperature.

Frozen ground.—Soil whose moisture has changed predominantly to ice, with the unfrozen portion remaining as adsorbed water or water in the vapor phase. Sometimes incorrectly called "frost" or "ground frost."

Glacier.—A large mass of ice formed at least in part on land by the compaction and recrystallization of snow. It moves slowly downslope by creep or outward in all directions by its own weight, and survives from year to year. Included are small mountain glaciers, continental ice sheets, and ice

shelves that float on the ocean but are fed in part by ice formed on land. (b) Glaciers (as above) that occur in mountains only, excluding ice caps, ice sheets, and ice shelves; this restricted usage is not preferred.

Glacierized.—Covered with glacier ice. Syn: *ice covered.*

Graupel (also called snow pellets, soft hail, tapioca snow).—White, opaque ice particles that are approximately round and 2 to 5 mm in diameter, falling as precipitation. They are crisp and easily crushed in contrast to snow grains, which are hard. Graupel rebound and often break up when they fall on a hard surface. They usually fall in showers when air temperatures are near 0°C.

Ground frost.—In British usage, a freezing condition injurious to vegetation, that occurs when the temperature just above the grass is −0.9°C or below.

Ice. Water in its solid state; specifically, the dense substance formed by the freezing of liquid water, by the condensation of water vapor directly into ice crystals, or by the recrystallization or elimination of the interconnected pore spaces of fallen snow.

Icing (see *naled*)

Liquid-water content (of snow) (also called water content or free-water content).—The liquid water within a snow sample, usually expressed in percent by weight, although some prefer to express it as fraction by volume. The liquid-water content, in percent of water equivalent, is 100 minus the quality of the snow.

Mass balance (of a glacier).—The change in mass of a glacier over some defined interval of time, determined either as a value at a point, an average over an area, or the total mass change for the glacier. Units of mm, m, or m^3 of water equivalent are normally used, but kg/m^2 or kg are sometimes used.

Melt-freeze (MF) metamorphism.—The development of coarse, rounded grains within a warm or wet snow layer or snowpack. At or near the snow surface, the process is due to melting and refreezing. Deep in a warm snowpack, the process is related to the slight difference in melting temperature between small and large snow grains, which leads to the disappearances of the small grains and the enlargement of the larger grains.

Manometer.—An instrument that measures pressure differences.

Metamorphism.—Recrystallization of ice after deposition (see *Equitemperature metamorphism, Melt-Freeze metamorphism,* and *Temperature-gradient metamorphism*).

Naled.—A deposit of ice formed when flowing water works upward to the surface and freezes on top of it. The process often continues for much of the winter, so that large ice accumulations may cover a flood plain and last even through the summer. Syn: *Aufeis.* Cf: *icing* or *flood icing.*

Net balance (total net balance).—The change in snow, firn, and ice storage from the time of minimum mass in one year to the time of minimum mass in the succeeding year (the balance year). May be determined at a point, as an average for an area, or as a total mass change for the glacier. Units of mm, m, or m^3 of water equivalent are normally used. See *annual balance, mass balance, summer balance.*

Passive microwave (measurement techniques or procedures).—Those techniques and procedures that measure the electromagnetic radiation that emanates from a body (i.e., snowpack) as a function of the body's emittance, transmittance, reflectance, and temperature under ambient conditions.

Photogrammetry.—The sciences of measuring images on photographs.

Precipitation.—The products of condensation in the atmosphere that fall to earth in the form of rain, snow, or hail.

Pyrheliometer.—An instrument that measures the intensity of direct solar radiation.

Quality of snow (also called thermal quality of snow and snow quality).—The amount of ice in a snow sample, expressed as a percentage of the weight of the sample.

Snow density (see also *specific gravity*).—The mass of snow per unit volume, usually given in kg/m^3 or mg/m^3.

Snow quality (see *quality of snow*)

Specific gravity of snow (see also *snow density*).—The ratio of the weight of a unit volume of snow to the weight of the same volume of water. The ratio of the volume of meltwater derived from a sample of snow to the original volume of the sample. Note: these definitions and that for snow density are numerically equal if measured in units of mg/m^3.

Stereoscopic image.—Three-dimensional image produced by viewing two pictures with a special optical instrument that has a lens for each eye.

Stratigraphy (of snow cover).—The snow layers that make up the snowpack; usually in the walls of a snow pit revealed for description or study.

Sublimation.—Change from the frozen state directly to the vapor state.

Summer balance.—The change in mass or balance of a glacier from the maximum value of a balance year to the following minimum value. Sometimes erroneously called net ablation.

Temperature gradient (TG) metamorphism (formerly called constructive metamorphism).—One of several processes that cause changes in snow grains within a cold snowpack having a strong temperature gradient. Water vapor is transported from the warmer (lower) layers to the colder (upper) layers by sublimation and deposition. The relatively rapid vapor transport causes the lower portions of each snow grain to be in a supersaturated environment while the upper portions are in an undersaturated environment. This leads to sublimation from the top of the grains and deposition on the bottom of the grains above. The final result is well-oriented grains with stepped or faceted surfaces and, in advanced stages, hollow, cup like crystals.

Temperature glacier.—A glacier that at the end of summer consists of firn and ice at the melting point.

Water content (of snow) (see *liquid-water content*).

Water equivalent (of snow).—The depth of water that would result from the melting of the snowpack or a snow sample. Thus, the water equivalent of a new snowfall is the same as the amount of liquid precipitation represented by that snowfall.

Wetness (of snow) (see *liquid-water content*).

Wind shield.—A device that surrounds a precipitation gage to maintain horizontal windflow near the mouth of the gage. The wind shield prevents the catch from being influenced by eddies generated near the gage.

Winter balance.—Maximum value of glacier mass each year, measured with respect to its mass at the time of minimum balance near the beginning of the hydrologic year.

9.B. MEASUREMENT OF SNOW AND ICE

9.B.1. INSTRUMENTS AND METHODS

9.B.1.a. SEASONAL SNOW AND ICE

9.B.1.a.1. EXTENT OF COVER

Snow covers a large percentage of the Earth's surface during much of the year. Knowing its extent and rate of disappearance is important for hydrologic and climatic interpretations (IASH, 1970a, 1970b; U.S. Army Corps of Engineers, 1956). As with most hydrologic data, information on the extent of the snow cover may be of limited value unless it is accompanied by other hydrometeorologic data.

Data on the areal extent of snow cover may be useful in water-supply forecasting, particularly when the data are accompanied by quantitative measurements of the water equivalent of the snowpack. In some areas, data on snow-cover extent are useful in revising water-supply forecasts during the course of the spring snowmelt. Knowing the snow-cover extent may also help in determining the snowmelt and runoff rates.

Although the areal extent of snow cover can be estimated relatively easily, few locations have long historic records. However, recent technological developments have increased the availability of data. Problems in identifying the areal extent of snow cover include the difficulty of obtaining information during stormy periods; difficulty in interpreting the extent of areal snowcover either visually, from photography, or from other raw data; and the often rapid change in snowline position after storms. Depending on the area of investigation, snowline data may or may not have hydrologic importance.

9.B.1.a.1.a. Visual Estimation

Visual estimation of the percentage of total area covered by snow, or the snowline elevation, in mountainous terrain, is recommended as an inexpensive, rapid method for determining the extent of snow cover in small areas. These observations should be made from the same place and at approximately the same time every year, and photographs should be taken for the permanent record.

9.b.1.a.1.b. Aerial Photography

Vertical aerial photographs are recommended for (1) areas larger than 50 km^2, (2) for terrain not readily observed from accessible vantage points, or (3) when more precise information is needed

than can be obtained by visual observations. The allowable amount of overlap, tilt, crab, elevation, scale, and other photographic specifications will vary with the type of terrain and the accuracy required. The degree of accuracy needed for determining areal extent of snow cover is generally much less than that required for most other purposes. However, ground control should be established in areas of high relief; in other areas, geographical features such as streams and lakes offer sufficient ground control. Determining snow cover in forested areas presents special identification problems (Haeffner and Barnes, 1972; Blythe and Painter, 1974).

9.B.1.a.1.c. Satellite Imagery

When snow cover over very large areas must be mapped, satellite imagery offers a possibility (Barnes and Bowley, 1969; NASA, 1974; and Evans, 1974). Watersheds as small as 200 km^2 have been mapped successfully by this method. Results of snow-cover mapping seem promising; however, difficulties still remain in applying satellite imagery to operational problems (NASA, 1975). For example, cloud cover is a major hindrance, as is the time delay between date of overflight and receipt of the images or other information. In addition, it may be difficult to interpret snow cover in forests, rocks, or declilvities (Barnes and Bowley, 1969; Evans, 1974; Wiesnet, 1974; Lauer and Draeger, 1974; and Smith, 1967). Techniques for interpreting satellite imagery and advantages in using the imagery to determine areal extent of snow cover are similar to those used for aerial photography. Most interpreters now determine snow-cover extent from satellite imagery by visual interpretation supplemented by other techniques and equipment, and computers are now being used to enhance visual interpretation as well as to produce snow-cover maps and to analyze snow-covered areas by watersheds or elevation bands. Remote sensors in different frequency bands now provide an additional means for determining snow-cover extent as well as other characteristics of the snowpack, in spite of cloud cover (Meier, 1973 and Linlor, 1974).

9.B.1.a.1.d. Mapping

The extent of the snow cover or snow lines should be plotted on topographic maps (IASH, 1970b). Map scale and degree of simplification (fig. 9-1) for delineating snow edge will vary with the size of the mapping unit and the type of study. For example, in figure 9-1, line A gives a detailed outline of snow cover, line B shows a moderate degree of simplification, and line C shows a gross simplification. The dotted line delineates the extent of snow patches.

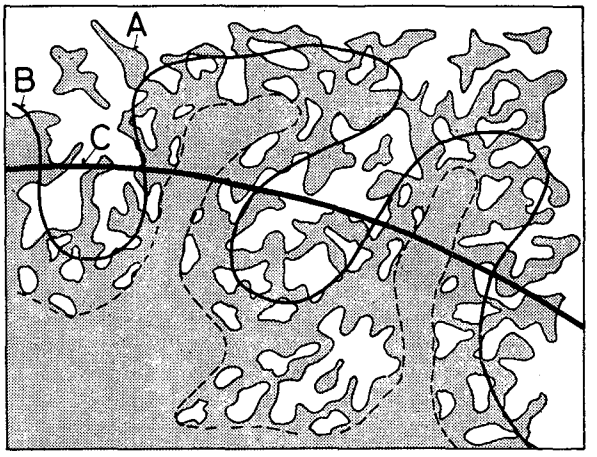

Figure 9-1.—Schematic diagram of snow lines drawn with three different degrees of resolution (A, B, and C) as an example of simplification. Dotted line represents snow-patch margin. (From International Association of Scientific Hydrology, 1970b).

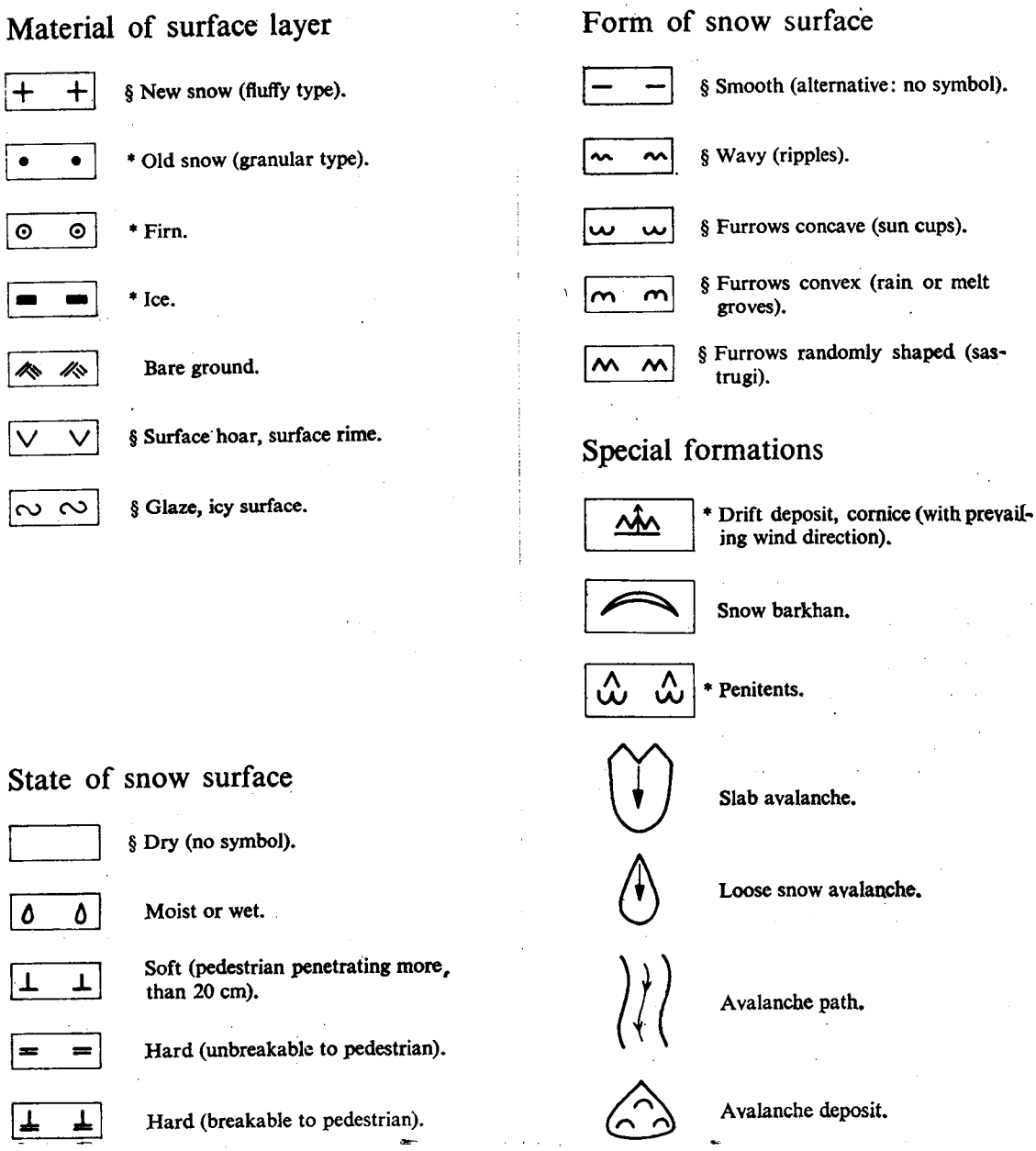

Figure 9–2 A. – Symbols recommended for depicting snow-surface features (From International Association of Scientific Hydrology, 1970b).

When applicable, snow-surface features may also be plotted on topographic maps; the recommended symbols are shown in figure 9-2A. Many are the same as those used to plot snow-pit data; others are derived from the snow-pit symbols (fig. 9-2B); still others are new.

9.B.1.a.2 DEPTH

The vertical dimension of the snow cover is called depth or height; the dimension perpendicular to the slope is called thickness. Either dimension can be measured by inserting a ruler or a probe into a shallow snowpack. Fixed or moveable stakes may also be used, but fixed stakes on steep slopes may be destroyed or moved by avalanches and snow creep. Note that techniques for measuring variation

Grain type

Symbol	*Description*
	Freshly deposited snow. Initial forms can be easily recognized.
	Irregular grains, mostly rounded but often branched. Structure often feltlike. Early stages of ET metamorphism.
	Rounded, often elongated, isometric grains. End stages of ET metamorphism. Grains usually less than 2 mm in diameter.
	Angular grains with flat sides or faces. Early stages of TG metamorphism.
	Angular grains with stepped faces; at least some hollow cups. Advanced stages of TG metamorphism.
	Rounded grains formed by MF metamorphism. Grains usually larger than 1 mm and often strongly bonded.
	Graupel. Occasionally appreciable layers of this form of solid precipitation can be identified in the snow cover.
	Ice layer, lens, or pocket.

Hardness

Symbol	*Description*	*Hand test**	*Ram number (kg)***
	Very soft	Fist	0–2
	Soft	Four fingers	3–15
	Medium hard	One finger	16–50
	Hard	Pencil	51–100
	Very hard	Knife	Over 100
	Ice	—	—

* In the hand test the specified object can be pushed into the snow in the pit wall with a force of about 5 kg. In hard snow, for example, a pencil can be pushed into the snow, but with the same pressure, a finger cannot.

** Ram number is from a cone penetrometer with a 60° apex and 4-cm diameter.

Figure 9-2 B. – International symbols for depicting grain type and hardness of ice and snow (from Perla and Martinelli, 1976).

in snow depth with time at the same place are not necessarily the techniques used for measuring variation in snow depth at the same time from place to place.

9.B.1.a.2.a. Snow Stakes

Snow stakes are recommended for measuring snow depths at the same site as the season progresses, provided that the site is accessible and relatively level. Snow stakes should be made of straight-grained wood or a material with similar heat-transfer properties. The vertical part should be either round or square in cross section, 6 to 8 cm in diameter (or on a side), tall enough to extend above the maximum snow depth, and painted white. The stake should be firmly fixed to the ground with a base or another stake. A centimeter or inch scale should be painted, etched, or attached to the stake with the zero at ground level. Numbers should be in contrasting colors and large enough to be read easily from a distance of several meters, even in poor light. To read the scale, the observer should stand several meters away and sight along the snow surface. Snow stakes are not recommended in sloping terrain because snow creep pushes them out of plumb. In irregular terrain and uneven snow cover, the readings from several stakes should be averaged to obtain a representative snow depth.

9.B.1.a.2.b. Aerial Markers

Aerial markers, which are large, permanent stakes that can be read or photographed from low-flying aircraft, are recommended for remote sites if successive readings are needed for the same place during one season or from season to season. If the weather is good, the observer can read many markers in a short time. However, this technique is severely hampered by low clouds or fog.

Aerial snow-depth markers have a common design, but the materials and dimensions vary. The markers consist of a vertical support or post with horizontal crossbars attached at predetermined intervals. The post is usually a 5-cm wrought-iron pipe, although a 10- × 10-cm treated wooden post is preferred for permafrost areas. Pipes of larger diameter are desirable where snow depth exceeds 4 m.

The vertical post should be made of 1- to 2-m sections connected by couplings. However, in areas of strong wind, a 15-cm welded sleeve with two bolts has proved to be more durable. The crosspieces should be designed to be bolted onto the support post with 1-cm bolts, which makes the snow stakes easy to transport to field locations and makes the crosspieces easy to replace.

Crossbars are made of wood or sheet metal. Metal crossbars should be approximately 1.5 mm thick; wood crossbars should be 2 cm thick by 15 cm wide by 60 to 90 cm long. They should be placed at 0.5-m intervals on the pipe and attached to a 2.5 × 8-cm wide wood or sheet-metal diagonal between the outside edges of the crossbars for bracing, if necessary. The diagonals should cross the pipe midway between the crossbars. An alternative design uses 5- × 30- cm horizontal bars instead of diagonal bars.

The preferred paint for markers is bright orange, heavy-duty enamel similar to that used for highway signs. It should be renewed every 3 to 5 years. Although bright orange is easy to see, darker colors or black may be less objectionable to summer travelers.

The support post should be set in concrete to a minimum of 0.9 m or one-fourth the marker height. The total height of the marker and the spacing of crossbars should be recorded. The total height of the marker should be 1 m more than the maximum expected snow depth. If the marker is too long, the extra crossbars are difficult to count and increase the chance of error. However, the center crossbar can be enlarged so that depth can be measured from it instead of from the top of the marker. To assure positive identification, each marker should have a clearly visible number or letter.

Observations are usually taken from light planes flown by experienced mountain pilots. The plane must have adequate power and lift for operating in the mountains and must be capable of sustained flight at speeds as low as 65 to 100 km/h. For safety, the plane should be serviced for flying at least four times the length of time anticipated for an observation trip.

The plane should fly over markers from uphill to downhill to give the pilot more room to maneuver after each observation. To get a good view, the plane should fly slightly to one side of the marker approximately parallel to the crossbars. The pilot should make two passes to ensure accurate observations.

Generally, pilots fly between 100 and 150 m above the marker to make observations. Flying any lower than 100 m above ground should be avoided under all conditions. Photographs taken 300 m above terrain by motor-driven 35-mm camera with a 500-mm lens and high-speed color film have given accuracies of ± 7.5 mm (Schumann, 1975).

9.B.1.a.2.c. Snowboards

Snowboards are recommended for measuring newly fallen snow depths over short time periods. The selected sites should be easily accessible and should not have excessive melting or drifting. For some purposes, several snowboards may be read at one site, for example, one to determine 24-hour snowfall, another to measure storm snowfall, and another to measure snowfall intensity for periods shorter than 24 hours. The 24-hour and intensity measurements are important for avalanche predic-

tions. Most snowboards consist of a white wooden or plastic platform about 30 cm^2 with a vertical stake marked in centimeters or inches attached firmly to its center. The board must be flush with the snow surface at the beginning of the observation period. At the end of the observation period, the depth of snow on the board should be read. A can 20 cm in diameter should be used to take a snow sample at the time of reading for determination of water equivalent. The board should then be cleaned and replaced on the snow surface for subsequent readings (Perla and Martinelli, 1976, p. 16).

9.B.1.a.2.d. Oversnow Transects

Oversnow transects are recommended for repeated measurements of snow depths in irregular terrain with moderate to deep snow cover, especially on slopes where creep would push stakes out of plumb. In areas of shallow snow cover, where stakes will remain vertical and where repeated oversnow travel along the transect will disturb the snow, a grid of stakes may be better.

Transects have proved useful for measuring snow accumulation and erosion around snow fences and other wind barriers and at natural drift sites. In such situations, properly alined transects often reveal changes in snow depth that are missed by a grid of stakes because the stakes give only point readings.

Transects should be marked at each end with a pair of stakes several meters apart. The stakes should extend well above the snow, and at least one pair should be visible from any place along the line. Two observers using hand levels and a tape or chain usually run the first transect before snowfall to serve as a base; several transects are run over the snow subsequently. Plotting several transects gives areal and temporal snow depth distribution. Two experienced observers can measure snow depths quickly to the nearest 10–15 cm with this technique even under severe weather conditions. In gentle terrain, a self-leveling level with stadia hairs and a long, clearly marked leveling rod are faster and more accurate than hand levels and a chain.

9.B.1.a.2.e. Probes

Probes are recommended for measuring snow depths at widely scattered sites, where a single set of readings is needed, where no base transect is available, and where snow depths do not exceed 5 to 6 m. Snow probes are sectional rods that go through the snow to the ground and are read to the nearest centimeter from marks stamped on the rods. Jairell (1974) gives a successful probe design. Commonly, the investigator lays the probe on the snow to measure the distance between probe points at a given location. During warm weather with a deep (>2-m), cold snowpack, probes without the enlarged, tapered bit described by Jairell (1974) tend to freeze into the pack, which makes probing difficult and slow.

9.B.1.a.2.f. Aerial Photography

Where snow depths over a large area are needed, aerial photogrammetric techniques are recommended. For this technique, two sets of vertical aerial photographs with proper overlap for stereoscopic viewing are needed—one set without snow cover to establish a grid of surface elevations, and the other set with snow cover so that the snow elevation over the grid points can be measured. The difference between the two readings is the snow depth at each grid point.

An accurate ground-control survey is the most important requirement for satisfactorily determining snow depths photogrammetrically. Control points should be identifiable with and without snow on the ground. The number of points and the accuracy with which they are located horizontally and vertically depend on the degree of accuracy needed for snow depths and the scale of the

photographs. For example, Smith, Cooper, and Chapman (1967) report that in an experiment on a mountainous watershed in Idaho where (a) horizontal controls were kept to third-order accuracy, (b) vertical control was kept to 1/10 of map-contour intervals, and (c) each stereomodel had at least five control points, the mean snow depth had a standard error of only 0.006 m. When less accurate snow depths are acceptable, less stringent surveying methods may be used to establish the ground control.

Even experienced photogrammetrists have difficulty reading snow-surface elevations unless there is some tonal contrast on the snow. Therefore, snow-depth measurements will be more accurate if the film is exposed and developed to emphasize snow-surface features. Surface features are greatly enhanced by differential melting, wind deposits, or light shadows. Photogrammetric snow surveys should not be made after new snowfalls until a noticeable surface texture has developed.

9.B.1.a.2.g. Isotopic Snow Gages

Isotopic snow gages, usually used to measure density, may also be used to measure depth. Recommended methods for their use are given in section 9.B.1.a.4.c.

9.B.1.a.3. WATER EQUIVALENT

Water equivalent is the depth of water that would result from the melting of a snow cover or a snow sample. Thus, the water equivalent of a new snowfall is the same as the amount of precipitation represented by the snowfall. Unfortunately, in California and perhaps elsewhere, the term "water content" is used to mean water equivalent, which causes confusion. (See "Definition of Elements" for distinction between water equivalent and water content).

The water equivalent of a snowpack is one of its most important features. Determining the water equivalent of a single snow sample or a given place is relatively simple. For some purposes, such as building designs and snow-avalanche studies, a few samples may be adequate. However, for hydrologic problems such as runoff or ground-water recharge, a statistical approach is needed to estimate the average water equivalent of large areas from relatively few samples. This procedure, which usually involves developing regression analyses of streamflow based on the water equivalent of the snowpack at selected places within the basin, is described in Section 22 of Soil Conservation Service's National Engineering Handbook (1972).

9.B.1.a.3.a. Federal Snow Samplers

The Federal snow sampler is recommended for determining density, depth, and water equivalent of a snow pack greater than or equal to 0.75 m in depth when data are to be read infrequently at numerous locations. Although the sampler was designed and manufactured to U.S. customary dimensions, it is currently available with depth markings in both U.S. customary and metric dimensions. Metric samplers with a cross-section area of 10 cm^2 and compatible scales are now being developed.

The sampler is made of 1¾-inch (4.4-cm) outside diameter duralumin tubing, which is cut in 30-inch (76-cm) sections marked at ½-inch (1.3-cm) intervals. The first, or lower section, has a 16-tooth steel cutter bit with an inside diameter of 1.485 inches (3.772 cm), which is about 3.16 inches (0.48 cm) smaller than the inside diameter of the tubing. This size difference permits easier sampling and removal of the snow core. A diameter of 1.485 inches (3.772 cm) was selected for the cutter so that each ounce of core is equivalent to 1 inch (2.54 cm) of water (a cylinder of water 1.485 inches (3.703 cm) in diameter and 1 inch (2.54 cm) long weighs 1 ounce (28.4g)).

The tube sections fit together with threaded couplings to lengths of 300 inches (762 cm) or more. Slots spaced along the tube sections are provided for observing the length of core.

After the sampler is assembled and a sample obtained, snow-water equivalent should be determined by weighing the tube and its snow content on a spring scale. The weighing cradle that holds the snow tube is attached to a spring clip on the bottom of the scale; the scales register in inches of water equivalent and come in three sizes for snow depths of 12.5 feet (3.8 m), 20 feet (6.1 m), and 30 feet (9.1 m).

A driving wrench is clamped onto the tube to drive it into deep, hard, compact snow and to cut through layers of ice. If sections of the sampler tighten during use, spanner wrenches can be used to unscrew them.

Federal snow samplers tend to overestimate water equivalent by as much as 12 percent. The error is proportional to both snow density and thickness of the cutter teeth but is not a serious problem when readings are used merely as an index of the water equivalent of the snowpack for water-supply purposes. Well-sharpened cutter teeth reduce the error considerably. When absolute values are required, the readings can be corrected or the cutter teeth modified to obtain more accurate values (Work and others, 1965; Peterson and Brown, 1975).

The Federal snow sampler is relatively inexpensive, light, easily portable, and simple to use. Under most conditions, replication of results is good. However, it is difficult to obtain complete snow cores when the snowpack contains thick ice layers, standing water, or basal layers of unconsolidated depth hoar. Also, frozen ground, brush, fallen trees, and logging slash make it difficult to obtain a proper core. Such sites should be avoided, or the obstacles should be removed, before the snow season. Because the snow sampler is a destructive sampling device, it is not recommended when many measurements are needed for an extended period in the same relatively small sample area.

Detailed instructions for using the snow sampler are given in Section 22 of Soil Conservation Service's Engineering Handbook and "Snow Survey Sampling Guide" (Soil Conservation Service, 1972 and 1973).

9.B.1.a.3.b. Adirondack Snow Samplers

Where the snow cover is shallow (0.75 m) and not frequently dense or icy, the Adirondack sampler is preferred by many workers, especially in the northeastern States. This sampler consists of a tube 154 cm long with a circular steel cutter of 6.74-cm inside diameter on one end. The tube is pushed to the ground, and a small metal plate is slipped over the lower end to hold the core. The tube and core are then weighed on a special scale that is calibrated in 0.25 cm of water equivalent and allows the tare weight of the empty tube to be set to zero. Work and others (1965) found this sampler to be the most accurate of the five samplers they tested.

9.B.1.a.3.c. Snow-Pressure Sensors

Snow-pressure sensors, also called snow-pressure pillows, are recommended when continuous or frequent water-equivalent data are needed from the same place, provided the snow cover does not contain extensive ice lenses. These devices must be installed level with the ground surface to weigh the snow that accumulates on them. The pillows are made from a variety of materials including butyl rubber, rubber fabric, neoprene, stainless steel, and galvanized sheet metal. The fabric pillows are round or polygonal; the metal ones are rectangular. Both are filled with an antifreeze solution. When filled, metal pillows are 1 to 5 cm thick; the fabric ones are thicker. The pillows can be filled with antifreeze through the pressure-line opening near the edge. Another opening near the top allows air to escape during filling and is used to remove all air from the sensor. Pressure transducers,

electronic converters, and mechanical float devices are used to translate snow load into water equivalent for onsite recording and radio transmission.

A standard diameter size is 3 to 3.7 m for the butyl pillows and 2.4 to 3.1 m for the steel pillows. The steel pillows come in 1.2 × 1.5 m modules that may be used singly or in multiples of two to six to make the pillow. Both fabric and metal types are filled with a mixture of antifreeze and water. A recommended mixture is 35 percent methanol and 65 percent ethylene glycol, mixed with equal parts of water, which gives a specific gravity of 1.

Keeping the system free of leaks is the major problem with snow-pressure pillows. Leaks resulting from fractures made by man, animals, or excessive stresses are common. Other problems include bridging of the pillow by ice lenses, ponding of water on the pillow, lag time of sensor response, difficulty in maintaining an accurate zero setting during the season, and the need for an onsite recorder to assure data collection if the telemetry system fails.

9.B.1.a.3.d. Recording Precipitation Gages

Standard weighing-type precipitation gages are recommended for continuous records of the water equivalent of new snowfall. To measure snow in this type of gage, the funnel should be removed to reduce clogging by wet snow. A mixture of antifreeze and water should be added to the bucket to melt the snow as it is caught, and a small amount (5 mm) of lightweight motor oil should float on the water to prevent evaporation. In spite of precautions, a snow cap will still form under certain atmospheric conditions. Where this is a serious problem, larger orifices and steeper gage sides may help but probably will not alleviate the problem. Because precipitation gages catch less than the true amount of precipitation that falls as snow, an Alter shield with blades that extend about 0.1 m below the tapered sides of the gage is recommended for most sites. Such a shield reduces wind action at the gage orifice and usually improves the catch. The shield may, however, increase the likelihood of capping under severe conditions.

Tipping-bucket gages are not recommended for measuring snowfall because they must be heated. The heat evaporates moisture from the funnel, which results in serious underestimation of total snowfall, especially where frequent light snowfalls are common.

9.B.1.a.3.e. Storage Precipitation Gages

Storage precipitation gages are recommended for remote sites. Although these gages were originally designed for seasonal data, interim data can be obtained from storage gages with stick measurements or onsite recorders.

The capacity of the gages must be large enough to hold a charge of antifreeze, water, and light oil (Mayo, 1972), plus the water equivalent of the expected catch. The gage should be shielded at windy sites (Warnick, 1956). The large snow-fence shield developed by Rechard and Larson (1971a and 1971b) has proved satisfactory at windswept sites in many places.

Snow capping occurs under certain conditions and often goes undetected at remote sites. Seasonal deficiencies in storage gages may exceed 10 percent, even with shielded gages and well-protected sites. Such deficiencies are especially noticeable in areas of light, dry snow.

9.B.1.a.3.f. Snowboards

Snowboards are recommended for measuring water equivalent of new snowfall at manned or readily accessible sites where precipitation gages are not available. A sample of the snow on the board is collected by pushing an inverted can of known diameter (usually 20 cm) through the snow to the board. The board is then picked up and turned upside down with the can still pressed against the board so that the snow falls into the can. Either the can and sample are weighed on scales

calibrated to read depth of water, or the sample may be melted and water equivalent measured directly. This system is quick and requires a minimum of equipment; the chief disadvantage is the lack of short-term data when the observer is not present or is busy with other duties.

9.B.1.a.3.g Open Pits

Open-pit determination of water equivalent is recommended only where high accuracy is required or where several additional snow properties are needed for the individual layers within the pack. Although accurate results can be obtained by the open-pit method, it is laborious and slow, especially in deep snow and under adverse weather conditions.

