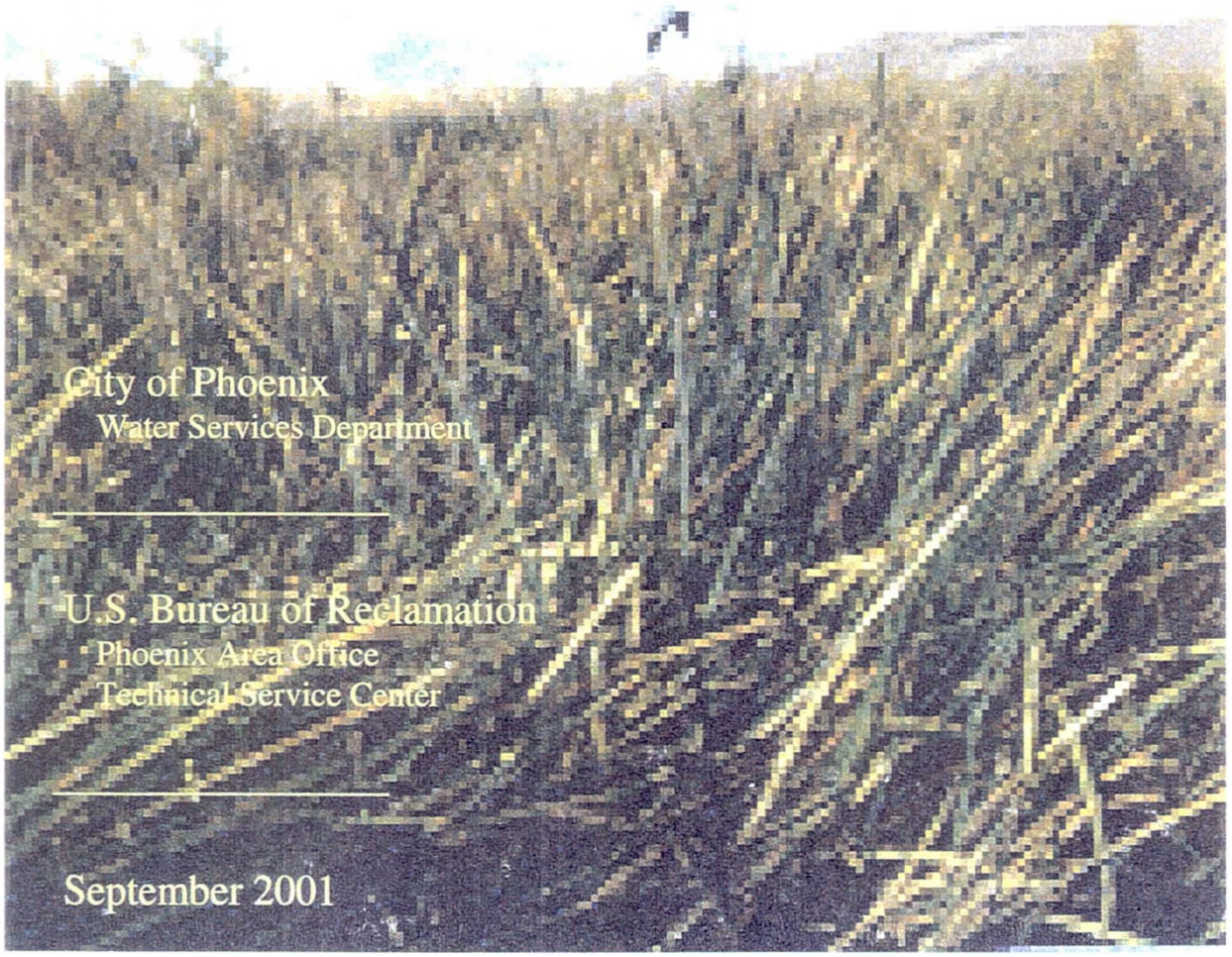
Tres Rios Demonstration Constructed Wetlands Project

Project Status and Water Quality Data Analysis Report Phase 1 - 1995 to 1998



City of Phoenix
Water Services Department

U.S. Bureau of Reclamation
Phoenix Area Office
Technical Service Center

September 2001

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instrucitons, searching exisitng data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suit 1204, Arlington VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Report (0704-0188), Washington DC 20503.

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2001	Final

4. TITLE AND SUBTITLE
Tres Rios Demonstration Constructed Wetlands Project
Project Status and Water Quality Data Analysis Report Phase 1, 1995 to 1998

5. FUNDING NUMBERS
PR

6. AUTHOR(S)
Jim Yahnke
Eric Stiles

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of the Interior
Bureau of Reclamation
Denver, Colorado

City of Phoenix
Water Services Department
Phoenix, Arizona

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Technical Service Center
PO Box 25007
Denver CO 80225-0007

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DIBR

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Available from the National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Tres Rios Demonstration Constructed Wetlands Project reflects widespread interest in pursuing more effective, integrated approaches to sustain valuable water and environmental resources in arid regions of the western United States. When considered collectively, the demonstration monitoring program and parallel activities have provided a wealth of information to advance constructed wetlands technology and insight into practical and institutional considerations to effectively incorporate wetlands in water resource planning. This report summarizes project activities and water quality characteristics of the demonstration wetlands based on the first phase of monitoring from 1995 through 1998. Water quality results and findings are interpreted with respect to the demonstration objectives, the status of constructed wetlands technology, and implications for future water resource planning.

Several general conclusions were evident from the results of these initial investigations: (1) the net removal for all monitored constituents, even at very low concentration levels, the significant effects of hydraulic operations including depths and flow rates, and the transient shifts in temperature, oxygen, and related transformation properties that may indicate the balance between external and internal loading and effective assimilation processes (2) constructed wetlands offer the potential to attain water quality objectives and provide additional wildlife and public use benefits in an area where wetland and aquatic habitat are scarce, (3) it appears there is ample opportunity to provide ecosystem diversity and habitat in full scale wetland plans.

14. SUBJECT TERMS– water resource/wetland planning/chemical constituent/constructed wetlands/water quality transformation/municipal wastewater effluent/wetland and aquatic habitat

15. NUMBER OF PAGES
213

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UL	UL	UL	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

Tres Rios Demonstration Constructed Wetlands Project

Project Status and Water Quality Data Analysis Report Phase 1 - 1995 to 1998

City of Phoenix
Water Services Department

U.S. Department of the Interior
Bureau of Reclamation
Phoenix Area Office
Technical Service Center

September 2001

Contents

Chapter 1—Introduction 1
Location and Setting 1
Site Description 1
Reclaimed Water Operations 3
Water Quality and Wetland Systems 4
Project Authorization 4
Cooperative Participation 5
Goals and Objectives 6
Overall Demonstration Approach 6
Research Plan Objectives 7
Water Quality Issues 8
Scope of this Report 8
Timeline of Events 8

Chapter 2—Background Information 13
Phoenix Wastewater Reclamation and Reuse Study 13
Advanced Treatment Plant Upgrades 14
Groundwater Recharge and Reuse 15
Full Scale Constructed Wetlands 15
Current Status of Alternatives 16
Tres Rios Demonstration Wetlands Project 17
Demonstration Project Planning 17
Demonstration Wetlands Development 17
Operations and Monitoring Phases 18
Related Tres Rios Wetland Investigations 20
Baseline Characterization 20
Wetland Vegetation Aerial Surveys 21
Bird Use and Habitat Evaluations 21
Macroinvertebrate Monitoring 21
Animal Control Problems 22
Chronic Toxicity Monitoring 22
Viruses and Pathogenic Organisms 22
Metals and Trace Elements 22
Organic Matter and Biotoxicity 23
Hydraulics and Solute Transport 23
Mosquitos and Vector Control 24
Environmental Technology Initiative 24
Guiding Principles for Constructed Treatment Wetlands 25
Treatment Wetland Habitat and Wildlife Use Assessment 25
Wastewater Treatment Wetlands Technology Assessment 26

Chapter 3—Facilities, Strategy, and Methods 27
Demonstration Wetland Facilities 27
Research Cells 27
Hayfield Site Features 29
Cobble Site Features 31
Demonstration Monitoring Strategy 32
Site Configuration 32
Operating Conditions 33
Monitoring Parameters 35
Overall Experimental Plan 36
Water Quality Evaluation Approach 37
General Performance Evaluations 38
Water Budget and Mass Balance 38
Hydraulic Loading Functions 39
Internal Configuration 40
Seepage Evaluations 41
Demonstration Site Comparison 41
Removal Rate Functions 41
Data Analysis Methods 43
Statistical Analysis Methods 43
Data Review and Preprocessing 46
Water Budget Data Review 47
Operations Data Conversion 50

Chapter 4—Water Quality Results and Findings 57
Initial Data Review 57
Temperature Effects—Example 57
Daily Field Data Review 62
Laboratory Data Review 63
General Water Quality Results 63
Hayfield Site Summary 63
Cobble Site Summary 68
Hydraulic Function Results 72
Hydraulic Load Rate Effects 72
Operational Depth Effects 76
Retention Time Effects 80
Hydraulics Cross-Comparison 82
Correlation of Physical Factors 83
Open Water Comparison 86
Dissolved Oxygen 86
Other Cell Differences 89
Seepage Loss Effects 91
Seepage Adjusted Removal 91
Hayfield Site Seepage 93
Seepage Changes Over Time 94

Combined Site Comparison 101
Water Budget Comparison 101
Water Quality Comparison 102
Rate Function Comparison 104
Volumetric Rate Model 105
Areal Rate Model 107
Tres Rios Predicted Results 108

Chapter 5—Discussion and Conclusions 111
Discussion of Water Quality Results 111
Initial Data Review 111
Field Measurement Results 112
Overall Water Quality Results 113
Hydraulic Operations 114
Open Water Configuration 115
Seepage Loss Effects 116
Combined Site Comparison 117
Rate Function Comparison 118
Wetlands Project Planning Considerations 118
Water Quality Implications 119
Transferability to Full-scale Planning 120
Integrated Planning Issues 123
Additional Research Needs 125
Water Quality Standards 125
Biological Effects 126
Hydraulic Characteristics 126
Wetlands Vegetation 127
Active Operations 127
Mosquitos and Vector Control 127
Conclusions 128
This Demonstration Evaluation Effort 128
Water Management and Wetlands Planning 129
Integration of Public and Environmental Benefits 129
Cell Configuration Comparison 130

References 131

Appendix A — Working notes, operations, and planning information
Appendix B — Description of statistical methods applied
Appendix C — Time series plots for Hayfield and Cobble sites water quality data
Appendix D — Cumulative frequency plots for Hayfield site water quality data
Appendix E — Descriptive statistics by operating condition and regression plots

Tables

3-1 Demonstration wetlands design information. 32
3-2 Post construction measurements from aerial survey. 33
3-3 Initial operations schedule from research plan (CH2MHill, 1995). 33
3-4 Revised operations schedule for second year monitoring. 34
3-5 Events affecting wetland operations and monitoring. 34
3-6 Monitored water quality parameters. 35
3-7 Water quality monitoring schedule. 36
3-8 Water quality evaluation sequence and approach. 37
3-9 Data analysis methods applied by topic. 44

4-1 T-test summary of field measurements at the Hayfield site. 58
4-2 Wilcoxon [Z] test summary of field measurements at the Hayfield site. 58
4-3 Summary statistics, skewness, and kurtosis for Hayfield site daily field data. 62
4-4 Summary of t-test results for the Hayfield site water quality data. 64
4-5 Summary of Wilcoxon [Z] test results for the Hayfield site water quality data. 64
4-6 Descriptive statistics for the Hayfield site water quality data (mg/L). . . . 65
4-7 Summary of t-test results for the Cobble site water quality data. 69
4-8 Summary of Wilcoxon [Z] test results for the Cobble site water quality data. 69
4-9 Descriptive statistics for the Cobble site water quality data. 70
4-10 Mann-Whitney test of hydraulic load rates 0.25 ft/day (7.6 cm/day) versus 0.5 ft/day (15.2 cm/day) on inflow-outflow water quality changes at the Hayfield site. 72
4-11 Descriptive statistics by Hydraulic Load Rate (HLR) for the Hayfield site H1 cell. 74
4-12 Descriptive statistics by Hydraulic Load Rate (HLR) for the Hayfield site H2 cell. 75
4-13 Kruskal-Wallis one-way ANOVA of water depth effects For 0.5, 1.0, and 1.5 feet (15.2, 30.5, 45.7 cm) on inflow-outflow changes at the Hayfield site. 76
4-14 Descriptive statistics by depth for the Hayfield site H1 cell. 78
4-15 Descriptive statistics by depth for the Hayfield site H2 cell. 79
4-16 Two-way ANOVA comparing Hayfield site cells and HLR effects. 82
4-17 Two-way ANOVA comparing Hayfield site cells and depth effects. . . . 83
4-18 Spearman (rank-order) correlations between percent change in inflow-outflow concentration and selected physical factors and initial inflow concentration. 84