The open-pit procedure for measuring water equivalent as given by the International Association of Scientific Hydrology (1970b), is as follows:

> First a rectangular pit of suitable size, depending on depth (usually about 1.5 × 2 m), is dug to the ground. Along one of the walls—preferably on the shady side—a sampling tube of duraluminum or steel about 60 cm long and 5-9 cm in diameter (thickness of the wall 1 to 1.5 mm) and sharpened at one end is pushed vertically down to a metal sheet which is put in the snow from the side at a convenient level. The net weight of the sample divided by its cross section is a measure for the water equivalent of the layer (in centimeters of H_2O if grams for the weight and square centimeters for the area are used). The procedure is continued down to the ground.
>
> With this troublesome method the highest accuracy is achieved. Difficult layers like ice lenses can easily be avoided by adapting the length of the samples to the stratification. If the water equivalent of single strata is required (for example for identifying precipitation periods) the snow surface is marked with colored threads on certain dates and before and after snow falls. In the pit the marked levels are easily found and the intermediate layers investigated separately.
>
> The total water equivalent of the snow cover divided by the snow depth results in an average density which in turn may be combined with snowdepth values of neighboring points for calculating an average water equivalent of the area.
>
> Snow-pit studies are worthwhile, especially if other snow characteristics such as stratification, snow temperature, vertical variation of density, etc., are included in the observation.
>
> Snow-pits should be carefully refilled even if no further snow observations are planned in the same area.
>
> If the sampling is to be repeated periodically, the front of the old pit should be marked with a stake and the front of the new pit moved in the direction of undisturbed snow by several decimeters or by at least one meter if undisturbed temperatures are essential.

9.b.1.a.3.h. Isotopic Snow Gages

See section 9.B.1.a.4.c.

9.B.1.a.3.i. Aerial Gamma-Radiation Surveys

An airborne system for measuring passive terrestrial radiation is now operational. This system can be used for measuring the water equivalent of extensive areas of shallow snow cover (0.30-m water equivalent or less) (Peck, VanDemark, and Fritzche, 1978). This technique is based on the fact that the gamma-radiation flux originating from natural radioactive isotopes in the soil is attenuated by any water between the source and the detector. The usual practice for determining water equivalent of the snow cover is to fly over a selected flight line before a snowfall to obtain natural background-

radiation information and again at maximum snow cover to obtain attenuated flux data. Once the amount of attenuation is known, the water equivalent of the snow cover can be calculated, provided that adjustments are made on the flux data. These adjustments compensate for changes in cosmic radiation flux, aircraft background radiation, radon gas in the atmosphere, and changes in soil moisture. Soil moisture is usually sampled by standard gravitational techniques at the time of the first flight (before snowfall) and is either estimated or sampled again at the time of the second flight. Average water equivalent for the snow cover is based on a large sample—460 m times the length of the flight line, which is usually 10 to 15 km. The standard error of the mean water equivalent is reported to be about 0.01 m of water for a 16-km flight line (Peck, VanDemark, and Fritzche, 1978).

Another airborne system of radiometric snow surveying is capable of detecting snow-cover water equivalent up to about 0.75 to 1 m with an error of ± ⅓ in. (0.85 cm) or 6 percent water equivalent, whichever is larger (Jordan, 1974). This system uses an artificial source of gamma rays and an airborne detector. To measure water equivalent, a specially designed container containing cesium 137 or cobalt 60 is placed at ground level prior to snowfall. Gamma rays are restricted to a vertical cone by a collimating shield. Detectors and counters are flown through this cone at elevations of a few meters and at speeds of about 150 km/h whenever a water equivalent reading is desired. The reduction in count rate with snow cover compared to the count rate with no snow cover can be translated into water equivalent through the relationship of the attenuation of gamma flux as a function of water content.

9.B.1.a.4. DENSITY

Snow density is an important property related to its strength, ease of removal, suitability for skiing, and other factors. Average snowpack density is usually fairly uniform at a given time at sites of the same elevation and aspect. This means that the water equivalent of the snow cover on a small drainage basin or similar area can often be estimated by taking a relatively large number of snow depths and relatively few density samples.

9.B.1.a.4.a. Sample Tubes

Sample tubes of known volume are recommended for measuring snow density, especially when the density of individual layers within the pack is to be determined. Most sample tubes are cut from seamless, hardened aluminum or stainless steel tubing 50 to 60 mm in diameter and long enough to have a volume of 500 cm^3. Samples may be taken horizontally if layer density is required, or vertically if average density is needed. The weight of the sample is determined by weighing the tube plus the sample and then subtracting tube weight. Doubling the sample weight in grams for a 500-cm^3 volume gives density in kg/m^3. This technique requires an open pit, which creates a problem if duplicate samples are required.

9.B.1.a.4.b. Federal Snow Samplers

The Federal snow sampler is recommended when average density of the entire snowpack is to be determined by sampling. This instrument gives water equivalent directly (sec. 9.C.1.a.3.a.). Water equivalent divided by total snow depth, then multiplied by the density of water, gives the density of the snow sample.

9.B.1.a.4.c. Isotopic Snow Gages

The isotopic profiling snow gage (Smith 1967; Smith, Halverson, and Jones, 1970) is a twin probe system that gives onsite profiles of snow depth, density, and water equivalent as often as desired.

Under controlled laboratory conditions, density can be measured to within ± 0.015 gm/cm^3 of true density. Under normal field conditions, it can be measured to better than $\pm$ 5 percent. Vertical intervals can be measured to within 1.5 cm using sodium-iodine detector crystals and electronic discrimination. This gage uses the principle of gamma transmission between a source and a detector moved vertically in two tubes extending through the snowpack and located between ⅓ m and 1 m apart. Fabrication and operation of this system are described by Smith, Halverson, and Jones (1972). Randolph, Coates, and Killian (1973) have developed a remotely operated, telemetered version of this system, and Blincow and Dominey (1974) have developed a portable profiling isotope snow gage based upon gamma scatter. This gage gives rapid onsite depth (to within about 4 cm), density, and water equivalent.

A third isotope gage is the zig-zag gage (Shreve and Brown, 1974; Morrison, 1976), which has no moving parts. It consists of two tubes set 1 m apart. Several Geiger-Mueller detectors and cobalt sources are set in each tube so that average density over the plane determined by the tubes is measured in 0.75-m segments of the snowpack. Where precise data are needed, the twin probe system (Smith, Halverson, and Jones, 1972), is the recommended instrument even though it is expensive. Where definition of ice lenses and other density configurations is not necessary, the zig-zag system is adequate, less expensive, and less costly to maintain. The scatter system is recommended where a portable instrument is needed.

9.B.1.a.5. TEMPERATURE

Snow temperature and temperature gradients are important for determining the timing and amount of melt-water release and the crystal changes (metamorphic processes) within the snowpack.

9.B.1.a.5.a. Thermistors and Thermocouples

In recent years, a number of temperature-sensing systems that have become commercially available can be recommended for snow studies. The sensors are thermistors or thermocouples and are usually mounted in metal jackets. Sensors are connected to portable, digital, electronic-readout meters (single or multiple channel) by cables. Some instruments are battery operated for field use; others are designed for line power. They are accurate, rugged, quick, and easy to read.

For pit work, a probe with a short cable and a battery-powered meter works well. For numerous readings in a shallow snowpack or in the upper layers of a deep pack, a probe pole of convenient length can be equipped with a sensor on one end and the readout meter on the other (Gottfried and Campbell, 1968). For long-term temperature data for the same snow layer at a given place, the sensor can be mounted on a light-weight float that is allowed to become part of the snow layer (Swanson, 1967, 1968). In this case, the readout meter is usually housed in a shelter nearby or brought to the site.

9.B.1.a.5.b. Dial-Stem Thermometers

Dial-stem thermometers are recommended for snow-pit work when high accuracy is not needed. These inexpensive, rugged temperature sensors can be read to the nearest 0.5°C. Temperatures should be taken in the shaded face of the pit as it is being opened, and every instrument used should be kept in the shade.

9.B.1.a.6. FREE-WATER CONTENT

Free-water content is the amount of liquid water in a warm or wet snowpack (0°C for full depth), usually expressed in percent by weight. This definition includes all liquid water in the sample, regardless of whether it is ponded, draining under the influence of gravity, trapped in the interstices between grains, or held on grain surfaces by surface tension.

The amount of ice in a snow sample, in percent by weight, is called the quality of the snow or the thermal quality of the snow. Quantitatively, this is 100 minus the free-water content (expressed as a percentage of the water equivalent) of the snow sample.

For most free-draining snows, free-water content ranges from 0 to 10 or 15 percent, depending on air temperature and texture of the snowpack. Before water can run off from a snowpack, the snowpack's liquid-water-holding capacity must be satisfied.

Several techniques have been used to measure free-water content of snow, including calorimetric, centrifugal, dielectric, and electromagnetic. None of these are recommended highly, however. Of the two calorimetric techniques—melting and freezing—the latter requires less precise temperature measurements and is generally preferred (Radok, Stephens, and Southerland, 1961).

A capacitance-bridge technique is discussed by Ambach and Denoth (1972); Linlor, Meier, and Smith (1974) give further information on free-water-content measurements.

9.B.1.a.7. IMPURITIES

The snow cover may contain a large number of impurities including algae, leaves, twigs, soil, radioactive fallout, and trace elements. Techniques for detecting and quantifying impurities will vary greatly, depending on the impurity being sought and the degree of accuracy and precision needed. Weighing impurities sieved or filtered from the snow or melt water may be adequate for some studies, whereas highly sophisticated chemical or physical laboratory techniques are needed for studying isotopes, trace elements, or radioactive impurities. No specific chemical- and biological-quality methods are recommended here because the problems involved are complex and these methods are discussed in depth in chapters 4 and 5 of this handbook. Numerous references to specific studies are given by the U.S. Army Corps of Engineers (1975).

Special care is required in extracting and handling samples to prevent further contamination. The simplest method is to cut fairly large samples from freshly revealed snow with clean tools. The samples should be transferred to specially cleaned containers with a minimum of handling. If possible, these samples should be transported to the test laboratory before melting. In the laboratory, contaminated outer layers of snow can be stripped away under clean conditons, leaving the remaining clean snow available for testing.

9.B.1.a.8. ALBEDO

Albedo is the ratio of the amount of electromagnetic radiation reflected by a body to the amount incident upon it, commonly expressed as a percentage. Usage varies with regard to the exact wavelength involved in albedo values. Sometimes only the visible spectrum is considered; sometimes the total solar spectrum is used. Albedo for visible wavelengths for fresh snow is 80 to 85 percent but may be as low as 40 percent for old, damp snow. The ability of the surface of a body to absorb (or reflect) the radiant energy impinging on it is of utmost importance in determining its heating or cooling and the energy available from the body for further energy exchange. Energy is absorbed at or near the surface in soils, shallow layers of snow, or water.

The following precautions should be observed when measuring albedo:

1. Select a pyranometer that
   a. is equally sensitive to all wavelengths from about 0.3 to 3μm;
   b. has little if any shift in calibration constant when inverted. Thermoelectric pyranometers are recommended.
2. Avoid taking readings when the sun is less than 15° above the horizon. All pyranometers show a deviation from the exact cosine response at such low sun angles. They tend to underestimate the incoming radiation while properly measuring reflected radiation. The lower the sun angle, the greater this error.

3. Recalibrate field instruments against a secondary standard at frequent intervals. If the calibration constant should change for one or more of the field instruments, the instrument can continue to be used as long as the proper correction is applied to the readings.

Careful checks should be made with the specific sensors selected for use to be sure they have equal sensitivity at all important wavelengths and that they show no serious shifts in calibration constants when inverted. Photovoltaic or photo-conductive cells are not as good as thermoelectric pyranometers for snow work because their high sensitivity in the short wavelengths tends to cause overestimation of the snow reflectance.

Albedo readings may be taken with hand-held or permanently-mounted instruments that are held or mounted parallel to the surface. A single instrument is sufficient for hand-held measurements. For level or nearly level surfaces, the pyranometer may be placed directly on the surface to measure incident irradiation. It may then be held parallel to the surface to read reflected radiation. A short handle (0.5 to 0.6 m) is convenient. The distance of the instrument from the surface varies with the size and uniformity of the surface to be measured. For uniform surfaces, the distance should be short—0.3 m or less; for highly variable surfaces, a longer distance is better—1.25 m for hand-held readings and 3 m or more for permanently mounted instruments.

The hand-held technique is recommended when occasional readings are required or when a survey procedure demands portability. When many readings are needed from a given location, permanent installations are recommended. A stable mount is used to support two pyranometers, one upright, the other inverted. The height of the instruments should be varied to some extent as a function of the surface being observed (see above).

The frequently large daily variation in albedo, with a high in the mornings and evenings and a low around noon on clear days, is the result of the erroneous cosine response mentioned above. At times, this factor may cause an apparent difference between albedo on cloudy days and albedo on clear days.

9.B.1.a.9. HARDNESS OR RESISTENCE TO PENETRATION

Snow strength is important in many engineering purposes. Because strength is difficult to measure, hardness or resistance to penetration is often measured instead and is considered to be an index of strength. Hardness is also correlated to a certain extent to density (Ueda and others, 1975, p. 5–7). Because hardness is a complex property that is closely related to the instrument and method of measurement, any hardness data must be accompanied by a statement of the techniques and instruments used.

9.B.1.a.9.a Ramsonde

The ramsonde (fig. 9–3) is recommended for measuring snow hardness. Used internationally, the ramsonde is simple to use and requires no pit. The ramsonde consists of a hollow metal tube made up of one or more sections, a guide rod, and a 1-kg driving weight (hammer). The sections are 1 m long, 2 cm in diameter, and are graduated in centimeters from the lower end. The first section has a 60° conical tip 4 cm in diameter. The guide rod, 55 to 60 cm long, fits in the upper end of the tubular section and guides the driving weight. The first section and guide rod together weigh 1 kg; each additional tubular section also weighs 1 kg.

To determine surface hardness, the guide rod is placed, without the hammer, in the top of the first section, the conical tip is placed on the snow surface, and the entire assembly is allowed to sink freely into the snow. The depth of penetration is then read and recorded. This measure of the snow's surface hardness is referred to in Europe as *Einsinktiefe.*

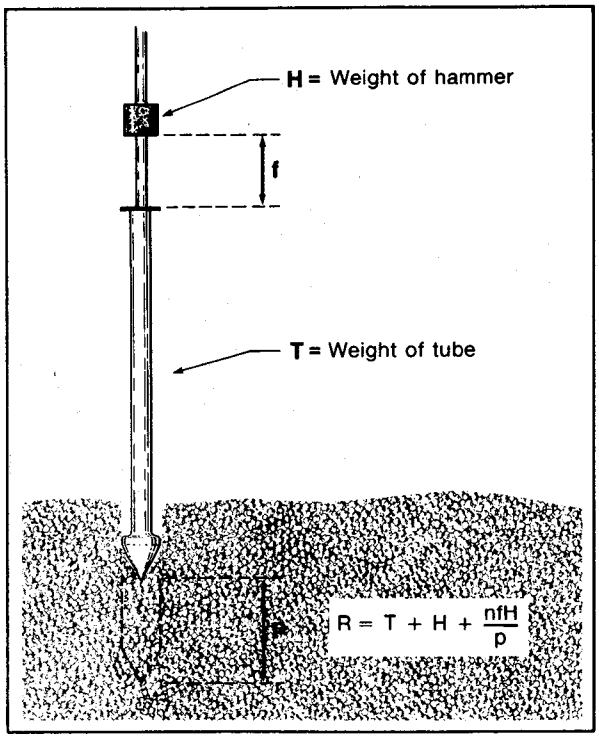

Figure 9-3.—Schematic diagram of ramsonde in operations position. The ram number for a snow layer is computed from the amount of ram penetration p for a hammer-fall height f; N is the number of hammer blows. (From Perla and Martinelli, 1976).

To measure hardness at depth, the above process is repeated. The weight of the section and guide rod is recorded as T, then the driving weight or hammer, whose weight is recorded as H, is gently slipped down the guide rod and allowed to rest against the collar. This new total weight $T+H$, and any further penetration, are recorded. On packed snow, the initial penetration is usually small.

Next, the hammer is slipped up the guide rod and allowed to fall freely. The fall distance is chosen so that the first blow will drive the ramsonde 5 to 10 cm. If the first blow drives the ram less than 5 cm, the hammer is lifted to the same height and dropped again and again until the appropriate penetration is achieved. The number of drops n and the height of the drops f are recorded along with the penetration p. This process is repeated in 5- to 10-cm increments, with the height of the drop for each series of blows adjusted to the expected hardness of the snow. When another section is added, the value of T is changed to reflect the total weight of the tube. The ram is driven to the ground to obtain a full hardness profile. The field notes (fig. 9-4) are then converted to a hardness index called the ram number, or ram index, R by the formula:

$$R = T + H + \frac{n f H}{P}$$

A ram profile is shown as figure 9–5; the profile was plotted from the field notes in figure 9–4.

9.B.1.a.9.b. Depth of Footprint or Ski Track

A rough estimate of surface hardness can be obtained by measuring the depth of penetration of a person with all his weight on one foot or by the depth of penetration of a ski with all the person's weight on one ski. This index can be obtained quickly and with minimum equipment. Variables such as the weight of the person, shoe size, and running surface of the ski must be recorded.

Rammsonde Data

Location: Pat's Knob
Time: 13:00

Date: 25 Mar. 1974
Obser: mm

$R = T + H + \frac{nfH}{P}$

Wt. of Tube + Hammer T+H	No. of Blows n	Fall Height f	Location of Point	Penetration cm P	$\frac{nfH}{P}$	Ram Number R	Height above ground cm	
								(H) Hammer wt. = 1 kg
			0 @ snow surface				190	
1	0	0	11	11	0	1	179	
2	0	0	11	0			179	Added Guide Rod + Hammer
	6	5	13	2	$\frac{30}{2}=15$	17	177	
	3	10	20	7	$\frac{30}{7}=4\frac{1}{2}$	$6\frac{1}{2}$	170	
	4	10	34	14	$\frac{40}{14}=3$	5	156	
	8	10	48	14	$\frac{80}{14}=5.7$	7.7	142	
	1	5	50	2	$\frac{5}{2}=2\frac{1}{2}$	4.5	140	
	15	10	62	12	$\frac{150}{12}=12\frac{1}{2}$	14.5	128	
	15	10	72	10	$\frac{150}{10}=15$	17	118	
	16	10	80	8	$\frac{160}{8}=20$	22	110	
	8	10	82	2	$\frac{80}{2}=40$	42	108	
3			82	0			108	Added 2nd section of tube
	12	15	90	10	$\frac{180}{10}=18$	21	100	
	6	20	95	5	$\frac{120}{5}=24$	27	95	
	5	20	103	8	$\frac{100}{8}=12\frac{1}{2}$	$15\frac{1}{2}$	87	
	5	20	118	15	$\frac{100}{15}=6.6$	9.6	72	
	1	20	138	20	$\frac{20}{20}=1$	4	52	
	30	10	144	6	$\frac{300}{6}=50$	53	46	
	35	25	160	16	$\frac{875}{16}=55$	58	30	
	2	25	174	14	$\frac{50}{14}=3.6$	6.6	16	
4			174	0			16	Added 3rd section of tube
4	1	10	190	16	$\frac{10}{16}=.6$	4.6	0	Ground

Figure 9–4.—Example of ramsonde field notes. (From Perla and Martinelli, 1976).

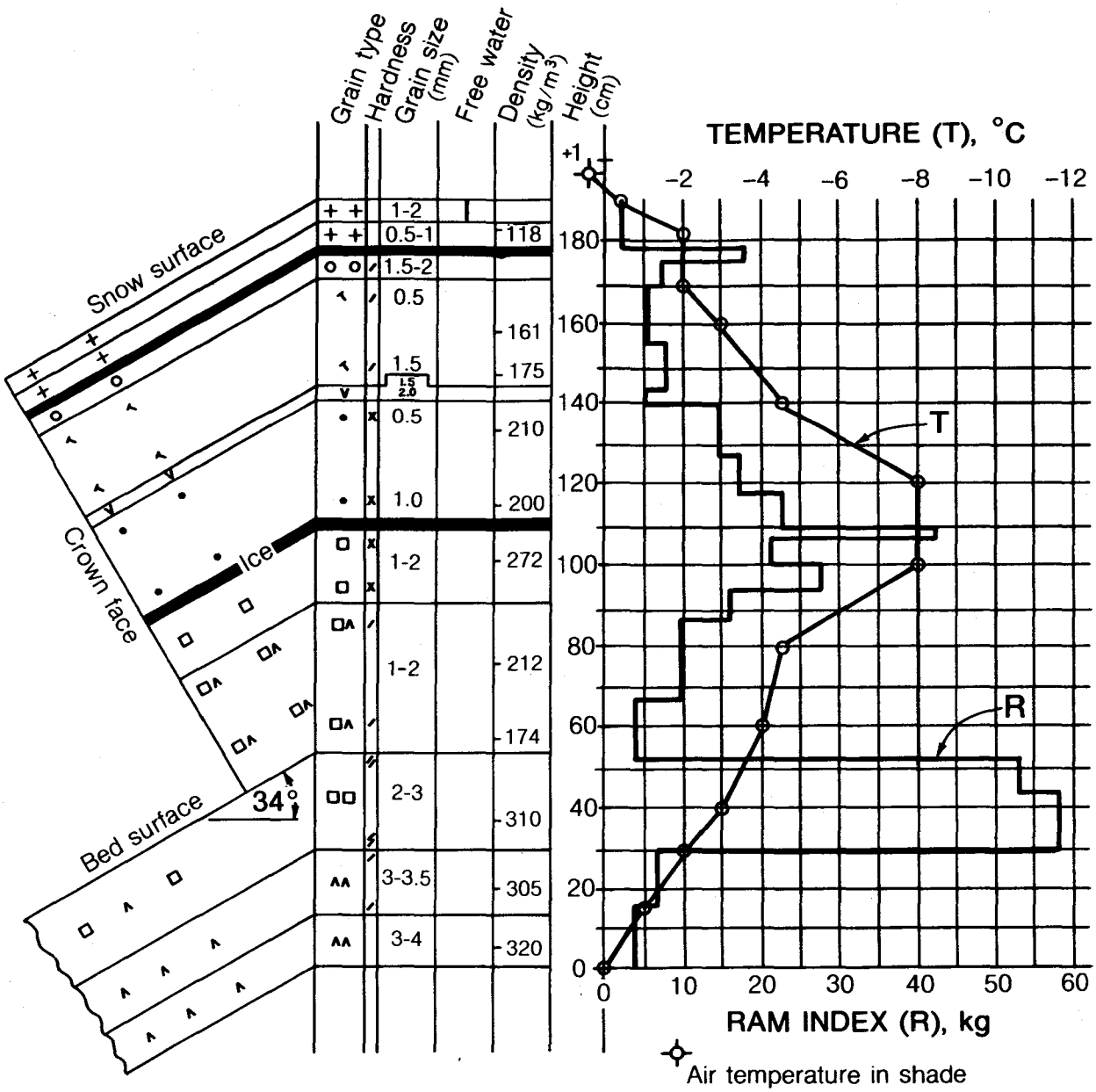

Figure 9-5.—Ram profile from data taken in a snow pit. (From Perla and Martinelli, 1976).

9.B.1.a.10. BLOWING SNOW

Total snow cover at many sites in cold, dry climates is the combination of direct precipitation and snow blown to the site by wind. At some sites, the volume of blown snow may be 2 to 4 times that deposited as precipitation. The amount of snow moved is a function of wind speed and duration, snow-surface conditions, extent of snow cover, topography, and exposure. The amount of snow deposited depends on the size and shape of the upwind contributing area, the amount of available snow, the size of particles, the temperature and humidity of the air, and the size and shape of the deposition area. The wind, under severe conditions, can move more than 3,000 kg of snow per hour per meter width (Mellor and Malcolm, 1965).

There is no standard, well-tested instrument that can be recommended for measuring blowing snow. For many purposes it is sufficient to measure the snow cover at given sites regardless of the origin of the snow. However, where it is necessary to measure blowing snow, either trapping gages or the experimental optical drift meter should be used. The selection will depend primarily on the manpower skills available to build, install, maintain, and read the instruments.

9.B.1.a.10.a. Trapping Gages

Trapping gages of various designs have been used to measure the amount and intensity of blowing snow (Mellor and Malcolm, 1965; Tabler and Jairell, 1971). Some gages are exposed for only a short time and are then either weighed directly or emptied and the catch weighed. Others are combined with weighing mechanisms that give a continuous record. These recording gages can usually operate for several days before they must be emptied. Some trapping gages have fins and a pivot system that keep the intake pointed into the wind. Others are set for given wind directions. All trapping gages suffer from the disturbance they create in the wind-flow pattern and the uncertainty in determining their trapping efficiency. Most are awkward and difficult to service and to keep properly positioned in relation to the snow surface. None are available commercially.

9.B.1.a.10.a.1. Mellor Traps.—The best known trapping gage is the rocket-type trap built and described by Mellor (1965). This carefully tested and calibrated instrument has been used to gather much of the recent Antarctic snowdrift data, and is as close to a standard as exists. Under moderate to heavy snow drifting, the Mellor trap must be emptied at frequent intervals.

9.B.1.a.10.a.2. Modified Mellor Traps.—Tabler and Jairell (1971) modified the Mellor rocket trap and mounted it on top of a recording precipitation gage that was in turn mounted on a pivot. The instrument is buried in a pit so that only the drift trap is above ground. The fins on the trap and the sensitive pivot system allow the entire instrument to rotate so that the trap orifice always faces the wind. This gage gives a continuous record of blowing-snow amounts for several days under most North American conditions. Unfortunately, it is awkward to service and must be custom fabricated. However, it is the only recording drift snow gage of the trapping variety known at present.

9.B.1.a.10.b. Optical Drift Meters

Optical drift meters that measure blowing snow without trapping the particles have been designed and field tested, but they must be custom built. Some count the individual particles that interrupt a collimated beam of light; others are based on the reduction of intensity or the amount of back-scattering from a light source. Such meters have a faster response time, interfere less with wind flow pattern, and are easier and quicker to set up and to read than traps. On the other hand, they are more expensive and require careful calibration and periodic maintenance by electronics experts (Schmidt and Sommerfeld, 1969; Schmidt, 1971; Schmidt and Holub, 1971).

9.B.1.a.11. FROZEN GROUND

Changes in the ice content depth of freezing, and other conditions in frozen ground during snowmelt periods affect the rate of snowmelt runoff. To measure this periodic change, the test site must remain as undisturbed as possible. This eliminates the possibility of pit or core sampling techniques, which would disrupt the sampling site.

9.B.1.a.11.a Site Selection

Because snow cover influences frost depth, sites should be representative of the type of ground conditions in the area of concern; conditions may range from natural to highly disturbed. The following items should be considered:

1. Instrumentation for undisturbed ground should be at least 30 m from any all-weather road.
2. Sites should have representative snow cover. Unless snow-free areas are of concern, avoid areas that are smooth and may be blown free of snow during early winter when open fields are snow covered.
3. Instrumentation for natural conditions should not be near heated buildings or in areas that are sheltered.
4. Snow cover in the immediate area of the instrument should be protected against disturbance. Only one path to the instrument should be used, and the observations must be made carefully.
5. The immediate area should have at least as good drainage as the general area surveyed.
6. The most suitable locations are in open fields with ground roughness comparable to the general area.

Data should be collected weekly or semimonthly during the formation of frost and before the period of melt. Once the melt begins, readings should be daily if possible, but no more than two days apart.

9.B.1.a.11.b. Frost Tubes

The frost tube is a simple, direct method of monitoring ground frost without disturbing the test site. It is basically a tube within a tube (DeByle, 1970; Harris, 1970; Patric and Fridley, 1969). The outer tube, made of metal or PVC pipe, is approximately 4 cm inside diameter and is permanently set in the ground to a depth of approximately 1.5 m. It should extend above ground enough that it can be found easily during winter, and the bottom must be water tight. The inner tube is clear plastic and should be able to slide into the outer pipe without binding. An outside diameter of 2 to 3 cm is satisfactory. The inner tube is filled with a mixture of water and 0.01-percent fluorescein sodium dye and sealed. The dye helps identify the ice-water interface. Because frost melts at both top and bottom, a wooden dowel, a stiff wire, or white sand must be placed inside the tube to prevent the intermediate ice from floating during the melt period. The inner tube is suspended from the cap of the outer tube by a chain so that it can be extracted for observation. The inner tube is calibrated in centimeters, with zero at the ground surface, increasing with depth.

9.B.1.a.11.c. Thermocouples

An array of thermocouples in good contact with the native soil gives data on frost depth and soil-temperature profile, and it can be read onsite, recorded, or telemetered. The accuracy of this relatively inexpensive system depends on the spacing of the thermocouples. Thermistors can be used in place of thermocouples but are more expensive.

9.B.1.b. PERENNIAL SNOW AND ICE

Measurements of the total mass, physical properties, and fluctuations of perennial ice and snow are becoming increasingly important because they are already important to human life and they are

likely to become a more important source of fresh water. It is essential that methods for measuring perennial ice and snow be standardized because even small changes in total mass can critically influence Earth's hydrologic cycle. In addition, understanding the relationship between glaciers and climate requires precise measurements of the fluctuations of glaciers and other ice bodies.

Perennial snow and ice is defined as any snow, firn, or ice lying on or just below the Earth's surface that does not disappear over a 1-year period. Glaciers, ice caps, and permafrost dominate the total mass of this hydrologic component. Although many local ice features such as intermittent snowfields and masses of aufeis (flood icing) that have survived one ablation season are not perennial, they should be considered in hydrologic studies.

Because practical and scientific interest in Earth's cover of perennial and seasonal ice and snow has increased, a monograph series has been published by the International Association of Scientific Hydrology, as a contribution to the International Hydrological Decade. These papers cover nearly all measuring techniques of snow and ice and should be procured by anyone interested in internationally accepted measuring methods (IASH, 1969a, 1969b, 1970a, 1970b, 1970c, 1973).

9.B.1.b.1 AREAL EXTENT AND FLUCTUATIONS

The area of Earth's surface covered by permanent snow and ice is determined most efficiently by photographic methods. For precise measurements of small areas (less than 0.1 km^2), surveying methods that use theodolites and distance-measuring devices are adequate without photographs. Satellite imagery is rapidly becoming a means for determining the extent and variation of large (10,000- km^2) ice masses and provides approximately 100-m resolution (Krimmel and Meier, 1975). Vertical aerial photography is still the most practical, accurate, and recommended method to map smaller (100-km^2) areas. However, the necessary ground control must still be obtained by precise surveys. Terrestrial photographs are recommended for documenting terminus changes (Veatch, 1969), and time-lapse photography is a valuable means of analyzing glacier flow and snowline changes.

9.B.1.b.2. DEPTH

Developing and applying methods for measuring the thickness of glaciers and other ice bodies has been an important research effort for the past two decades. Drilling by mechanical or thermal methods (Shreve, 1962), gravimetric methods (Corbato, 1965), and seismic and radio-echo sounding have been the predominant methods used. Radio-echo soundings using both surface-borne and aerially-borne instruments have been in operation for more than a decade (Robins, Evans, and Bailey, 1969) and are recommended for dry polar glaciers. Recently, a portable radio-echo sounding instrument was developed; this is a revolutionary advance that accurately determines the thickness of wet, temperate glaciers (Watts, and others, 1975).

9.B.1.b.3. PHYSICAL PROPERTIES

The physical properties of perennial snow and ice considered most important for standardized measurements, because they can be directly applied to the practical aspects of snow and ice hydrology, are reflectivity to solar radiation (the albedo—essential for heat-balance calculations), the free-water content (important both for heat-balance and melt-water-movement studies), and temperature (water cannot travel in steady state as a liquid through firn or any material that is colder than 0°C).

Glaciers are classified as either temperate or polar on the basis of their temperature below the depth affected by seasonal temperature variations. Temperatures can be measured to a depth of a few meters with simple thermometers, but most measurements at depth are made by electronic means (Harrison, 1975).

Standard measurements of albedo (sec. 9.B.1.a.8) are made by radiometric instruments, usually by two simultaneous pyrheliometer measurements of the total incoming short-wave radiation and the total amount reflected by the surface (Sellers, 1965).

Methods used for measuring the amount of liquid water in perennial snow are identical to methods used for measuring water in seasonal snow. Centrifugal, calorimetric, dielectric, and electromagnetic methods have all been used with varying degrees of success, but consistently accurate determinations are still difficult to obtain. (See sec. 9.B.1.a.6). Work by Linlor and others (1974) on microwave methods, and by Ambach and Denoth (1972) on dielectric methods, show promise of eventually providing the most fruitful means of measuring liquid water. Microwave techniques have the potential of future use in remotely operated data-gathering systems.

The ponding or entrapment of large amounts of liquid water is common in large temperature ice masses. This water is important for both hydrologic and mass-balance measurements of glaciers and also for studies of glacier-flow dynamics. The only feasible means of measuring the liquid-water content is through a complex series of measurements of input and output that continuously monitors the transport of water through the glacier (Tangborn, Krimmel, and Meier, 1975).

9.B.1.b.4. ABLATION

Ablation is the process by which snow and ice are lost from a glacier, snowfield, or floating icepack by calving, melting, evaporation, sublimation, or wind erosion, The main ablation processes in the Arctic and Antarctic are calving, sublimation, evaporation, and wind erosion. Calving causes iceberg hazard to shipping and affects glacier variations (Post, 1975). The possibility of using icebergs as a source of fresh water has prompted interest in this form of ablation (Weeks and Campbell, 1973, Weeks and Mellor, 1978).

The most important factor in nonpolar regions is melt, most of which occurs on the surface. Melting (evaporation is implicit in most measuring techniques) is usually measured at a series of points on the surface with ablation stakes. The stakes are set in holes drilled into the ice or snow by mechanical or thermal drills (Hodge, 1971). Stake dimensions vary depending on the amount of ablation expected and on logistical aspects of the field study. The usual size is about 4 cm in diameter and 2 m in length; although the length is often extended by locking several stakes together (Ostrem, Gunner, and Stanley, 1969).

Another method of measuring ablation and melting is to use a lysimeter—a device that catches and measures the melt water produced by ablation of ice or snow surfaces (Haupt, 1969). Ablation may also be measured indirectly by heat-balance observations (Hoinkes, 1955).