4-19 Comparison of percent mass load removal with and without seepage adjustment for various water quality constituents in the Cobble site C1 and C2 wetland cells. 92
4-20 Comparison of mean percent mass removal for the Cobble site C1 and C2 cells with and without adjustments for seepage infiltration losses. 93
4-21 Comparison of hydrologic factors in the Cobble site C2 cell and the H1 and H2 wetland cells of the Hayfield site 94
4-22 Comparison of mean and median water budget factors for Hayfield and Cobble cells. 101
4-23 Summary statistics of maximum and median percent difference in the concentration of various constituents in each of the Hayfield and Cobble site wetland cells. 102
4-24 Mann-Whitney comparison of percent changes between cells and across sites. 103
4-25 Median concentration under different operationg conditions at the Hayfield site. 105
4-26 Volumetric model k_{VT} rate constants for the Hayfield site and typical reported values. 106
4-27 Background C* minimum concentration for Hayfield cells and reported values. 107
4-28 Areal model k_A rate constants for the Hayfield Site data and reported values. 107
4-29 Measured and predicted concentrations using areal rate model for Hayfield site data. 109

5-1 Climate trends during the first three years Tres Rios demonstration wetlands monitoring. 115
5-2 Comparison of percent removal expectations for wetlands receiving secondary treated wastewater and Tres Rios demonstration wetlands results for first 3-years monitoring. 118

Figures

1-1 Tres Rios Location Map 2

2-1 Aerial view of the Tres Rios Demonstration Wetlands facilities 19

3-1 Hayfield site 1997 infrared aerial photo and concept design site plan 28
3-2 Cobble site 1997 infrared aerial photo and concept design site plan 30
3-3 Inflow, outflow, and seepage for the Hayfield site H1 and H2 wetland cells 48

3-4 Inflow, outflow, and seepage for the Cobble site C1 and C2 wetland cells 49
3-5 Depth and inflow hydraulic load rate (HLR) for the Hayfield site wetlands 52
3-6 Operational test phases for the Hayfield site monitoring data. 53
3-7 Depth and inflow hydraulic load rate (HLR) for the Cobble site wetlands 54
3-8 Operational test phases for the Cobble site monitoring data. 55

4-1 Inflow and outflow temperatures of the Hayfield site wetland cells. . . . 59
4-2 Time series and cumulative frequency distributions for outflow water temperatures of the Hayfield site H1 and H2 wetland cells. 60
4-3 Cumulative frequency distributions of inflow and outflow temperature data for the Hayfield site H1 and H2 wetland cells. 61
4-4 Median percent change in selected water quality constituents by water depth for the Hayfield site H1 and H2 wetland cells. 77
4-5 Median percent change in selected water quality constituents by hydraulic retention time index (HRT_i) for the Hayfield site H1 and H2 wetland cells. 81
4-6 Cumulative frequency distributions of inflow and outflow dissolved oxygen (DO) for the Hayfield site wetland cells. 87
4-7 Regression of outflow dissolved oxygen (DO) on the inflow DO daily measurements for the Hayfield site H1 and H2 wetland cells. 88
4-8 Comparison of seepage adjusted and unadjusted percent removal of Total Kjeldahl Nitrogen (TKN) in the Cobble site C1 and C2 wetland cells. . . 96
4-9 Comparison of seepage adjusted and unadjusted percent removal of Nitrate Nitrogen (NO_3-N) in the Cobble site C1 and C2 wetland cells. . 97
4-10 Comparison of seepage adjusted and unadjusted percent removal of Ammonia Nitrogen (NH_4-N) in the Cobble site C1 and C2 wetland cells. 98
4-11 Comparison of seepage adjusted and unadjusted percent removal of Total Nitrogen (Total N) in the Cobble site C1 and C2 wetland cells. 99
4-12 Comparison of seepage adjusted and unadjusted percent removal of Total Dissolved Phosphorus (Diss. P) in the Cobble site C1 and C2 wetland cells. 100

Symbols, Acronyms, Abbreviations

ADEQ	Arizona Department of Environmental Quality
ADGF	Arizona Department of Game and Fish
ADWR	Arizona Department of Water Resources
Alk	Alkalinity
ANPP	Arizona Nuclear Powr Plant
AWWARF	American Water Works Association Research Foundation
AZMET	Arizona Meteorological Network
BIC	Buckeye Irrigation Company
BOD	Biochemical oxygen demand
C1 and C2	Cobble site cells
Cl^-	Chloride
COD	Chemical oxygen demand
DBP	Disinfection by-products
DO	Dissolved oxygen
EC	Electrical conductivity
ETI	Environmental Technology Initiative
FWS	Fish and Wildlife Service, U.S.
gpm	gallons per minute
H1 and H2	Hayfield site cells
HLR	Hydraulic load rate
HRT	Hydraulic retention time
µS/cm	Electrical conductivity—microSiemens per centimenter
mg/L	milligrams per liter
MGD	million gallons per day
NADB	North American Treatment Wetlands Data Base
NO_2–N	Nitrite nitrogen
NO_3–N	Nitrate nitrogen
NO_2+NO_3–N	Nitrite plus Nitrate
NH_3–N	Ammonia nitrogen
TOC	Total organic carbon
Total N	Total nitrogen
PO_4–P	Ortho-phosphate
Diss. P (or TDP)	Total dissolved phosphorus
NPDES	National Pollutant Discharge Elimination System
pH	Measure of the log of the hydrogen ion concentration (acid/base condition)
Reclamation	Bureau of Reclamation
Res Cl_2	Residual chlorine
SAT	Soil aquifer treatment
SEK	Standard. error kurtosis

water is released to the Salt-Gila River. These contract diversions, plus evapotranspiration and soil infiltration, reduce the water remaining in the river to about 55 MGD (85 cfs) in the summer and 110 MGD (170 cfs) in the winter (Reclamation, 1996).

Water Quality and Wetland Systems

Reclaimed wastewater released from the 91st Avenue WWTP is permitted under the National Pollutant Discharge Elimination System (NPDES) and is also subject to local water quality standards specified by the Arizona Department of Environmental Quality. Discharge permit requirements are reviewed periodically to consider public and environmental health issues associated with the receiving stream system and potential downstream water uses. In arid regions, reclaimed water reuse programs and discharges to ephemeral streams has lead to considerable discussion regarding appropriate standards for effluent dependent streams and the balance between water reuse demands and the ability to sustain valuable environmental resources.

In recent years, these issues became increasingly important in the Phoenix area as SROG considered alternatives to effectively manage water supply, conservation, wastewater reclamation, and reuse operations within comprehensive water resource management plans (Reclamation, 1996). Constructed wetlands were considered a viable alternative because of the potential to take advantage of natural water quality functions and opportunities to establish additional wildlife and public recreation benefits in an area where aquatic and wetlands habitat is scarce. In 1992 Phoenix, SROG, and Reclamation initiated plans for a demonstration constructed wetlands effort to examine all aspects involved to integrate wetlands with conventional water management programs and thereby provide more effective coordination of available water supplies and competing water needs. The demonstration constructed wetland facilities were constructed at the Tres Rios site in August 1995. Since then, the demonstration wetlands have successfully polished about 2 million gallons a day of advanced secondary-treated municipal wastewater.

Project Authorization

The demonstration project facilities were constructed with funds provided by the city of Phoenix and the multi-city operating group SROG, with federal cost-share funding authorized under Title XVI of Public Law 102-575 (P.L.102-575, 1992) concerning Reclamation Wastewater and Groundwater Studies. Section 1608 of P.L.102-575 specifically addresses the Phoenix Metropolitan Water Reclamation Study and Program, and authorizes Reclamation, in cooperation with Phoenix, to

conduct a study of the potential for development of facilities to utilize wastewater from the regional wastewater treatment plant for municipal, industrial, agricultural and environmental purposes, groundwater recharge, and direct potable reuse. The legislation further authorized Reclamation and Phoenix to cooperate in the design and construction of facilities for environmental purposes, groundwater recharge, and direct potable reuse. Federal cost-share funds for the demonstration project were appropriated under the Drainage and Minor Construction Act of 1956.

Cooperative Participation

Initial planning for the wetlands demonstration project involved extensive discussion between different agencies and interest groups to address technical, regulatory, and research issues. Other individuals, consultants, and organizations too numerous to mention have also participated constructively in various activities since the project inception. Agencies involved in the initial project planning included:

- City of Phoenix
- Bureau of Reclamation
- Environmental Protection Agency
- U.S. Geological Survey
- Army Corps of Engineers
- Maricopa County
- Subregional Operating Group (6 member cities)
- Arizona Department of Environmental Quality
- Arizona Game and Fish Department
- Arizona Department of Water Resources
- University of Arizona
- Arizona State University

To date, the program funding and ongoing coordination of demonstration activities have been accomplished primarily through the cooperative arrangements between Phoenix (representing SROG) and Reclamation. Reclamation has a long-standing relationship with Phoenix through coordination of the multi-state use of water resources in the Colorado River and implementation of the Central Arizona Project which provides water to the Phoenix area. This cooperative relationship was reinforced by the passage of Public Law 102-575 which included specific provisions for Phoenix, SROG, and Reclamation to participate in cooperative investigations of wastewater reclamation and reuse in the Phoenix metropolitan area, and ultimately lead to the Tres Rios Demonstration Constructed Wetlands Project.

Limited water resources, arid climate, and population growth have contributed to the increasing emphasis on stretching all water supplies in the Phoenix area. Water conservation, groundwater management, and wastewater reclamation and reuse have all received attention as important water management components. The working relationship between Phoenix water services and the SROG wastewater authority is well-situated to integrate water reclamation and reuse into water operations. These issues lad to further interest in exploring a constructed wetlands as an option or component in long- range planning to improve effluent

quality, provide continued discharge to enhance and sustain the Salt River riparian corridor, and integrate groundwater recharge and direct water reuse.

Reclamation water management programs also recognize the inherent, unavoidable interrelationships between municipal and agricultural water use and the implications of return flows on hydrologic patterns and water quality. Severe water constraints in arid areas can amplify these issues and reinforce the need to coordinate water use, conservation, water quality protection and improvement plans, conjunctive surface and groundwater planning, and water reuse activities. Better coordination between different water management districts, legal provisions, and administrative procedures is increasingly important to provide essential water resources to sustain agricultural, municipal, and environmental water needs.

Goals and Objectives

The Tres Rios Demonstration Constructed Wetlands Project was initiated to allow evaluation of multipurpose characteristics, economic factors, and institutional issues before committing resources to develop a full-scale wetlands system or integrating wetland components into water operations. The demonstration facilities were designed to examine actual water quality, wildlife, and public use considerations that can influence the effectiveness of constructed wetlands in the Phoenix area.

An advisory group was assembled during the early conceptual planning to identify major objectives for demonstration (Reclamation, 1993). Although some of the interests and specific details shifted during the course of the project, these original wetlands demonstration goals are generally still valid.

Overall Demonstration Approach

The demonstration wetlands project objectives centered primarily on evaluating the wetland water quality characteristics with respect to anticipated discharge standards and developing appropriate design and operating criteria for planning a full-scale wetlands system in the Tres Rios vicinity. Additional objectives included evaluation of wildlife habitat characteristics and practical considerations associated with site management needs, public education, and recreational use considerations.

In addition to regulatory issues, other wetland water quality considerations include the suitability of wetlands treated water for groundwater recharge or reuse purposes, environmental risks and benefits, and public health and safety issues.

Examples of overriding technical, practical, and institutional demonstration topics include:

Technical Questions — Water quality properties, planning criteria, public health, secondary reuse, ecosystem functions, habitat values, water budget impacts.

Practical Considerations — Site management, animal control, vector control, public access and safety, site amenities and planning, operations and maintenance.

Institutional Factors — Discharge permitting, wetlands protection and permitting, mitigation banking potential, point of compliance, water rights implications.