Lysimeters are recommended for laboratory or field studies of small size where the investigator needs a direct measure of melt water. Such studies require careful control study of conditions as well as reliable and accurate lysimeters. Heat-balance studies involve an indirect, computational approach and are best suited to general determinations for large areas except when direct comparisons are to be made with measured ablation.

A series of density-depth determinations of the snowpack is recommended for measuring ablation rates in terms of days or weeks. This accurate but laborious method requires digging a snow pit and measuring the water equivalent of the snowpack by standard techniques (Tangborn, Krimmel, and Meier, 1975).

Some of the problems associated with ablation measurements are compaction of the snowpack (LaChapelle, 1959), refreezing of melt water beneath the surface (superimposed ice) (Schytt, 1949), and density variations in both ice and snow (Muller and Keeler, 1969).

9.B.1.b.5. MOVEMENT

The recommended method for flow determination is a triangulation technique that uses both theodolites and distance-measuring devices simultaneously. This method involves making a time

series of determinations of the positions of a point (usually marked by a stake implanted in the ice) moving with the snow or ice.

Many studies of glacier-flow characteristics have been made by triangulation techniques. Probably the most detailed and well documented work, covering all aspects of triangulation over rough terrain, was done on the Nisqually Glacier (Hodge, 1972). When accuracy can be sacrificed, repetitive aerial photographs are used if the ice mass contains sufficient well-defined points. An even less detailed analysis of movement can be made with satellite images. Recent work with high-altitude (Landsat) images has shown that sufficiently accurate flow measurements of large glaciers are possible with current technology (Krimmel and Meier, 1975).

9.B.1.b.6. MASS BALANCE

Three methods are now available for measuring annual changes in mass of glaciers and other perennial ice and snow.

9.B.1.b.6.a. Glaciologic Method

The glaciologic method is probably the most widely used and is generally recommended. Stakes are placed in holes drilled in the ice and snow. Ablation (or accumulation) is measured periodically by observing the surface lowering or raising adjacent to these stakes through at least a full season. Density is also measured periodically to obtain the total water equivalent of the mass loss or gain. Both the summer and winter ablation and balance can be determined, which permits the calculation of the net or annual balance. Both stratigraphic (Ostrem, Gunner, and Stanley, 1969) and annual balance systems can be used; they may be used simultaneously if necessitated by the climate or size of the glacier (Mayo, Meier, and Tangborn, 1972).

9.B.1.b.6.b. Hydrologic Method

The hydrologic method is recommended if the glacier occupies a large portion of the basin and if both input (chiefly precipitation) and output (chiefly runoff) are known for the glacier or the glacier basin (Tangborn 1968). If only the solid (ice and snow) phase of the mass balance is desired, the liquid-water balance must be determined and used in the calculation.

9.B.1.b.6.c. Mapping (Geodetic) Method

The mapping (geodetic) method defines the change in surface altitude of a snow or ice surface by comparing two maps made at different times (Meier 1966). The main disadvantage of this method is that it measures only the total change in mass between the two times of mapping and provides no information on any intermediate changes in longitudinal distribution of mass or the extent the distribution is related to glacier flow.

9.B.1.c. OBSERVATION SITES

Because it is not possible to measure snow properties simultaneously over extensive areas, some type of representative sampling is used. It is recommended by the International Association of Scientific Hydrology (1970b), that snow-observation sites be selected on the basis of following:

> All measurements related to snow accumulation and ablation are greatly dependent on the characteristics of the site, above all on the exposure to sun and wind and on the frequency and velocity of wind in particular. Within a narrow area a con-

siderable variation in snow properties may be observed, and even the same site will not always behave identically with respect to its neighborhood. The selection of a suitable measuring site is therefore the basic problem of all snow measurements. Unfortunately it cannot be solved for all conditions with satisfactory results.

Two basically different requirements for a site can be defined:

1. A site may be selected to represent "characteristic" or "representative" conditions of a specific area, i.e., typical topography and exposure to sun, wind, etc.

2. A site may be selected as a "standard site", i.e., a location where certain basic instruments and methods can be applied unaffected by disturbing effects. To observe snow distribution in a catchment area, sites of type 1 have to be selected, whereas for measurements such as snowfall in the meteorological sense, type 2 is required. The specifications of type 1 cannot be given in general terms. The representativeness of a selected site for a whole area has to be proved by detailed investigation for each property in question (snow deposit, ablation, etc.).

Type-1 sites, as described above, should be chosen to avoid unusual drifting and exposure and to be within the interior of the mountain range to be indexed. Low mountain passes and end parts of mountain ranges have proved to be undesirable for representing large interior areas. Sites near roads that go through passes or around the ends of ranges should not be used. Any sites within transportation corridors are generally undesirable because they may be destroyed in time. To improve the index, several sites having elevation differences of 200 to 300 m should be selected.

For type-2 sites, as defined above, the area should be horizontal, open to snowfall and insolation, and sheltered from wind and drifting snow. The site should be protected in all directions by objects of uniform height. The distance between the sheltering objects and the gage should be at least one but no more than two times the height of the objects; that is, the angle between the gage and the top of the objects should be between 45° and 25°.

Suitable sites are rarely found in vast, flat areas devoid of trees. In such locations, artificial shelters such as large wind shelters made of several layers of snow fencing (Rechard and Larson, 1971a, 1971b) have proven useful. In mountainous terrain, snow is often blown from high crests over large depressions and valleys, which produces excessive snow deposition that cannot be distinguished from precipitation.

9.B.2. PRESENTATION OF DATA

9.B.2.a. TABLES

It is recommended that data be presented as tables whenever possible. This is the most convenient and generally accepted format for such data as snow depths, new snowfall amounts, temperatures and water equivalent of new snow, beginning of snow cover, end of snow cover, duration of snow cover, etc.

9.B.2.b. GRAPHS

Graphs may be highly informative and are recommended when a quick, visual impression of time trends or the relationships among several variables would be useful.

9.B.2.b.1. TIME PLOTS

Figure 9–6 is a time plot of selected snow and weather features used by Swiss scientists in their snow and avalanche studies. It shows a full winter's data from one observation site. To be most useful, the plot should be kept current. To facilitate plotting and legibility, the original plot is often a meter or more in length.

The top part of figure 9–6 consists of a continuous record of snow depth, which is represented by the heavy black line, and six coded summaries of open-pit data taken at approximately biweekly intervals. (A discussion of the symbols and methods of plotting pit data is given in sec. 9.B.2.b.2). The thin black lines numbered 1 through 8 represent the position of colored threads placed on the snow surface during major storms (3, 5, 7) or when the pits were dug (1, 2, 4, 6, 8). The threads become part of the surface-snow layer for the date they were set out. Their positions at later dates as revealed by subsequent pits, give an indication of snowpack and layer settlement with time. The starlike symbols attached to the snow-temperature lines by dashed lines indicate air temperature at the time the pit was dug. Temperatures are determined by scaling the distance left (negative) or right (positive) from the left side of the column of symbols. The lower part of the figure represents selected weather and snow conditions by dates.

9.B.2.b.2 SNOW-PIT DATA—SNOW PROFILES

Most open-pit studies are undertaken when considerable data on the various layers within the snowpack are required. Pit data should be presented in the form of snow profiles, and the international symbols and plotting techniques depicted in figure 9–2B should be used because they provide a concise way to present a large amount of data.

Grain size should be determined visually with a hand lens and a millimeter grid. The average long dimension of the grain is estimated and recorded, either as a single number or as a range. For general use, grain sizes have been described as follows:

Diameter	*Term*
0–0.5 mm	Very fine
0.5–1.0 mm	Fine
1.0–2.0 mm	Average
2.0–4.0 mm	Coarse
More than 4.0 mm	Very coarse

Symbols for free-water content and snow-surface deposits are depicted by the symbols given in figure 9–7.

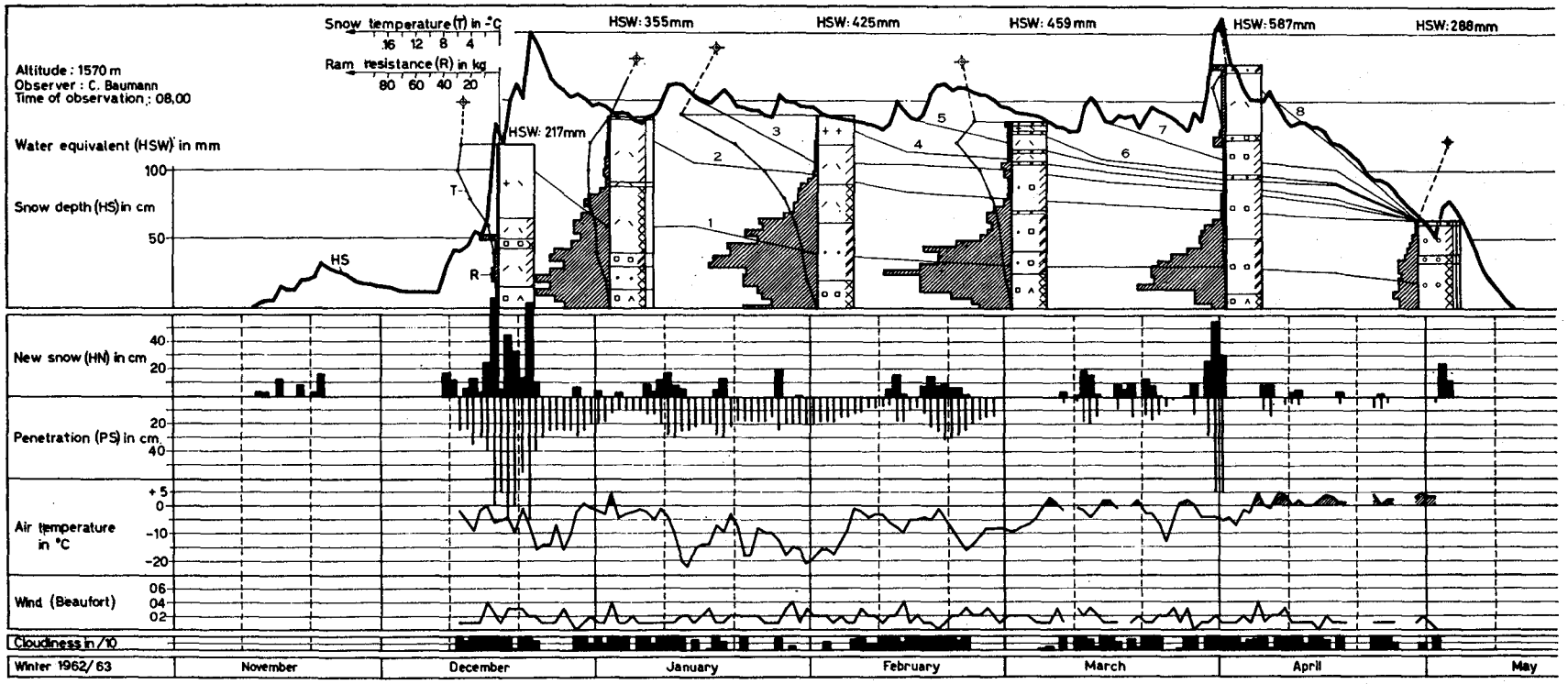

Figure 9–6. – Time evolution of snow profiles, Station Grindelwald-Bart. (From IASH, 1970)

Free water content

Symbol	*Term*	*Description*
	Dry	Snow usually, but not necessarily, below 0° C. Grains have little tendency to stick together in a snowball when lightly pressed in gloved hand.
	Moist	Snow at 0° C. No water visible even with hand lens. Snow makes good snowball.
	Wet	Snow at 0° C. Water visible as a meniscus between grains but cannot be pressed out by moderate squeezing in the hand.
	Very wet	Snow at 0° C. Water can be pressed out by moderate squeezing in the hand. There is still an appreciable amount of air confined within the snow.
	Slush	Snow at 0° C. Snow flooded with water and containing relatively small amounts of air.

Snow surface deposits

Symbol	*Deposit*	*Description*
∪ or ∨	Surface hoar	Sublimation crystals formed directly on the snow surface.
∨	Soft rime	White, opaque deposit formed on objects by rapid freezing of supercooled water droplets.
∨	Hard rime	Formed the same way as soft rime but more compact and amorphous.
∿	Glazed frost (Verglas or glaze)	Coating of ice, generally clear and smooth but usually including some air pockets formed on objects by freezing of films of supercooled water. Denser, harder, more transparent than rime or surface hoar.

These symbols are also used in snow profiles if the deposits are identified inside the snowpack.

Figure 9-7.—Symbols for free-water content of snow and ice and for snow-surface deposits. (From Perla and Martinelli, 1976)

In pits, density is usually determined by sample tubes for each major snow layer. These are recorded in kg/m³ opposite a tick mark that indicates height of the sample.

Total snow depth and location of layer boundaries, temperature readings, and density samples are determined from the ramsonde number or from a probe propped against the pit wall.

The snow profile—a graphic representation of snowpit data—is shown as figure 9-5. This profile was taken on a 34° slope where an avalanche had run. It shows the bed surface of the avalanche and

the snow layers that have avalanched as well as those that remained in place. The profile shows also the conventional way of rotating the layers from a slope to the horizontal for recording.

The snow profiles in figure 9-6 are abbreviated forms; they contain the grain type and hardness symbols in the same box. Free-water content is given only for the second and sixth profiles, and temperature and ram hardness are zeroed at the left vertical line of the symbol boxes for compactness.

9.B.3. REFERENCES

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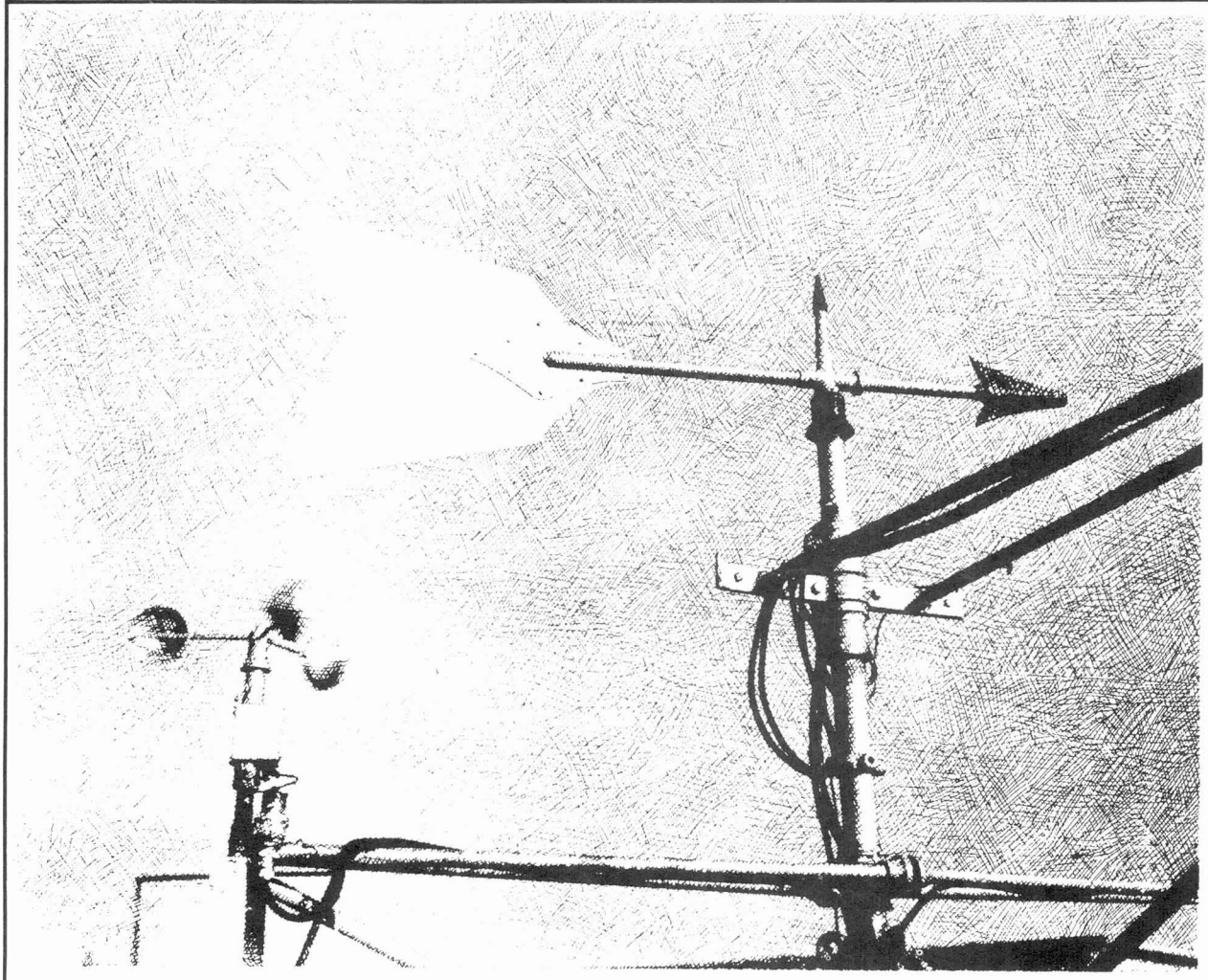

Hydrometeorological Observations

CHAPTER 10 – HYDROMETEOROLOGICAL OBSERVATIONS

Prepared by
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January 1980

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COMMENTS ON CHAPTER 10

National Handbook of Recommended Methods for Water-Data Acquisition

I found this "National Handbook" chapter to be useful. Comments:

_____

_____

_____

I found the following method to be unsatisfactory: _____

Method _____

Reference _____

The method is unsatisfactory for the following reason(s): _____

_____

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CHAPTER 10 – HYDROMETEOROLOGICAL OBSERVATIONS

10.A. INTRODUCTION

This chapter presents information on the measurement and analysis of various facets of the atmosphere and interactive solar processes that are of particular interest to the hydrologist, for example, precipitation, air temperature, dew point, atmospheric pressure, and wind. Meteorological terms used in this chapter are defined in a manner that is both understandable to the generalist and acceptable to the specialist. Equipment and techniques that are commonly used for the measurement and observation of data, including remote-sensing techniques, are described in detail. Also described are the quality-control procedures needed to maintain the standards and integrity of the equipment and data. Finally, a list of selected publications containing detailed information on equipment and methods is presented at the end of each main section.

10.B. PRECIPITATION

10.B.1. DEFINITION OF ELEMENTS

10.B.1.a. TYPES OF PRECIPITATION

Precipitation is defined as any or all forms of water particles, liquid or solid, that fall from the atmosphere and reach the ground. It is distinguished from cloud, fog, dew, rime, frost, etc., in that it must fall; it is distinguished from cloud and virga in that it must reach the ground. Precipitation includes the following forms:

Rain—Precipitation of liquid water particles, either as drops larger than 0.5 mm in diameter or as smaller, widely separated drops.

Drizzle—Fairly uniform precipitation composed exclusively of fine drops (diameter less than 0.5 mm) close together. Drizzle appears to float while following air currents, although, unlike fog droplets, it falls to the ground. Drizzle drops are too small to disturb stillwater puddles.

Freezing rain and drizzle—Rain or drizzle that freezes upon impact with the ground or with objects on the ground or in flight.

Snow—Precipitation composed of white or translucent ice crystals, chiefly in complex, branched hexagonal form and often agglomerated into snowflakes.

Snow pellets (also called soft hail, graupel, tapioca snow)—Precipitation consisting of white, opaque, approximately round (sometimes conical) ice particles having a snowlike structure. Diameters range from 2 to 5 mm. Snow pellets differ from snow grains in that they are crisp and easily crushed. They rebound and often break up when they fall on a hard surface.

Snow grains (also called granular snow)—Precipitation in the form of very small, white opaque particles of ice; the solid equivalent of drizzle. They resemble snow pellets in external appearance, but are more flattened and elongated and generally have a diameter of less than 1 mm. They usually fall in small quantities, mostly from stratus and never as showers, and do not shatter or bounce when they hit a hard surface.

Ice pellets—Precipitation of transparent or translucent pellets of ice that are round or irregular, rarely conical, and have a diameter of 5 mm or less. The pellets usually rebound when striking a hard surface and make a sound on impact. Ice pellets are of two main types:

1. Hard grains of ice consisting of frozen raindrops or largely melted and refrozen snowflakes (formerly called sleet).
2. Pellets of snow encased in a thin layer of ice that has formed either from the freezing of droplets intercepted by the pellets or from the freezing of water resulting from the partial melting of the pellets. Ice pellets of type (1) fall as continuous precipitation, whereas type (2) is showery.

Ice crystals—Unbranched crystals (snow crystals are branched) in the form of needles, columns, or plates. Ice crystals are often so tiny that they seem to be suspended in the air. They may fall from a cloud or from clear air. The crystals are visible mainly when they glitter in the sunshine or other bright light; they may then produce a luminous pillar or other optical phenomenon. This hydrometeor, which rarely forms more than the lightest precipitation, is frequent in polar regions and occurs only at very low temperatures in stable air masses.

Hail—Precipitation in the form of balls or irregular lumps of ice (hailstones). Hail is always produced by convective clouds (nearly always cumulonimbus) and is usually associated with thunderstorms and surface temperatures above freezing. Most hailstones consist of alternate opaque and clear layers of ice. Diameters range from 5 to 50 mm or more, whereas smaller particles of similar origin, formerly called small hail, may be classed as either ice pellets or snow pellets. In the United States, hail occurs most frequently in the Great Plains region.

10.B.1.b. CHARACTER OF PRECIPITATION

Continuous—Intensity changes gradually if at all.

Intermittent—Intensity changes gradually if at all, but precipitation stops and starts at least once within the hour preceeding the observation.

Showery—Precipitation changes in intensity or starts and stops abruptly. Showers fall from cumuliform clouds.

10.B.1.c. INTENSITY OF PRECIPITATION

Precipitation intensity is an indication of the amount of precipitation falling at the time of observation. It is expressed as very light, light, moderate, or heavy. The meaning of each intensity depends on the type of precipitation and the method used to determine the intensity. The different intensities are described in Table 10–1, which have been modified (from National Weather Service, 1970) to include metric units.

Table 10–1.—*Criteria for describing intensity of selected forms of precipitation*

A.—INTENSITY OF PRECIPITATION (OTHER THAN DRIZZLE) ON RATE-OF-FALL BASIS

Very Light	Scattered drops or flakes that do not completely wet or cover an exposed surface, regardless of duration.
Light	Trace to 2.54 mm/h; maximum 0.25 mm in 6 min.
Moderate	2.8 to 7.6 mm/h; more than 0.25 mm to 0.76 mm in 6 min.
Heavy	More than 7.6 mm/h; more than 0.76 mm in 6 min.

B.—INTENSITY OF DRIZZLE ON RATE-OF-FALL BASIS

Very light	Scattered drops that do not completely wet an exposed surface, regardless of duration.
Light	Trace to 0.25 mm/h.
Moderate	More than 0.25 mm/h to 0.5 mm/h.
Heavy	More than 0.5 mm/h.

C.—INTENSITY OF DRIZZLE AND SNOW WITH VISIBILITY AS CRITERIA

Very light	Scattered flakes or droplets that do not completely cover or wet an exposed surface, regardless of duration.
Light	Visibility 1 km or more.
Moderate	Visibility less than 1 km but not less than ½ km.
Heavy	Visibility less than ½ km.

D.—ESTIMATING THE INTENSITY OF ICE PELLETS

Very light ....Scattered pellets with no accumulation.
Light .....Few pellets falling with no appreciable accumulation.
Moderate ....Slow accumulation.
Heavy .....Rapid accumulation.

E.—ESTIMATING THE INTENSITY OF RAIN

Very light ....Scattered drops that do not completely wet an exposed surface, regardless of duration.

Light .....Individual drops easily seen; slight spray observed over pavements; puddles form slowly; more than 2 minutes may be required to wet pavements completely; sound on roofs ranges from slow pattering to gentle swishing; steady small streams may flow in gutters and downspouts.

Moderate ....Individual drops are not clearly identifiable; spray is observable just above pavements and other hard surfaces. Puddles form rapidly; downspouts on buildings seen one-fourth to one-half full; sound on roofs ranges from swishing to gentle roar.

Heavy .....Rain seemingly falls in sheets; individual drops are not identifiable; heavy spray to height of several inches is observed over hard surfaces; downspouts run more than one-half full; visibility is greatly reduced; sound on roofs resembles roll of drums or distant roar.

10.B.2. MEASUREMENT OF PRECIPITATION

The amount of precipitation is expressed in terms of the vertical depth of water that would accumulate on a horizontal projection of the earth's surface if all components, including snow and ice, were in the form of water. Snowfall may be measured as the depth of fresh snow covering an even horizontal surface. The chief aim of any method of measurement should be to obtain a sample that is representative of the precipitation over the observed area. The following paragraphs describe several instruments and methods recommended for measurement of precipitation.

10.B.2.a. INSTRUMENTS AND METHODS

Although precipitation has been measured for thousands of years, the reliability of measurements has generally been questioned. Data-collection systems range from fencepost gages to satellites; instruments such as automatic siphons and digitally recording radar have been tested with varying degrees of success. The ordinary rain gage typically consists of a collector above a funnel that leads into a receiver (container) having some sort of measuring device. Measurements may be made either manually or automatically. The size of the mouth of the collector is not important except in areas of heavy snowfall, where standard 4- and 8-in (10.2- and 20.3-cm) gages may be blocked if a snow bridge forms over the opening. In such areas, a 12-in (30.5-cm) gage is recommended.

10.B.2.a.1.a. Standard gages

Standard gages are recommended for measuring precipitation over short time periods and where continuous records are not required. Two devices are used commonly to measure precipitation in the gage—a graduated measuring cylinder and a graduated dipstick. A measuring cylinder should be made of clear glass or similar material with a low coefficient of expansion and should indicate the size of the gage for which it is to be used. Its diameter should not exceed one-third of the gage's rim diameter. In all measurements, the bottom of the water meniscus should be used as the defining line. It is important to keep the cylinder vertical and to avoid errors due to parallax. Parallax is minimized if the main graduation lines are repeated on the back of the cylinder.

A dipstick should be made of cedar wood or other material that does not absorb water to an appreciable extent and has low capillarity. It should have a brass foot to avoid wear and should be graduated according to the relative areas of cross section of the gage orifice and the receiving container and should make allowance for displacement by the stick itself.

10.B.2.a.1.b. Storage gages

Storage gages are used to measure total seasonal precipitation in remote, sparsely inhabited areas. These gages consist of a collector above a funnel that leads into a receiver large enough to store the seasonal catch. In areas having extremely heavy snowfall, the collector must be placed above the maximum expected snow level. An antifreeze solution should be used in the receiver to convert the snow that falls into the gage to liquid. In addition, a small amount of oil or other evaporation-suppressing material should be placed in the receiver to reduce evaporation. The seasonal precipitation catch is determined either by weighing or measuring the volume of the contents of the receiver, taking into account the amounts of antifreeze or other materials placed in the receiver at the beginning of the season.

10.B.2.a.1.c. Snowboards

Snowboards are recommended for measuring new snowfall. The board is a piece of thin, light-colored wood or plastic, at least 30 cm square, with a vertical stake marked in centimeters attached to its center. The board is placed in horizontal position flush with land or snow surface at the beginning of the observation period. At the end of the observation period, the depth of snow on the board is read on the vertical stake, and a container 20 cm in diameter is used to take a sample of snow for determining water equivalent. The board is then cleaned and replaced on the surface of the snow for subsequent measurements.

10.B.2.a.1.d. Snowstakes

Snowstakes should be used only as a last resort to obtain depth measurements. They should be placed in the most representative area possible. It is better to measure snow depth by thrusting sticks through the snow down to ground surface at several spots and averaging the measured depths.

For additional information concerning snowboards and snowstakes and their use, refer to Chapter 9 on snow and ice in the National Handbook.

10.B.2.a.2. RECORDING GAGES

Recording precipitation gages are recommended when continuous records of precipitation are required. Three types of precipitation recorders are in general use—the weighing type, the tipping-bucket type, and the float type. The only satisfactory instrument for measuring all kinds of precipitation uses the weight principle. The other two types are used primarily to measure rainfall.

10.B.2.a.2.a. Weighing type

With these instruments, the weight of a receiving container plus the precipitation that has fallen since the record began is recorded continuously, either by a spring mechanism or with a system of balance weights. Thus, all precipitation is recorded as it falls. This type of gage normally has no provision for emptying itself, but by a system of levers it is possible to make the recording pen traverse the chart a number of times. Evaporation losses and oscillation of the balance in strong winds may be reduced by evaporation suppressants and damping mechanisms. This type of instrument is useful for recording snow, hail, and mixtures of snow and rain because it does not require the solid precipitation to be melted before it can be recorded.

10.B.2.a.2.b. Tipping-bucket type

A light-weight container divided into two equal compartments, or buckets, is balanced above a horizontal axis. Two stops, one on each side of the container, limit its motion. Rain runs from a collecting funnel into one of the compartments until the pair of buckets becomes unbalanced and tips to its other position. This drains the water out of the first compartment and places the second compartment in position to receive rain from the funnel. The tipping of the bucket operates an electrical contact to produce a record. The recorded distance between each tip represents the time taken for a specified amount of rain to fall. This amount should not be greater than 0.2 mm if detailed records are required.

10.B.2.a.2.c. Float type

In this type of instrument, the rain is led into a chamber containing a float. The vertical movement of the float is transmitted to a pen on a chart. By adjusting the dimensions of the receiving funnel, float, and float chamber, one can obtain any desired scale on the chart. Sufficient water must be kept in the bottom of the chamber so that the float is actually floating at all times; consequently, it may be necessary to add water to make up for evaporation losses during dry periods. It is also good practice to empty the chamber each time the station is serviced, to avoid dependence on the automatic emptying device.

To provide a record over a useful period (at least 24 hours), either the float chamber must be very large (in which case a compressed scale on the chart is obtained), or some automatic means must be provided for emptying the float chamber quickly whenever it becomes full. When the float chamber empties, the pen returns to the bottom of the chart. The chamber is usually emptied by a siphoning arrangement. The siphoning should begin when the water reaches a specific level, so that no water can dribble over at the beginning or the end of the siphoning. The process should not take longer than 15 seconds. In some instruments, the float chamber assembly is mounted on knife-edge bearings so that the chamber overbalances when full. The surge of water assists in the siphoning process, and, when the chamber is empty, it returns to its original position. Some rain recorders have a forced siphon that operates in less than 5 seconds, and one type has a small chamber, separate from the main chamber, that catches rain during siphoning. The small chamber empties into the main one when the siphoning ceases, which ensures a correct record of total rainfall. A heating device should be installed inside the gage if there is a possibility of freezing.

10.B.2.a.2.d. Rainfall-intensity recorders

Several rainfall-intensity recorders have been designed and used for special purposes; however, they are not recommended for general network purposes because of their complexity. A satisfactory record of rainfall intensity can be determined from a float or weighing recorder by providing a proper time scale.

10.B.2.a.2.e. Recording snow gages

The most commonly used recording snow gage is the weighing type. If rain is not expected during the winter, the funnel may be removed so that any precipitation can fall directly into the receiver. A float gage is not satisfactory for recording snowfalls because the heat required to melt the snow would cause excessive evaporation.

Snow-pressure sensors (snow pillows) are recommended when continuous or frequent water-equivalent data are needed. Although isotopic snow gages have been used primarily for research thus far, they are recommended when unusual sensitivity is required. For additional information on these gages, refer to Chapter 9 (snow and ice) of the Handbook.

10.B.2.a.3. RADAR

Radar is now a standard instrument in weather-observation networks and is the best system available to detect and describe weather events that have potential for causing disasters. Radar also permits continuous and almost instantaneous observation of the location, intensity, type, vertical and horizontal extent, and movement of precipitation. Certain types of equipment can provide quantitative information from which precipitation rates and amounts can be calculated.

10.B.2.a.3.a. Factors affecting measurement

Precipitation measurements by radar are affected by the type of precipitation, by the width and refraction of the radar beam, and by attenuation. These factors are described in some detail by the World Meteorological Organization (1970).

10.B.2.a.3.b. Methods

When radar is used to evaluate precipitation, the following methods of analyses are recommended.

10.B.2.a.3.b.1. Photographic methods—An automatic camera with rapid-development facilities is used to photograph the repeater scope to provide multiple-exposure transparencies. These multiple exposures are taken every 10 minutes and are used to detect areas of persistent and/or intense rainfall during the last hour or two. The brightest areas on the film represent either the most intense precipitation, where the image is most brilliant in each exposure, or that of greatest persistence, where the image is reinforced in brilliance with successive exposures. After the transparency has been developed, it is mounted as a slide, and projected onto a map so that the images can be outlined and compared with observed rainfall reports.

Ideally, echo areas strong enough to saturate the same film area during every exposure would produce a fully exposed area on the multiple-exposure photograph. If a saturated area did not persist for the total number of exposures, the photograph would contain an echo area of something less than total exposure and would appear gray in the photograph.

If the radar is equipped with a step-gain receiver control (attenuators), an intensity factor can be introduced into a multiple-exposure photograph by stepping the attenuators through selected decibel increments and taking a picture at each decibel level. This system further enhances the echoes on the transparency, which facilitates recognition of the high-intensity rainfall areas. For analysis of storms in retrospect, periodic photographs of the radarscope are taken.

10.B.2.a.3.b.2. Contour tracing—The simplest analysis involves periodic tracing of echo positions on transparent-acetate-radarscope overlays that have geographic boundaries outlined on them. Qualitative estimates can be made on the instantaneous storm intensity on the basis of echo

appearance (weak, moderate, or strong). Successive tracings at 15-minute intervals can be superimposed to determine the areas affected, the direction of storm motion, echo persistence, and the area-intensity relationship.

10.B.2.a.3.b.3. Stepped-gain contour tracing—If the radar is equipped with a stepped-gain receiver control (attenuators), an intensity factor can be introduced onto the radarscope overlay by contouring the echoes at each of the selected decibel-attenuator levels every 15 minutes for one hour. Different colors can be used to delineate the most intense cores of rainfall as well as the areal extent of the storm. Each level at a specific range has a corresponding rate of rainfall. With the attenuators, it is possible to determine the radar-depicted rainfall rate for any precipitation echo within range of the radar. Determinations beyond 180 km are of limited value because they correlate poorly with observed rainfall on the ground.

10.B.2.a.3.b.4. Grid-overlay method—The grid-overlay method provides information on whether precipitation is occurring at a given location and gives some indication of duration. In this method, a grid overlay is placed at selected time intervals on the radarscope, and a mark is placed where a precipitation echo is observed. At the end of the time interval, the pattern of marks shows where precipitation has been occurring and its duration.

Rainfall patterns can also be determined with the attenuator controls on the radar. The attenuators should be frequently stepped through selected intervals. At each interval and a corresponding range, the instantaneous rate of rainfall can be estimated and entered in the appropriate grid. These values can later be processed to determine rainfall distribution in space and time.

10.B.2.a.3.b.5. Automatic techniques—An automatic electronic radar digitizer capable of sampling radar echoes at the rate of 80-range increments for each 2 degrees of azimuth has been developed. These data are recorded on magnetic tape for immediate onsite computer analysis, for transmission to a remote computer, or for retention and later analysis. The results of this type of sampling are similar to those obtained by manual methods, except that the number of discrete samples is larger by at least one order of magnitude than the finest grid overlay. The time required to sample and record the entire radar sweep is about 4 minutes.

10.B.2.a.4. SPECIALTY INSTRUMENTS

Several instruments that are not generally part of any standard hydrometeorological network are used for special purposes or for research in measuring precipitation. The most prominent of these are briefly mentioned below. Other references may be consulted for detailed descriptions of these instruments and their uses.

10.B.2.a.4.a. Hail pads

Hail pads, which are still experimental, are used to measure hail intensity. They may be made of a variety of materials. One type, designed for use in the National Hail Research Experiment (NHRE), uses a deformable styrofoam (florist-type) substrate covered by a thin (0.18 mm) aluminum foil. To prevent tearing by the wind, the foil is cemented to the styrofoam substrate.

10.B.2.a.4.b. Hail separator

This instrument, developed for use in NHRE, measures daily accumulated totals of rain and hail by separating them into two containers through a system of baffles and screens.

10.B.2.a.4.c. Doppler radar

This method is being tested and developed to detect and measure rates and amounts of precipitation, particularly rainfall and hail intensities from convective cloud systems.

10.B.2.a.4.d. Satellites

Although satellites cannot yet be used for quantitative precipitation measurements, observations obtained from satellites can provide information about the areal extent and time distribution of precipitation. Satellite information is being used in conjunction with precipitation networks and data-collection platforms to provide reliable, near real-time precipitation data to project managers. Satellite telemetry will become increasingly important in water-resources monitoring and management.

10.B.2.b. UNITS OF MEASUREMENT

Members of the World Meteorological Organization (WMO) have agreed to use the Celsius temperature scale and the International System (SI) metric system for evaluation of meteorological elements included in reports for international exchange, and WMO recommends the use of these units for all meteorological observations and publications. The recommended unit for measuring precipitation is the millimeter (mm); precipitation intensity is measured in millimeters per hour (mm/h). Daily gages should be read to the nearest 0.2 mm and preferably to the nearest 0.1 mm; weekly or monthly gages should be read to the nearest 1 mm. Depth of snow should be measured in centimeters (cm). As a rough approximation, 1 cm of fresh snow is equivalent to 1 mm of rainfall. However, this ratio depends largely on the texture of the snow.

10.B.2.c. QUALITY CONTROL

10.B.2.c.1. ACCURACY AND CALIBRATION OF INSTRUMENTS

The accuracy with which a meteorological element should be measured depends on the specific purpose of the measurement. The various technical commissions of the World Meteorological Organization have established accuracy requirements for selected meteorological measurements. For use in hydrometeorology, these are as follows:

1. Total precipitation between two observations ..... ±1 mm
2. Intensity ..... ±1 mm/h
3. Depth of snow ..... ±1 cm

To achieve accuracy in measurement, instruments should be calibrated periodically against National standards. Calibration should, as far as possible, be done at the time instruments are issued to a station and during each periodic inspection of the station.

10.B.2.c.2. CONTROL OF DATA

Basic data of good quality can be obtained by establishing a system of quality control that includes not only periodic inspection of stations and maintenance or repair of equipment, but preliminary checking of data by internal consistency checks. One important facet of preliminary checking is to ensure completeness of the data, including such information as dates and locations.

Because precipitation data are usually tabulated in an array by station, district, or region, it is easy to detect gross errors in measurements or to detect stations where data are consistently credited to the wrong day. In most cases, computer programs have been prepared for quality control of precipitation data.

10.B.2.d. INSTRUMENT SITING

In general, precipitation gages should be distributed uniformly and should be consistent with practical needs for data and with the location of observers and data-collection facilities.

In mountainous regions, attention must be given to vertical zonality, and storage gages should be used to measure precipitation at high altitudes.

The minimum network should consist of three kinds of gages:

1. Standard gages—These gages are read daily.
2. Recorders—At least 10 percent of the stations in warm climates should be equipped with recorders, and 5 percent in cold climates. these stations will provide information on the intensity, distribution, and duration of precipitation.
3. Storage gages (totalizers)—Storage gages may be used in sparsely settled or remote regions such as desert or mountainous terrain. These gages are usually read monthly, seasonally, or whenever it is possible to inspect them. It is also possible to read them daily with automatic telemetry equipment.

In a perfect exposure, the catch of a rain gage would represent the precipitation falling at that point and on the surrounding area. This is difficult to attain in practice, however, because of the effect of the wind; consequently, much care should be given to the choice of individual sites for each gage in a network. Precipitation gages should be located on level ground at a distance from any object (including the instrument shelter) of at least two, and preferably four, times the height of the object above the top of the gage. On all types of gages, the rim of the receiver must be exposed in a horizontal plane and well above the average level of snow surfaces. Rain gages should not be installed on roofs.

Objects that individually, or in groups, reduce the prevailing wind speed, the turbulence, and eddy currents in the vicinity of the gage may provide a more accurate catch. Thus, the best exposures are often found in orchards, openings in groves of trees, bushes or shrubbery, or where fences and other objects together form effective windbreaks. As a general rule, where the height and distance of the objects from the gage are fairly uniform, their height above the gage should not exceed twice their distance from the gage.

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10.C. SURFACE TEMPERATURE

10.C.1. DEFINITION OF ELEMENTS

Temperature is the degree of hotness or coldness as measured on given temperature scales by any of various types of thermometers.

Dry-bulb temperature—The ambient temperature of the air; the temperature measured by the dry-bulb thermometer of a psychrometer.

Thermodynamic wet-bulb temperature—The temperature that moist air at pressure p, temperature, t, and mixing ratio r will attain when brought adiabatically to saturation at pressure p by the evaporation of pure liquid water into the moist air.

Thermodynamic dew-point temperature—The temperature at which moist air with mixing ratio r and total pressure p, when saturated with respect to liquid water at the same pressure p, will have a saturation mixing ratio r_w equal to the given mixing ratio r.

Celsius temperature scale—A temperature scale with the ice point at 0 degrees and the boiling point of water at 100 degrees. Conversion to the Fahrenheit temperature scale is by the formula:

$$°F = \left(\frac{9}{5}\,°C\right) + 32$$

Fahrenheit temperature scale—A temperature scale with the ice point at 32° and the boiling point of water at 212°. Conversion to the Celsius temperature scale is by the formula:

$$°C = \frac{5}{9}\,(°F - 32)$$

Kelvin temperature (absolute)—The Kelvin is the unit of temperature that is equal to 1/273.16 of the thermodynamic temperature of the triple point of water. The ice point is 273.15K. Conversion from the Celsius scale to the absolute scale is by the formula:

$$K = °C + 273.15$$

Rankine temperature scale—An absolute temperature scale in Fahrenheit temperature units that is equivalent to the absolute temperature scale in Kelvin units. The unit of temperature is the degree Rankine that is identical in size to the degree Fahrenheit. The ice point is 491.67 °R. Conversion from the Fahrenheit scale to the Rankine scale is by the formula:

$$°R = °F + 459.67$$

10.C.2. MEASUREMENT OF SURFACE TEMPERATURE

10.C.2.a. INSTRUMENTS AND METHODS

10.C.2.a.1. THERMOMETER SCREENS (INSTRUMENT SHELTERS)

The thermometer screen (thermoscreen), or instrument shelter, is a specially designed enclosure that minimizes radiant heat while allowing air to move freely past the instruments inside the shelter. Thermometers that are properly exposed in such shelters will give temperature readings that represent the temperature of the surrounding air.

10.C.2.a.1.a. Cotton Region Shelter

The shelter most often used for exposure of thermometers is the National Weather Service medium-sized type, which has louvered sides and a double top designed to protect the thermometers

from precipitation and radiation. The louvered construction permits air to circulate around the instruments inside the shelter. Thermometers that are exposed properly in such shelters will give temperature readings that represent the temperature of the surrounding air.

10.C.2.a.1.b. Stevenson Screen

The Stevenson thermometer screen is a rectangular wooden box with doors at the back and front. The sides, back, and front are double louvered; the roof is double, and the base consists of overlapping boards separated vertically by an air space. A series of 1-in (2.54-cm) diameter holes with brass liners in the inner roof helps the air to circulate between the inner and outer roofs. The two sides of the louvers act in a manner similar to double walls and allow the air to circulate freely. The screen is painted white.

10.C.2.a.1.c. Airways Instrument Shelter

The Airways Instrument Shelter is a small shelter 20 inches high, 12 inches wide, and 12 inches deep (about $50 \times 30 \times 30$ cm) that is used for ventilation of a psychrometer only.

10.C.2.a.1.d. Israeli (Thaller) Shelter

The Israeli (Thaller) shelter consists of stacks of profiled louvers suitably spaced to shield their contents against solar radiation and precipitation and to permit an optimum of ventilation to reach the measuring elements. Thaller shelters are made of opaque white fiberglass that is almost unbreakable, has a low heat capacity, and has negligible heat conductivity.

10.C.2.a.1.e. Thermo-Shelter, Orchard type

The Thermo-Shelter is recommended for agricultural applications and as a low-cost shelter for general use. It is made from a highly reflective, molded, impact-resistant thermoplastic.

10.C.2.a.2. THERMOMETERS

10.C.2.a.2.a. Liquid-in-glass thermometers

Liquid-in-glass thermometers vary in length of stem and shape of bulb. As a general rule, long-stemmed thermometers can be read more precisely than those with short stems. All other factors being equal, a thermometer with a cylindrical bulb will indicate changes in air temperature faster; that is, will have less lag time, than one with a round bulb.

For routine observations of air temperature, including maximum, minimum, and wet-bulb temperatures, liquid-in-glass thermometers are used almost invariably. Mercury can be used as the thermometer liquid to as low as −36°C, just above its freezing point. For lower temperatures, absolute ethyl alcohol is generally suitable.

10.C.2.a.2.a.1. Mercury thermometers—Mercury-filled thermometers are designed to measure temperature above the freezing point of mercury (−38.9°C or −38.0°F). The mercury used to fill the thermometer should be chemically clean and free from gases. After the mercury has been introduced into the thermometer, a vacuum is produced in the stem before sealing; although, in some thermometers, an inert gas such as nitrogen is placed in the stem above the mercury.

10.C.2.a.2.a.2. Spirit thermometers—Liquids used in spirit thermometers have a much larger expansion coefficient and a much lower freezing point than mercury (ethyl alcohol freezes at −117°C). These liquids are used in minimum thermometers because they are transparent and because their larger expansion coefficients enable a larger bore to be used. However, spirit thermometers are less accurate than mercury thermometers of similar cost and quality.

10.C.2.a.2.a.3. Mercury-thallium thermometers—Mercury-thallium alloy is now used as a thermometric liquid for extremely low temperatures down to −59°C.

10.C.2.a.2.b. Mercury-in-steel thermometers

In the mercury-in-steel thermometer, which is used for indicating and recording temperatures remotely, a hollow, flexible metal coil (a form of Bourdon tube) is attached to a steel bulb by a thin metal capillary tube, and the system is filled with mercury under high pressure. Changes in volume of mercury in the bulb cause the coil to expand or contract (unroll or roll up more tightly), and these movements are transferred to a pointer or pen arm.

10.C.2.a.2.c. Bimetallic thermometers

The sensing element in a bimetallic thermometer is usually a strip of curved or helical metal made by welding together two bars of metals having different coefficients of expansion, then rolling the resultant compound bar into a thin strip. When the temperature of the strip changes, the two metals expand or contract by differing amounts so that the curvature of the strip varies. One end of the strip is fixed; the other end is free to move. The movement of the free end can be transferred to a pointer or other device for indicating the temperature.

10.C.2.a.2.d. Electrical-resistance thermometers

In this type of thermometer, a measurement of the electrical resistance of a mass of metal or other material whose resistance varies in a known manner with temperature is translated into temperature. The resistance of the element and its leads is usually measured by connecting it into a Wheatsone Bridge circuit. It is preferable to use a balanced-bridge circuit; that is, to adjust one of the remaining resistances in the bridge circuit until there is zero current through a galvanometer, and to then calculate the resistance of the element from knowledge of the other resistances. An alternative method is to ensure that the electromotive force applied to the bridge is stabilized by some means and to measure the out-of-balance current in the galvanometer. Changes in the resistance of the element will produce changes in the out-of-balance current in the galvanometer, and, if necessary, the galvanometer can be calibrated directly in terms of temperature. A special form of galvanometer known as a "ratiometer" or cross-coil galvanometer can also be used.

10.C.2.a.2.e. Bourdon-tube thermometers

The Bourdon-tube thermometer is closely related to mercury-in-steel bimetallic thermometers in principle and method of operation. A curved metal tube of elliptical cross section is filled with liquid, and one end of the tube is fixed while the other is free to move. Because the cubical coefficient of expansion of the liquid is larger than that of the metal, an increase in temperature causes the radius of curvature to increase. Movement of the free end is translated into a movement of a pointer or a pen arm.

10.C.2.a.2.f. Thermocouple thermometers

In a thermocouple, two different metals are joined together to make two junctions in a continuous circuit. If one junction has a different temperature than the other, an electromotive force is set up in the circuit so that a current flows. The magnitude of the electromotive force varies with the temperature difference between the junctions. Thus, if one junction is kept at a fixed or reference temperature and the other junction is allowed to take up the temperature to be measured, the electromotive force developed in the circuit gives a measure of the difference in temperature between the hot and cold junctions, and the temperature can be found. The electromotive force may be

measured by connecting a galvanometer in the circuit, or, for more accurate work, a potentiometer may be used. Several combinations of metals may be used in making a thermocouple; the choice depends on the temperature range over which it is to be used and the accuracy and sensitivity required.

10.C.2.a.2.g. Maximum thermometers

The maximum thermometer is filled with mercury and has a small constriction in the capillary (the fine bore of the tube) just above the bulb. As the mercury in the bulb expands with increasing temperature, some of it is forced past this constriction. When the temperature drops, the mercury above the constriction does not retreat into the bulb; therefore, the top of the column remains at the highest point attained. The thermometer is reset by whirling in its mount, which forces the mercury back through the constriction into the bulb.

10.C.2.a.2.h. Minimum thermometers

10.C.2.a.2.h.1. Spirit minimum thermometers—The most common device for indicating minimum temperature is a glass thermometer filled with colorless liquid (spirit). A small index is placed in the bore below the liquid surface. If the thermometer is tilted so that the bulb is higher than the stem, the index falls to the lower end of the spirit column. Surface tension prevents the index from breaking through the spirit surface. The thermometer is then mounted horizontally so that, as the temperature falls, the index is pulled along the bore by the contracting spirit. If the temperature rises, causing the spirit to expand, the index remains stationary. Thus, the top of the index indicates the lowest temperature reached since the instrument was set. The thermometer is reset by tilting the instrument so that the index moves back down to the end of the spirit column.

10.C.2.a.2.h.2. Grass minimum thermometers—Sometimes known as the terrestrial-radiation thermometer, this instrument is an ordinary minimum thermometer used mainly to obtain information about ground frosts at night. It should be exposed horizontally over short grass with its bulb just touching the grass-blade tips. When the ground is snow covered, the thermometer should be supported just above the snow without touching it. To avoid condensation of spirit, the grass minimum thermometer should not be exposed out of doors during the day. Condensation can also be prevented or minimized by fitting the upper part of the stem with a black metal sheath, about 5 cm in length, which will absorb radiation and keep that part of the stem slightly warmer than the bulb.

10.C.2.a.2.i. Soil thermometers

Soil temperature is generally measured with a mercury-in-glass thermometer. For depths of 5, 10, and 20 cm, thermometers with stems bent at a right angle or other suitable angle are the most convenient because, with the scale facing upward, they can be read without being disturbed. If the exposed part of the stem is in bright sunlight, significant error may be introduced. For depths of 50 and 100 cm, a thermometer suspended in an iron tube sunk into the earth to the required depth is recommended. The thermometer should be enclosed in a glass tube with the bulb embedded in wax. This lagging allows the instrument to be removed from the tube and read before the temperature has time to change appreciably.

In cold climates, soil thermometers should be suspended in thin, preferably plastic, tubes that have been sunk into the earth to the required depth. The upper ends of these tubes should extend above the ground high enough to exceed the expected depth of snow cover and should be supported securely. The tubes should be lightly capped to prevent moisture from penetrating. To lift the thermometer to the surface, a flexible rod of negligible heat conduction may be used.

Any of the following types of thermographs may be used for meteorological purposes, provided they can be adapted to cover the required ranges:

1. bimetal
2. Bourdon tube
3. mercury-in-steel
4. electrical thermographs

The first two types are used mostly for routine recording because they are inexpensive, reliable, and portable. However, they are not readily adaptable for remote recording. The mercury-in-steel type can be used for remote recording up to about 50 meters and is often preferred because it is simpler to operate than the electrical type.

All thermographs incorporate some form of rotating chart. In general, thermographs should be capable of operating over a range of about 60°C or, if used in continental climates, a range of 80°C. To obtain a scale that can be read to within 0.2°C on a chart of reasonable size, provision should be made for altering the zero setting of the instrument according to season. The maximum error at any point within the range of a thermograph should not exceed 1°C.

10.C.2.a.3.a. Bimetal thermographs

In this instrument, the movement of the recording pen is controlled by the change in curvature of a bimetallic strip or helix, one end of which is fixed to an arm attached to the frame. This arm should be adjustable so that the zero of the instrument can be altered when necessary. If the scale value can also be altered by adjusting the length the strip or helix used to operate the pen, this should be done only by the instrument maker. The bimetallic element should be protected from corrosion with heavy copper plating or other suitable material. The instrument has a lag coefficient of about 30 seconds in a wind of 5 m/s.

10.C.2.a.3.b. Bourdon-tube thermographs

This is similar in general arrangement to the bimetallic type except that it has a temperature-sensitive element made of a curved metal tube of flat, elliptical cross section filled with a liquid such as alcohol. The Bourdon tube is less sensitive than the bimetallic element and usually requires some form of multiplying lever to give sufficient scale value. Its lag coefficient is about 60 seconds in a wind of 5 m/s.

10.C.2.a.3.c. Mercury-in-steel thermographs

This instrument uses a Bourdon tube to operate the recording pen, but the thermometer itself is a steel bulb filled with mercury at high pressure and connected by steel capillary tubing to the Bourdon tube. The instrument is useful for remote recording to distances of about 50 meters. When the capillary tubing exceeds 10 meters, compensating links should be inserted to counteract any difference between the temperature of the mercury in the tubing and that within the bulb. The compensation may be regarded as adequate if the error caused by a know difference between these two temperatures is less than 2 percent of the difference. Fine adjustment should be provided for setting the pen.

For meteorological purposes, the mercury-in-steel thermograph is probably the most reliable, durable, and accurate type of instrument. If it has a narrow bulb, it is also suitable for recording soil temperatures. A minor drawback is that its lag coefficient is rather large (about 4 minutes in a wind speed of 5 m/s), but this does not matter appreciably in the case of soil-temperature records. Even if the difference in height between the thermometer bulb and the recorder is other than that for which the instrument is calibrated, error will not be introduced.

10.C.2.a.3.d. Electrical thermographs

Resistance and thermocouple thermometers are used at airfields for aeronautical purposes and are equally suitable for special investigations such as the measurement of temperature gradient. Thermocouple instruments are especially useful for differential measurements and can be made to have very small lag coefficients (1 or 2 seconds). For precision measurements, some form of potentiometer circuit should be used; for less accurate work, an out-of-balance bridge circuit (in the case of the resistance thermometer) and a direct deflection circuit (in the case of thermocouple) may be used.

10.C.2.a.4. HYGROTHERMOMETERS

The hygrothermometer indicates or records the ambient temperature of air that is drawn by a forced-air system past the temperature-and humidity-sensing elements. The temperature sensor is a resistance thermometer encased in a stainless-steel cylinder. One type of humidity sensor consists of a pair of parallel gold alloy wires wound around a wick of woven glass tape that is, in turn, wound around an electrical temperature sensor. Meter readouts of temperature and humidity are provided by the indicator unit.

Differential expansion of materials used in construction may introduce temperature-dependent shifts in reading. The hygrometer should be provided with a correction chart or built-in-mechanical compensation.

10.C.2.b. UNITS OF MEASUREMENT

Although the World Meteorological Organization has officially adopted the Celsius scale for observations used in international exchange of temperature data, all surface meteorological observations by the National Weather Service in the U.S. are made on the Fahrenheit scale. The temperature t, in degrees Celsius, is related to the absolute temperature T, in Kelvin, by the formula:

$$t = T - 273.15\text{K}$$

where the Kelvin is the fraction 1/273.16 of the thermodynamic temperature at the triple point.

The size of the degree Celsius is identical to the Kelvin. The following table summaries the relationship between the various temperature scales used in scientific work:

Relationship among various temperature scales

Scale	*Ice point*	*Steam point*	*Relative size of degrees*
Fahrenheit	32°	212°	9
Celsius	0°	100°	5
Kelvin	273.15K	373.15K	5

The Kelvin scale is most useful for theoretical work, and its use avoids negative temperatures. The Celsius scale is used most by scientists for practical work.

10.C.2.c.1.a. World Meteorological Organization (WMO)

It is recommended that the following manufacturing tolerance requirements for thermometers not be exceeded:

Item	*Temperature range*	*Maximum tolerance (°celsius)*
Maximum thermometers	above – 18°C	±0.2
	below – 18°C	±0.3
Minimum thermometers	above – 18°C	±0.3
	– 18° to –35°C	±0.6
	below – 35°C	±0.8
Ordinary thermometers	above 0°C	–0.2
		+0.1
	below 0°C	–0.3
		+0.2
Change of error in an interval of 17°C	above 0°C	0.2
	below 0°C	0.3

Calibration of ordinary mercury-in-glass thermometers permits greater negative errors than positive errors because the zero has a tendency to rise with time. Thermometers that are used for psychrometry should have a certificate giving corrections (with an accuracy of ±0.1°C) for at least six points equally spaced over the range. All thermometers should be checked against the ice point at least once every 5 years, and, at synoptic stations, the thermometers should be checked against a reference instrument every year or two. Frequent checking is especially desirable with maximum or minimum thermometers.

Where thermometers are used in pairs (such as maximum and minimum, wet and dry), it is desirable that they be selected to minimize the differences in readings between them. The following tolerances are suggested for these differences:

Type of thermometer	*Range of error*	
Maximum and minimum	.....	±0.3°C
Wet and dry	above 0°C	±0.2°C
	below 0°C	±0.1°C

10.C.2.c.1.b. United States

10.C.2.c.1.b.1. Liquid-in-glass thermometers—Specifications for liquid-in-glass thermometers require that readings not deviate from calibration-bath temperatures by more than the following:

Type of thermometer	*Range of error*	
Maximum thermometers and psychrometer types (Readings from tubes paired for a pyschrometer should not differ from each other by more than 0.3°F.)	above 0°F	±0.3°F
Minimum thermometers	0°F and above	±0.4°F
	0°F to – 50°F	±1.0°F
	below – 50°F	±1.5°F

10.C.2.c.1.b.2. Thermographs—The readings of a thermograph should be checked regularly by comparison with standard thermometers. A convenient method is to use reference-standard maximum and minimum thermometers. It should be remembered that some types of thermographs, for example the mercury-in-steel type, have different lag coefficients from those of thermometers. In such cases, comparisons should be restricted to occasions when the air temperature is not changing rapidly. A more accurate method of checking a thermograph is to test it in a properly designed and operated thermostatic chamber in the laboratory. Such checks should be carried out at least once every 2 years.

10.C.2.c.2. CONTROL OF DATA

A good observational quality-control program ensures that the data are valid and representative. This can be achieved by establishing a system that includes not only periodic inspection of stations and maintenance or repair of equipment, but preliminary checking of data and detection of errors by review for internal consistency.

Three main steps should be included in the quality control of data:

1. Stations should be inspected periodically to ensure accurate observations. At least once a year is suggested for nonrecording stations; twice a year is recommended for recording or automatic stations.
2. Preliminary data checks should verify that the following steps have been included in the data-collection process:
   a. Logging date of receipt of report form.
   b. Ensuring completeness and correctness of information.
   c. Ensuring completeness of station data, including totals, means, and extremes where required.
   d. Checking observers' computations.
3. Error detection should be by machine if possible. Where such equipment is not available, the procedures can be done by hand by clerical and technical staff. Most quality-control procedures for manually collected temperature data use machine-tabulated arrays of daily data by district or region. From these arrays, it is easy to detect by inspection those stations at which the data have been consistently credited to the wrong day or at which gross errors in measurements have occurred.

10.C.2.d. INSTRUMENT SITING

10.C.2.d.1. SHELTERS

In general, the ground upon which the shelter is sited should be representative of the surrounding area. A level, open space or clearing is desirable so that the thermometers are ventilated by an unobstructed flow of air. Installation on a steep slope or in a sheltered hollow should be avoided unless the site is representative of the area, or unless data from that particular site are desired. Whenever possible, the shelter should be no closer to any obstruction (tree, fence, or building) than four times the height of the obstruction. The shelter should be at least 30 meters from any area having extensive concrete or paved surfaces. The shelter should be:

1. Installed with the bottom about 1.2 meters above the ground and the door facing north (in the northern hemisphere) so that the sun cannot shine on the thermometers when the door is opened during the day.
2. Mounted rigidly to minimize vibrations. For example, vibrations from strong winds tend to displace the index of liquid-in-glass minimum thermometers, which could result in erroneous readings. In installations where errors from vibration of the shelter are frequent, the thermometers should be mounted on a solidly constructed post that enters the shelter through a hole in the bottom without touching the shelter or its supports.

Temperature sensors should be located over terrain (earth or sod) that is typical of the area around the station. The site selected should be:

1. At least 30 meters from any extensive concrete or paved surface.
2. At least 150 meters from any structure, building, or area that might influence temperature readings (for example, a jetblast area).
3. A distance of at least four times the height of any smaller obstructions (trees, solid fence, low sheds) that rise above the height of the sensor and might hinder the free flow of air over the sensor. Open towers, open fences, or other partially-open objects that do not materially restrict the free flow of air are not regarded as obstructions.
4. Readily accessible for routine servicing of equipment.

It is essential that the site be selected so that the sensors are exposed to an unobstructed flow of air. Grass or other vegetation within 30 meters of the sensor should be kept to a height of 2.5 cm or less. Areas where rough terrain or air drainage would result in nonrepresentative temperature data should be avoided. Areas where snow drifts are frequent, as well as swampy locations or other areas where water might collect and remain after periods of precipitation, should also be avoided.

If temperature sensors are to be mounted within an instrument shelter, the shelter should be positioned so that it opens to the north (in the northern hemisphere), and the floor should be at least 1.2 meters above the ground. In the case of remote sensors exposed in structures other than instrument shelters (such as the hygrothermometer), the device should be mounted so that the air intake is at least 1.2 meters above the ground.

New locations for temperature-sensing equipment should conform to the above criteria. Existing installations that fail to meet these criteria need not be relocated; however, these criteria should be considered when it becomes necessary to move temperature-measuring equipment to a new site.

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10.D. SURFACE HUMIDITY

10.D.1. DEFINITION OF ELEMENTS

Mixing ratio, r—The ratio of the mass of water vapor m_v to the mass of dry air m_a present in the moist air is:

$$r=\frac{m_v}{m_a}$$

Specific humidity, q—The ratio of the mass of water vapor m_v to the total mass m_v+m_a of the moist air is:

$$q=\frac{m_v}{m_v+m_a}$$

Absolute humidity, vapor concentration, vapor density, d_v—The ratio of the mass of water vapor m_v to the total volume of the moist air V is:

$$d_v=\frac{m_v}{V}$$

Mole fraction of water vapor, X_v—The ratio of the number of moles of water vapor n_v to the total number of moles of water and dry air is:

$$X_v=\frac{n_v}{n_v+n_a}$$

where

$$n_v=\frac{m_v}{M_v}$$

and

$$n_a=\frac{m_a}{M_a}$$

and M_v and M_a are the molecular weights of water vapor and air, respectively.

Vapor pressure, e—The partial pressure of water vapor in moist air.

Saturation—The condition in which water vapor would be in equilibrium with the plane surface of a condensed phase (liquid or solid).

Saturation mixing ratio, r_w and r_i—The ratio of the mass of water vapor m_v to mass of dry air m_a present in saturated air. The saturation mixing ratio is designated by r_w when saturation is with respect to the plane surface of liquid water, and by r_i when saturation is with respect to the plane surface of ice.

Saturation vapor pressure, e_s—The pressure of water vapor that would be in equilibrium with the plane surface of a condensed phase. When the condensed phase is water, the saturation vapor pressure is designated by e_w and, when the condensed phase is ice, the saturation vapor pressure is designated by e_i. The saturation vapor pressure is a function of temperature only.

Thermodynamic dew-point temperature, T_d—The temperature at which moist air with mixing ratio r and total pressure p, when saturated with respect to liquid water at the same pressure p, will have a saturation mixing ratio r_w equal to the given mixing ratio r.

Thermodynamic frost-point temperature, T_f—The temperature at which moist air with mixing ratio r and total pressure p, when saturated with respect to ice at the same pressure p, will have a saturation mixing ratio r_i equal to the given mixing ratio r.

Relative humidity with respect to water, RH_w—The ratio, in percent of the mole fraction of water vapor X_v in moist air to the mole fraction of water vapor X_{vw}, that the moist air would have if it were saturated with respect to water at the same pressure p and temperature T, is:

$$RH_w = \frac{X_v}{X_{vw}}(100)$$

If water vapor and air are assumed to behave as ideal gases, then

$$RH_w = \frac{e}{e_w}(100)$$

where e is the partial pressure of the water vapor in the moist air, and e_w is the saturation vapor pressure at the same temperature T.

Relative humidity with respect to ice, RH_i—The ratio, in percent of the mole fraction of water vapor X_v in moist air to the mole fraction of water vapor X_{vi}, that moist air would have if it were saturated with respect to ice at the same pressure p and temperature T, is:

$$RH_i = \frac{X_v}{X_{vi}}(100)$$

If the vapor and air are assumed to behave as ideal gases, then

$$RH_i = \frac{e}{e_i}(100)$$

where e is the partial pressure of the water vapor in the moist air, and e_i is the saturation vapor pressure at the same temperature T.

Dry-bulb temperature, T—The ambient temperature of air; the temperature that is measured by the dry-bulb thermometer of a psychrometer. (See sec. 10.C.1.)

Thermodynamic wet-bulb temperature, T_w—The temperature that moist air at pressure p, temperature T, and mixing ratio r will attain when brought adiabatically to saturation at pressure p by the evaporation of pure liquid water into the moist air.

10.D.2. MEASUREMENT OF SURFACE HUMIDITY

10.D.2.a. INSTRUMENTS AND METHODS

This section describes several instruments that are suitable for measuring humidity for hydrometeorological purposes. No hygrometer has all the characteristics that would make it the ideal choice for every application; rather, choice must be on the basis of features that are most important for a given measurement.

10.D.2.a.1. PSYCHROMETERS

The psychrometer consists of two thermometers. The bulb of one is covered with a wick that can be moistened with water; the bulb of the second is left bare and dry. The evaporation of water from the moistened wick of the wet-bulb thermometer lowers its temperature; the dry bulb measures ambient air temperature. The humidity is calculated from the difference between wet- and dry-bulb thermometer readings and from the atmospheric pressure. Three versions of the psychrometer are commonly used—the unventilated psychrometer, the sling psychrometer, and the aspirated psychrometer. The unventilated psychrometer, sometimes called the Mason hygrometer and occasionally located in a thermometer (Stevenson) screen, is unreliable and not recommended for general use. The thermometers of the sling psychrometer and the aspirated psychrometer are ventilated by moving air.

10.D.2.a.1.a. Sling psychrometers

10.D.2.a.1.a.1. Description—The sling psychrometer uses two matched mercury-in-glass thermometers mounted on a metal frame attached to a handle so that the frame can be rotated or whirled by hand. The thermometers should be attached to the supporting frame in a manner that prevents passage of the test air over the dry bulb after it has passed over the wet bulb. One way of achieving this is to place the wet-bulb thermometer beyond the dry bulb a distance of at least twice the length of the wick.