Each of these demonstration categories could have important implications for water quality. For example, the point of compliance for meeting water quality standards is tied to wetlands protection determinations. Wildlife attracted to the wetlands could suffer from poor water quality, or cause disturbances that degrade water quality. The demonstration evaluations were intended to examine any factors that contribute to the overall performance and feasibility of developing wetland components under the prevalent conditions and water management circumstances.

Research Plan Objectives

Demonstration topics were defined by a combination of issue priority, appropriate scope and scale for the facilities, and available funds. Specific research topics were identified in developing detailed monitoring and experimental testing plans for the demonstration project. The following general demonstration topic categories were identified in the first phase research plan (CH2MHill, 1995):

- Wildlife utilization
- Food chain effects
- Public use / public opinion
- Water quality performance as a scale-up of pilot wetland tests
- Ability to reduce whole-effluent toxicity
- Water balance issues
- Effective flow distribution
- Construction issues
- Cost issues
- Operation issues
- Wetland management issues

These topics were addressed through the demonstration monitoring program, project management information, and specialized research investigations. Other important issues that emerged during the course of the project were incorporated later stages of the demonstration project evaluations.

Water Quality Issues

Water quality is a central issue of the demonstration project. All of the issues above are linked in some way to the wetlands water quality characteristics. Water quality issues range from simple to complex and consequently, the demonstration approach involved both routine monitoring and specialized investigations. In addition, the demonstration wetlands were designed to evaluate the effects of specific features and operational test conditions on different aspects of water quality.

Scope of this Report

This report presents analysis and interpretation of the water quality data collected at the Tres Rios demonstration wetlands during the first phase of monitoring and research investigations from 1995 to 1998. Relevant background materials and review of the Tres Rios demonstration wetlands development and project planning activities are briefly summarized. Related investigations and research studies conducted in conjunction with the demonstration wetland project are also cited, although results of these studies are not described in detail.

A discussion of the findings and the conclusions of the data analysis to date can be found in chapter 5.

Timeline of Events

Events associated with the Tres Rios Demonstration Wetlands Project are cited to show the sequence of wetlands demonstration activities and illustrate how the wetlands project fits with other investigations associated with Phoenix long range water management plans. Major activities of the Phoenix Wastewater Reclamation and Reuse Study and the Environmental Technology Initiative are described in greater detail in the following chapter on program historical perspective.

January 1992 - Public Law 102-575 passed authorizing cooperative participation in the Reclamation Wastewater and Groundwater Studies and specific provisions for the Phoenix Metropolitan Water Reclamation Study and Program.

Spring 1992 - The *Phoenix Wastewater Reclamation and Reuse Study* is initiated as a cooperative effort between Phoenix and Reclamation to evaluate alternatives for comprehensive water and wastewater management in the Phoenix area.

October 1993 - The *Phoenix Water Reclamation and Reuse Study, Tres Rios Demonstration Wetlands, Conceptual Design* is published (Reclamation, 1993).

June 1994 - Ongoing wastewater reclamation and reuse discussions lead to active interest in pursuing a cooperative effort to demonstrate and evaluate the technical and institutional considerations associated with constructed wetlands.

September 1994 - Phoenix and Reclamation signed a cooperative agreement to undertake a demonstration wetland project at the 91st Avenue WWTP.

February 1995 - The *Tres Rios Wetlands Research Plan* (CH2MHill, 1995) was produced to guide the first phase of wetland operational control and monitoring.

May 1995 - Arizona Guidance Manual for Constructed Wetlands for Water Quality Improvement (ADEQ, 1995) produced in response to issues raised in ETI interagency planning.

Summer 1995 - Construction of the three separate Tres Rios demonstration wetland facilities is completed, followed by wetland vegetation and water supply operations to establish designated water depths and flows.

August 1995 - Demonstration wetlands are under operational flows and systematic monitoring started to collect data according to the research plans.

November 1995 - Formation of the Technical Advisory Review Panel (TARP) to provide coordination and oversight of the Demonstration Wetlands technical evaluations.

November 1995 - Environmental Technology Initiative kick-off meeting and formation of oversight committee and technical workgroups.

February 1996 - ETI Constructed Wetlands Technology Assessment workshop held in Tempe, Arizona, to raise issues and compile information on the current status of constructed wetlands science and applications.

March 1996 - The *Phoenix Wastewater Reclamation and Reuse Study* is published (Reclamation, 1996) to evaluate advanced treatment plant upgrades, groundwater recharge and recovery, and full-scale wetlands treatment alternatives.

June 1996 - The first Tres Rios data report is produced: *Tres Rios Demonstration Constructed Treatment Wetland Project, Data Summary of Selected Water Quality Parameters and Constituents: August 1995 Through March 1996*, (Phoenix, 1996).

July 1996 - Reclamation and U.S. Geological Survey initiate an interagency agreement to undertake specialized studies of organic matter transformations in conjunction with the City of Phoenix and Tres Rios Demonstration Constructed Wetlands Project.

April 1997 - Phoenix produces first baseline report for the Salt-Gila River management planning (Phoenix, 1997).

September 1997 - The second monitoring data report was prepared: *Tres Rios Demonstration Constructed Wetland Project, 1996/1997 Operation & Water Quality Report* (Phoenix, 1997).

November 1997 - ETI workshop on constructed wetlands policy and permitting issues with representatives from EPA regions, office of wetlands and office of wastewater management.

November 1997 - First progress report, *Soil Aquifer Treatment for Sustainable Water Reuse*, summarizes this AWWARF and WEFRF sponsored investigation on soil processes during surface recharge operations using reclaimed water.

November 1997 - ETI report, *Treatment Wetland Habitat and Wildlife Use Assessment*, summarized findings of this ETI sponsored investigation.

November 1997 - Subsurface sampling probes installed at Cobble site to support USGS interagency studies of AWWARF and Phoenix soil aquifer treatment processes.

March 1998 - Masters of Science thesis (Martin, 1998) based on organic carbon and disinfection by-product studies sponsored by USGS through interagency agreement with Phoenix and Reclamation.

July 1998 - Tres Rios wetland report, *Invertebrates in the Tres Rios Constructed Wetlands*, presents results of initial invertebrate monitoring studies.

July 1998 - Cobble site cells are reconfigured to examine other hydraulic properties. Hayfield H1 cell is dried to remove dead vegetation and restore soils.

July 1998 - Reclamation and USGS enter interagency agreement to conduct investigations of potential biotoxicity and solute transport modeling in conjunction with Phoenix and Tres Rios Demonstration Constructed Wetlands Project.

December 1998 - A project report, *Tres Rios Demonstration Constructed Wetlands — Construction Report* (Reclamation, 1998), prepared to review and summarize activities and experience gained in the demonstration wetlands planning and site construction work.

Summer 1999 - EPA published a series of reports for the Environmental Technology Initiative on *Treatment Wetland Habitat and Wildlife Use Assessment* (EPA, 1999), *Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment* (EPA. 1999b), and *Treatment Wetland Habitat and Wildlife Use Assessment and North American Treatment Wetland Database—Version 2.0* (EPA, 1999c).

Winter 1999 - The first demonstration phase is completed and the demonstration wetlands are rehabilitated to restore certain features and modify the configuration to support further investigation of constructed wetland properties.

2000 - EPA published its *Guiding Principles for Constructed Treatment Wetlands: Provididng Water Quality and Wildlife Habitat*, an ETI report (EPA, 2000a).

Spring 2000 - Publication on disinfection by-products sponsored by interagency, USGS, Reclamation, and Phoenix cooperative research (Rostad, et al. 2000).

April 2000 - Research report, *Evaluation of Flow Fields in Wetlands Using Physical Models*, presents findings of laboratory studies of wetland hydraulic properties.

September 2000 - EPA published its *Manual for Constructed Wetlands Treatment of Municipal Wastewaters* (EPA, 2000b).

December 2000 - Report compiled to present the series of quarterly aerial photos for the three Tres Rios demonstration wetlands (Reclamation, 2000).

May 2001 - Master of Science thesis (Keefe, 2001) based on hydraulic tracer testing and model studies sponsored by USGS through interagency agreement with Phoenix and Reclamation.

Chapter 2

Background Information

Constructed wetlands have been used successfully in many locations nationwide to provide water quality improvement, habitat functions, and public benefits. There is a significant amount of relevant information available regarding functional properties of wetlands and planning considerations for wetland projects. The recent manual for constructed wetlands treating municipal wastewater (EPA, 2000b) is a good starting point and provides references to other information sources. Additional references for constructed treatment wetlands include EPA, 1999b, Kadlec and Knight, 1996; Reed, Crites, and Middlebrooks, 1995; Moshiri (ed.), 1993; Mitch and Gosselink, 1993; Hammer, 1992; WPCF, 1990; Hammer (ed.), 1989; and EPA, 1988;

In spite of the current information available, wetlands are complicated ecosystems and many questions remain for adaptation to specific conditions. The interrelated water quality processes and ecological functions in wetlands can change with climate, hydrology, and geologic conditions. Water management constraints could further influence wetlands water quality and other important wetland functions.

The Tres Rios Demonstration Wetlands Project is an important step to evaluate the feasibility of using wetlands components to address local needs and the overall role of wetlands in managing water and environmental resources. This section provides a brief review of how the demonstration wetlands project was formulated and parallel activities undertaken to examine technical and institutional factors associated with wetlands projects nationwide. The historical perspective focuses on events related to the wetlands demonstration project, but also illustrates how the demonstration efforts fit within the overall scheme of current water management issues.

Phoenix Wastewater Reclamation and Reuse Study

Phoenix and Reclamation initiated the Phoenix Water Reclamation and Reuse Study in 1992 to evaluate alternatives for water reclamation and beneficial reuse of the reclaimed wastewater produced by the 91st Avenue WWTP. The study was completed in 1995 which overlapped with the wetlands demonstration planning

(Reclamation, 1996). Alternative features and costs were compiled for three basic alternatives although several optional components and strategies were considered to address different water management problems.

1992 marked a culmination of important water and wastewater management issues in the area. Before 1992, Phoenix had completed studies of advanced treatment plant upgrades to anticipate the possibility of more stringent water quality permit standards (Greeley and Hansen, 1991). The estimated cost of these upgrades and increasing pressures to meet water demands lead to increased interest in reclaimed wastewater as a valuable water resource.

A zero-discharge option was considered that would use all of the available reclaimed wastewater for direct reuse purposes or supplemental groundwater recharge (Greeley and Hansen, 1994). At the same time, the value of reclaimed water to sustain the riparian corridor habitat was also recognized.

These events contributed to the need to explore integrated approaches to coordinate water supply, conservation, wastewater reclamation, and reuse. Phoenix and SROG have combined water supply and wastewater treatment service operations which can help to coordinate competing water uses.

The three basic alternatives presented in the Phoenix Wastewater Reclamation and Reuse Study report included upgrades to the conventional treatment plant processes, groundwater recharge and recovery, and a full-scale constructed wetlands system (Reclamation, 1996). The features of these alternatives were described separately and compared on an equal cost basis. Although these alternatives were considered independently in the report, by the end of this study the advantages and opportunities for combined reclaimed water components were readily apparent.

Advanced Treatment Plant Upgrades

Treatment plant upgrades developed in previous studies were revised to reflect current planning and updated cost estimates. Treatment process upgrades originally included facilities for nitrogen removal (N/de-N), and advanced physical chemical processes to remove certain trace elements (Greeley and Hansen, 1991). Additional treatment processes described include removal of organic substances, pathogenic viruses, biomonitoring, and whole effluent toxicity.

This alternative would produce highly treated reclaimed water for the downstream riparian area and non-potable reuses. This level of treatment is often operationally defined as *tertiary*; however, in this case the term *advanced-secondary treatment* is used in the Phoenix water services planning documentation.

The nitrogen removal component was eliminated from the alternative comparison when Phoenix initiated plans to proceed with the N/de-N facilities. The nitrogen removal process was constructed at the 91st Avenue WWTP and fully incorporated into the plant operations in December 1996. Consequently, the water supplied to the demonstration wetlands consistently had low levels of total nitrogen.

Groundwater Recharge and Reuse

This alternative involved surface infiltration or direct injection to store reclaimed water in aquifer formations for subsequent recovery and reuse. The recharge features for this alternative were based on a recharge site identified near the floodplain of the Agua Fria River north of the Tres Rios site.