10.D.2.a.1.a.2. Thermometers—The sling psychrometer contains two thermometers of the solid-stem type that are identical in design and construction and are graduated for total immersion (typically with a range of −20° to 50°C). Generally, the stem is cylindrical, about 6 mm in diameter, and has a round or oval capillary bore. The bulb is also cylindrical, about 6 mm in diameter, and is about 22 mm in length. The scale is graduated into 1.0°C or 0.5°C intervals.

10.D.2.a.1.a.3. Wicks—Wicks should be made of chemically clean, unsized, thin, bleached muslin, cotton, or linen material that has a tight weave and is sewn or woven into a seamless tube. It should have high water absorbency. The diameter should be such that the wick will fit snugly over the bulb of the wet-bulb thermometer and extend onto the stem for a distance of at least 25 mm. A wet wick should be fastened to the thermometer with a clean cotton thread. The wick should first be tied at the end covering the stem of the thermometer, then at the top of the thermometer bulb. It should then be drawn tightly over the bulb and tied snugly against the bottom of the bulb.

10.D.2.a.1.a.4. Water—Distilled and/or deionized water should be used to wet the wick. For the highest accuracy, the water should be at or no more than slightly above the wet-bulb temperature, especially when the relative humidity is low and the dry-bulb temperature high. The water may be stored in a porous porcelain cup before use so that evaporation will cool the water. Alternatively, ice cubes made from distilled water may be added to the water to reduce the temperature.

10.D.2.a.1.a.5. Ventilation—For cylindrical bulbs 6 mm in diameter or less, the air speed should be at least 4 m/s but not more than 10 m/s. The air speed may be reduced for bulbs of smaller diameter. The procedure for achieving proper ventilation rate is described later.

10.D.2.a.1.a.6. Radiation shielding—Radiation shields are not generally supplied with sling psychrometers.

10.D.2.a.1.b. Aspirated psychrometers

10.D.2.a.1.b.1. Description—In the aspirated psychrometer, a motordriven fan or blower draws air over the wet- and dry-bulb thermometers at a constant rate.

10.D.2.a.1.b.2. Thermometers—It is recommended that two thermometers identical in design and construction, graduated for total immersion, and encompassing a range of −20°C to 50°C, be used. The thermometers should be mounted to prevent air that passes over the wet bulb from coming into contact with the dry bulb. The thermometers may be arranged so that the air flows across the dry bulb before it reaches the wet bulb, or, alternatively, the air stream may be divided into two parts, one flowing across the dry bulb and the other flowing across the wet bulb. The thermometers are generally the mercury-in-glass type, although other types such as thermocouples, resistance thermometers, or thermistors are commonly used, Whatever type is used, the thermometer bulbs should be cylindrical and not exceed 6 mm in diameter or 22 mm in length. If other sizes and shapes are used, the rate of ventilation must be adjusted accordingly. The scale should be graduated into intervals of 0.5°C, 0.2°, or 0.1°C.

10.D.2.a.1.b.3. Wicks—Wicks should be made of chemically clean, unsized, thin, bleached muslin, cotton, or linen material that has a tight weave and is sewn or woven into a seamless tube. They should have high water absorbency and capillary action. The wick should be of a diameter that will fit snugly over the bulb of the wet-bulb thermometer and extend onto the stem for a distance of at least 25 mm. The wick should be fastened to the thermometer with a clean cotton thread. For psychrometers that require manual, intermittent wetting of the wick, the lower end of the wick should be tied by a clean cotton thread immediately below the wet bulb. For psychrometers in which the lower end of the wick is kept immersed in a reservoir of water to keep the bulb continuously moistened, the wick should extend below the lower end of the wet bulb for a distance of at least two bulb diameters before entering the water.

10.D.2.a.1.b.4. Water—Distilled and/or deionized water should be used to wet the wick. For the highest accuracy, the water should be at or no more than slightly above the wet-bulb temperature, especially when the relative humidity is low and the dry-bulb temperature high. The water may by stored in a porous porcelain cup so that it will be cooled by evaporation. Alternatively, ice cubes made from distilled water may be added to cool the water. In psychrometers with a wick that dips into a reservoir of water, the reservoir should be located so any water evaporated from the reservoir or the wick will not affect the humidity of the test air. For example, both the wick and the reservoir could be arranged below and downwind from the wet bulb.

10.D.2.a.1.b.5. Ventilation—For cylindrical bulbs 6 mm in diameter or less, the air speed should be at least 4 m/s and not more than 10 m/s; the air speed may be reduced for bulbs of smaller diameter. The air flow should be directed so as to prevent reentry into the psychrometer, and the fan or blower should be located downwind from the thermometer bulbs. The motor should be isolated and/or insulated from the thermometers to prevent motor heat from altering the thermometer readings.

10.D.2.a.1.b.6. Radiation shielding—The bulbs of both thermometers should be protected from radiation by suitable shields. One method of shielding is to surround each bulb with a highly polished, thin metal, cylindrical primary shield and to insert an auxiliary shield between the primary shield and the bulb. This auxiliary shield should also be made of highly polished thin metal, and be cylindrical, and blackened on the interior surface. The auxiliary shield surrounding the wet bulb is often covered with a wick, so that when moistened and ventilated, it will be close to the wet-bulb temperature, which will practically eliminate radiation resulting from the difference between the wet- and dry-bulb temperatures.

10.D.2.a.1.b.7. Indication or recording of reading—When mercury-in-glass thermometers are used, the readings are made visually and recorded manually. If the wet bulb is continuously moist, the psychrometer can continuously indicate the wet- and dry-bulb temperatures. To obtain a record of these readings, thermometers capable of yielding a continuous record must be used. Therefore, thermocouples, resistance thermometers, and thermistors are usually used for continuous recording. These have the advantage that they permit the use of the psychrometer in locations remote from the indicating or recording instruments.

10.D.2.a.2. HYGROMETERS

10.D.2.a.2.a. Dew-point and frost-point hygrometers

10.D.2.a.2.a.1. Description—These are instruments that measure the temperature at which dew or frost condenses from the air on a cooled surface, usually a polished mirror. This temperature can be converted into vapor pressure from vapor-pressure formulations or tables. If the relative-humidity value is required, the dry-bulb temperature must be measured also. If the mixing ratio is required, the atmospheric pressure must be measured.

Most hygrometers are a small test cell or chamber through which the stream of test air flows. Within the cell is a mirror or other surface on which the condesate can deposit. The hygrometer is equipped to cool and heat the mirror, detect the condensate, and measure the temperature of the condensate. This instrument has two basic versions—the manually operated type with visual detection of dew or frost, and the automatic type, in which the dew or frost is detected indirectly and the amount of condensate is maintained constant.

10.D.2.a.2.a.2. Illumination of mirror—Many instruments in which the dew of frost is detected visually are illuminated by ambient lighting. Where ambient lighting is inadequate, a beam of light from an incandescent lamp may be used. Instruments that use a photoelectric or photoresistive cell to detect dew or frost require a carefully designed illuminating system.

10.D.2.a.2.a.3. Observation of mirror—Because it is difficult to observe the formation, growth, or disappearance of condensate with the unaided eye, a telescope or microscope is often used to view the mirror surface. The magnification should be such that the entire mirror is within view. In automatic instruments, photocells or photoresistors are used to detect the condensate. The formation of dew or frost on a surface can also be sensed by measuring the resistivity of that surface. Automatic instruments should include supplementary means for visual observation of the mirror to distinguish between supercooled water and frost when either phase can appear on the mirror; visual observation is also useful for checking droplet size and the presence of dust, oil, or other contamination on the mirror.

10.D.2.a.2.a.4. Mirror temperature—In manually operated instruments, the mirror temperature

is sometimes sensed by a mercury-in-glass thermometer. The more general and preferred means of sensing mirror temperature on both the manual and automatic types are thermocouples, thermistors, and resistance thermometers. These sensors should be attached to or embedded in the mirror as close to the condensation surface as possible.

10.D.2.a.2.a.5. Methods of cooling the mirror—The mirror may be cooled by such techniques as adiabatic expansion of a compressed gas, evaporation of a volatile liquid, dry ice, liquid nitrogen, mechanical refrigeration, and Peltier effect. Peltier cooling is a convenient method that is frequently employed with automatic instruments.

10.D.2.a.2.a.6. Mirror chamber—The mirror chamber should be small, made with nonhygroscopic materials, and contain an entrance and exit port for the test air. It should be provided with a pressure tap, especially if it operates at a pressure significantly different from the source of the airstream. The chamber should have a window through which the mirror may be observed, and must contain no sources or sinks of humidity. Also, it must be leakproof so that water vapor cannot diffuse out of or into it if the test air is different from the surrounding atmosphere.

10.D.2.a.2.a.7. Control circuitry—Automatic instruments must be provided with suitable circuitry that will maintain a constant thickness or quantity of condensate on the mirror. This circuitry often includes a provision for the intermittent manual, or periodic automatic, clearing of the mirror by application of heat. It should also include means for compensating for time-related changes in components, particularly the intensity of light from the incandescent lamp and the response of the photocell or photoresistor.

10.D.2.a.2.a.8. Indication or recording of reading—Instruments with mercury-in-glass thermometers are intended to operate manually and read visually. Instruments with electrical temperature sensors, especially automatic instruments, may indicate the dew-point or frost-point temperature on a dial-type meter or recorder.

10.D.2.a.2.b. Mechanical hygrometers

10.D.2.a.2.b.1. Description—The mechanical hygrometer is an instrument in which a material that changes dimensions with humidity is coupled to a simple lever system or rack and pinion to rotate a pointer over a dial or move a pen across a chart.

10.D.2.a.2.b.2. Sensing element—A material such as human hair, gold-beater's skin, cotton, silk, nylon, plastic, wood, or paper is used as the humidity-sensitive element in the mechanical hygrometer. The most common sensing element, by far, is human hair because its length is not affected by any common vapor or gas except water vapor. As the ambient relative humidity increases from 0 to 100 percent, human hair undergoes a 2.5-percent increase in length. Because hair in its natural state is impregnated with fat, it is first treated with a degreasing solvent. Further improvement is obtained by mechanical and chemical treatments that modify the structure and increase its ability to absorb moisture into its pores.

10.D.2.a.2.b.3. Indication or recording of reading—In the typical humidity-indicating instrument, the pointer moves over a scale calibrated in units of relative humidity. In the recording instrument, called a hygrograph, the pointer is replaced by a pen that moves over a paper chart mounted on a clock-driven drum. The drum can be adjusted to make either one revolution per day or one revolution per week. The chart is graduated into units of relative humidity along one axis and in

units of time along the other axis. Some recording instruments, called hygrothermographs, are equipped with a second pen that is coupled to a bimetal element and records temperature.

10.D.2.a.2.b.4. Range—The mechanical hygrometer is normally used to measure relative humidities between 20 and 100 percent at ambient temperatures between 10° and 40°C.

10.D.2.a.2.b.5. Temperature compensation—Differential expansion of materials used in the construction of the intrument may introduce temperature-dependent shifts in reading. To compensate for these effects, the hygrometer should have a correction chart or built-in mechanical compensation.

10.D.2.a.2.b.6. Adjusting mechanisms—The instrument should have a means for adjusting the setting of the pointer and changing the span of the scale without dismantling the instrument.

10.D.2.a.2.c. Dew cells and dew probes

10.D.2.a.2.c.1. Description—The equilibrium vapor pressure of a saturated solution is a function of the temperature of the solution. When such a solution is exposed to moist air, there is a net flow of water vapor from the region of higher vapor pressure to the region of lower vapor pressure. The temperature of the solution can be raised or lowered until its equilibrium vapor pressure equals that of the moist air, at which point the net exchange of water vapor between the two is decreased to zero. By measuring the solution temperature at equilibrium, the information necessary to establish its vapor pressure can be determined; this is the same as the vapor pressure of the ambient air.

The dew cell consists of a temperature sensor surrounded by a wick impregnated with a saturated solution of a salt such as lithium chloride. A control circuit maintains the solution at the temperature at which the equilibrium vapor pressure of the solution is equal to the vapor pressure of the ambient air. The output from the sensor is indicated on a dial or is recorded on a chart that is calibrated in terms of the dew-point temperature of the ambient air.

10.D.2.a.2.c.2. Temperature sensor—Any type of remote temperature sensor may be used; thermistors and resistance thermometers are employed most often.

10.D.2.a.2.c.3. Wick—The wick should be fabricated from a material such as glass wool that can absorb and retain the saturated solution. Two wire electrodes are wound on the outside of the wick to form a bifilar coil.

10.D.2.a.2.c.4. Circuitry—Alternating current is impressed across electrodes in the solution. The flow of current generates heat to raise the temperature of the solution, which causes water to evaporate from it. As water is lost, the resistance of the solution increases, the current decreases, the heat generated by the current flow decreases, and the solution then tends to cool. Thus, this process automatically adjusts the resistance of the solution to a constant value, which in turn keeps it at a constant temperature.

10.D.2.a.2.c.5. Ventilation—Air flowing at speeds greater than 0.25 m/s conducts too much heat away from the wick and lowers the equilibrium temperature. Therefore, the instrument should be mounted in a screen or shelter that prevents the air from flowing at excessive speeds.

10.D.2.a.2.c.6. Range—The range of humidities that the instrument can measure at a given ambient temperature is limited. In terms of relative humidity, this range extends from 100 percent to

the equilibrium value of the saturated salt solution. For lithium chloride, the range at 25°C is from 100 percent to 10 percent; at 0°C, the range is from 100 to 15 percent.

10.D.2.a.2.d. Electric hygrometer

10.D.2.a.2.d.1. Description—The electric hygrometer is an instrument in which the changes in resistance or capacitance of a thin film of hygroscopic material is used as a measure of the ambient humidity. Most instruments consist of a sensor and a measuring circuit; the output is indicated on a meter or recorded. The response of the sensor is an empirical function of relative humidity and is also temperature dependent; thus, the instrument must be calibrated in terms of relative humidity and temperature. In some models, temperature compensation is included in the circuitry.

10.D.2.a.2.d.2. Sensor—The sensor typically consists of a substrate made from a nonhygroscopic dielectric material to which the electrodes are affixed by sputtering, evaporation, silk screening, or some similar process. Alternatively, the electrode may consist of a bifilar coil of wire wound on a tubular substrate that is coated by dipping, brushing, evaporation, or spraying with a humidity-sensitive film. An aqueous-salt solution in an organic binder is an example of the type of film that is applied.

10.D.2.a.2.d.3. Circuitry—The direct-current (DC) ohmmeter or the DC Wheatstone bridge are sometimes used for measuring the resistance of sensors. However, they are not well suited to electric hygrometry because some of the better sensors are wholly or partly ionic conductors and thus subject to polarization. With DC circuitry, even with small impressed voltages on the sensor, significant error may result from polarization. Alternating current (AC) circuitry is preferable. When the sensor is measuring resistance, and when the resistance changes several decades as the relative humidity increases from 0 to 100 percent, the circuitry in many models is designed to yield an output proportional to the logarithm of the resistance. The output can be read on an indicating instrument or it can be recorded.

10.D.2.a.2.d.4. Range—This instrument normally measures relative humidities from 5 to 98 percent. At ambient temperatures below 0°C, it is current meteorological practice to have the instrument indicate relative humidity with respect to supercooled water rather than to ice. Some electric hygrometers will operate at temperatures from −40°C to 40°C. Below 0°C, accuracy and sensitivity tend to decrease, and response time increases.

10.D.2.b. UNITS OF MEASUREMENT

Table 10-2 lists the units that should be used for expressing quantities associated with the water vapor in atmospheric air.

Table 10-2.—*Units of measurement for water vapor in atmospheric air*

Element	Preferred SI metric unit	Unit in common use
mixing ratio	kg/kg (kilogram per kilogram)	g/kg (gram per kilogram)
specific humidity	kg/kg (kilogram per kilogram)	g/kg (gram per kilogram)
absolute humidity	kg/m^3 (kilogram per cubic meter)	g/cm^3 (gram per cubic centimeter)
mole fraction	mol/mol (mol H_20 per mole mixture)	mol/mol (mol H_20 per mole mixture)
vapor pressure	Pa (Pascal)	mb (millibar)
dew-point temperature	K (Kelvin)	°C (degrees Celsius)
relative humidity	% (percent)	% (percent)
dry-bulb temperature	K (Kelvin)	°C (degrees Celsius)
wet-bulb temperature	K (Kelvin)	°C (degrees Celsius)
wet-bulb depression	K (Kelvin)	°C (degrees Celsius)

10.D.2.c. SENSITIVITY AND ACCURACY

There is no general agreement about the sensitivity and accuracy of the instruments used to measure humidity for hydrometeorological purposes; therefore, the observer or investigator should set these limits according to specific needs. Table 10-3 lists the sensitivity and accuracy that can be obtained with currently available instruments. Sensitivity is defined as the smallest fraction of a division on a scale on which a reading can be made directly or be estimation; accuracy is defined as the closeness with which an observation approaches the true value of the measured quantity.

Table 10–3. — *Sensitivity and accuracy of instruments used to measure humidity*

Instrument and quantity measured	Sensitivity	Accuracy
Psychrometer		
(a) sling		
wet-bulb temperature (K)	0.1	0.5
dry-bulb temperature (K)	0.1	0.5
(b) aspirated		
wet-bulb temperature (K)	0.02	0.1
dry-bulb temperature (K)	0.02	0.1
Dew-point and frost-point hygrometer		
dew-point temperature (K)	0.05	0.25
Mechanical hygrometer,		
relative humidity (percent)	1	5
Dew cell, dew probe		
dew-point temperature (K)	0.5	2
Electric hygrometer		
relative humidity (percent)	0.5	2

10.D.2.d. QUALITY CONTROL AND CALIBRATION

Hygrometers should be returned periodically to a laboratory for testing and calibration. For this purpose, an instrument with high sensitivity, reproducibility, and long-term stability (preferably one that has a firm theoretical basis) is used as the laboratory standard to calibrate the working or field hygrometer. Calibration is done by simultaneously exposing or subjecting the two instruments to the same humidity. A range of humidities can be produced in a humidity cabinet, chamber, or room. One method of obtaining a range of humidities is to use selected chemical solutions (such as saturated salt solutions) in a sealed enclosure. With these solutions, the equilibrium relative humidity in the enclosure can be calculated with adequate accuracy to eliminate the need for a secondary standard. When a secondary standard is used, it should also be sent to a standards laboratory periodically (such as the National Bureau of Standards) for calibration against higher order standards. This procedure is especially important when the secondary standard is an empirical device, that is, an instrument that yields an arbitrary indication that can be related to humidity units only through calibration.

10.D.2.d.1 PSYCHROMETERS

The thermometers used in a psychrometer should be compared once a year at four or more temperatures with the wick removed from the wet-bulb thermometer. Once every 3 months, the thermometers should be compared, with the wick removed from the wet-bulb thermometer, at the ambient dry-bulb temperature. The readings should agree to at least 0.2°C when the instruments are

totally immersed. For highest accuracy, the thermometers should be calibrated over their range of use while totally immersed. The corrections thus determined should be added to the reading when making a measurement.

For thermometers with intervals of 0.5° or 1.0°C the tolerance (difference between the reading and the true temperature) should not exceed 0.3°C; for thermometers with 0.2°C intervals, the tolerance should not exceed 0.1°C; and for thermometers with 0.1°C intervals, the tolerance should not exceed .05°C.

10.D.2.d.2. HYGROMETERS

10.D.2.d.2.a. Dew-point and frost-point hygrometers

The readings of this instrument should be checked at least once every year against a secondary standard. If the secondary standard is portable, it may be set up at or near the test instrument as long as precautions are taken to ensure that both instruments sample the same air. Simultaneous readings over a period of one or more days should yield enough data points to give a good comparison. If a humidity chamber or other source of variable humidity is available in a laboratory, both the test instrument and the secondary standard should be exposed simultaneously to this variable humidity. Five to eight dew points or frost points over the intended range of use should be sufficient for calibration.

10.D.2.d.2.b. Mechanical hygrometers

A single-point calibration should be made once every week by comparing the hygrometer with a secondary standard. Alternatively, the instrument or the sensing element should be covered with a moistened cloth until an equilibrium reading is obtained. The hygrometer should be adjusted to correspond with the reading of the secondary standard. If the hygrometer has been covered with a moistened cloth, it should be adjusted to read 96 percent. If the reading deviates by a relative humidity of 5 percent or more from the secondary standard or 96 percent, a calibration should be made for the entire scale at five to eight evenly spaced points.

10.D.2.d.2.c. Dew cells and dew probes

The readings of these instruments should be checked at least once each year against a secondary standard. If the secondary standard is portable, it may be set up at or near the test instrument as long as precautions are taken to ensure that both instruments sample the same air. Simultaneous readings over a period of one or more days should yield enough data points to give a good comparison. If a humidity chamber or other source of variable humidity is available in a laboratory, the test instrument and the secondary standard may be exposed simultaneously to this variable humidity. If two or more readings deviate from the secondary standard by 2°C or more, the wick should be cleaned and recoated in accordance with manufacturer's instructions, and the instrument should be recalibrated.

10.D.2.d.2.d. Electric hygrometer

A single-point calibration check should be made once every month by comparing the hygrometer with a secondary standard. If the reading of the instrument deviates by 5 percent or more in relative humidity from that of the secondary standard, the instrument should be subjected to a full-range calibration in a temperature-controlled humidity cabinet or chamber together with the secondary standard. Another method is to remove a sample flow of air from the cabinet or chamber and to feed it to the standard through a stainless steel (or similar nonhygroscopic) sampling tube. The

calibration should be made with the electric hygrometer maintained at a fixed temperature, and, to cover the span of the instrument, at least eight test points should be observed. The calibration should be repeated at a second temperature to establish the temperature coefficient of the instrument.

10.D.2.e. MEASUREMENT AND PROCEDURES

10.D.2.e.1. PSYCHROMETERS

10.D.2.e.1.a. Sling psychrometer

Because this instrument is generally not shielded from radiation, it should be used in a place sheltered from direct sun, for example, in the shade of a building or tree or under an umbrella. In addition, there should be free natural circulation of air. The observer should face the wind, holding the psychrometer in front and as far as possible from his body to prevent body moisture from perturbing the ambient humidity. The wick should be thoroughly saturated with distilled water (preferably precooled to wet-bulb temperature). The psychrometer should be whirled rapidly (about 4 revolutions per second for a 0.3-meter long sling psychrometer) for 15 to 20 seconds. The whirling should be stopped in one revolution, without shock or jerk, and the thermometers read immediately, the wet-bulb thermometer first and the dry-bulb thermometer second. The readings should be recorded and the psychrometer whirled again for a second set of readings. This procedure should be repeated three or more times, with the wet-bulb temperature decreasing until at least two successive readings repeat or agree very closely. A minute or more is generally required to obtain the correct wet-bulb temperature. When the wet-bulb depression is large, the water on the wick may evaporate before the minimum wet-bulb reading is observed, unless the water is precooled. It may then be necessary to moisten the wick a second or third time before a minimum is obtained.

10.D.2.e.1.b. Aspirated psychrometer

10.D.2.e.1.b.1. Temperatures above freezing—The wick should be thoroughly saturated with distilled water (preferably cooled to the wet-bulb temperature). If the wet bulb has a radiation shield that is also covered by a wick, the latter should be thoroughly moistened also. If the instrument is hand held, the observer should face the wind, start the air flow, and continually observe the wet-bulb thermometer until a constant reading is obtained. This procedure should be repeated until at least two successive readings repeat or agree very closely. When the wet-bulb depression is large, the water on the wick may evaporate before the minimum wet-bulb reading is observed unless the water is precooled. The wet-bulb thermometer should maintain a constant reading for at least 10 seconds before the reading begins to increase. For psychrometers that operate continuously and have wicks that are automatically moistened, a maintenance schedule should be established for cleaning the wick and to ensure an adequate supply of water in the reservoir.

10.D.2.e.1.b.2. Temperatures below freezing—At wet-bulb temperatures below 0°C, the wick should be removed, and a thin film of ice about 0.5 mm in thickness should be frozen on the bulb and for at least 25 mm along the stem. This ice film can be formed by dipping the chilled thermometer into ice water, removing it, allowing the water film to freeze, then repeating the process as needed to build up the desired thickness. If required, freezing can be started by touching the bulb to a piece of ice or by dipping the moistened bulb into crushed dry ice. With ice on the bulb, the time required for the thermometer to reach equilibrium will be about four times longer than for a water-moistened wick.

10.D.2.e.2.a. Dew-point and frost-point hygrometers

10.D.2.e.2.a.1. Sampling—The instrument is often located at the site where the humidity is to be measured. The observer should not breathe near the inlet to the instrument; rather, the inlet should face upwind and away from the observer to minimize all perturbations introduced by the observer. The instrument may also be located at some place remote from the sampling site, and the test air may be fed to the test chamber of the instrument trough a tube. This tube should be leaktight, fabricated from nonhygroscopic material (such as stainless steel), and contain no humidity sources or sinks. If the instrument does not have a built-in vacuum pump or other means of drawing in the air sample, an auxiliary vacuum pump should be attached to the downstream side of the test chamber. Total pressure within the mirror chamber must be measured so that correction can be made for the difference between pressure at the instrument and that at the sampling site.

10.D.2.e.2.a.2. Contamination—Dirt, dust, oil, or other particulate matter that may deposit on the mirror should be removed periodically with a camel's-hair brush and/or lint-free tissue that has been wetted with pure ethanol or solvent.

10.D.2.e.2.a.3. Condensation—The sampling tube should not be exposed to temperatures that could produce condensation on the interior walls. If required, a heater or insulation should be wrapped around the exterior of the sampling tube.

10.D.2.e.2.a.4. Operation of manual instrument—In the manually operated instrument, the rate of cooling and heating of the mirror should be adjusted so that a film of dew or ice of constant size or thickness is maintained. The temperature at which this occurs is taken as the dew point or frost point. Alternatively, the average of the temperatures at which dew or frost appear and disappear may also be taken as the dew point or frost point. The rate at which the mirror is cooled or heated should be adjusted to allow easy detection and to prevent overshoot.

10.D.2.e.2.a.5. Operation of automatic instrument—In this type of instrument, the cooling and heating are automatically controlled. If the amount of condensate on the mirror is excessive, the mirror should be cleaned and a new layer of condensate allowed to form.

10.D.2.e.2.a.6. Phase of condensate—Below 0°C, ice or supercooled liquid may form on the mirror, particularly between −20° and 0°C. In this range it is therefore necessary to check the mirror visually and to observe which phase is present. Once ice appears, the solid phase will persist until the mirror is cleaned and new condensate is allowed to deposit.

10.D.2.e.2.b. Mechanical hygrometers

10.D.2.e.2.b.1. Exposure—A mechanical hygrometer should be located at the measurement site in a weather shelter or thermometer screen. The shelter or screen must be adequately ventilated and constructed so that it does not act as either a sink or a source of humidity.

10.D.2.e.2.b.2. Maintenance—The sensing element should be cleaned frequently to remove dust, dirt, or other particulate matter that may be deposited from the ambient air. A camel's-hair brush should be used for cleaning the element. The element should not be touched with bare fingers because they may leave oil, salt, or other contamination that could impair operation. The clock mechanism on the hygrograph or hygrothermograph must be wound periodically and the chart replaced on the drum. In some instruments it is possible to replace a defective element.

10.D.2.e.2.b.3. Observation—The indicating (nonrecording) instrument should be tapped lightly before each reading. The hygrograph or hygrothermograph should not be touched between changes of the chart.

10.D.2.e.2.c. Dew cells and dew probes

10.D.2.e.2.c.1. Exposure—The sensors of these instruments should be located at the measurement site in a weather shelter or thermometer screen that does not act as a sink or source of humidity. The flow of air across the unprotected sensor should not exceed 0.25 m/s. The indicator or recorder may be remotely located.

10.D.2.e.2.c.2. Maintenance—The wick should be washed occasionally to remove any dust, oil, dirt, or particulate matter that could impair operation. After the wick has been washed and rinsed with distilled water, a fresh solution should be applied and the sensor returned to service. Washing frequency depends on the rate of contamination.

10.D.2.e.2.d. Electric hygrometer

10.D.2.e.2.d.1. Exposure—This instrument should be located at the measurement site in a weather shelter or thermometer screen that is ventilated and constructed so that it does not act as a sink or source of humidity. Exposure to saturated air, fog, clouds, or rain may be deleterious to the sensor. Contamination of the sensor, especially by ionizable materials, may shift or ruin the calibration. Therefore, the sensor should not be touched by the fingers and should be protected by a perforated metal shield to prevent accidental contact with its surface. When not in use, the sensor should be removed from the shelter or screen and stored in a container.

10.D.2.e.2.d.2. Observation—Most models indicate or record relative humidity in arbitrary units or in units of percent. Unless the instrument has a built-in temperature compensation, the dry-bulb temperature should be recorded simultaneously, and the reading should be corrected for temperature.

10.D.2.f. SITING

A site for measuring the humidity of the ambient atmosphere must be chosen so that the data obtained represent the water-vapor content of the free air. A plot of level, cleared ground about 9 m×6 m, preferably covered by short grass, is adequate for locating a humidity-sensing instrument. This location should be remote from any trees and buildings that could perturb the humidity of the ambient air, and it should not be close to steep slopes, ridges, cliffs, or hollows.

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10.E. ATMOSPHERIC PRESSURE

10.E.1. DEFINITION OF ELEMENTS

Barometric pressure—The pressure exerted by the atmosphere as a consequence of gravitational attraction exerted upon the column of air directly above the point in question.

Station pressure—The atmospheric pressure computed for the level of the station elevation H_p. Note that H_p may be different from climatologic station elevation H_{p_c} or the zero point of the barometer H_z.

Reduction of pressure—The conversion of a barometric pressure to the value it would theoretically have at another level. This applies most often to reducing observed pressure at H_z to a computed value for H_p or H_{p_c} (the removal correction) and reducing the pressure to that of sea level. The removal correction is generally used for height changes of less than 100 ft (30 m), whereas reduction to sea level is done for stations at both high and low altitudes. For the latter case, the pressure is reduced through an imaginary air column from the station to sea level. The temperature and humidity characteristics of this column are based on climatological and empirical factors. Pressure is sometimes reduced to other standard levels. The height above mean sea level (MSL) of a particular pressure surface (for example, 850 millibars), is sometimes computed also.

Sea-level pressure—The atmospheric pressure at mean sea level. It is either measured directly or, most commonly, reduced from the station pressure.

Standard atmosphere—A hypothetical vertical distribution of atmospheric temperature, pressure, density, and other physical properties that, by international agreement, is taken to be representative of the atmosphere for such purposes as pressure-altimeter calibrations, aircraft and missile design, or space operations. The current standard is the U.S. Standard Atmosphere of 1962, and U.S. Standard Atmosphere Supplements (1966). For values from the surface to 20 km, the U.S. Standard Atmosphere of 1962 is the same as the International Civil Aviation Organization (ICAO) Standard Atmosphere of 1952.

Altimeter setting—The pressure value to which an aircraft altimeter scale is set so that it will indicate the altitude above mean sea level of an aircraft on the ground.

Geopotential—A measure of the gravitational potential energy of a unit mass relative to mean sea level. It is commonly measured in terms of geopotential height, which depends on the geometric height and the latitude. The usual unit of measurement is the geopotential meter, which is closely related to the geometric or standard meter.

Ground elevation (H), termed "elevation of the ground"—The vertical distance, above mean sea level, of the ground at the meteorological station. It is given in feet or meters. Its value is considered to be the average height above mean sea level of the terrain within a circle having a 20-m radius and centered on the instrument shelter (thermometer screen).

Field elevation (H_a)—The officially designated field elevation of an airport above mean sea level. It is the elevation of the highest point on any of the runways of the airport.

Zero point (H_z), termed "elevation of the zero point of the barometer"—Also referred to as "actual elevation of the barometer." The vertical distance of the zero point of the barometer above mean sea level. The zero point of the barometer is the point corresponding to the zero of the scale

of the instrument. In the case of the Fortin-type barometer, this is the level of the ivory point in the cistern to which the mercury surface must be reset when making readings.

Station elevation (H_p)—The officially designated height above mean sea level to which station pressure pertains. At Air Force stations, it is generally 10 ft (3 m) higher than the field elevation. At old, established meteorological stations in the U.S., the elevation adopted for H_p was the elevation of the zero point of barometer H_z in effect on January 1, 1900. At stations established since that date, the practice has varied. However, two general rules are:

1. At stations in cities or at points some distance from airports and seaplane bases, H_p is taken as the value of H_z when the station was first established.
2. At stations at airport or seaplane bases, H_p is the same as H_a above field elevation.

If it is necessary to adopt a new value of H_p for any reason, rules (1) and (2) should be used as guides in choosing the value for the new station elevation, considering the new zero point or field elevation in place of the original one.

Climatological station elevation (H_{p_c})—The vertical distance above mean sea level that is chosen as the datum (level of reference) for records of barometric pressure. H_{p_c} will generally differ from H_p at a given station if earlier stations have had extensive tabulations of barometric pressure referring to another level. National Weather Service headquarters determines the H_{p_c} value for all stations.

Geopotential of the station (H_{p_g})—The geopotential corresponding to the station elevation H_p.

10.E.2. MEASUREMENT OF ATMOSPHERIC PRESSURE

10.E.2.a. INSTRUMENTS AND METHODS

10.E.2.a.1. MERCURY BAROMETERS

10.E.2.a.1.a. Fortin type

The Fortin barometer is the type of mercury barometer used by the National Weather Service and recommended for use at land stations. A pointer made of noncorrodible material such as ivory or stainless steel projects down from the roof of the cistern. The tip of this pointer is called the ivory point, index point, or zero point. The cistern is constructed so that the level of the mercury within it may be lowered or raised by turning a thumb screw beneath the cistern. The mercury in the cistern is set at the zero point. The height of the mercury column is measured and read to a thousandth of an inch or a tenth of a millibar with a vernier on the scale. This reading is then corrected to read station pressure.