This alternative was considered to accommodate continued reuse by the Arizona Nuclear Power Plant and the Buckeye Irrigation Company via the irrigation company connection on the ANPP pipeline. The amount of water released to the Salt River would depend on seasonal recharge and reuse demands.

Water quality was a major topic of interest for this alternative both to protect groundwater resources and to allow for intended reuse purposes. Surface infiltration basins were preferred to take advantage of natural soil-aquifer treatment (SAT) properties during the infiltration and percolation to the water table. SAT processes can effectively transform, deactivate, or sequester certain water quality residuals found in reclaimed water.

Phoenix sponsored a series of specialized SAT investigations conducted by several universities with funding support provided by the American Water Works Research Foundation and the Water Environment Research Foundation. The first research phase involved detailed laboratory tests to examine transformation process during soil percolation (Fox and Nellor, 1997). This research included a wide array of inorganic, organic, and bacteriological water quality constituents.

Subsequent research included preliminary recharge investigations were conducted at the Aqua Fria site (figure 1-1). These recharge tests were intended to evaluate actual in-situ water quality transformation characteristics and operational considerations involved in implementing groundwater recharge and recovery.

Full Scale Constructed Wetlands

A constructed wetlands alternative was also considered in the Phoenix Wastewater Reclamation and Reuse Study. The full-scale wetlands alternative

offered a means of achieving additional water quality improvement through natural wetland treatment processes. This alternative also retains the in-river conveyance of water for BIC and would preserve the Salt River stream corridor, enhance the existing wetland habitat, and provide additional public use opportunities.

A full-scale wetlands system would have to function adequately within the seasonal reclaimed water supply fluctuations and the prevalent site conditions. It would also have to be practically feasible within economic limitations, management capabilities, and land use constraints.

A conceptual plan was prepared to represent the overall size, layout, and major components of a full-scale wetlands system to provide a realistic basis for estimating costs for comparison with other alternatives (Appendix A). A total wetlands system area of 800 acres was determined for the wetlands alternative based on the capacity, water budget constraints, and land use constraints. The system layout also illustrated practical considerations involved to manage the wetland facilities, address seasonal water supply fluctuations, and reduce construction costs (Reclamation, 1996).

Apparent advantages of the full-scale constructed wetlands alternative included the potential to improve water quality at relatively low cost, ability to integrate wetlands with current and future reuse plans, and wildlife and public use benefits associated with aquatic and wetlands habitat. The demonstration project at the Tres Rios site was pursued to evaluate these characteristics. Planning for a full-scale wetlands has continued to emphasize integrating constructed wetland components with long term plans for the Salt River and reclaimed water reuse operations.

Current Status of Alternatives

Each of these alternatives were pursued beyond the reuse study. Upgrades have been implemented at the 91st Avenue WWTP, groundwater recharge testing and planning are still in progress, and the wetland demonstration project was initiated based on the early study results. Although the three alternatives represent different approaches or management components, the water quality attributes of one activity could affect the other components and subsequent reuse.

In addition, it was evident that groundwater recharge, direct reuse, wetlands, and riverine habitat represent competing uses for reclaimed water and had important implications with regard to the optimal allocation of water supplies. The concept of net environmental benefit was raised to represent possible trade-offs between water quantity and appropriate water quality standards for different types of water reuse demands. The associated regulatory and administrative issues have

remained in the forefront of the wetlands demonstration effort and the ongoing full-scale wetlands and Salt River management plans.

Tres Rios Demonstration Wetlands Project

The wetlands demonstration project and Tres Rios was conceived as somewhat of a prototype effort—to provide a mechanism to assess important questions with fewer resources than full build-out would entail, and yet have sufficient scope and scale to obtain objective information useful in full-scale project planning. To accomplish this the demonstration project included construction, operation, and monitoring of the wetlands facilities, specialized technical investigations, and an extensive interagency effort conducted to examine regulatory and institutional issues.

Demonstration Project Planning

In early discussions regarding full-scale constructed wetlands, a number of important questions were evident that could be addressed through an applied demonstration project. Generally, this involved the ability to directly demonstrate the application of wetlands technology under specific circumstances concerning water use, water quality, and climate conditions in the area.

Initial planning for the demonstration wetlands project started shortly after the early planning for the Phoenix Wastewater Reclamation and Reuse study. A conceptual design planning report entitled *Phoenix Water Reclamation and Reuse Study, Tres Rios Demonstration Wetlands, Conceptual Design* (Reclamation, 1993) was produced by Phoenix, Reclamation, and SROG in cooperation with EPA, Arizona Game and Fish Department, Arizona Department of Environmental Quality, Maricopa County Department of Parks and Recreation, and Maricopa County Flood Control District.

This concept report provided a basic layout for two demonstration wetland facilities and discussed further information and regulatory questions to resolve in further plans to establish demonstration wetlands at the Tres Rios site. The conceptual plans were intended to support both broad-based demonstration evaluations and detailed water quality investigations.

Demonstration Wetlands Development

Phoenix and Reclamation agreed to proceed with the cooperative demonstration wetlands effort in the spring of 1994 and by early 1995 a research plan report was

prepared to guide the investigations anticipated during the first phase of monitoring (CH2MHill, 1995). Final design plans and specifications were prepared by the spring of 1995 and the major construction work was completed during the following summer (Reclamation, 1998).

Three separate wetland facilities, the Cobble Site, Hayfield Site, and Research Cells were established for demonstration purposes. The three demonstration facilities are located near the 91st Avenue WWTP as shown in the aerial photo in figure 2-1.

The size and physical configuration of the three wetland facilities were designed to explore multiple issues including site selection factors and specific site conditions, the capacity sizing guidelines for water quality performance, cross-comparison of different hydraulic configurations, and site management, operations, and maintenance considerations. All three sites were planted with specific varieties of wetlands vegetation to encourage uniform and rapid growth of desirable wetlands species. The plants were arranged according to designated patterns to promote uniform hydraulic conditions and establish certain water quality testing conditions.

Operations and Monitoring Phases

Once the planting was completed the demonstration wetlands cells were filled and operated at the operating design depths and flow rates indicated in the research plan (CH2MHill, 1995). Operating conditions were held for specified intervals, generally about three months, to collect data under defined conditions. The routine water quality monitoring program was started immediately after the wetland cells were filled and fully operational.

The demonstration monitoring is divided into two general components. The routine monitoring involved collecting data on a series of water quality parameters at regular intervals. Other specialized investigations included additional monitoring to meet individual requirements of other studies at the demonstration wetlands. This report focuses on water quality data collected during the routine monitoring program for the first three years of demonstration operations.

Routine monitoring samples were collected at daily, weekly, or monthly intervals to characterize water quality characteristics under defined conditions. Data collected included daily field tests, flow rate measurements, climate data, and monthly water quality sampled. Hourly diurnal sampling and depth profiles were also made on a couple occasions, but these data are not considered routine. Further details of the water quality parameters and monitoring techniques are provided later in the description of the monitoring strategy and data analysis methods.

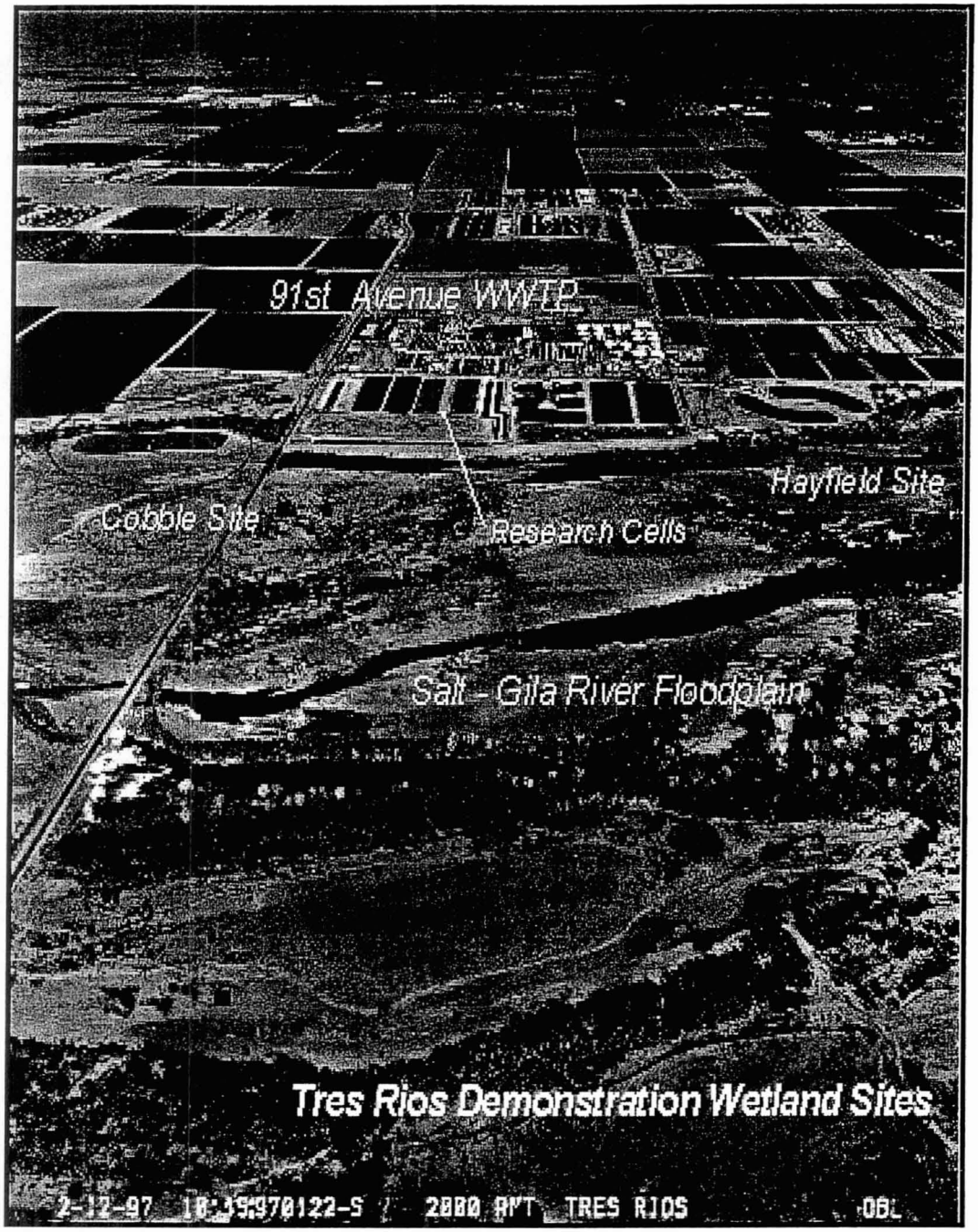


Figure 2-1. Aerial view of the Tres Rios demonstration wetland facilities.

Routine monitoring included water data collected during the first phase monitoring program which was summarized in two data reports. The first data report (Phoenix, 1996) presented data collected from start-up in August 1995 to March 1996. The second operations and monitoring report (Phoenix, 1997) described data and results collected from April 1996 through the end of the summer of 1997.

Ongoing review and oversight of the research and monitoring program was provided by a Technical Advisory Review Panel (TARP) comprised of members from seven agencies. The operating schedule and monitoring plans were reviewed periodically by the TARP and changes made as appropriate. TARP review meetings were held approximately quarterly during the first phase of demonstration investigations.

The first phase of operations and monitoring ran through 1998. Flow rates and conditions in the wetlands were variable during this last year due to animal control problems, vegetation die-off and succession, and implementation of mosquito abatement measures at the wetlands sites. Some of the demonstration wetland cells were subsequently modified and reconditioned before starting the second phase of demonstration studies that is currently in progress.

Related Tres Rios Wetland Investigations

The routine monitoring program was carried out primarily by the Phoenix water services personnel. The demonstration wetlands are also open to other compatible investigations undertaken concurrently in cooperation with other agencies, or studies conducted by universities and research organizations. Activities included a variety of intensive short-term studies and specialized investigations of water quality, wildlife use and habitat suitability, and disturbance factors.

These related wetlands investigations are briefly described to indicate other important components of the demonstration program and to illustrate the functional conditions occurring in the wetlands that could have influenced water quality during the first phase of water quality monitoring addressed in this report.