10.E.2.a.1.b. Fixed-cistern type

The fixed-cistern barometer contains a given mass of mercury that, if changed, would alter the calibration of the instrument. No adjustment of the mercury level in the cistern to the zero of the scale is necessary. A special contracted scale is used to obtain pressure readings. This type of barometer is primarily for shipboard use.

10.E.2.a.1.c. Other types

Movable-scale and siphon barometers are used as standardizing instruments.

Pressure measurement from an aneroid barometer is based on the response of a capsule that is partially evacuated of gas. The response may be measured either by deflection of a spring connected to the cell, by the change in curvature of a Bourdon tube, or by a change in natural resonant frequency. It is necessary to interpret the aneroid readings on the basis of a calibration. Because most aneroid barometers drift somewhat from the calibration with time, it is necessary to check them periodically against mercury barometers and to apply corrections if necessary. The aneroid barometer must be temperature compensated at a given pressure level by adjusting the residual gas in the aneroid or by a bimetallic-link arrangement. The instrument is also subject to uncertainties because the elastic properties of the spring and capsules may vary. It is also subject to wear in the mechanical linkages or change in electronic properties.

10.E.2.a.2.a. Precision aneroid

The direct-reading precision aneroid has a pointer and a dial calibrated in millibars or inches. The pointer is linked mechanically to the aneroid capsules. Precision aneroids should be checked against mercury barometers periodically.

Recently, accurate digital-readout barometers have been developed that use electronic indicators instead of the mechanical linkages. Sensor types used in these instruments may be a fused quartz Bourdon tube (the quartz barometer), an aneroid capsule with which the natural frequency related to pressure is measured (the vibrating-diaphragm barometer), or the conventional aneroid capsule with which spring deflection is measured. These instruments have accuracies of ±.01 to .002 in Hg (inches of mercury), are portable, and have only minor long-term drift. Some need to be compared only every six months.

10.E.2.a.2.b. Altimeter-setting indicator

This is a special type of aneroid barometer designed to indicate the altimeter setting. Its scale is calibrated in terms of the standard atmosphere. The barometer is provided with an elevation scale that is set at the station elevation and adjusted for instrument drift. Both direct-reading and digital-readout models are in use.

10.E.2.a.2.c. Altimeter

There are two main types of altimeters—surveying and aircraft. Information on surveying altimeters is given in Federal Meteorological Handbook No. 8 (1963). Aircraft altimeters are aneroid barometers calibrated in terms of the standard atmosphere. Altimeters read out pressure-altitude directly. When set at the current altimeter setting, they will read the correct field elevation when the aircraft is on the field.

10.E.2.a.2.d. Microbarograph

The microbarograph is a recording aneroid barometer equipped with a pen that makes a trace of ambient-pressure variations on a chart having a magnified scale. The most common magnification is 2.5 to 1.0 (that is, a change of pressure of 1 in Hg causes a vertical displacement of the pen of 2.5 in). This type of barometer is called an open-scale barograph. Clock drives in the drum are set for either 4 days, 24 hours, or 12 hours; drum charts (barograms) are available for each of those periods.

Because of the extra linkages involved, dashpots and dampers are used to eliminate friction of the pen on the chart. To ensure records of highest precision, barographs should be compared to the station barometer daily or, if possible, every 6 hours.

Inch of mercury (standard)—The difference between pressure at the base and at the top of a layer of mercury at 0°C between two horizontal planes 1 inch apart and of unit cross-section area. The mercury is subjected to a gravitational acceleration of 980.665 cm/s^2 (about 32 ft/s^2) (standard gravity), where the density of the mercury under these standard conditions is considered to be 13.5951 g/cm^3.

Millimeter of mercury (standard)—Similar to "inch of mercury (standard)" except that the phrase "1 inch" is replaced by "1 millimeter."

Millibar—A value of atmospheric pressure equal to 1,000 dynes/cm^2.

Pascal—The preferred unit of atmospheric pressure in the SI metric system. It is defined as 1 newton per square meter (N/m^2). Numerically, it is .01 mb (millibar).

Standard atmosphere pressure—Defined as a pressure of 1013.250 mb by action of the International Committee on Weights and Measures, Paris, 1954.

Torr—Defined as 1/760 of 1 standard atmosphere pressure, or 1,013.250/760 mb. The result of this division carried to seven significant figures is 1.333224 mb. By the definition of "1 mm Hg," the Torr has the same numerical value as the millibar expressed to seven significant figures.

Table 10–4 lists conversion factors that are useful in relating the various units of pressure on the assumption that 1 inch = 2.54 cm:

Table 10–4.—*Conversion factors for selected units of atmospheric pressure*

1 millibar	= 1,000 dynes per square centimeter = 100 pascals = 0.0295300 inch of mercury (standard) = 0.750062 millimeter of mercury (standard)
1 inch of mercury (standard)	= 33.8639 millibars = 25.4 millimeters of mercury (standard)
1 millimeter of mercury (standard)	= 1.333224 millibars = 0.03937008 inch of mercury (standard)
1 pascal	= .01 millibar

10.E.2.c. MEASUREMENT AND PROCEDURES

10.E.2.c.1. READING FORTIN-TYPE MERCURY BAROMETERS

The following instructions apply to adjustable-cistern barometers. Instructions for reading fixed-cistern-type barometers are given in Federal Meteorological Handbook No. 8 (1963).

10.E.2.c.1.a. Temperature

The thermometer (attached to the barrel) should be read to the nearest 0.5°F (0.3°C).

10.E.2.c.1.b. Adjusting cistern

10.E.2.c.1.b.1. Cistern with clamping ring—The thumbscrew at the bottom of the barometer should be turned until the surface of the mercury in the cistern touches the tip of the ivory point (that is, until the tip coincides with its image in the mercury). This contact can be seen more easily against a white background. If a dimple forms on the surface, the mercury has been raised too far.

The barometer should be maintained in a vertical position in accordance with applicable instructions.

10.E.2.c.1.b.2. Cistern with nonclamping ring—The cistern should be steadied against the side of the ring, as depicted in figure 10–1, by turning the cistern end of the barometer so that the cistern touches the ring at a point where line AB (through the center of the cistern and the point of contact) is at right angles to line I (through the center of the cistern and the ivory point). When this is done properly, the mercury level will not be changed with respect to the tip of the ivory point when the barometer is released and returns to its vertical position.

10.E.2.c.1.c Setting the vernier

This procedure entails the three following steps: (1) Tap the barrel near the top of the mercury column; (2) set the vernier (movable scale) so that the base just cuts off light at the highest point of the meniscus (the curved upper surface of the mercury column). A white background facilitates this setting; (3) Lower the mercury about 0.25 inch (6 mm) from the ivory point, but do not change the setting of the vernier.

10.E.2.c.1.d. Reading the barometer scale

Mercury barometers are provided with verniers as an adjunct to the primary stationary scale so that the primary scale can be read to thousandths of an inch. Verniers are available in several ratios; these ratios represent the ratio of the number of lines on the scale to the number of lines in an equivalent distance on the venier. The zero line of the vernier is also the index for primary-scale readings. Whenever the index coincides exactly with a line on the scale, the barometer reading corresponds exactly to the value of this line. When the index is intermediate between two lines of the scale, the reading is the sum of several increments made up of a primary-scale reading and a vernier reading.

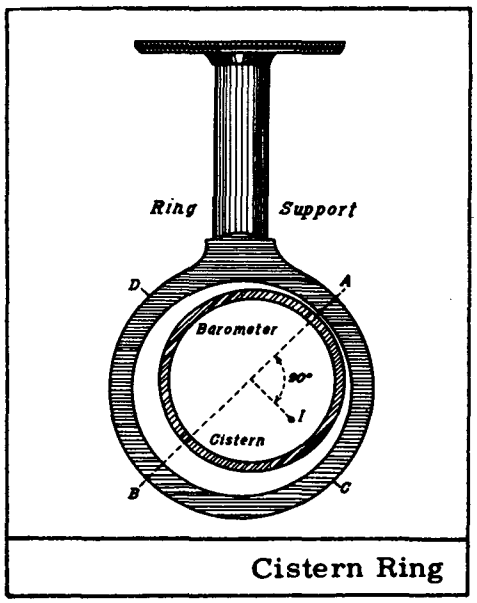

Figure 10–1.—Diagram showing adjustment position for barometer cistern with nonclamping ring. (From National Weather Service, Federal Meteorological Handbook No. 1, 1970, Chapter A.7, figure A7–1.)

10.E.2.c.1.d.1. Primary scale—The reading is the value corresponding to the line on the scale immediately below the index.

10.E.2.c.1.d.2. Vernier scale—The reading is determined as follows: If a line of the vernier other than the index and top lines coincides exactly with a line on the scale, the vernier reading corresponds exactly to the value of this vernier line. If none of the lines of the vernier coincides with lines of the scale, find the two lines of the scale that include a successive pair of vernier lines between them and are also the scale lines most nearly adjacent to this pair of vernier lines. The vernier reading in this case is the sum of two increments, obtained as follows:

a. The first increment is the value of the lower of the successive pair of vernier lines selected above.
b. The second increment is interpolated. It is the fractional value of one vernier division represented by the displacement of the vernier from a setting corresponding exactly to the *a* value and toward a value exactly one vernier division greater than *a*.
c. The vernier reading is the sum of values *a* and *b*. The barometer reading is the sum of the primary—scale reading in *a* and the vernier reading in *b*.

10.E.2.c.1.e. Total correction

After the barometer is read, the temperature correction and the sum of corrections are applied to obtain total correction. When all corrections have been applied to the barometer reading, the station pressure is the result.

10.E.2.c.2. READING PRECISION ANEROID

Reading a precision aneroid involves three steps:

1. Tap the face of the instrument lightly with the finger to reduce the effect of friction.
2. Read the scale at the pointer to the nearest 0.005 inch (0.1 mm) or 0.1 mb, estimating values between the graduations.
3. Apply the posted correction.

10.E.2.c.3. OBTAINING STATION PRESSURE

10.E.2.c.3.a. Mercury barometers

The principle of the mercury barometer is that the weight of the mercury in the tube is supported by the pressure of the atmosphere on the surface of the mercury in the cistern. To obtain representative readings, it is necessary to allow for capillarity, scale error, and instrument temperature. Moreover, barometer readings are corrected to standard gravity so that readings can be compared over large regions in which gravity differences may cause noticeable changes in the weight of mercury. The reading, when suitably corrected, is called station pressure.

10.E.2.c.3.a.1. Barometer-correction—This card, posted on or near the barometer, contains the gravity correction, the corrections for scale error and capillarity, and the removal and residual corrections. The combination of these corrections is called the sum of corrections.

10.E.2.c.3.a.2. Gravity correction—The gravity correction changes the barometer reading to what it would be if the barometer were located where the acceleration of gravity is "standard" (980.665 cm/s^2 or 32 ft/s^2). The correction is expressed mathematically as:

$$\frac{g_i - g_o}{g_o} B$$

Where:

g_i = local acceleration of gravity
g_o = standard gravity
B = annual mean barometer reading.

The local acceleration of gravity can be obtained from the Gravity Astronomy and Satellite Branch, National Ocean Survey. Alternatively, a theoretical value based on latitude, altitude, and terrain can be obtained from tables in Federal Meteorological Handbook No. 8 (1963), but this is likely to be less accurate than measured values.

10.E.2.c.3.a.3. Removal correction—The removal correction is applied to reduce the pressure at the actual elevation of the barometer to the pressure at an adopted station elevation. The advantage of this correction is that pressure records will refer to a constant adopted station elevation even if the barometer is moved from time to time. If the removal correction does not vary by more than 0.004 in Hg over the range of temperatures expected at a particular site (generally a height difference less than 30 ft or about 9 m), it is regarded as a constant. If this tolerance is exceeded, a variable removal correction is used that takes into account the current temperature.

10.E.2.c.3.a.4. Correction for scale error and capillarity—This is an instrument correction that is determined by comparison in a laboratory before the instrument is put into use.

10.E.2.c.3.a.5. Residual correction—This is a correction for instrument error that may be required after the barometers have been in use in the field. When the departure of a barometer instrument from its previous calibration exceeds a certain tolerance, a residual correction should be determined by comparing the instrument with the inspection barometer. More than one comparison should be made before a correction is determined.

10.E.2.c.3.a.6. Temperature correction—All mercury barometers require this correction to account for (a) the effects of temperature on the density of mercury; (b) the effects of temperature on the length of the scale; and (c) the effects of temperature on the volume of mercury in the barometer in relation to the effective cross-sectional areas of the cistern and the glass tube.

Unless otherwise noted, Fortin-type barometer scales calibrated in inches read true at 62°F; those reading in millibars or millimeters read true at 0°C. The temperature-correction tables and instructions for use are given in Federal Meteorological Handbook No. 8 (1963) and the Smithsonian Meteorological Tables. Because of the difference in scales, barometer readings should not be converted from one system of units to another until after the temperature correction has been applied.

10.E.2.c.3.a.7. Total correction—The sum of corrections and the temperature correction combine to make the total correction. First, the barometer reading is corrected for temperature, then the sum of corrections listed on the barometer-correction card is applied. This can be arranged in one table for each barometer. When all corrections have been applied to the barometer reading, the station pressure is the result.

10.E.2.c.3.b. Aneroid barometers

10.E.2.c.3.b.1. Temperature compensation—Temperature compensation is necessary because increases in temperature change the elasticity of the aneroid capsule and the spring, and cause thermal expansion of the parts. Most instruments are temperature compensated in the factory. However, for highly accurate readings, an additional temperature-correction chart, made from laboratory tests against standard barometers, should be used.

10.E.2.c.3.b.2. Posted Correction—To compensate for the effects of drift, scale error, and other factors, it is necessary to use a posted correction to the aneroid reading. This correction is derived from barometer comparisons. The removal correction is included in the computations. Where altimeter-setting indicators or aircraft altimeters are used for pressure measurements, the elevation scale should be adjusted to yield either a consistently positive or negative correction. Use of a positive correction usually results in fewer errors.

10.E.2.d. STANDARDIZATION AND COMPARISON

10.E.2.d.1. GENERAL INFORMATION

The air pressure at a station is a scalar quantity. Although a single pressure measurement at a point is valuable as an altimeter setting for aircraft operations, simultaneous pressure readings from a network of stations defining a field of pressure and the change of pressure with time are important for meteorological purposes. On a day with average weather in a typical U.S. city, the horizontal pressure gradient is approximately 0.9 mb/100 mi, or a 0.09-percent difference per 100 miles. Because even small differences in pressure over time and space are significant, rigorous barometer standards and comparison procedures are necessary.

The procedures given in this section for comparing and standardizing barometers are those used by the National Weather Service. The procedures for mercury barometers differ from those for aneroid barometers because the two types differ in construction. The mercury barometer directly measures the weight of mercury that the atmosphere is able to support and is therefore a primary measure of atmospheric pressue. In general, this instrument is stable and requires comparisons only every 6 months unless it is moved or cleaned. In contrast, the aneroid barometer relies on the response of a partially-evacuated elastic cell. This instrument requires calibration and more frequent comparison because it is subject to drift.

10.E.2.d.2. COMPARING STATION BAROMETERS WITH U.S. NATIONAL STANDARDS

The barometer standardization and comparison program practiced in the U.S. by the National Weather Service has three components.

10.E.2.d.2.a. Test and calibration with the National Weather Service primary standard barometer (at Headquarters)

The National Weather Service Regional Office secondary standard barometers are compared periodically with the primary standard using transfer standard barometers. At present, these are highly stable, accurate, and portable precision aneroids. Calibration data are kept for all National Weather Service mercury barometers, transfer standards, and inspection aneroids.

10.E.2.d.2.b. Regional Inspection Program

National Weather Service field inspectors with portable mercury or precision aneroid barometers compare station barometers periodically. The portable barometers, in turn, are compared with the secondary standard barometers before and after each inspection trip.

10.E.2.d.2.c. Onstation standardization

A continuing onstation standardization, comparison, and monitoring program is maintained between the station barometers, the precision aneroid and/or altimeter-setting indicator, and microbarograph. These procedures are described in following sections. Stations in the same

geographic vicinity (such as airports and city offices) can compare barometers simultaneously by coordinating the observations by phone. This should be done on days with fair weather and only light winds.

10.E.2.d.3. COMPARISON OF MERCURY BAROMETERS

10.E.2.d.3.a. Description of barometer comparisons

A barometer comparison is made by taking simultaneous or near-simultaneous readings on two or more barometers, then comparing the readings. In general, a series of five or more simultaneous readings at least 15 minutes apart is considered a satisfactory set. The means of the five readings on each of the "compared" barometers are compared with the mean of the readings of the "comparison" standard barometer (the inspection barometer). In the case of mercury barometers, the results are used to judge whether the instrument is functioning properly and whether the calibration has changed.

10.E.2.d.3.b. Tolerances between station and standard values

As a rule, when the station mercury barometer deviates from the primary standard barometer in National Weather Service headquarters by more than 0.68 mb (.020 in Hg), the barometer is considered defective. The causes may be an imperfect vacuum above the meniscus in the barometer tube, or pollution of the mercury in the cistern with a resultant change of capillarity, or adhesion of foreign material to the ivory point. If two or more comparisons made on different trips within a few years yield differences that are within tolerances (.020 in Hg) and agree within .005 in Hg., a fairly reliable mean departure can be determined and can be used as a residual correction entered on the barometer-correction card. If the .020-inch Hg limit is exceeded, consideration should be given to replacing or repairing the barometer.

10.E.2.d.3.c. Conditions Requiring Comparisons

Conditions that require comparisons may be (a) an excessive time lapse, or whenever an inspection comparison has not been made in the last 6 months; (b) unsatisfactory performance; that is, whenever recent station comparisons between station mercury barometers and precision aneroids or other evidence indicates questionable or unsatisfactory performance, or (c) disturbance, such as whenever a mercury barometer is cleaned, relocated, replaced, or otherwise disturbed. Comparisons should be made both before and after the disturbance, preferably at least 2 hours after the disturbance.

10.E.2.d.4. COMPARISON OF ANEROID BAROMETERS

To obtain readings of highest accuracy, a period of standardization is needed after the aneroid is installed, and continual comparisons with a mercury barometer or portable inspection aneroids must be made. The purpose of the initial standardization is to determine when the rate of drift from calibration becomes small enough to assure satisfactory operation of the instrument. This rate is 0.21 mb (.006 in Hg) in 29 days. Procedures to determine this are described in the following section.

10.E.2.d.4.a. Adjusting aneroid barometers

The aneroid barometer is provided with a zero-setting device for adjusting the position of the pointer with respect to the scale. This permits adjustment of the correction if desired. It is advisable that the correction have a small positive value rather than a zero or negative value so that the correction will always be applied with a positive sign (see 10.E.2.c.3.b.2). Once the instrument has been

standardized and accepted in accordance with the following instructions, the adjustment screw (or elevation scale on an altimeter setting indicator) should not be reset without authorization from the appropriate headquarters or maintenance shop.

10.E.2.d.4.b. Initial standardization

Beginning with the 5th day after the barometer arrives at the station, two comparisons per day at 6-hour intervals should be taken for 36 days. Thereafter, if the drift criteria described below are met, pairs of comparisons should be taken 6 hours apart once each week, on the same day each week. If, at the end of 136 days, the drift criteria are still not met, the daily readings should be continued until the tolerances are met. If they have not been met at the end of 15 weeks, considerations should be given to rejecting the instrument.

10.E.2.d.4.c. The 29-day criteria

The tolerance is applied in the following manner:

1. Take two comparisons daily and number them serially, beginning with comparison 1 on day 1, comparison 2 on day 1, comparison 3 on day 2, etc. for at least 5 weeks.
2. Take the sum of the differences for the first week (comparisons 1–14) and the fifth week (comparison 57–70).
3. Subtract the sum of the corrections for the fifth week from the sum of the corrections from the first week.
4. If this difference is 3.0 mb or less, the tolerances are met and the barometers should be compared twice on one day each week.
5. If the difference still exceeds 3.0 mb, continue the daily comparisons for another week, and subtract the sum of the corrections from the sixth week from the sum of corrections from the second week (comparisons 15–28 minus comparisons 71–84). If the 3.0-mb tolerance is met, continue as in step (4) above. If the tolerance is not met, continue with the next set (3d and 7th week) until the difference becomes 3.0 mb or less.
6. If the criteria cannot be met after 15 weeks, consider taking the barometer out of use.

10.E.2.d.4.d. Computing posted correction

The posted correction is added to the aneroid-barometer reading to obtain station pressure. After the instrument has been standardized, it is satisfactory for use. The posted correction is computed as follows:

1. Take the sum of the values of the difference between the compared barometers consisting of twice-daily values for 5 different days spaced at weekly intervals, working backward from the last values pertaining to the day of the week on which the comparative readings will be taken in the future.
2. Divide this sum by 10 to obtain the correction. Compute a new correction every week after the second comparison of the day is made.

10.E.2.d.5. COMPARISON OF ALTIMETER-SETTING INDICATORS

The altimeter-setting indicator is a specialized form of aneroid barometer designed to indicate the altimeter setting directly, provided that the instrument is properly calibrated and adjusted. It is capable of indicating changes in altimeter setting with precision. Because accurate altimeter settings are required on an absolute basis to satisfy the needs of aviation, the data provided by the instrument must always be properly corrected. For this reason, it is necessary to compare the readings of the altimeter setting by converting station pressure to the corresponding altimeter setting by means

of an appropriate table. (The station pressure is determined from a standardized mercurial barometer.) Such comparisons permit corrections to the readings of the altimeter-setting indicator, and these corrections must be applied to the readings of the indicator after suitable averaging to yield accurate altimeter settings. The procedures for obtaining these corrections are similar to those used for securing corrections to be applied to aneroid barometers.

10.E.2.d.6. CAUSES OF UNRELIABLE ANEROID PERFORMANCE

Rapid changes of temperature, or exposure to direct heat or sunlight, may cause erratic performance of aneroid instruments. Jarring of instruments may dislocate elements of the linkage system, and excessive friction or leaking pressure cells may result in erroneous pressure readings. After all erratic or excessive corrections that exceed the limits given in the following paragraph have been verified, use of the unreliable instrument should be discontinued and the appropriate headquarters or maintenance shop notified. Questionable corrections noted infrequently at the time of strong, gusty wind should be disregarded.

Whenever the difference between the station pressure derived from the mercury barometer and the corrected reading of the aneroid instrument exceeds 0.010 in Hg (0.3 mb), the difference should be verified immediately by a second comparison, preferably by another observer. If the difference between the second set of corrected readings does not exceed 0.010 in Hg (0.3 mb), the first set of readings may be disregarded and the second set used in computing posted corrections. If verified differences between corrected readings for both the first and second comparisons are from 0.011 to 0.015 in Hg (0.31 to 0.5 mb), the instrument must be restandardized through procedures described in section 10.E.2.d.4.c. If the verified difference exceeds 0.015 in Hg (0.5 mb), the instrument is not accurate.

10.E.2.e. SITING

10.E.2.e.1. SELECTING A BAROMETER SITE

The most suitable location for the barometer is where the instrument will be readily accessible to the observer, safe from tampering, free from rough treatment or jolts, and least likely to receive vibrations or be jarred. The location must be clean, relatively dry, maintained at as steady a temperature as practicable, and without direct sunshine on the instrument. The location must be free from drafts, hot-air currents, or other causes of rapid temperature fluctuations. For maximum protection, the mercury barometer should be installed in a case mounted on the wall and provided with a door or hinged cover to keep out dust and moisture; this also helps to maintain the temperature at a uniform level and to protect it from damage. For economy, the barometer at some stations may be installed without a cover on a board, provided that it is never exposed to direct sunlight. As a rule, the best location for the barometer is on an inside wall. Sites on outside walls should be avoided because they vary more in temperature throughout the day; also, it is important not to install the barometer where there are steep horizontal or vertical gradients of temperature. If practicable, locations with chimneys, windows, doors, ventilators, or any other arrangements producing significant pressure differences with respect to the outside atmosphere should be avoided.

10.E.2.e.2. WIND EFFECTS

When the wind blows against a building, it produces an impact pressure on the windward side and a suction on the leeward side. Through air leaks in open windows and doors, cracks, crevices, and chimneys, the impact pressure and suction cause positive and negative deviations, respectively, in the static pressure. (Static pressure is the pressure of the undisturbed air, well away from obstacles, within the building, and is the pressure desired for normal meteorologic use.) The influence of the wind depends greatly on the location and size of the openings.

It is possible to determine the static pressure by means of a special static-pressure head mounted on a tube above the building. The tube may be conducted into the building and, in the case of fixed-cistern barometers, the static pressure tube may be connected to the cistern. When this connection is made, the building does not influence the pressure indicated by the barometer. However, in the case of barometers installed without advantage of a static-pressure connection, the wind's pressure on the building may cause the barometers to yield a value different from the static pressure. At some points on the exposed windward face of the structure, the impact pressure may reach a maximum value, denoted as q, in excess of the static pressure. At some points on the leeward face of the structure, the deviation of the actual observed pressure from the static pressure may attain an extreme value of $-q$, a suction equal in magnitude to the maximum impact pressure on the windward face.

10.E.3. REFERENCES

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10.F. SURFACE WIND

10.F.1. DEFINITION OF ELEMENTS

Wind velocity is a three-dimensional vector quantity that has small-sclae random fluctuations in space and time superimposed upon a larger-scale more-organized flow. For the purpose of this handbook, the vertical component is disregarded; surface wind is considered as a two-dimensional vector quantity specified by two numbers representing direction and speed.

Wind—The motion of air in relation to the surface of the earth. Because vertical components of atmospheric motion are relatively small, especially near land surface, meteorologists use the term "wind" almost exclusively to denote the horizontal component.

Wind direction—The direction from which the wind is blowing.

True wind direction—The direction, with respect to true north, from which the wind is blowing. In all standard surface-weather observations, it is the true wind direction that is reported, usually in terms of tens of degrees on the 360° compass.

Magnetic wind direction—The direction, with respect to magnetic north, from which the wind is blowing. Magnetic wind directions are frequently used in aircraft operation, owing to the magnetic frame of reference applied to air-navigation facilities (such as designation of runway alinement).

Gust—A sudden, brief increase in the speed of the wind. According to U.S. weather-observation practice, gusts are reported when the variation in windspeed between the peaks and lulls is at least 10 or more knots. The duration of a gust is usually less than 20 seconds.

Vector gust—A vector departure of the wind velocity from its mean value over a specified interval of time, usually not more than 2 minutes.

Component gust—A positive or negative departure of the component of wind velocity in a specified direction from its mean value in that direction over a specified interval of time, usually not more than 2 minutes.

Squall—A strong wind characterized by a sudden onset, a duration of several minutes, and a rather sudden decrease in speed. In U.S. observation practice, a squall is reported only if a windspeed has a sudden increase of at least 15 knots and sustains 20 knots or more for at least 1 minute.

Wind shift—An abrupt change of wind direction. In the U.S., this term is applied to a change in wind direction of 45° or more that takes place in less than 15 minutes.

Peak gust—The highest instantaneous windspeed recorded at a station during a specified period, usually the 24-hour observational day.

Fastest mile—The fastest speed, in miles per hour (mi/h), at which 1 mile of wind passes the station.

Calm—The absence of apparent motion of the air. In the Beaufort wind scale, this condition is reported when smoke is observed to rise vertically or the surface of the sea is smooth and mirrorlike.

In U.S. weather-observation practice, the wind is reported as calm if it is determined to have a speed of less than 1 mi/h or 1 knot.

Variable wind direction—One that fluctuates by 60° or more during the period of observation.

Wind-chill index—The cooling effect of any combination of temperature and wind expressed as the loss of body heat, in kilogram-calories per hour per square meter of skin surface. Usually converted to and expressed as an equivalent still-wind temperature.

Windbreak—Any device designated to obstruct windflow and intended for protection against ill effects of wind, for example, snow fences and rain-gage shields.

Downwind—The direction toward which wind is blowing; that is, with the wind. The opposite is upwind.

Prevailing wind direction—The wind direction most frequently observed during a given period. The periods most commonly used are the observational day, month, season, and year.

Resultant wind—In climatology, the vectorial average of all wind directions and speeds at a given place for a certain period, such as a month.

Shear wind—Local variation of the wind vector or any of its components in a given direction.

Wind pressure (velocity pressure)—The total force exerted upon a structure by wind.

Mountain wind (mountain breezes)—The wind that descends a mountain valley at night; the nocturnal component of a system of mountain-and-valley winds.

Valley wind—A wind that ascends a mountain valley (upvalley wind) during the day; the daytime component of a mountain-and-valley wind system.

Knot—The unit of speed in the nautical system; 1 nautical mile per hour. Equal to 1.1508 statute miles per hour or 0.5144 meters per second (m/s).

10.F.2. MEASUREMENT OF SURFACE WIND

In the early 19th Century, Admiral Beaufort of the British Navy invented a system for estimating and reporting windspeeds, now referred to as the Beaufort scale. It was originally based on the effects of various windspeeds on the amount of canvas that a full-rigged frigate of the period could carry, but it has been modified and modernized. In its present form for international meteorological use, it equates to (1) Beaufort force (or number); (2) windspeed; (3) descriptive term; and (4) visible effects upon land objects or sea surface.

10.F.2.a. INSTRUMENTS AND METHODS

10.F.2.a.1. WINDSPEED SENSORS (ANEMOMETERS)

Both cup and propeller anemometers are commonly used for determination of windspeed. They consist of two subassemblies—the rotor and the signal generator. In well-designed systems, the angular velocity of the rotor is nearly proportional to the windspeed, or, more precisely in the case of the propeller rotor, to the component of the windspeed parallel to the axis of rotation. Near the

threshold speed, however, substantial deviations from linearity may occur. Also, well-designed anemometers have a linearity of response independent of air density, good zero and range stability, and are easily reproduced in a manufacturing process.

The response of the cup-type and propeller-type windspeed sensors to changes in windspeed can be characterized by a distance constant, the magnitude of which varies directly as the moment of inertia of the rotor and inversely as the air density, and in addition varies with several geometric factors. Because this response is described by a distance constant (which yields either too long or too short a response time for a given range of speed, depending on whether the wind is increasing or decreasing), the windspeed average measured by these rotors may over- or under-estimate the actual average by as much as 15 percent. This effect is minimized when the distance constant for the entire system (sensors, indicators, recorders, etc.) is small.

Because both cup and propeller rotors turn with an angular velocity that is directly proportional to speed or to one component of velocity, they are particularly convenient for driving a wide variety of signal generators. Alternating and direct-current generators, optical and magnetic pulse generators, and turn-counting dials and registers have been used successfully. The choice of signal generator is largely a matter of the type of data processor and readout used. Bearings and signal generator must have low starting and running frictional torques, and the moment of inertia of the signal generator must not enlarge the distance constant to an unreasonable extent.

10.F.2.a.1.a. Bridled-cup anemometer

A combination cup anemometer and pressure-plate anemometer that consists of an array of cups around a vertical axis of rotation, the free rotation of which is restricted by a suitable spring arrangement. By properly adjusting the force constant of the spring, it is possible to obtain an angular displacement that is proportional to wind velocity. A bridled-cup anemometer is frequently used to measure high windspeeds.

10.F.2.a.1.b. Dines anemometer

A pressure-tube anemometer that has a pressure head on the windward end of a weather vane and is kept facing into the wind. Another head develops suction independent of wind direction so that the pressure difference between the two heads is proportional to the square of the windspeed and is measured by a specially designed float manometer with linear wind scale.

10.F.2.a.1.c. Windmill anemometer

A rotation anemometer in which the axis of rotation is horizontal. The instrument has either flat vanes (as in the air meter) or helicoidal vanes (as in the propeller anemometer). The relation between windspeed and angular rotation is almost linear.

10.F.2.a.1.d. Air meter

A small, sensitive windmill anemometer having flat vanes. It indicates the number of linear feet (or meters) of air that has passed the instrument during its exposure.

10.F.2.a.1.e. Propeller anemometer

A rotation anemometer that has a horizontal axis upon which helicoidal vanes are mounted.

10.F.2.a.1.f. Hot-wire anemometer

An anemometer designed on the principle that the convection of heat from a body is a function of its ventilation. In its usual form, the hot-wire anemometer consists of a thin platinum wire that is

heated to approximately 1,000°C so that its response is relatively independent of ambient-temperature variation. Windspeed is determined by measuring either the current required to maintain the hot wire at a constant temperature or the variation in resistance of the hot wire while a constant current through it is maintained. Windspeeds as low as a few centimeters per second can be measured in this manner. The response-time constant of the wire can be made very small.

10.F.2.a.1.g. Cup anemometer

A rotation anemometer whose axis of rotation is vertical. Most cup anemometers consist of three or four hemispherical or conical cups mounted with their diametrical planes vertical and distributed symmetrically about the axis of rotation. The rate of rotation of the cups, which is a measure of the windspeed, is often determined indirectly by gearing a mechanical or electrical counter to the shaft. Another frequently used method that gives a direct determination of cup rotation consists of connecting the cup shaft to a magneto and then measuring the generated output voltage.

10.F.2.a.1.h. Contact anemometer

An anemometer that actuates an electrical contact at a rate dependent on windspeed. The number of contacts occurring during a given time is indicated by the number of flashes of a lamp or sounds of a buzzer.

10.F.2.a.1.i. Condenser-discharge anemometer

A contact anemometer connected to an electrical circuit in a way that indicates the average windspeed. The contacts of the anemometer are connected to an electrical relay that transfers the charge of a small condenser to a larger condenser at each closing. The second condenser is in series with an ammeter and a resistance whose value determines the time constant (or averaging time) of the indicating circuit.