Baseline Characterization

Soil samples were collected from within the wetlands cells to establish baseline conditions for the presence of organic compounds, metals, and trace elements (Phoenix, unpublished data) in the wetlands soils. Shortly after water was supplied to the wetlands a series of water samples were collected to further characterize the presence of organic pesticides in the water supply (Phoenix,

1996). No significant contaminants of concern were detected in these baseline studies.

Wetland Vegetation Aerial Surveys

An aerial photograph survey was sponsored by Reclamation to document the vegetation growth in the wetlands and provide a basis for studies of vegetation patterns on other conditions in the wetlands (Reclamation, 2000). The aerial photos were taken three times each year. Wetland vegetation directly or indirectly related to wetland primary productivity, energy dynamics, hydraulic properties, internal organic loading, and associated water quality transformation processes.

Vegetation observations associated with die-off conditions in 1998 were also briefly described in the second data report (Phoenix, 1997). Studies of wetland vegetation sustainability have been initiated with interagency support by Phoenix, Reclamation, and the Arizona Department of Water Resources (ADWR).

Bird Use and Habitat Evaluations

Synoptic surveys of bird species and observed counts at the constructed wetlands were conducted by Reclamation (Laush, unpublished data). Although observed bird use and potential habitat values were discussed, the location and scale of the demonstration wetlands limited these evaluations to subjective review. Relationships between bird use and wetlands water quality were not evaluated quantitatively.

Bird observations at Tres Rios are summarized in a visitor information brochure (Phoenix, 1998). Bird use data (and other wildlife data) from the Tres Rios demonstration wetlands site were incorporated into the North American Treatment Wetlands Database (NADB), Version 2.0 (EPA, 1999c).

Macroinvertebrate Monitoring

The species diversity and numbers of macro-invertebrates were also monitored by Reclamation biologists (Kubly, 1998). Invertebrate characteristics are important because they reflect primary productivity, oxygen status, water quality conditions, and potential food sources to support other wildlife species. The invertebrate data from Tres Rios were also included in the NADB Version 2.0 (EPA, 1999c).

Animal Control Problems

A population of muskrats moved into the wetlands in the third year of demonstration operations. The muskrat feeding on new emergent plant shoots consumed most of the newly planted vegetation and inhibited re-growth of existing plants. Although quantitative studies were not possible, potential effects on water quality are evident due to the changes in vegetation, microbial dynamics, hydraulic effects, disturbance effects (turbidity, nutrients, and bacteria) and impacts on basin integrity caused by burrowing into the wetland containment berms.

Chronic Toxicity Monitoring

A standardized 7-day test using *Ceriodaphnia dubia* was performed throughout the first phase monitoring to evaluate the potential chronic toxicity of water flowing through the wetlands. Results were presented in both data reports (Phoenix, 1996, 1997) and monitoring is ongoing. Chronic toxicity, or whole effluent toxicity, testing is intended to evaluate the presence of unknown contaminants, or possible synergistic effects of residuals in the water. Results to date have indicated chronic toxicity is not prevalent in the Tres Rios demonstration wetlands. Results also lead to more detailed biotoxicity studies through USGS.

Viruses and Pathogenic Organisms

Investigations of the presence, survival, and transport of pathogenic organisms were discussed, but not undertaken in the first demonstration phase. A study in progress was initiated to evaluate wildlife implications for enteric pathogens (Gerba and Karpiscatz, in progress).

Metals and Trace Elements

Potentially toxic heavy metals and trace elements of concern were monitored in the wetlands water during the first monitoring phase (Phoenix, 1996, 1997). These studies were expanded to examine concentrations in water, plants, and fish thriving in the wetlands through an interagency effort between Phoenix, ADWR, and the Arizona Department of Game and Fish (ADGF). Another independent study by the U.S. Geological Survey (USGS) was also conducted to examine a comprehensive series of inorganic elements including low detection limit analysis for elements in the wetlands water, plant biomass, and fish tissues (Barter, et. al., in preparation).

Organic Matter and Biotoxicity

A series of studies concerning organic substances in wetlands were undertaken by the USGS with cooperative support by Phoenix and Reclamation. The first study involved overall characterization of organic matter in the reclaimed water supply and transformation processes in the wetlands as a follow up on previous studies of distinctive aquatic and wetland systems (Reclamation, 1999; Barber, et al., in press). These preliminary studies provided a basis for investigations to examine the potential for removal of disinfection by-products (DBP) in the wetlands and also the potential to produce organic matter in the wetlands that can act as DBP pre-cursors (Rostad, et. al., 2000; Martin, 1998).

Further investigations were initiated to examine the transport and transformations of specific trace-level wastewater-derived organic residuals and potential biological pathways in wetland systems. These studies may help to understand potential risks of bioaccumulation or biotoxicity effects of certain organic compounds on organisms found in constructed wetlands or receiving streams (Barber, et. al., in review). These investigations are currently ongoing in conjunction with hydraulic tracer testing. Better information regarding sub-lethal, cumulative, or synergistic effects may have important implications for all effluent dependent aquatic systems including receiving streams and wetland systems (University of Arizona, 1993).

Hydraulics and Solute Transport

The complexity and importance of hydraulic properties in the wetlands was recognized early in the Tres Rios demonstration planning. Inflow loading, retention time, hydraulic controls, and water budget factors were included in the routine monitoring plans. In addition, more detailed tracer studies were initiated by the USGS, Phoenix, and Reclamation (Wass, 1997; Phoenix, 1997) to evaluate the hydraulic efficiency and correlate transport characteristics to the operating conditions and vegetation patterns in the wetlands. These initial tracer studies were presented recently (Keefe, 2001) and further studies are ongoing. These results will be used to define transport characteristics for chemical solute transport modeling.

Laboratory modeling studies of the Tres Rios wetlands hydraulic properties were completed by Arizona State University (Fox, et. al., 2000) with interagency support from Reclamation. These studies examined fundamental flow characteristics associated with idealized models of the different wetlands configurations and operating conditions. In particular, these results provide insight into micro-scale fluid flow and mixing properties that can influence wetland functions.

Mosquitos and Vector Control

Biological mosquito control methods such as bats, mosquito fish (*Gambusia affinis*), and Gila topminnow (*Poeciliopsis occidentalis*) were considered early in planning for the Tres Rios demonstration wetlands. During the first phase monitoring, mosquito control became an immediate concern, and several studies were undertaken to monitor and test various control measures.

Studies were undertaken to identify mosquito species, propogation, and movement characteristics. Active abatement measures tested included direct application of surfactants and chemical pesticides. Biological control was also tested using bacterial larvicides (e.g. *Bacillus thuringiensis*, *Bacillus sphaericus*). Results from these tests were used to develop a detailed mosquito control strategy (Phoenix, 1999).

Ultimately, structural mosquito control methods were considered as a more practical approach, particularly for managing a full-scale wetlands complex. Flow routing and vegetation patterns were evaluated to reduce isolated mosquito breeding zones, provide access for predator fish, and facilitate insecticide application. Modifications were made on the Cobble Site basins in 1998 to support evaluations of structural measures and corresponding impacts on the water quality performance.

Environmental Technology Initiative

The Tres Rios wetlands demonstration activities also provided a forum to evaluate broad-ranging policies and institutional factors commonly encountered in planning constructed wetlands projects nationwide. Many policies and institutional practices have some relationship or connection to water quality. For example, water quality is a prominent issue in discharge permit requirements for wetlands. Other functional qualities of wetlands associated with wildlife use and ecosystem interactions are important factors in considering treatment wetlands as part of national wetlands resources and the associated goals of wetland protection provisions.

In 1996, EPA awarded an Environmental Technology Initiative (ETI) grant to the wetlands demonstration project cooperative partners (Phoenix, SROG, Reclamation) to examine major technical, policy, and regulatory issues and promote innovative solutions to integrate wetlands in plans for wastewater reclamation, reuse, and environmental enhancement. The demonstration wetlands and long-term planning activities were considered important test cases to evaluate these issues.

The ETI effort was organized into a management oversight team and workgroups that were established to assess three major topic areas. Workgroups were comprised of technical experts and practitioners from universities, consulting firms, and agencies that are actively involved in the issues. In recent months, each of the ETI workgroups have produced reports that are useful references in planning wetland projects that integrate water management and environmental resource objectives.

Guiding Principles for Constructed Treatment Wetlands

This report is currently in final review stages (EPA, 2000a). The document does not alter any existing policies or regulations concerning wetlands or constructed wetland treatment systems. It is intended as a guide for practitioners to consider:

- Basic guidelines for siting, design, construction, operation, maintenance, and monitoring of constructed treatment wetlands
- Information on current policies and regulations
- Answers to common questions

Water quality is a central factor in the discussion of wetlands siting, design criteria, and the discharge permits and wetland protection provisions of the Clean Water Act. The emphasis is on municipal wastewater treatment wetlands. Moreover, the full title of the report: *Guiding Principles for Constructed Treatment Wetlands: Providing Water Quality and Wildlife Habitat*, indicates the intent to focus upon and encourage those projects that not only provide water treatment, but also strive to provide water reuse, wildlife habitat, and public use benefits.

These issues were prominent in initial discussions of full-scale constructed wetlands in water management planning and in developing the water quality approach and monitoring strategy for the Tres Rios demonstration wetlands project.

Treatment Wetland Habitat and Wildlife Use Assessment

This assessment was supported by the ETI to compile information on wildlife use in constructed wetlands. Wildlife values in wetlands are often discussed, but little data were available to confirm the functions and values. This assessment included vegetation, wildlife, toxicity risks, and human uses. Results were compiled in a data report (EPA, 1999a) and incorporated into the NADB (EPA, 1999c).

Wildlife habitat, environmental, and public use benefits were considered important aspects of constructed wetlands since the inception of the Phoenix Wastewater Reclamation and Reuse Study. Although investigations of wildlife values are limited by the scope and scale of the Tres Rios demonstration wetlands project, some initial data were collected and water quality monitoring and research investigations were undertaken to examine the potential risks for wildlife and public use.

Wastewater Treatment Wetlands Technology Assessment

This component of the ETI was directed primarily toward water quality performance and related attributes of constructed wetland systems. The overall purpose was to assess the current level of scientific understanding and engineering experience as a basis for using free water surface (FWS) wetlands to treat municipal wastewater and provide other social and ecological benefits. A workgroup comprised of experienced wetland researchers and practitioners from universities, public works, consulting engineers, regulatory agencies, and interest groups was assembled for the technology assessment. This effort resulted in a considerable amount of review and discussion regarding different experience, opinions, data, and information available.

Ultimately, a summary report entitled *Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment*, (EPA, 1999b) was prepared. Although full consensus on some topics was not reached, the technology assessment report provides a review of treatment processes operating in FWS wetlands, treatment wetland performance data, and important considerations for planning and operation of wetland systems. The results and discussion of the technology assessment were also instrumental in developing practical guidelines incorporated in the recent manual *Constructed Wetlands Treatment of Municipal Wastewaters* (EPA, 2000b).

Chapter 3

Facilities, Strategy, and Methods

The wetlands demonstration facilities were designed to evaluate specific questions and conditions associated with constructed wetlands in the area. Site monitoring plans were developed accordingly to address key issues identified within funding limitations and demonstration time constraints. The overall monitoring plan has produced a significant amount of data useful to directly examine water quality characteristics in the wetlands and has also provided essential information to support other specialized studies conducted at the demonstration wetland facilities.

This section describes the principles and processes applied to develop the wetlands demonstration monitoring plans, and the procedures employed to examine the bulk of water quality data collected during the first phase operations.