10.F.2.a.1.j. Hand-held wind meter

A portable venturi-action wind meter designed for quickly obtaining the approximate windspeed close to the ground. It is accurate to within 1 or 2 mi/h (2 or 3 km/h). The slightly tapered outer plastic shell contains a double scale and a small plastic tube in which a tiny white indicator ball is enclosed. The action of the wind around the meter causes the ball to rise in relation to the windspeed. The meter indicates windspeeds as high as 10 mi/h (16 km/h) on the low scale and as high as 60 mi/h (100 km/h) on the high scale.

10.F.2.a.1.k. Acoustic-wave anemometer

A type designed to determine wind velocity by passing a continuous-wave acoustic signal through the air. The velocity of the sound with respect to the ground is the vector sum of the velocity of sound in the air plus the velocity of the wind. This velocity is determined from the phase delay of the acoustic signal as it propagates over several known paths. The geometry of the paths is selected so that velocity variations caused by environmental effects (such as changes in temperature) are cancelled. the paths are also arranged to allow resolution of the velocity vector of the wind into two orthogonal horizontal components.

10.F.2.a.2. WIND-DIRECTION SENSORS

Wind direction is the direction from which the wind is blowing. This can either be estimated or it can be measured by wind vanes.

In the absence of instruments, or if the instruments are unserviceable, wind direction can be estimated by observing the drift of smoke from an elevated chimney, the movement of leaves, etc., in an open area or from the direction of a streamer fixed to a tall flagstaff. Also, the wind drogue or tee at an airport may be used when the wind is sufficient to move them.

Instruments used to measure the direction of the wind are called wind vanes. Most vanes have a relatively long tail and are mounted on a vertical axis. The lateral forces of the wind on the tail cause the vane to aline itself with the horizontal component of the mean flow. Small mass relative to tail area and a bifurcated, spread, or split shape are incorporated into vanes designed for sensitive response to small changes in direction, especially with light winds. Omnidirectional wind vanes—that is, those mounted in gimbals so that they may point in any direction—afford three-dimensional measurements of eddy patterns.

10.F.2.a.2.a. Flat-plate vanes

A flat plate mounted on a horizontal shaft that is attached to a vertical bearing shaft that is free to rotate. The other end of the horizontal shaft has a weight to counterbalance the flat plate.

10.F.2.a.2.b. Aerodynamic-shaped vanes

A vane with an airfoil section instead of a flat plate as the sensor. These vanes are usually heavier than the flat-plate type.

10.F.2.a.2.c. Splayed vanes

A vane having two flat plates joined at a small angle at the end of the horizontal shaft. Splayed vanes react to small changes in the wind somewhat better than flat-plate vanes or aerodynamic-shaped vanes.

10.F.2.a.2.d. Bivanes

A bidirectional wind vane used in turbulence studies to obtain a record of the horizontal and vertical components of the wind. The instrument consists of two light-weight airfoil sections mounted orthogonally on the end of a counter-balanced rod that is free to rotate in the horizontal and vertical planes. The positions of the rod may be recorded electrically.

10.F.2.a.2.e. Wind cone (also called wind sleeve, wind sock)

A tapered, fabric sleeve, shaped like a truncated cone and pivoted at its larger end on a standard, used to indicate wind direction. Because the air enters the fixed (larger) end, the free (smaller) end of the cone points downwind.

10.F.2.a.3. OTHER INSTRUMENTS

10.F.2.a.3.a. Wind-direction and speed recorders

A two-element recorder that produces simultaneously, in separate channels, inked traces of wind direction and speed on a continuous-strip paper chart. The mechanisms are housed in a case that is mounted in a standard electrical equipment rack. The unit consists basically of a wind-direction mechanism, windspeed mechanism, chart-drive mechanism, pen mechanism, chart, and case.

10.F.2.a.3.b. Wind-direction and speed indicators

These indicators are actuated by contact anemometers and contact or commutator-type wind vanes. A buzzer or gong is sometimes used instead of a light for windspeed indications.

10.F.2.a.3.c. Wind-direction and speed dials

Wind direction is transmitted to a remote dial by direct-current, remote-positioning indicators similar to those used in aircraft instruments, or by a pair of alternating-current, self-synchronous motors. Windspeed is measured by a direct-current magneto generator driven by the rotor and is indicated on a voltmeter calibrated in miles per hour or other appropriate speed units.

10.F.2.a.3.d. Wind totalizers

This anemometer contains two registering dials—one that registers miles, the other tens of miles. The rotary motion of the cups is transmitted to the dials through a system of gears. The main divisions on the upper dial each represent 1 mile of wind, the lower dial is graduated for each 10 miles. An index marker on the upper dial registers the number of complete revolutions of 100 miles each from the lower dial. Therefore, the anemometer registers hundreds, tens, units and tenths of miles of wind.

10.F.2.b. UNITS OF MEASUREMENT

Surface windspeed may be reported in miles per hour, meters per second, or knots. Surface wind direction should be reported in degrees to the nearest 10 using a 01 to 36 code and should represent an average over 10 minutes or, if the wind changes markedly in the 10-minute period, it should be reported as the average over the period after the change.

10.F.2.c. QUALITY CONTROL

10.F.2.c.1. ACCURACY AND PRECISION OF INSTRUMENTS

10.F.2.c.1.a. World Meteorological Organization guidelines

10.F.2.c.1.a.1. Windspeed—Attainable and satisfactory characteristics for windspeed sensors are:

Range ..... 1 to 50 m/s (2 to 100 knots)
Linearity ..... ±0.5 m/s (±1 knot)
Distance constant ..... 2 to 5 m

10.F.2.c.1.a.2. Wind direction—Attainable and satisfactory characteristics for wind direction are:

Windspeed operating range .. 0.5 to 50 m/s (1 to 100 knots)
Linearity and resolution ..... ±2° to ±5°
Damping ratio ..... 0.3 to 0.7

10.F.2.c.1.b. United States guidelines

10.F.2.c.1.b.1. Windspeed—Reported windspeed above 3 knots is nominally accurate to ±1.5 knots under steady-state conditions. The variability in windspeed under field conditions and the characteristics of anemometers reduce this accuracy to approximately ±10 percent of the true value within the range of 0 to 100 knots.

10.F.2.c.1.b.2. Wind direction—Wind vanes and associated position motors are constructed to indicate direction within ±5°. Problems in the orientation of the vane may add a few degrees to the error; however, the total error should be less than 15°.

10.F.2.c.2. MAINTENANCE REQUIREMENTS

Maintenance of wind equipment should be performed at specified intervals to ensure continuity of data and to prevent malfunctions. It is suggested that this maintenance be performed at least semi-annually.

10.F.2.d. INSTRUMENT SITING

Surface-wind-sensing equipment should be placed 20 ft (6 m) above the ground on a freely exposed tower over terrain that is relatively level and free from obstructions to wind flow. In general, obstructions include hills or other subjects whose height above the ground at the exposure site is more than one-tenth their distance from the site.

Sites where topography or other obstructions are known to create appreciable updrafts, downdrafts, eddy currents, or jet-flow effects should be avoided. When a compromise must be made, the sensing units should be exposed at least 12 ft (4 m) above any obstruction lying within 100 ft (30 m) and at least as high as any obstruction between 100 and 200 ft (30 m and 60 m) of the wind equipment. Supporting towers should not be of such bulk or shape as to create an appreciable obstruction to the windflow.

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10.G. FOG

10.G.1. DEFINITION OF ELEMENTS

Fog is defined as a hydrometeor consisting of a visible aggregate of minute water droplets suspended in the atmosphere near the earth's surface. According to international definition, fog reduces visibility to less than 1 km.

Fogs of all types originate when the temperature and dew point of the air become identical or nearly so, provided that sufficient condensation nuclei are available. Fog seldom forms when the temperature is more than 2°C from the dew point. Various types of fog are defined as follows:

Ground fog—A local phenomenon usually formed by radiation cooling of the air. It is often patchy and forms first in low-lying areas. Ground fog has little vertical extent (normally less than 6 m). It reduces visibility horizontally and to a lesser extent vertically; it does not generally hide the stars or the sun.

Ice fog—A suspension of numerous, minute ice crystals in the air near the earth's surface. Like ground fog, it reduces horizontal visibility. Ice fog occurs at very low temperatures, usually in clear, calm weather at high latitudes. It is rare at temperatures above −30°C and increases in frequency with decreasing temperature. It is almost always present at air temperatures of −45°C or −50°C near a source of water vapor.

Fogbow—A faintly colored, circular arc similar to a rainbow but formed in fog layers containing drops with diameters of 100 microns or less.

Fog drip—Water dripping to the ground from trees or other objects that have collected moisture from drifting fog.

Fog drop—An elementary particle of fog, the same as a cloud drop. A diameter of 200 microns has been suggested as an upper limit to the size of fog drops.

Fog bank—A fairly well-defined mass of fog observed in the distance, most commonly at sea. This term is not applied to "patches" of shallow fog.

Fog deposit—An ice coating deposited on exposed surfaces by freezing fog.

Fog horizon—The top of a fog layer that is confined by a low-level temperature inversion in such a way as to give the appearance of the horizon when viewed from above against the sky. The true horizon is usually obscured by the fog in such instances.

Advection fog—A type of fog caused by the advection of moist air over a cold surface, and the consequent cooling of that air to or below its dew point.

Frontal fog—Fog associated with frontal zones and frontal passages. It is classified into three types—warm-front prefrontal fog, cold-front postfrontal fog, and frontal-passage fog.

Steam fog—Fog formed when water vapor is added to air that is much colder than the vapor's source; most commonly, when cold air drifts across relatively warm water.

Upslope fog—A type of fog formed when air flows upward over rising terrain and is consequently cooled adiabatically to or below its dew point.

Precipitation-induced fog—Fog caused by the addition of moisture to the air through evaporation of rain or drizzle.

Radiation fog—A major type of fog produced over a land area when radiation cools the air to or below its dew point.

Dry fog—A fog that does not moisten exposed surfaces.

Smog—A natural fog contaminated by industrial pollutants; a mixture of smoke and fog.

Sea fog—A type of advection fog formed when air that has been lying over a warm water surface is transported over a colder water surface, resulting in cooling of the lower layer of air to below its dew point.

10.G.2. FOG DETECTION AND MEASUREMENT

Fog, expressed in the most simple terms, is a cloud whose base rests on or very close to the earth's surface, and that reduces visibility to less than 1 km. Although the substance of fog and cloud is exactly the same, the processes of cloud and fog formation are quite different. Clouds form chiefly above the earth's surface in air that expands and cools as it rises as a result of convection, whereas fog results from the cooling of air that remains at the earth's surface.

The formation of fog becomes possible when the surface-air temperature is within about 2°C of the dew point and the difference between the two is decreasing or becomes zero. Whenever the formation of fog is anticipated or predicted, it is recommended that this difference be plotted and the trend closely watched. As the spread approaches zero, fog is imminent. The following table contains a summary of fog-producing and fog-dissipating processes:

Table 10-5.—*Summary of fog-producing and fog-dissipating processes in the atmosphere*

Fog-producing process	Fog-dissipating process
A. Evaporation from: 1. Rain that is warmer than the air (frontal rain-area fog). 2. Water surface that is warmer than the air (steam fog).	A. Condensation on: 1. Snow with an air temperature below 0°C (except ice-crystal fog). 2. Snow with an air temperature above 0°C (melting snow).
B. Cooling from: 1. Adiabatic expansion caused by upslope motion (upslope fog). 2. Radiation (radiation fog). 3. Advection of warmer air over a colder surface (advection fog).	B. Heating from: 1. Adiabatic compression caused by downslope motion. 2. Radiation absorbed by the fog or by the underlying surface. 3. Advection of colder air over a warmer surface.
C. Mixing: Horizontal mixing (unimportant by itself and strongly counteracted by vertical mixing).	C. Mixing: Vertical mixing (important in the dissipation of fogs and the production of stratus clouds).

Visibility is used as a criterion for estimating the intensity of fog. To accomplish this, either visual estimation or instruments may be used. Both methods are described in the following paragraphs.

10.G.2.a. INSTRUMENTS AND METHODS

10.G.2.a.1. VISUAL ESTIMATION

Visual observations should be taken under the following conditions:

1. Observers should have at least average visual acuity.
2. A stationary observation point should be used.
3. By day, stationary visibility markers should be viewed against the sky. At night, stationary, low- to moderate-intensity, unfocused lights should be used.

Visibility observations should be taken from as many points as necessary to view the appropriate markers. Observations should be made with respect to a plane about 2 m above the ground or as close to this height as practicable.

10.G.2.a.2. VISIBILITY-MEASURING INSTRUMENTS

Most instruments for measuring visibility employ one of two principles—scattering or extinction of light.

Most particles in the atmosphere have different indices of refraction than the medium in which they are suspended. The different refractions cause a portion of incident luminance to be scattered. This scattering is a major factor in the attenuation of luminous intensity. The angle between the incident ray and the scattered ray is the scatter angle. If this angle is acute, the scattering is known as forward scatter. If it is at an obtuse angle, the scattering is backward. Instruments have been designed that give the visibility as a function of the amount of light scattered.

10.G.2.a.2.a. Transmissometer

An instrument that consists of a projector, a detector, and a meter or recorder to indicate the transmission of light through the atmosphere. The projector emits a light of known intensity; the detector measures the amount of light received as a percentage of the amount that would be received through a clear atmosphere; and the meter converts this into a measure of visibility. In effect, the transmissometer samples the visibility along a known baseline and then extrapolates to determine the visibility over a greater distance.

10.G.2.a.2.b. Videograph

A meter based on the measurement of back-scatter light from visibility-limiting hydrometeors and aerosols such as rain, snow, fog, or atmospheric pollution. Whereas some devices rely on the infrared emission of a filament lamp, this device operates within the spectral range of the human eye to ensure that the automatic measurements are equivalent to those of observers. With all the components in a single housing, an upward-angled projector flashes white light from a xenon lamp for 1 microsecond, 3 times per second, and this light is intercepted by a receiver that looks out a distance of approximately 15 meters. The back-scattered light is converted to an electrical signal and reads out in terms of distance on a meter, recorder, or alarm device.

10.G.2.a.2.c. Fog detector

A compact, permanently alined instrument for the measurement of atmospheric visibility as it is affected by fog. Visibilities ranging from 10 m to 1 km can be measured and recorded. An analog output is provided for recording or display, as well as an alarm that indicates when the visibility reaches a predetermined level.

10.G.2.b. UNITS OF MEASUREMENT

The intensity of fog is measured in terms of the reduction of visibility. The unit of measurement is the horizontal visibility, measured in either feet, miles, meters, or kilometers.

10.G.2.c. MEASUREMENT AND PROCEDURES

10.G.2.c.1. VISIBILITY OBJECTS

Each station should prepare a plan of objects used for the observation showing their distances and bearings from the point of observation. The plan should include objects suitable for determining the visibility by night as well as by day, and in all directions from the measuring point.

10.G.2.c.1.a. Daytime-visibility objects

Provided they meet the following requirements, objects selected for daytime observations should represent as many different distances as possible. Only black or nearly black objects that stand out against the sky on the horizon should be chosen. Light-colored objects or objects close to a terrestrial background should be avoided. This is particularly important when the sun is shining on the object. Thus, a white house or a metal hangar would nearly always be unsuitable, whereas a group of dark trees would be satisfactory unless it were brightly illuminated by sunlight. If an object against a terrestrial background must be used, it should stand well in front of it, no further than halfway between the observer and the background. A tree at the edge of a wood, for example, would not be suitable for visibility observations. To ensure that daytime-visibility measurements are representative, they should be made from objects subtending an angle of at least 0.5° at the observer's eye. An object subtending an angle less than this becomes invisible at less distance than would larger objects in the same circumstances. A hole 7.5 mm in diameter punched in a card and held at arm's length subtends this angle approximately; a visibility object viewed through such an aperture should, therefore, completely fill it. An object should not subtend an angle of more than 5°.

10.G.2.c.1.b. Night-visibility objects

Illuminated objects are used primarily for measurements of visibility at night. Any source of light may be used as a visibility object, provided that the intensity in the direction of observation is known and well defined. It is generally desirable to use lights that can be regarded as point sources. The intensity should not be greater in any one direction than in any other and should not be confined to a small solid angle. Care must be taken to ensure the mechanical and optical stability of the light source. Point sources that are not close to other sources or areas of light are preferable to clusters of lights, even though the individual lights in clusters may be separated from each other. Clusters may affect the visibility of individual sources considered separately. For measurements of visibility at night, only suitably distributed point sources are recommended.

Night observations of illuminated objects are affected appreciably by the illumination of the objects' surroundings and by the physiological effects of dazzling by other lights, even outside the field of vision, particularly if the observation is made through a window. An accurate and reliable observation can be made only from a dark and otherwise suitable location outdoors.

Physiological factors are an important source of dispersion of the measurements. It is essential that qualified observers with normal vision make all visual measurements. In addition, it is necessary to allow for visual adaptation to dark conditions (usually 5 to 15 minutes).

10.G.2.c.2. MEASURING INSTRUMENTS

Measuring instruments and any necessary lights should be located where the measurements will be representative for the intended purpose. Thus, for general synoptic purposes, instruments and lights should be in locations free from local atmospheric pollution.

10.G.2.d. QUALITY CONTROL

10.G.2.d.1. VISIBILITY OBSERVATIONS

The supervisor of each observation station should arrange for periodic review of all visibility charts and lists of markers used in taking visibility observations at each point of observation. In this review, he should make certain that all checkpoints shown on the charts and lists are still valid and that any new objects suitable for checkpoints are identified and entered on all charts and lists.

10.G.2.d.2. INSTRUMENT CHECKS

All models of instruments for measuring visibility must be carefully checked and maintained in good working order. The albedo of daytime-visibility objects must be kept from changing; for example, snow and mud splash should be removed before observations are made. Lights used for determining visibility at night must be kept clean and correctly oriented. Measuring instruments should be regularly cleaned and checked after snowfall or strong winds and in any other circumstances that may have upset the mechanical adjustment or caused a decrease in optical performance. In particular, for transmissometers, the intensity of the projector lamp should be checked, especially for incandescent lamps, which have short life. The receiver, amplifier, and the frequency of modulation of the beam should be checked. Optical and mechanical adjustments should also be checked, as well as the electricity supply. An overall check of the instrument can easily be carried out when visibility is good.

Systematic and regular maintenance is recommended for recording devices with special attention to ensure that detectors are clean, especially when operated near runways.

After any repair has been carried out or any lamps or other parts have been replaced, thorough adjustments should be made to ensure that performance is up to standard. The instruments should be checked over the entire range of measurements.

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10.H. RADIATION

The sun's radiation is the ultimate energy source for all biological and physical processes. Thus, many disciplines use radiation data. For example, agriculturalists and hydrologists use solar-radiation data to forecast crop growth, evaporation, and snowmelt; meteorologists use these data to help interpret the uneven heating of the earth-atmosphere system, which is the driving force for weather; and the Nation is looking to the possible direct use of solar radiation as an alternative fuel. Therefore, it is important to monitor and report solar-radiation measurements in a standard language.

10.H.1. DEFINITION OF ELEMENTS

All definitions follow recommendations of the World Meteorological Organization (WMO) (1971).

Solar radiation—The radiation emitted by the sun and reaching the observer; frequently called insolation.

Terrestrial radiation—The radiation emitted by the earth and the objects thereon.

Atmospheric radiation—The radiation emitted by the atmosphere.

Solar-radiation flux (See terms defined below and fig. 10-2).

1. *Direct solar radiation*—Solar radiation coming from the solid angle of the sun's disk on a surface perpendicular to the axis of the solid angle.
2. *Global solar radiation*—The downward direct and diffuse solar radiation as received on a horizontal surface from a solid angle of 2π (often called total or hemispheric radiation).
3. *Sky radiation (diffuse solar radiation)*—Downward diffuse solar radiation as received on a horizontal surface from a solid angle of 2π, with the exception of the solid angle subtended by the sun's disk.
4. *Reflected solar radiation*—Upward solar radiation reflected by the earth's surface and diffused by the atmospheric layer between the ground and the point of observation.
5. *Net radiation*—The difference between downward and upward solar radiation.

Radiant flux (flux of radiation, radiant power)—Power emitted, transferred, or received in the form of radiation.

Total radiation—The combined solar, atmospheric, and terrestrial radiation.

Spectral measurements—Measurements of the spectral composition of solar, terrestrial, or atmospheric radiation.

Spherical-surface measurements—Measurements of radiation falling on a spherical surface. These attempt to simulate the radiation environment on an isolated object.

Sunshine—Periods of daytime during which sunlight is intense enough to cast a shadow. Generally reported in hours.

Sensors:

1. *Radiometer*—An instrument for measuring radiation.
2. *Pyrheliometer*—An instrument for measuring direct solar radiation.
3. *Pyranometer*—An instrument for measuring solar radiation falling from the solid angle 2π on a plane surface.
4. *Pyrradiometer*—An instrument for measuring total radiation falling from the solid angle 2π on a plane surface.
5. *Pyrgeometer*—An instrument for measuring net atmospheric radiation on a horizontal upward-facing black surface at the ambient air temperature.
6. *Net pyrradiometer*—An instrument for measuring the net flux of upward and downward total radiation through a horizontal surface.
7. *Net pyranometer*—An instrument for measuring the net upward and downward solar radiation flux through a horizontal surface.
8. *Spherical pyrradiometer*—An instrument for measuring total radiation received on a spherical surface.
9. *Spherical pyranometer*—An instrument for measuring the solar radiation on a spherical surface.

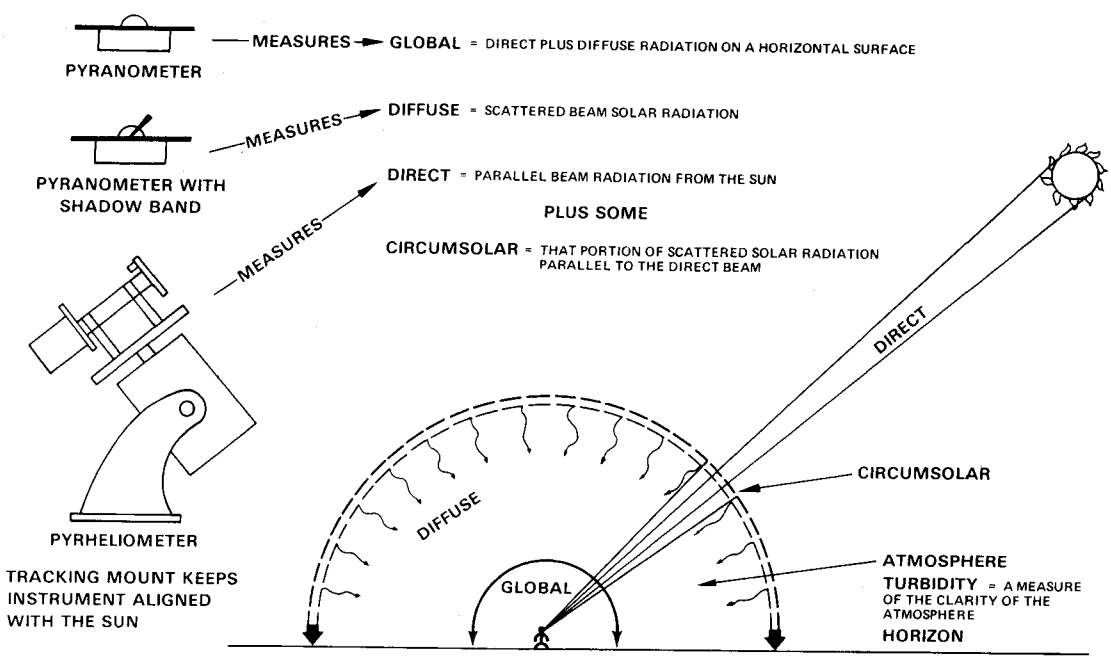

Figure 10.2.—Kinds of insolation and types of measuring instruments (From Summary Report, October 1976: ERDA 76-138, Solar Energy Environmental and Resource Assessment Program, p. 8.)

10.H.2. MEASUREMENT OF RADIATION

10.H.2.a. INSTRUMENTS AND METHODS

10.H.2.a.1. DIRECT SOLAR RADIATION

The first measurements of direct solar radiation were done mainly to establish the value of the solar constant and the variations of that value with time. Two instruments developed around the turn of the century for this purpose are still used as primary reference standard pyrheliometers; these are the Angstrom electrical-compensation pyrheliometers (Abbot, 1911) and the Smithsonian silver-disk (Abbot, 1911; Foster and MacDonald, 1955) pyrheliometer. The Angstrom and the silver disk are the reference standard pyrheliometer recognized by WMO (1971). All other radiometers trace their calibration to the International Pyrheliometric Scale of 1956 through an Angstrom and/or silver-disk pyrheliometer, which are not used for routine observations. A pyrheliometer with a sealed glass or quartz cover, such as an Eppley normal incidence pyrheliometer or a Moll-Gorczynski pyrheliometer is used for routine measurements. The new absolute radiometers (see 10.H.2.a.1.c.) are now used by WMO to determine the "absolute radiation scale," but recalibrated Angstrom and silver-disk pyrheliometers are still used by many nations as the primary reference standards.

10.H.2.a.1.a. Angstrom electrical compensating pyrheliometer

The Angstrom electrical compensating pyrheliometer heats a blackened, shaded manganin-foil strip electrically until the strip reaches the same temperature as a similar strip exposed to solar radiation. Under steady-state conditions, the absorbed solar energy is equal to the electrical energy used for heating. Thermocouples connected in opposition to the back of each strip through a galvanometer (or other null detector) are used to test for equality of strip temperature (assuming the steady-state condition). The energy, I, of the direct solar radiation is then calculated by

$$I = ki^2,$$

where i is the heating current, in amperes, and k is a dimensionless instrumental constant. In actual use, i is a mean from alternate shadings of the left (L) and right (R) strip as follows:

$$\frac{i_{L_1} + 2i_R + i_{L_2}}{4} = i$$

Subscripts 1 and 2 reflect the alternations left-right-left measurement scheme. Unlike most other pyrheliometers, the Angstrom aperture is rectangular. The apertures in use are $24° \times 60°$ for the short-tube instrument and $6° \times 3°$ for the long-tube instrument.

The instrument can be made absolute by calculating k (Angstrom, 1899) but, in practice, most Angstrom pyrheliometers are calibrated by comparison with a working standard instrument.

Auxiliary equipment for precise regulation of the compensation current is important. The control units sold by manufacturers of the Angstrom pyrheliometers generally meet accuracy requirements. Several schemes exist for partial automation of the reading procedures; for example, Marsh (1965) has introduced a servo-operated electronic system to automatically control the current to the heated strip, which reduces the possibility of human errors in the measurements.

10.H.2.a.1.b. Silver-disk pyrheliometer

The silver-disk pyrheliometer was designed originally as a secondary instrument by the Smithsonian Institution (Abbot, 1911); now it is used primarily as a transfer standard for calibrating other

radiometers. The instrument consists of a blackened silver disk positioned at the lower end of a tube with diaphragms set to limit the aperture angle to 5.7°. The disk temperature is measured with a mercury-in-glass thermometer. The disk is alternately shaded and exposed to solar radiation following a precise routine. The temperature at each setting (shaded or exposed) must be read within 0.2 second of the prescribed time (Abbot, 1911). Consistent errors of 1 second may result in errors of about 1 percent (WMO, 1971). The modifications made by Foster and MacDonald (1955) greatly facilitate accurate measurements. These consist of an automatic shutter controlled by a synchronous electric clock, and a crank-operated pointer, which help remove possible timing and thermometer-reading errors. The thermometer readings must be corrected for air, stem, and bulb temperature.

The silver-disk pyrheliometer is not absolute and must, therefore, be calibrated against a primary standard. The calibration constants originally furnished with the instrument refer to the Smithsonian 1913 Radiation Scale. Experience shows the characteristics of the instrument to be extremely stable (WMO, 1971).

10.H.2.a.1.c. Absolute pyrheliometers

Two types of absolute pyrheliometers have been marketed recently by three companies. These are the absolute Kendall Mark VI (Technical Measurements, Inc., La Canada, Calif.), Eppley-Kendall (Eppley Laboratory, Inc., Newport, R.I.), and the Willson Active Cavity Radiometer (Radiometrics Corporation, Altedena, Calif.). The Kendall and Willson pyrheliometers were developed to make absolute measurements of the solar constant on satellite and balloon-flight experiments. They define the absolute radiation scale through accurate knowledge of the sensor characteristics. The "absoluteness" has been verified by Kendall (1968) with measurements of the Stefan-Boltzmann constant (σ). Kendall's measured σ averaged within 0.3 percent of the theoretical value.

The Kendall pyrheliometer (Kendall, 1968) as manufactured by Eppley Laboratories and Technical Measurements, Inc., consists of a view-limiting aperture, a view-limiting tube, and a massive thermal guard serving as a heatsink. In the heatsink is the receptor, a blackened cavity connected to a thermal resistor that conducts the heat received by the cavity to the heatsink. A matching symmetrically arranged cavity and thermal resistor serve as compensating elements. When one receptor cavity is exposed to solar radiation, a temperature difference develops across the thermal resistors. This temperature difference is measured by a thermopile. The hot junctions of the thermopile are on the receptor thermal resistor; cold junctions of the thermopile are on the compensating thermal resistor.

The conical cavity has greater absorptivity (and emissivity) than a flat surface; it also decreases the effects of the thermal resistance of the black coating and makes the receptor less sensitive to the spectral quality of the incoming radiation.

A third type of Kendall pyrheliometer, built by Jet Propulsion Laboratory and called PACRAD III (Kendall, 1969), now forms the basis for the absolute-radiation scale used by WMO.

The Willson pyrheliometer (Willson, 1969), unlike the Kendall pyrheliometer, is an active-cavity radiometer. It determines the incoming irradiance by measuring the amount of electrical heating required to maintain a given positive temperature difference between cavity and heatsink. This differential mode of operation requires chopping the incoming insolation at low frequency. The irradiance is then determined from the heating power monitored in each phase (dark and light).

The pyrheliometer consists of a view limiter and aluminum tubular case that houses the cavity, heatsink, heater, and electronics. No compensating cavity is used in this instrument; instead, the heat sink is insulated from the environment to minimize its rate of temperature change when the environmental temperature fluctuates. As with the Kendall model, a blackened conical cavity receiver is used to enhance the effective absorptance.

Both the Kendall and Willson pyrheliometers require the use of instrument constants to correct for the cavity's not being a perfect blackbody.

10.H.2.a.1.d. Operational pyrheliometers

Several types of pyrheliometers are used for operational measurements of direct solar radiation. These are the Eppley Normal Incidence pyrheliometer, the Michelson Bimetallic pyrheliometer, the Yanishevsky Thermoelectric pyrheliometer, and the pyrheliometer of the Japanese Meteorological Agency. These are described in detail by Coulson (1975). The Eppley Normal Incidence pyrheliometer (NIP, manufactured by Eppley Laboratory, Newport, R.I.), is the type used most widely in the U.S.

The sensing element of the current NIP is a fast-response, wire-wound, plated copper-constantan thermopile. The receiver is 9 mm in diameter and is coated with Parsons Optical Black lacquer. The thermopile heatsink contains a temperature-compensation circuit to stabilize sensor response. The view-limiter tube uses diaphragms to limit the circular aperture to 5.7°. The instrument is filled with dry air and is closed at the viewing end with a removable quartz crystal window. With an electrically driven equatorial mount for solar tracking, the instrument signal can be read remotely for continuous operation.

The instrument characteristics are stable; thus, after careful calibration, the NIP is suitable for use as a reference standard (WMO, 1971).

10.H.2.a.1.e. Standardization of pyrheliometers

An Angstrom pyrheliometer and/or silver-disk pyrheliometer is normally used as a reference standard or secondary reference standard on a cloudless day when the ratio of the transmission factor to optical airmass exceeds 0.17 (WMO, 1971). This eliminates the effects of the different-sized aperture angles of the instruments. Measurements should be taken for 2 hours each side of solar noon. Particular attention should be given to the temperature and the windspeed so that the temperature coefficients for the standard and the instrument to be calibrated can be applied as appropriate, and any measurements affected by wind can be eliminated. Some basic rules for comparisons are listed by WMO (1971).

10.H.2.a.1.f. General considerations

Several items must be considered when making any pyrheliometric measurement:

1. The site should be as free of obstruction as possible. Also, the site must be representative if the measurements are to be generalized for the area (for example, measurements in a heavily polluted city are not necessarily representative of the surrounding countryside).
2. At continuous-monitoring sites, the equatorial mount must be properly installed and maintained. Great care must be exercised to ensure that the principal axis of the mount is parallel to the axis of the earth's rotation. The alinement of the pyrheliometer should be checked at least once a day to ensure accurate measurements.
3. The viewing window and any filters should be checked daily and cleaned as required.
4. Practical pyrheliometers have a viewing aperture larger than the solar disk; therefore, they see radiation from the area around the sun as well as the direct solar radiation. Thus, any errors introduced will increase with increasing aperture.

10.H.2.a.2. GLOBAL RADIATION

Global radiation is the most commonly measured type of solar radiation. Its importance in energy-balance studies has led to the development of many instruments for continuous monitoring. The first instrument to attain wide use was the Callender pyranometer, invented by N. S. Callender in 1898. The improved 1905 model found wide use because of its capability to record global radiation. This and other early pyranometers are discussed in detail by Coulson (1975).

Modern pyranometers used widely throughout the world are classified by WMO (1971) into three groups, of which the first class is the most accurate. Photovoltaic pyranometers are not included. Examples of some sensors classified within this scheme are given below:

First class	*Second class*	*Third class*
Selected thermopile pyranometers	Moll-Gorczynski pyranometers Eppley pyranometer (180°) Volochine thermopile pyranometer Dirmhirn-Sauferer pyranometer Yanishevsky thermo-electric pyranometer Spherical Bellani pyranometer	Robitzsch bimetallic pyranometers

Within the three WMO classes are two basic types of pyranometers—thermopile and bimetallic. A third type, the photovoltaic pyranometer, is also in use, particularly in agriculture.