Demonstration Wetland Facilities

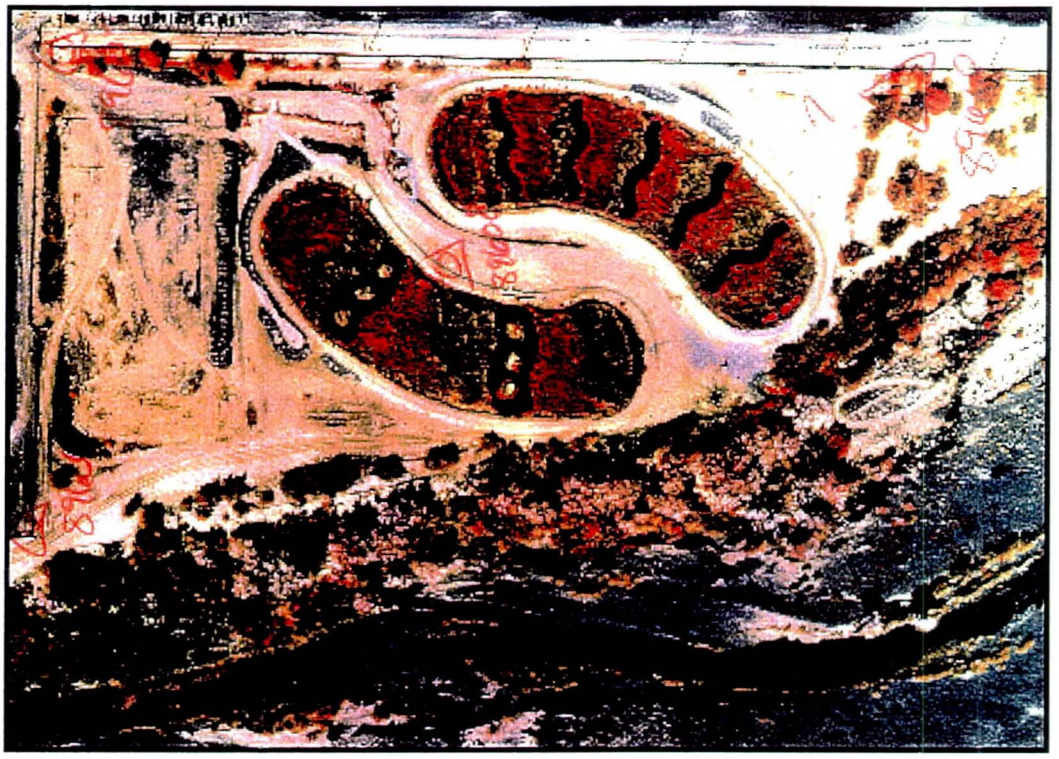
The Tres Rios Demonstration Constructed Wetlands Project includes three wetlands facilities, the Hayfield Site, Cobble Site, and Research Cells. These wetland sites are all located near the 91st Avenue and the Salt River (figure 2-1). All three wetland systems are supplied by reclaimed wastewater from the 91st Avenue WWTP through a common pumping and de-chlorination system.

The demonstration site features and wetlands system layout are described based on detailed information from the Tres Rios wetlands research plan (CH2MHill, 1995) and the follow-up construction report (Reclamation, 1998).

Research Cells

A series of twelve smaller wetlands cells with an area of about 0.3 acres were constructed in a former sludge drying bed on the treatment plant property. These cells were designed with specific ratios of open water and emergent marsh to allow detailed studies of wetlands transformation properties.

Water quality data collected from these research cells were not analyzed as part of this data analysis study, and the experimental plans and activities associated with the research cells are not discussed further.



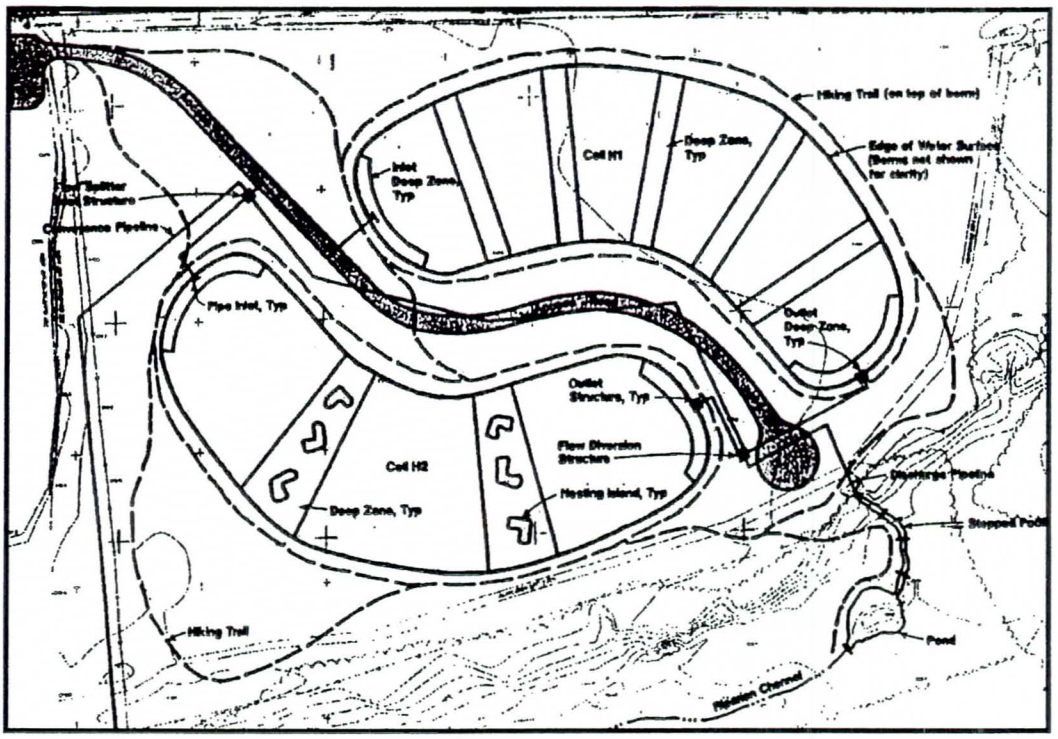


Figure 3-1. Hayfield site 1997 infrared aerial photo (Reclamation, 1998) and concept design site plan (CH2MHill, 1995).

Hayfield Site Features

The Hayfield Site is located southeast of the treatment facility on an upland terrace along the main Salt River flood channel as shown in figure 3-1. Two surface-flow wetland cells (H1 and H2) were constructed in an old fallow hayfield area. The site occupies about 10 acres (4.1 ha) including the flat hayfield site and a transitional riparian area sloping down to a small side channel along the north river bank.

The Hayfield Site allows evaluations of two representative constructed wetland systems. The two wetland cells were designed to have a different configuration of open water and emergent marsh to allow direct comparison of how these features could affect flow distribution, retention time, and related processes.

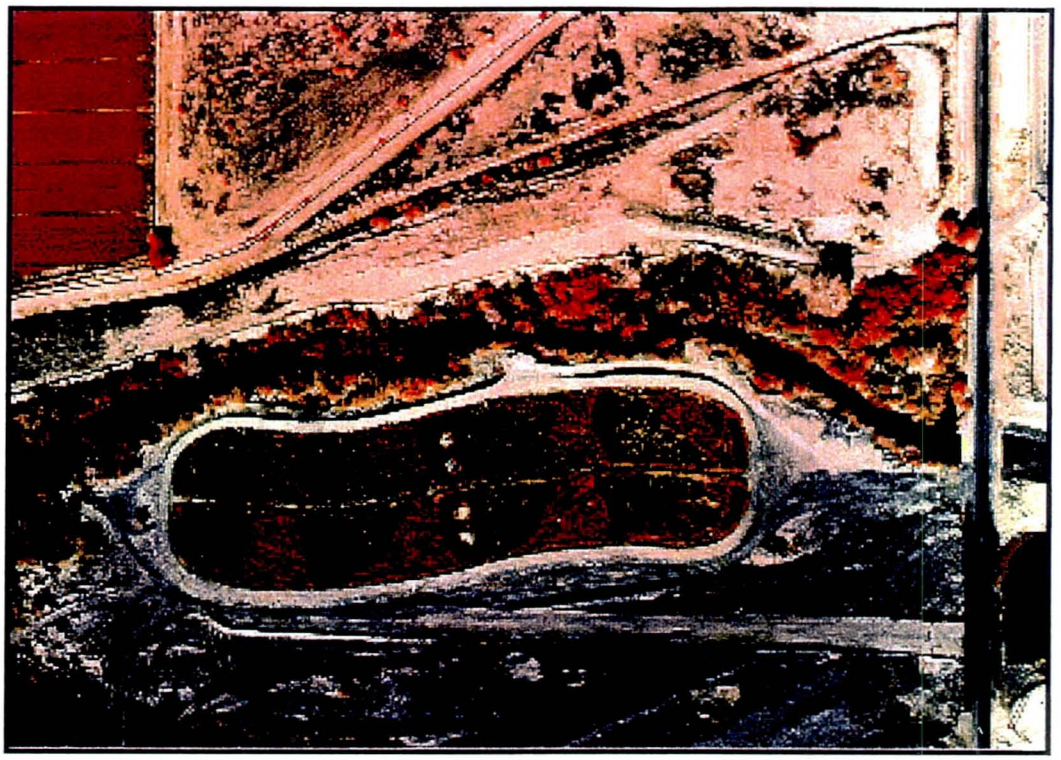
The wetland cells were designed to have a similar surface area; however, the H1 cell has five internal open water zones, whereas the H2 cell has two larger open water zones with islands (figure 3-1 and Appendix A). All open water bands extend across the flow path and are deeper to inhibit encroachment by emergent vegetation. Open water zones were designed to produce a ratio of 25 percent open area to 75 percent emergent area in both cells to provide a consistent basis for comparison.

Design plans indicated cells 748 ft (228 m) long by 200 ft (60 m) wide, resulting in an aspect ratio of about 3.8:1 (L:W) and surface area of about 3.4 acres (1.37ha) for each cell (CH2Mhill, 1995). A post-construction aerial survey (Reclamation, 1997) showed the actual wetland surface area for H1 was 3.30 acres (1.3 ha) and 3.16 acres (1.28 ha) for H2. Total open water areas measured for H1 and H2 were 0.84 acre (0.34 ha) and 0.80 acre (0.3 ha), respectively. Minor variations may be attributed to earthwork grading, vegetation growth, and soil movement after construction.

Water supplied from the 91st Avenue WWTP is distributed to the two wetland cells by a three-way splitter box. The water control systems allow the wetland cells to be operated in series, in parallel, separately, or by-passed; however, the cells were only operated as separate, parallel units during the first phase demonstration testing.

The cells also have an additional deep zone at the inlet and outlet ends to facilitate inflow distribution and collection near the outlet. Water from the inlet splitter box enters each cell through a sub-surface pipe manifold buried in a rock bed across the inlet zone. Weir boxes are used at the outlets to control operating depths and allow flow measurement. The outflow from both cells is combined in a small side channel that flows through the riparian area along the river channel.

Flow measurements and water samples are taken at the inlet splitter box for the individual cells or the combined inflow (HS) and the outflow at each cell outlet box (H1 and H2). In some cases, water samples were also taken at the outflow channel to evaluate the combined outflow (HS-EFF).



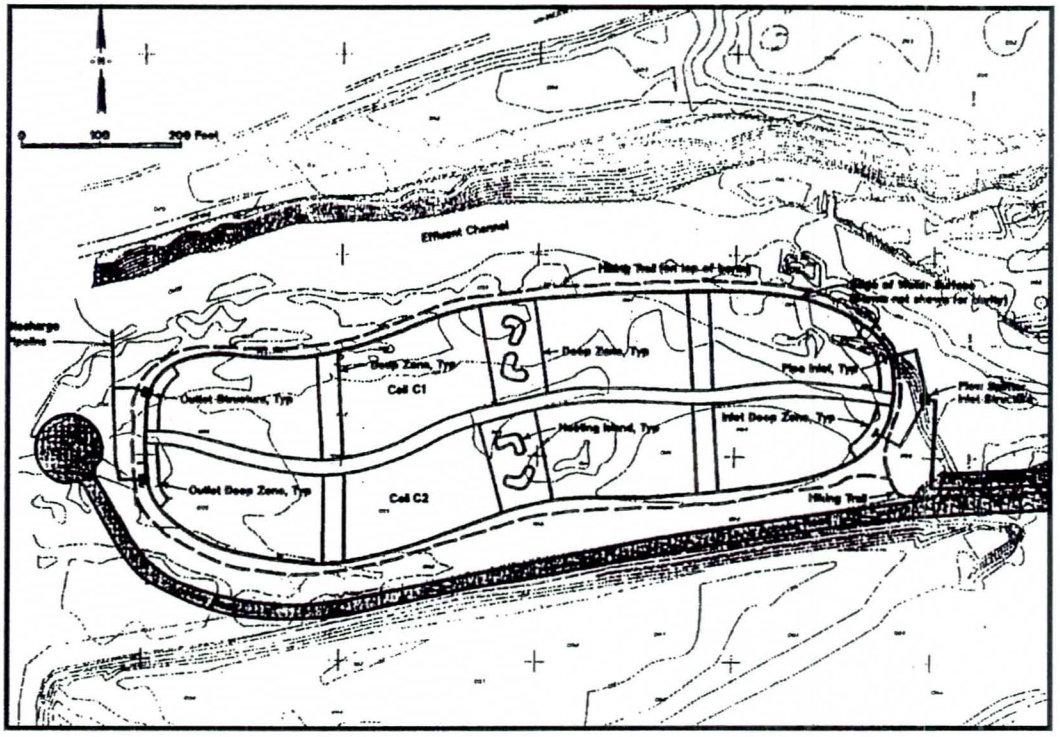


Figure 3-2. Cobble site 1997 infrared aerial photo (Reclamation, 1998) and concept design site plan (CH2MHill, 1996).

Cobble Site Features

The Cobble Site is located along the north bank of the Salt River floodway, next to the main 91st Avenue WWTP outflow channel. Site soils are exposed streambed deposits consisting of sand, gravel, and large cobbles. Most of the vegetation was scoured during a flood in 1993, and only scattered saltcedar seedlings were present at the time of construction. To the north, the site is bounded by the riparian corridor along the WWTP outflow channel and the wide, seasonally dry main Salt River flood channel runs past the Cobble site along the southern side. The design layout and aerial view of Cobble site are shown in figure 3-2 (also Appendix A).

The Cobble site has two elongated wetlands cells (C1 and C2) separated by an earth berm. The wetland cells allow investigation of representative constructed wetlands systems, and the two cells are also configured to directly evaluate practical factors associated with the site conditions. C1 was constructed on the permeable native alluvial material and cell C2 was lined with a layer of more impervious clay material to allows direct comparison of seepage loss effects in the wetlands.

The wetlands cells were constructed directly on the existing streambed alluvium by grading the native cobble-gravel materials to form the cell bottom and creating earth berms 2 ft (0.6 m) above the design water depth in the wetland cells. Impermeable clay material was imported to create containment berms and the C2 bottom liner.

Total area of the Cobble Site is about 4.4 acres (1.8 ha). Design plans called for cells 115 feet (35 m) wide by 902 feet (275 m) resulting in an aspect ratio of 7.9 and surface area of about 3.9 acres (.9 ha) for both cells (CH2MHill, 1995). Each cell has five deeper open water zones including a deep zone at the inlet and outlet. The center zone has two small islands that were designed to be about 30 feet (9.1 m) in diameter; however, in cell C2 the islands were constructed to form one large island about 35 by 155 feet (10.7 m by 47.2 m). The total open water area was intended to be about 20 percent of the total surface area (disregarding island area).

Subsequent aerial survey indicated C1 is 2.27 acres (0.92 ha) with five open water zones accounting for 0.35 acre (0.142 ha) or15 percent of the surface area. Cell C2 was measured at 2.24 acres (0.91 ha) with total open water area of 0.23 acre (0.09 ha) or 10 percent of the total surface area. These as-built variations are attributed to construction factors and site conditions at the Cobble Site.

The Cobble Site cells are operated in separate parallel mode. The water supply is controlled by a two-way splitter box and then enters each cell through a distribution manifold pipe buried in a rock bed at the inlet deep zone. Outlet boxes with movable v-notch weirs are used to regulate the water depth in each cell. Water samples and flow measurements are taken at the inlet splitter box for the combined inflow (CS) and the outflow at each outlet box (C1 and C2). Depth measurements are read directly from calibrated staff gauges installed near the wetlands outlet.

Demonstration Monitoring Strategy

Monitoring plans were developed to maximize the amount of data and information that could be derived from the Tres Rios investigations. The wetland evaluation plans involved overlaying compatible investigations with an appropriate sequence for activities that could interfere. As a result, the overall demonstration strategy is evident by reviewing the array of test conditions established by the demonstration wetlands configuration, operating conditions, and water quality parameters analyzed to address identified evaluation topics.

Major elements of the initial monitoring plans are summarized for reference to the water quality investigations. Modifications and important events are also noted to indicate factors that could influence the interpretation of water quality data.

Site Configuration

The demonstration wetland facilities were described previously. Design criteria for the Hayfield and Cobble sites are summarized in table 3-1. The actual surface area of the wetland cells varies somewhat from the design conditions. Post construction measurements made by aerial survey (Reclamation, 1997) are noted in table 3-2. The most prominent differences from design are evident in the surface areas for the Hayfield Site cells and the Cobble Site open water percentages.

Table 3-1. Demonstration wetlands design information.

	Hayfield Site		Cobble Site	
Surface area cell Total wetland area	3.4 acre 6.8 acre	(1.37 ha) (2.7 ha)	2.4 acre 4.8 acre	(0.96 ha) (1.9 ha)
Width x Length	200 x 750 ft	(60 x 228 m)	115 x 900 ft	(35 x 275 m)
Aspect ratio	3.8:1		7.9:1	
Deep zones / cell	H1 = 7 (Incl. inlet and outlet zones) H2 = 5		C1 = 5 (incl. inlet and outlet zones) C2 = 5	
% total area	20 %		20 %	
Design depth range deep zones typical	0.5 - 2.0 ft 3.5 - 5.0 ft 1.5 ft	(0.15 - 0.6 m) (1.15 - 1.6 m) (0.46 m)	0.5 - 2.0 ft 3.5 - 5.0 ft 1.5 ft	(0.15 - 0.6 m) (1.15 - 1.6 m) (0.46 m)
Design flow	130–260 gpm	(700 – 1400 m^3/d)	330–660 gpm	(1800 – 3600 m^3/d)
Areal load rate HLR Retention time HRT	1 - 2 in/d 10 - 20 days	2.5 - 5.0 cm/d	4 - 8 in/d 2 - 5 days	10 - 20 cm/d
Site specific features for demonstration	H1 has more open zones, but equal as percent of total surface area		C1 = native cobble / gravel alluvium C2 = lined with clay seepage barrier	

Table 3-2. Post construction measurements from aerial survey (Reclamation, 1997).

	Hayfield Site		Cobble Site	
	H1	H2	C1	C2
Surface area	3.30 a (1.34 ha)	3.16 a (1.28 ha)	2.27 a (0.92 ha)	2.24 a (0.91 ha)
Deep zone area	0.84 a (0.34 ha)	0.80 a (0.32 ha)	0.35 a (.142 ha)	0.23 a (.093 ha)
Percent total area	25 %	25 %	15 %	10 %
Calculated volume[1]				
a) at nominal depth	215,550 ft^3 (6105 m^3)	206,400 ft^3 (5845 m^3)	148,260 ft^3 (4200 m^3)	146,310 ft^3 (4145 m^3)
b) with deep zones	238,623 ft^3 (6761 m^3)	228,499 ft^3 (6475 m^3)	164,143 ft^3 (4651 m^3)	161,974 ft^3 (4590 m^3)

Notes: [1] Nominal design operating depth of 1.5 ft (.46 m); deep zone volumes based on design conditions; calculated volumes not adjusted for vegetation void volume.

Operating Conditions

Operating water depths and inflow rates are key factors that can influence wetland water quality. A series of operating conditions were specified for the demonstration evaluation studies. The initial schedule of operations set in the research plan report (CH2MHill, 1995) is summarized in table 3-3. Changes made during the course of first phase of demonstration testing are noted in table 3-4 and appendix A.

Table 3-3. Initial operations schedule from research plan (CH2MHill, 1995).

Operation period	Interval (months)	System/ cell	Average inflow[(1)] (m^3/d)	(gpm)	Water depth[(2)] (m)	(ft)	Description
Startup	0-6	Hayfield	≈600	1098	<0.1	<0.3	Only enough water to keep
		Cobble	≈2,000	3660	<0.1	<0.3	soil saturated continuously
Phase 1 [(3)]	7-12	H1	700	1281	0.3	1.0	Approximately 5 cm/d to both
		H2	700	1281	0.3	1.0	cells in parallel
(Nov 1995 - Oct 1996)		C1	900	1647	0.3	1.0	Approximately 10 cm/d to
		C2	900	1647	0.3	1.0	both cells
Phase 2	13-18	H1	350	641	0.45	1.5	Approximately 2.5 cm/d to
		H2	350	641	0.45	1.5	both cells in parallel.
(See revised)		C1	1,800	3294	0.45	1.5	Approximately 20 cm/d to
		C2	1,800	3294	0.45	1.5	both cells
Phase 3	19-24	H1	700	1281	0.15	0.5	Approximately 5 cm/d both
		H2	700	1281		0.5	operated in series (H1 to H2)
(See revised)		C1	1,350	2471	0.15	0.5	Approximately 15 cm/d to
		C2	1,350	2471	0.15	0.5	both cells

Notes: [1] m^3/d = cubic meters per day; gallons per day = gpd = m^3/d x 264
[2] Average water depth in emergent areas: feet (ft) = meters (m) x 3.3
[3] Phase 1 became test phase A in final revised operating plan

Several changes were made to the initial two-year operations schedule. The startup phase was August 1995 to October 1995 to allow time for wetland vegetation growth and hydraulic stabilization. The first full year of operations after startup followed the conditions indicated for phase 1. The second year operations (phases 2 and 3) were replaced by the modified operations schedule shown in table 3-4.

Table 3-4. Revised operations schedule for second year monitoring.

Operational Period	Interval (months)	System / Cell	HLR Hydraulic Load Rate (ft/d)	(cm/d)	Water Depth (ft)	(m)	HRT Residence Time (days)
Test phase B	0-4	H 1	0.5	15	1.0	0.30	3.50
		H 2	0.5	15	1.0	0.30	3.50
Nov 96 - Feb 97		C 1	0.8	25	1.0	0.30	2.00
		C 2	0.8	25	1.0	0.30	2.00
Test phase C	5-8	H 1	0.5	15	1.5	0.46	5.50
		H 2	0.5	15	1.5	0.46	5.50
Mar 97 - Jul 97		C 1	0.8	25	0.5	0.15	1.40
		C 2	0.8	25	0.5	0.15	1.40
Test phase D	9-12	H 1	0.5	15	0.5	0.15	2.40
		H 2	0.5	15	0.5	0.15	2.40
Aug 97 - Apr 98		C 1	0.8	25	1.5	0.46	5.25
		C 2	0.8	25	1.5	0.46	5.25

The actual operations varied from this schedule due to some interesting events and problems that were encountered during the second year operations. Events noted and possible effects on the operating conditions are summarized in Table 3-5.

Table 3-5. Events affecting wetland operations and monitoring.

Date / duration	Description	Effects
Oct 96 - Dec 96	C2 inflow rate raised to compensate for seepage attributed to a dewatering project	Hydraulic load rates increased significantly approx 2 months
Jan 97 - May 97	Emergent vegetation senescence and die-off; mainly in C2, less in C1	Internal loading and removal process effects unknown
May 97 - Feb 98	Revegetation of C2; inflow pulsed in C1 to test mosquito control effects; muskrats eat new shoots and cause burrowing damage	C2 inflow and depth reduced to non-functional; inflow loading conditions erratic in C1
Oct 97- Apr 98	Beavers from riparian area chew on stoplogs and attempt to plug outlet in H2, less in H1.	Depth regulations problems, unknown hydraulic efficiency
Sep 97 - Jun 98	Mosquito control concerns govern operating conditions at Hayfield Site	Inflow rates pulsed throughout this period
Mar 98 - Jul 98	Cobble site shut down in March for restoration work; Hayfield site shut in July down for H1 vegetation management work.	End of first demonstration testing phase

Monitoring Parameters

The routine monitoring program included a series of field measurements and analyses that were conducted at regular intervals by the 91st avenue WWTP plant operators and laboratory staff. The original research plan included a tentative list of parameter sampling schedules for chemical constituents, biological indicators, and hydrologic measurements for the initial monitoring. Changes were made as needed to adapt monitoring according to information obtained and maintain cost effective monitoring to address different demonstration objectives.

Routine water quality monitoring parameters and abbreviation symbols are shown in table 3-6. The actual sampling frequency for monitoring parameters that supported water quality characterization at the Hayfield Site and Cobble Site wetlands are shown in table 3-7. Photocopies of the initial monitoring schedule tables taken from the research plan (CH2MHill, 1995) are provided in Appendix A.

Table 3-6. Monitored water quality parameters.