10.H.2.a.2.a. Photovoltaic pyranometer

The silicon-cell pyranometer design is discussed in detail by Kerr and others (1967) and Selcuk and Yellott (1962). These sensors have the advantages of simplicity, low cost, nearly instantaneous response, and high current output. Unfortunately, they also have several disadvantages; for example, a small temperature-response variation is dependent on wavelength. For many applications, calibration at or near the expected operating temperature will make temperature corrections unnecessary, or a temperature-compensation circuit such as that described by Selcuk and Yellott (1962) can be added.

The cosine response of a bare silicon-cell sensor is not accurate. At an angle of incidence of 45°, the cosine response is approximately 10 percent below ideal (Kerr and others, 1967). At the expense of sensitivity, the cosine response can be greatly improved by covering the cell with a countoured plastic diffuser (Latimer, 1962).

The major disadvantage of silicon cells is that the sensitivity is a function of wavelength. The spectral range of silicon-cell pyranometers is approximately 0.04 μ to 1.1 μm, with a peak at 0.85 μm. This could be calibrated if the spectral distribution of the solar irradiance were constant, but it is not. The spectral distribution of solar irradiance varies with elevation angle, cloudiness, turbidity, water-vapor content, and surface albedo. The error is approximately 2 percent between the extremes of clear to overcast skies (Coulson, 1975). When the instrument is used for albedo measurements, errors are also caused by the variation of surface reflectance with wavelength and surface composition.

The overall accuracies obtainable with photovoltaic pyranometers are adequate for many uses as long as integration periods are one day or longer.

10.H.2.a.2.b. Robitzsch bimetallic pyranometer

The Robitzsch-type bimetallic pyranometer (Robitzsch, 1932) (often called an actinograph) depends on the thermal expansion of heated metals. Its resulting slow response time limits its applications to uses in which daily or longer intervals are required. In addition, the response is determined by the temperature of the strip, which is a function of both the incident solar flux and the ambient temperature. Thus, either a temperature-correction factor must be applied, or a temperature-compensation mechanism must be used. Because mechanical compensation is not perfect, some

temperature error remains in the record. The sensors also have large azimuth and cosine-response problems (WMO, 1971).

The Robitzsch design is popular in Europe, where it is used by about half the reporting stations (Robitzsch, 1932). In the U.S., no Robitzsch instruments are used in regular networks, but many are used in individual hydrologic and agricultural studies. Their popularity is due to sensor simplicity and their self-recording feature.

The basic Robitzsch model on the market today consists of a blackened bimetallic strip connected to a recorder pen through a mechanical linkage. The clock-driven drum recorder can be operated at two speeds—one rotation in 24 hours or one rotation in 7 days. The temperature-compensated model uses two highly reflective metal strips flanking the blackened detector; their response to ambient temperature changes compensates the instrument by moving the detector mount. The whole system is enclosed in a desiccated case with a hemispheric glass dome over the sensing element and a window for viewing the pen and recorder chart.

10.H.2.a.2.c. Thermopile pyranometer

Thermopile pyranometers are the most accurate type. The most accurate models are those with double domes (to minimize outgoing thermal radiation), cold junctions attached to a large heatsink, and heatsink-radiation shields. These instruments are capable of accuracies of ± 2 percent.

The Eppley Precision Spectral Pyranometer (often referred to as the Model II) and the Spectrolab SR-75 (manufactured by Spectrolab, 12484 Gladstone Avenue, Sylmar, Calif.) are examples. The double dome has the advantage that the outer dome can be replaced with a special dome for broadband spectral measurements. However, there are a few problems in operating these pyranometers. Sensors operated with filters show an apparent increase in sensitivity over those with clear domes. This problem and its correction are discussed by Drummond and Roche (1965). It is caused by an increase in the temperature of the filter glass by absorption of solar radiation, which, in turn, heat the inner dome and modifies the long-wave irradiance reaching the detector. The major problem with all modern pyranometers is the cosine and azimuth response. The nonuniform sensitivity of thermopiles and the lack of a perfect blackening agent may result in an uneven voltage output, poorly representing the actual sky irradiance. Lesser problems are imperfect temperature response, a lack of long-term stability, and uneven sensitivity. Most temperature-response characteristics of a pyranometer can be partially corrected by compensation circuits or by correcting the data using results of laboratory tests. Variations in sensitivity and long-term stability may be compensated for by frequent calibration to a standard.

Instruments with single domes and/or black-and-white receivers are less accurate (± 5 percent) than the all-black, double-domed sensors and also have similar problems with cosine, temperature, and azimuth response. An example of this type pyranometer is the Eppley Black and White (Model 8-48), the sensor of which has a wire-wound thermopile made by electroplating copper and constantan. The hot and cold junctions are coated with Parson's Optical Black and barium sulfate, respectively. The glass dome is removable for cleaning and repair.

The old-model black-and-white Eppley (or Eppley 180° pyrheliometer) was once the sensor used most widely in the U.S., but is no longer in production and is being replaced by more modern pyranometers. As originally designed, the instrument was not temperature compensated, although some later models were (Kimball and Hobbs, 1923). Discussion of sensor characteristics is available in MacDonald (1951) and Flowers and Helfert (1966).

The detector is a thermopile of gold-palladium and platinum-rhodium alloys, the junctions of which are electrically insulated from, but in good thermal contact with, the concentric rings of the sensor disk. The sensor disk consists of two concentric silver rings and a center silver disk that are thermally insulated from each other. The outer ring and center disk are coated with magnesium

oxide. The inside ring is coated with lamp black (or Parson's Optical Black if manufactured or repaired after the spring of 1956).

The sensors coated with Parson's Optical Black have two difficulties:

1. Parson's Optical Black tends to turn gray, then green, when exposed to solar radiation. The rate of aging depends on ambient temperature and insolation intensity; for example, sensors at National Weather Service's Alaskan solar-radiation sites have not changed color afer 2 to 3 year's exposure, whereas sensors in the southwestern U.S. change from black to green within the same exposure time.
2. When the National Weather Service used lamp black and an artificial light source to calibrate the Parson's Optical Black-coated sensors for field use the resulting calibration constant was approximately 7 percent low; that is, the data were approximately 7 percent high. More details on the entire National Oceanic and Atmospheric Administration Solar Radiation Program are available in Riches and others, 1975.

The Moll-Gorczynski pyranometer (often called the solarimeter) is based on the thermopile designed by Dr. W. J. Moll (1923). This design is used today by Kipp and Zonen and is used widely in Europe.

The current solarimeter consists of a thermopile of 14 blackened manganin-constantan thermojunction elements in a 12 to 11-mm rectangular arrangement. Two concentric hemispherical glass domes protect the detector from the environment. A desiccant is used to prevent condensation of moisture on the inside of the domes. No temperature compensation is built into the sensor; therefore, a temperature coefficient of 0.0015 to 0.0020/°C (decreasing sensitivity with increasing temperature) must be applied.

The "star" pyranometer, also known as the Dirmhirm-Sauberer pyranometer or the Stern pyranometer, uses a circular arrangement of wedge-shaped black-and-white copper plates as a detector surface. The 16 to 32 copper plates are about 50 mm thick, and each plate is thermally insulated from the others and from the sensor case and base unit. The thermojunctions are soldered to the bottom sides of the plates. The detector surface is covered by a glass hemisphere to protect it from the environment. The sensor is hermetically sealed, and a desiccant is enclosed to prevent moisture from condensing on the inside of the dome. For most applications, the temperature coefficient is negligible.

Some data on the accuracy of selected pyranometers are given in table 10-6.

Table 10-6 — *Classification of accuracy of pyranometers*

WMO Class	*1st class*	*2nd class*[9]	*3rd class*
Sensitivity[1]	0.1	0.5	1.0
Stability[2] (percent per year)	1	2	5
Temperature [3] (percent per °C)	1	2	5
Selectivity [4] (percent)	1	2	5
Linearity [5] (percent)	1	2	3
Maximum time constant [6] (seconds)	25	60	240
Cosine response [7] (percent)	3	5–7	10
Azimuth response [8] (percent)	3	5–7	10

See footnotes on next page.

1. Measured in mV/Joule $cm^{-2} min^{-1}$ Absolute change in output (millivolts) per unit change in input (Joule $cm^{-2} min^{-1}$) of the device.
2. Stability of calibration, i.e., maximum permissable change per year.
3. (°C): Maximum error due to variation in ambient temperature.
4. Maximum error due to departure from ideal spectral response.
5. Maximum error due to nonlinearity of response of device when this is assumed linear.
6. Maximum time taken by device to respond.
7. Deviation of directional response of device from ideal cosine response for device.
8. Deviation of directional response of device from ideal azimuth response.
9. For spherical Bellani, with regard to daily sums only.

10.H.2.a.3. DIFFUSE IRRADIANCE

Global solar radiation as measured by a pyranometer has basically two components—diffuse and direct. For many studies in solar energy, agriculture, and atmospheric turbidity, it is desirable to separate these components. Two methods can be used. In the first, the direct irradiance normal to the solar beam I can be measured with a pyrheliometer, and the global irradiance G, can be measured with a pyranometer. The diffuse irradiance D can be calculated by

$$D = G - I \cos Z$$

where Z is the solar zenith angle. This assumes that the pyrheliometer sees only the direct irradiance.

The second method is to use two pyranometers—one to measure the global irradiance, the other to measure diffuse irradiance. This method is more direct, but corrections must be applied for the portion of the diffuse radiation that is shaded from the sensor. Coulson (1975) summarizes methods for obtaining these corrections.

Many scientists and engineers, particularly those interested in solar-energy applications, need measurements of the solar-radiation flux on nonhorizontal surfaces. This is a function of the diffuse, direct, and reflected irradiance. The reflected component will be highly dependent on the site; thus, the data will be site specific.

A pyranometer mounted at the desired inclination can be used for these measurements. Consideration must be given to the response of a pyranometer when tilted (or inverted for albedo measurements). Latimer (1962) and Fuquay and Buettner (1957) have reported a 5.5-percent decrease in sensitivity for an inverted Eppley 180° instrument, and Fuquay and Buettner found a −2.7-percent change in 90° inclination from horizontal. Norris (1974) tested four pyranometers (Eppley 180°, Eppley PSP, Kipp and Zonen, and Trickett-Norris) at six angles between 0° and 90° from horizontal and inverted. His results for an inverted Eppley 180° pyranometer were similar to previous findings; the Eppley PSP at 60° had a 2-percent increase in sensitivity, at 90° an 110 percent increase, and, at 180°, a 1-percent increase. This research needs to be expanded to include more sensors of each type so that generalized corrections can be determined. An important point in this experiment is to keep the source intensity constant.

10.H.2.a.4. ULTRAVIOLET RADIATION AND SENSORS

The ultraviolet (UV) portion of the solar spectrum extends from the shortest visible wavelength, approximately 0.4μm, to X-rays, which begin at approximately 0.03μm. The wavelengths reaching the earth's surface are in the 0.295 to 0.40μm region. Wavelengths shorter than 0.295 μm are absorbed by the atmosphere, mainly by ozone and oxygen. UV plays an important role in many atmospheric photochemical reactions such as the production of ozone in the stratosphere. The longer ultraviolet wavelengths reaching the lower atmosphere promote photochemical smog reactions.

UV has many biological effects and uses. For example, it is the cause of sunburn (erythema) and has been used to treat tuberculosis, to prevent and cure rickets, and to destroy bacteria in municipal water supplies. It is also known to be a major causal factor in some types of skin cancer. The action spectrum is not yet well known, but the biologically most active region is 0.20 to 0.30μm. A special network, sponsored by the U.S. Department of Transportation, for skin-cancer research, uses a sensor designed by Berger and others (1975).

The World Meterological Organization does not recognize a standard UV sensor (WMO, 1971). Most instruments are designed for a specific research goal; an example is the vacuum technique used to measure UV at wavelengths below 0.20μm for the space program. A review of many special techniques has been written by Dunkleman (1963).

For medical uses, measurements of UV dose are based on the amount of erythema or the effectiveness in killing bacteria or viruses. These empirical indicators are useful for medical purposes but are nonspecific, somewhat subjective, and not suitable for routine monitoring.

Chemical methods for UV measurements were extensively investigated during the 1920's and 1930's. The advantage of chemical methods is their simplicity and their ability to integrate UV fluxes, but they also have the disadvantages of difficulty in calibration, nonreproducibility, temperature sensitivity, and long integration intervals. Despite these drawbacks, chemical methods are useful for some medical and bioclimatic research. A concise review of some of these techniques is provided by Coulson (1975).

A useful sensor for the biologically active UV region is the one designed by Berger and others (1975). This sensor is used by the U.S Department of Transportation, Climatic Impact Assessment Program/UV network, in cooperation with the National Oceanic and Atmospheric Administration. The instrument is designed to have a spectral response closely resembling the wavelength dependence of erythema. Upon exposure to radiation, a magnesium tungstate phosphor fluoresces, and this fluorescence irridates a vacuum phototube through a green filter. Thus, the output results from fluorescent conversion of wavelengths less tha 0.33μm. The sensing element is isolated from the rest of the spectrum by a Schott UV 11 filter. An integrating recorder prints out a half-hourly value of the sunburn effectiveness.

A useful instrument for broad-band UV measurements is the Eppley Ultraviolet pyranometer (Drummond and Wade, 1969). The detector is a selenium barrier-layer photocell with a quartz window, sealed inside a blackened tube.

The entrance aperature of the tube is covered with a quartz diffuser. The case and tube are sealed for all-weather use, and a desiccant is used to prevent condensation inside the sensor. The normal spectral range of the sensor is 0.295 to 0.385 μm, but filters are available for narrower ranges.

10.H.2.a.5. TERRESTRIAL AND ATMOSPHERIC (LONG-WAVE) RADIATION

Long-wave radiation is difficult to measure accurately. Because most substances normally emit maximum radiation in the long-wave region (4 to 100 μm), the sensor emits at the same wavelengths and at about the same intensity as the radiation being measured. In addition, materials available for making sensors do not approximate the ideal properties for long-wave as well as for the solar spectrum. The glass or quartz used to isolate the solar spectrum and protect the detector have no counterpart for long-wave detectors. Black absorptive coatings are generally spectrally dependent in the long-wave region and also are sensitive to solar radiation. Thus, sensor design is difficult, particularly if daytime measurements are desired.

Most of the pyranometers, net-pyradiometers, and pyrgeometers that are suitable for measuring long-wave radiation are designed for research projects. Few are suitable for continuous monitoring of irradiance.

10.H.2.a.5.a. Unshielded instruments

Unshielded sensors have the advantage that radiative exchanges take place freely without the selective reflections and absorptions of a window material. However, the sensing surfaces are exposed to the environment so that dust, dirt, and air pollutants can attack the black coating and degrade the instrument. Also, the instrument must be protected from moisture. Thus, unshielded detectors are not suited for continuous measurements. Radiative transfer is also affected by ventilation across the detector surface. As a result, either the instrument must be artificially ventilated to reduce wind effects, or empirical wind factors must be applied to the data. As with other radiation sensors, these instruments respond to ambient temperature. This effect can be corrected by a temperature-compensation circuit or by empirical correction factors.

The Geir and Dunkle pyrradiometer and net pyrradiometer are examples of unshielded sensors. These devices, designed on the principle of the heat-flow plate by Geir and Dunkle (1951) are

currently manufactured by Teledyne Geotech, 3401 Shiloh Road, Garland, Texas. (They were previously manufactured by Beckman and Whitley, San Carlos, Calif.)

The detector consists of two blackened, flat plates positioned back to back and separated by a spacer. The spacer serves as a heatsink, decreases wind effects, insulates, and serves as the mount for the silver-constantan thermopile. The magnitude of the temperature difference between the downfacing and upfacing plates is a function of the difference between the upward and downward radiation fluxes. Thus, the voltage produced by the thermopile is related to the net radiative flux. Of course, if net long-wave flux is desired, the solar flux must be measured separately and subtracted.

As currently manufactured, the sensor is temperature compensated. Also, a blower is used to minimize variance caused by convective heat loss. Best results are obtained if the air jet is in the same direction as the wind.

The pyrradiometer is of basically the same design, except that the bottom plate is covered by a highly reflective metal plate. The flux is then the downward irradiance (solar and longwave) plus the instrument temperature.

Other unshielded sensors are similar and have related problems. A summary of these is provided by Coulson (1975).

10.H.2.a.5.b. Shielded instruments

Shielded sensors minimize the wind effects and weathering problems associated with unshielded pyrradiometers or net pyrradiometers. However, the windows introduce reflection and absorption problems. Window materials such as polyethylene and KRS-5 approach the required level of transparency, but they are not perfect. As with other radiometers, temperature compensation remains a problem. For total flux measurements during the day, the cosine response of the sensor is important. Several shielded instruments are available.

The Suomi-Kuhn Economical net pyrradiometer (Suomi and Kuhn, 1958) (currently manufactured by UNECO, Inc., P.O. Box 487, Bellevue, Neb.) is most often used on radiosonde flights for measurements of the vertical profile of net radiation. It is simple and lightweight in design. Expanded polystyrene is used for the main body. The sensor surfaces are blackened and aluminum foil supported by low-heat conductive threads. The temperature of the sensors is measured by bead thermistors. The two sensor surfaces are insulated from each other by an air space. Two flat polyethylene films are used to cover each sensor surface (Note: These windows produce a large cosine error in the readings).

The Eppley pyrradiometer is designed to measure long-wave radiation from one hemisphere (Drummond and others, 1968). The sensor is a 100-junction, copper-constantan thermopile blackened with Parson's Optical Black lacquer. This sensor is temperature compensated and automatically corrects for radiation emitted by the sensor. Thus, the output depends only on the incident long-wave irradiance. The wave-length range is limited to the 4-μm to 50-μm range by a dome of KRS-5, on the inside of which is deposited an interference filter for the solar wavelength.

The KRS-5 dome must be protected from moisture for accurate long-term measurements. If the dome becomes wet, it soon changes color and no longer acts as an effective solar filter.

The Thornthwaite Miniature net pyrradiometer (manufactured by Thornthwaite Associates, Elmer, N.J.) is used mostly in biological applications. The sensor surfaces are protected by polyethylene hemispheres that are kept inflated with dry air. The instrument is available in two models with sensitivities of 0.25 and 3.5 mV cal^{-1} cm^{-2} min^{-1}. The manufacturer specifies that the sensor follows the cosine law and is virtually independent of ambient temperature and wind.

The CSIRO net pyrradiometer, originally designed by J. P. Funk (1959) of the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia, is sold in the U.S. by Science Associates, Inc., 230 Nassau Street, Box 230, Princeton, N.J. The detector surfaces are aluminum plates blackened with Parson's Optical Black lacquer. The temperature of each plate is sensed by a row of 125 thermojunctions separated from each other by a sheet of plastic. The plates are insulated electrically from the thermojunctions. The two hemispheric windows are of polyethylene and are kept inflated by dry nitrogen. The flow is controlled so that a cylinder of nitrogen will last from 4 to 6 months. The instrument can be converted from a net pyrradiometer to a pyrradiometer by replacing one hemisphere with an aluminum cap, the interior temperature of which is monitored with a thermocouple.

10.H.2.a.5.c. Calibration of long-wave sensors

Pyrradiometers and net pyrradiometers can be calibrated in four ways:

1. Both instruments can be calibrated by comparison with a previously calibrated instrument, as is done with pyranometers and pyrheliometers.
2. Long-wave sensors can be shade calibrated as discussed for pyranometer calibration. The accuracy for sun-shade calibration depends on the wave-length response of the pyrradiometer or net pyrradiometer. Although its absolute accuracy is questionable, the shade technique gives consistent long-wave flux data.
3. The calibration method used by Idso (1971) uses a large, temperature-controlled black plate. With laboratory conditions constant and the sensor positioned above or below the plate, the net radiation F_n is given by

$$F_n = F_L - \theta\epsilon\sigma T^4$$

where: F_L is constant net radiation of the surroundings, θ is view factor for the radiative exchange, ϵ and T are the emissivity and temperature of the plate, respectively, and σ is the Stefan-Boltzman constant, to be determined from a nomogram given by Idso (1971). The sensor constant for the combined short- and long-wave radiation of the laboratory environment is determined from the sensor voltage V by

$$V = CF_L - k\theta\epsilon\sigma T^4$$

where k is the factor for long-wave radiation. This constant k is determined from the slope of a plot of V versus σT^4 when T of the plate is varied. The accuracy is ± 3 percent.

4. Sensors can be calibrated with a blackbody calibration chamber as described by MacDowall (1955). The sensor element is placed inside a blackened chamber and positioned in front of an aperture in the chamber wall. The source, a blackbody, is positioned at the aperture. The long-wave constant of the sensor can be determined (Funk, 1959) from the temperature of the cavity, the chamber, and the sensing element. The accuracy depends on the accuracy to which the emissivity of the chamber walls is known and the degree of nonradiative heat transfer present. The overall accuracy is about ± 2 percent.

10.H.2.a.6. DURATION OF SUNSHINE AND AVAILABLE SENSORS

Sunshine-duration measurements have been made for about 140 years. These measurements have two main uses—to characterize the general cloudiness of a region, and as an input for models used to approximate global irradiance. Most of these models are variations of the model first suggested by Angstrom (1924), in which:

$$G = G_o\left(a + b\,\frac{S}{S_o}\right)$$

where: G is global irradiance on the given day, G_o is the global irradiance on a clear day (measured or estimated), a and b are constants for a given area, and $\frac{S}{S_o}$ is the fraction of the possible sunshine on the given day.

These models are used best to compute monthly means.

Four main types of sensors are available:

1. Campbell-Stokes, which uses focused light to burn a record on a chart;
2. Maring-Marvin, in which the heat actuates a thermoelectric switch controlling a pen;
3. Jordan, which uses the photochemical effect to record a trace on sensitized paper, and
4. Foster, which uses silicon photoelectric cells.

The Campbell-Stokes sunshine recorder consists of a glass sphere approximately 10 cm in diameter, mounted concentrically in a section of a spherical bowl. The diameter of the bowl is such that the sun's rays are focused on a card held in place by grooves in the bowl. This sensor is WMO's interim reference sunshine recorder (WMO, 1971) when built to British Meteorological Office specifications and certified by that office.

The record cards are available in three types: (1) long, curved cards required for summer use; (2) short, curved cards used in winter; and (3) straight cards used near the equinoxes. When using the long, summer cards, care must be taken that the "tails" of the card do not shade out the early morning or evening sun. The primary problem with these cards is humidity. In a dry atmosphere, the cards begin to burn at an intensity of about 7 mW/cm^2 (milliwatts per square centimeter); whereas, in a moist atmosphere, burning may not begin until 28 mW/cm^2 (WMO, 1971).

The Maring-Marvin sunshine recorder is usually referred to as the Marvin although it was originally designed by D. T. Maring (Maring, 1898). The instrument is essentially a differential air thermometer with a blackened bulb and a clear bulb in an evacuated glass jacket. The temperature difference between the bulbs causes differential expansion of the alcohol separating the bulbs, which drives a column of mercury and thereby closes an electric switch. Closure of the circuit can be made to drive a suitable recording system such as a chronograph. The instrument is set in the meridian plane at an angle adjusted so that the mercury activates the electric circuit when the sun's disk can be just faintly seen through the clouds. The instrument responds to diffuse as well as direct radiation. Weak points of the instrument are the subjective procedure and the temperature dependence.

The Jordan sunshine recorder consists of two semicylindrical cameras, each having an aperture slit on its flat side through which photographic paper is exposed to the sun. The cameras are mounted side by side, with one aperture facing east, the other facing west. Although the simple design and permanency of records are attractive , the daily adjustment to prevent overlapping traces and the special handling of the photographic paper cause operational problems. Considerably greater uncertainty exists in the Jordan measurements than in the Campbell-Stokes measurements.

The Foster sunshine switch was developed by N. B. Foster of the U.S. Weather Bureau (now the National Weather Service) in 1953 (Foster and Foskett, 1953). The sensor is currently used in the National Weather Service sunshine-switch network (about 116 stations). The sensor consists of two selenium barrier-layer photovoltaic cells with one cell exposed to direct solar radiation and the other cell shaded from direct solar radiation by a shade ring. The cells are connected in electrical opposition so that their response to diffuse light results in no output. Direct sunlight will produce an output from the exposed cell that cannot be balanced by the shaded cell. This signal is used to actuate a recorder. The lag of the sensor is negligible, and its sensitivity allows reliable measurements from sunrise to sunset.

10.H.2.b. UNITS OF MEASUREMENT AND RADIATION SCALES

The quantity of radiation per unit area generally used in the U.S. is the Langley, named after Samuel P. Langley, first director of the Smithsonian Astrophysical Observatory. The Langley is defined as a calorie per square centimeter (cal/cm^2). The internationally recommended units are combinations of the Joule (J), watt (W), and meter (m). The units now used in the U.S. are the kilojoule per square meter (kJ/m^2) for intensity, and watts per square meter (W/m^2) for radiant flux. Conversion factors between the commonly used units are given in publications by the World Meteorological Organization (WMO, 1971).

The Smithsonian 1913 (S 1913) radiation scale was used by the National Weather Service (NWS) network until July 1, 1957. In September 1956, at Davos, Switzerland, the International Pyrheliometric Scale of 1956 (IPS 1956). To convert the National Weather Service values to the International Pyrheliometric Scale of 1956 system, all values were lowered 2 percent (calibration constants were raised 2 percent) as of July 1, 1957. European values recorded on the Angstrom 1905 (A 1905) scale were raised 1.5 percent to achieve IPS 1956.

More recent data indicate that the 3.5-percent difference between the two scales should be about 5 percent (Frohlich, 1973); therefore, no standard is valid for defining IPS 1956. WMO World Radiation Center at Davos, Switzerland, and the U.S. calibration facility at Boulder, Colorado (operated by the National Oceanic and Atmospheric Administration), are continuing research to define and calibrate the various scales now in use and to establish proper corrections for the four international comparisons. This information will be used to tie all data to the "absolute scale" as standardization for the new cavity pyrheliometers.

The U.S. adopted the absolute scale as defined by PACRAD III on January 1, 1977. All U.S. data are now reported in relation to the new scale, which is about 2 percent higher than IPS 1956. The U.S. Energy Research and Development Administration's Division of Solar Energy has sponsored the correction of the U.S. historical solar-radiation data set. Data are now available for 51 locations throughout the U.S. in a special computer tape format called SOLMET from the National Climatic Center in Asheville, N.C.

10.H.2.c. INSTRUMENT CALIBRATION

Pyranometers can be calibrated in two ways. The first is by direct comparison to a standard pyranometer using sunlight or a solar simulator. The constant of the field sensor is calculated from

$$K_F = \frac{K_S V_S}{V_F}$$

where: K_F is the constant desired,
K_S is the standard's constant,
V_S is the voltage output of the standard, and
V_F is the voltage output of the sensor being calibrated.

Calibration is usually run 2 hours each side of solar noon on several clear days.

In the second method, calibration can be achieved by comparison to a standard pyrheliometer. This is done by shading the pyranometer from direct solar radiation. The shade disk should shade out the same solid angle as measured by the pyrheliometer (WMO, 1971). The calibration constant for the pyranometer is calculated from

$$K_F = \frac{(V_2 - V_1)}{I \cos Z}$$

where: K_F is the constant desired,
V_2 is the voltage output when unshaded,
V_1 is the voltage output when shaded,
I is the pyrheliometer intensity reading, and
Z is the solar zenith angle.

Ideally, pyranometers should be calibrated at least once a year. For networks of only a few instruments, this can easily be achieved, but in a large network, this frequency cannot be met economically. Calibration every third year represents a good compromise. This assumes that the data are checked monthly for quality and that corrective action is taken at any suggestion of trouble.

Recorder-integrators used with pyranometers (or pyrheliometers) should be calibrated every 3 to 6 months, depending on the recorder stability. No recorder should run for more than 1 year without a calibration. Calibration is achieved with a standard potentiometer or other standard DC voltage source.

10.H.2.d. INSTRUMENT SITING

Pyranometers should be installed at a site as free of obstructions as possible. Particular care should be taken to avoid obstructions from east-northeast to west-northwest in the northern hemisphere and from west-southwest to east-southeast in the southern hemisphere. No obstructions should extend more than 5° above the sensor field of view. Care should also be taken to ensure that no nearby objects will reflect solar radiation onto the pyranometer.

Pyranometers require only simple maintenance. The desiccant capsule must be checked regularly and changed as needed. In addition, the sensor must be kept level. A daily routine of level check, dome cleaning, and a general visual inspection will help ensure high-quality measurements (minimum of every third day). In areas where frost or dew are frequent, air may be blown on the dome to help prevent their formation on its surface.

10.H.3. REFERENCES

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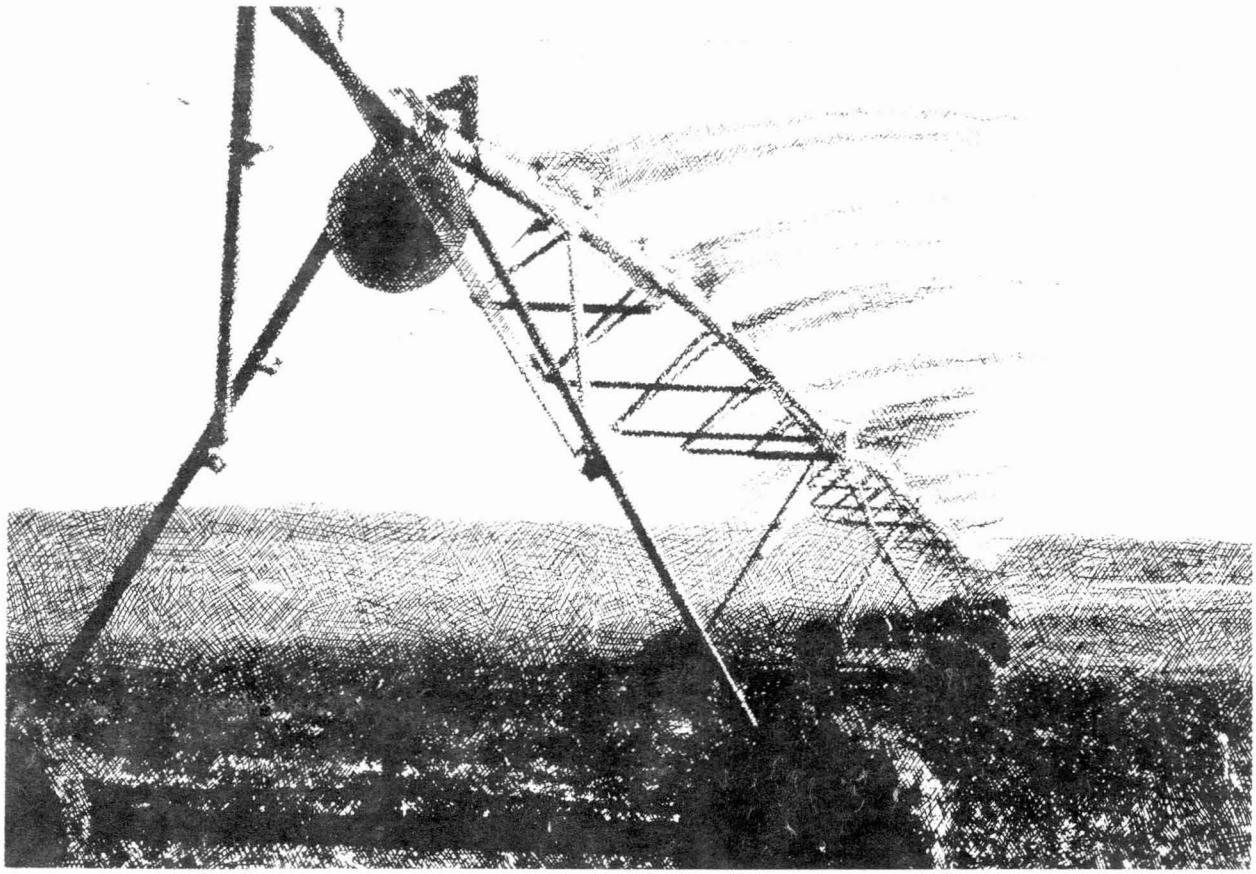
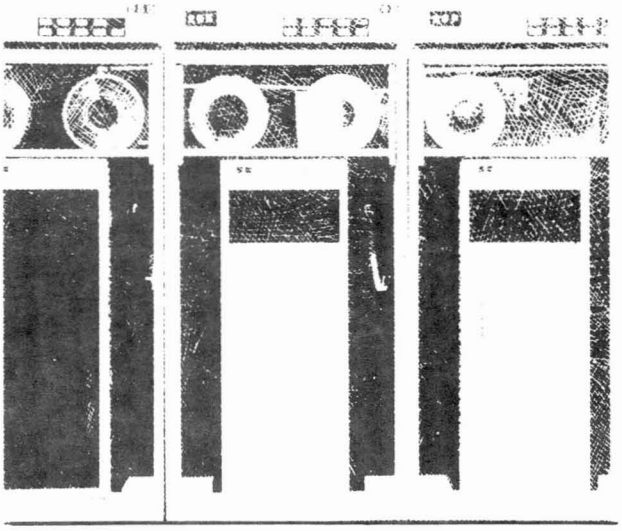
Chapter 11

Water Use



Chapter 12

Water-Data Handling and Exchange



Appendix

MHz

1 kg = 2.2lbs

$1\ m^3 = 35.3 ft^3$

MPa

kN

1 gal = 3.8L

1 ft = 305mm

25.4 mm = 1in

28.3 mL = 1oz