Parameter	Symbol	Units
Field test measurements		
Water temperature	Temp.	degrees ° C
Residual chlorine	Res Cl_2	mg/L (free)
Dissolved oxygen	DO	mg/L (gas)
pH	pH	relative
Electrical conductivity	EC	µ Siemens / cm
Inorganic water chemistry		
Alkalinity	Alk	mg/L (as $CaCo_3$)
Total suspended solids	TSS	mg/L
Total dissolved solids	TDS	mg/L
Chloride	Cl	mg/L
Sulfate	SO_4	mg/L
Nutrient components		
Total Kjeldahl nitrogen	TKN	mg/L (as N)
Nitrite nitrogen	NO_2–N	mg/L (as N)
Nitrate nitrogen	NO_3–N	mg/L (as N)
Nitrite plus Nitrate	NO_2+NO_3–N	mg/L (as N)
Ammonia nitrogen	NH_3–N	mg/L (as N)
Total nitrogen	Total N	mg/L
Ortho-phosphate	PO_4–P	mg/L (as P)
Total Dissolved Phosphorus	Diss. P (or TDP)	mg/L
Organic content indicators		
Chemical oxygen demand	COD	mg/L
Biochemical oxygen demand	BOD	mg/L (5-day)
Total organic carbon	TOC	mg/L

Table 3-7. Water quality monitoring schedule.

		Hayfield Site	Cobble Site
Sample locations:		HS = inflow at inlet splitter box H1 = outflow at H1 cell outlet box H2 = outflow at H2 cell outlet box HS-EFF = combined outflow	CS = inflow at inlet splitter box C1 = outflow at C1 cell outlet box C2 = outflow at C2 cell outlet box
Field tests:			
Temp. Res Cl_2 DO		Field measurements made at all inflow and outflow stations.	Field measurements made at all inflow and outflow stations.
pH EC		Daily from Nov-1995 to Oct-1996, 2 / week to end Jul-1998.	Daily from Nov-1995 to Oct-1996, 2 / week to end Mar-1998.
Laboratory analysis:			
Alk	NO_2+NO_3–N	Water samples taken at all inflow and outflow stations both sites.	Water samples taken at all inflow and outflow stations both sites.
TSS	NH_3–N		
TDS	Total N		
Cl^-	PO_4–P	Weekly sampling after startup Nov-1995 through Dec-1996.	Weekly sampling after startup Nov-1995 through Dec-1996.
SO_4	Diss. P		
TKN	COD		
NO_2–N	BOD	Monthly sampling through end Jan-1997 through Jul-1998.	Monthly sampling through end Jan-1997 through Mar-1998.
NO_3–N	TOC		
Hydrologic data:			
Inflow rate Outflow rate Water depth		Daily measurements throughout first 2 years monitoring.	Daily measurements throughout first 2 years monitoring.
Climate data:			
Precipitation Pan evaporation		Continuous climate data retrieved from Arizona Meteorological Network (AZMET) station in Tempe, Arizona (AZMET, 2001).	

Overall Experimental Plan

The monitoring parameters, operations testing phases, and site configurations form the matrix of conditions. The experimental plan incorporates different open water configurations, different conditions at the Hayfield and Cobble sites, and a series of hydraulic operations. To a certain extent this is advantageous because the data collected can support multiple research topics; however, this approach also requires significant coordination to avoid interference between activities, make changes and handle inevitable problems. Ideally, the period of each operating condition tested allows sufficient time for the wetland processes to stabilize and time to collect an adequate amount of data to compensate for the inherent variability in large wetland systems. Longer term monitoring is important to evaluate seasonal and long term changes in newly created wetlands. The overall experimental plan also allows flexibility to make adjustments

according to water operations, staff capabilities, and other problems encountered (e.g. flow control, de-watering, mosquitos, etc.).

Water Quality Evaluation Approach

The approach used to analyze and evaluate the water quality data were comprised of two main steps. First, appropriate data analysis methods were selected and applied to characterize water quality conditions based on all data collected for the entire matrix of test conditions. This was followed by a series of comparative evaluations using the subsets of the data corresponding to the different cell configuration and operating conditions described in the monitoring strategy. The sequence and overall approach applied in the water quality evaluations are indicated in table 3-8.

Table 3-8. Water quality evaluation sequence and approach.

Water Quality Evaluation	Sites	Evaluation Approach
General performance	Hayfield Cobble	All data - Inflow to outflow: Concentration change, percent change mass removal, percent mass removal.
Load rate functions	Hayfield	Data sets by operating condition, H1 and H2, with % change and % removal versus: a) Inflow areal hydraulic load rate (HLR) b) Theoretical hydraulic retention time (HRT)
Internal configuration	Hayfield	All data for each cell H1 and H2: Percent removal, cumulative probability, combined effects with HLR or HRT.
Seepage loss effects	Cobble	All data for each cell C1 and C2: Percent removal comparison with and without seepage correction applied.
Combined site effects	Hayfield/Cobble	All data site comparison for matrix of cells: H1/C1, H1/C2, H2/C1, and H2/C2.
Empirical comparison	Hayfield	All data for different operating conditions: Comparison of coefficients calculated using empirical areal and volumetric rate functions.

There are many different physical, chemical, and biochemical process mechanisms (e.g. sedimentation, adsorption, precipitation, hydrolysis, photolysis, oxidation, reduction, and bio-uptake) that influence the transport, transformation, and fate of water quality constituents (EPA, 1999b). Wetlands are diverse ecosystems that can produce a wide range of conditions that may vary spatially or temporally to mediate different processes (e.g. exposure to sunlight, primary production, soil interactions, hydraulic gradients, aerobic and anaerobic microbial assimilation).

The evaluation approach was intended to break down operative factors that regulate water quality (e.g. load rates, configuration, water budget) to obtain information and practical experience useful in planning for water reuse, wildlife habitat, and public use aspects of constructed wetlands in the Tres Rios area.

The following paragraphs briefly describe some of the basic concepts applied in the water quality evaluations. Detailed information concerning fundamental principles and experience from other wetland projects is available in the references cited (e.g. CH2MHill, 1995; Kadlec and Knight, 1996; EPA, 1999b; EPA, 2000).

General Performance Evaluations

The wetland water quality performance was evaluated first based on the net changes in chemical concentration from inflow to outflow using all of the data collected from the Hayfield and Cobble sites. Cobble site data were examined on a concentration and total mass basis to account for water budget (seepage loss) effects.

Change in concentration:	ΔC	$= C_i - C_o$
Percent change:	$\%C_i$	$= (C_o - C_i) / C_i \times 100$
Percent reduction:	$\%C_i$	$= 1 - (C_o / C_i) \times 100$
Change in total mass:	ΔM	$= C_i Q_i - C_o Q_o$
Percent mass removal:	$\%M_i$	$= 1 - (M_o/M_i) \times 100$

Where:	ΔC	=	change in concentration
	C_i	=	inflow concentration
	C_o	=	outflow concentration
	Q	=	inflow or outflow rates
	M	=	total mass, C x Q

Positive reduction or mass removal values imply net loss, and negative values would indicate an increase in concentration or net gain in total mass.

Water Budget and Mass Balance

A simplified water budget expression was used to evaluate hydrologic factors that could influence water quality in the demonstration wetlands.

Change in water volume: $\Delta V/\Delta t = Q_i - Q_o + (P - ET - I)\,A$

Where:	$\Delta V/\Delta t$	=	change in volume over time
	Q	=	inflow or outflow rates
	A	=	surface area of wetland basin
	P	=	precipitation on the wetlands
	ET	=	wetlands evapotranspiration
	I	=	infiltration (seepage) losses

The water budget may be combined with corresponding concentrations to represent the mass balance for a chemical constituent. For example, the areal mass balance based on the simplified water budget components is expressed:

Mass balance: $C_iQ_i = C_oQ_o + C_{pr}Q_{pr} - C_{et}Q_{et} - C_{inf}Q_{inf}$

Where:	C_iQ_i	=	mass loading from inflow
	C_oQ_o	=	wetlands outflow mass
	C_{pr}	=	precipitation mass loading
	C_{et}	=	evapotranspiration mass loss
	C_{inf}	=	infiltration seepage mass loss

For the water quality data analysis, storm runoff was considered insignificant because the demonstration sites are graded to direct moderate runoff flows away from the wetland cells. Data from a local weather station was used to estimate precipitation and evapotranspiration effects (AZMET, 2001). Groundwater discharge into the wetlands was not observed during construction, and subsurface inflow was neglected in the analysis. Seepage losses were estimated indirectly, by net subtraction of other components available in the hydrologic monitoring data.

Chemical concentrations of precipitation and evapotranspiration were assumed zero, whereas seepage from the wetlands was assumed to have the same concentration as wetlands outflow. Inflow and outflow concentrations were derived from the water quality data collected for the monitoring period indicated.

Hydraulic Loading Functions

The inflow loading and hydraulic conditions established in a wetland system are key factors that affect water quality. Hydraulic flow influences the nature of processes produced in the wetlands, the circulation and transport through different zones, and the total amount of time for transformations to occur.

The wetland operating conditions are often expressed as a function of the water supply inflow hydraulic load rate (HLR) or the theoretical hydraulic retention time (HRT) based on ideal steady-state, plug flow hydraulic conditions.

Areal hydraulic load rate: $HLR = Q_i/A$

Hydraulic retention time $HRT = V/Q_i$

Where: Q_i = inlet flow rate
A = surface area of wetland
V = volume of wetland basin (or void volume adjusted to exclude ineffective volume that is occupied by wetland vegetation)

The areal HLR is an easy reference to compare systems or operating conditions when the actual depths and water volumes are not known. Theoretical retention time, HRT is calculated based on defined system dimensions, depth, void volume (porosity), and ideal flow conditions. Comparing the actual retention time (measured) versus the calculated HRT is also useful to evaluate the hydraulic efficiency .

These expressions are of interest because they are tied to available design guidelines for wetland systems. For example, operating conditions reported for surface flow wetlands indicate HLR ranges from about 1 to 4 in/d (2.5 to 10 cm/d) and the typical range for HRT is about 5 to 15 days (EPA, 1999b).

A comparative approach was applied to evaluate HLR and HRT against water quality data for monitored constituents. Hayfield Site data were used because of the more consistent hydraulic control and seepage loss effects. The analysis was simplified by assuming the wetlands surface area, geometric shape, aspect ratio, and bottom grades were fixed. This allows direct correlation between HLR and inflow rate data, and HRT and water depth data for each respective inflow test condition.

HLR was evaluated by examining differences in the H1 and H2 data, the effects of the different HLR test conditions, and then cross-comparison of cell configuration effects against HLR changes. HRT effects were evaluated similarly using depth to represent retention time for the respective inflow rates tested. Correlations between percent change in concentration and HLR, HRT, depth, inflow temperature, and the inflow concentration were also compared for all H1 and H2 cell data.

Internal Configuration

The internal configuration refers to the different number of open water and emergent vegetation zones established in the H1 and H2 wetland cells. Data from the two cells were compared in the general performance evaluations and reviewed with respect to the hydraulic loading functions and empirical relationships. The

evaluation focused on the dissolved oxygen, BOD, and nitrogen parameters that would be sensitive to re-aeration or oxidation-reduction conditions and thereby help reveal differences associated with the alternative wetland open water configurations.

Seepage Evaluations

A comparative approach was also applied to evaluate differences in seepage losses from the Cobble Site lined (C1) and unlined (C2) wetland cells. This was done on a concentration basis in the general performance evaluations and on a mass basis to account for chemical loading that exit the wetland through infiltration and seepage flows. Percent removal was compared for the monitored water quality constituents with and without adjustment for seepage losses. Seepage effects were also evaluated based on the Hayfield site data, to compare against the cobble site results.

Demonstration Site Comparison

Water quality data from the Hayfield and Cobble sites were compared to evaluate any trends in the maximum and median values between the four demonstration cells. The significance of differences in percent concentration change were examined using a cross-comparison statistical approach. Operating conditions of the four cells were also evaluated to assess the significance of water budget effects.

Removal Rate Functions

Empirical removal rate functions have been derived to predict constituent removal and develop design sizing guidelines for treatment wetland projects. Design model relationships are currently reported for BOD, TSS, TN, NH_4, NO_3, TP, and coliform bacteria (EPA, 1999b). The resulting empirical relationships represent the end product of all collective reactions in a wetland system. Nevertheless, the reaction rate coefficients reported for other wetlands are a useful point of reference to evaluate treatment performance of the Tres Rios demonstration wetlands.

The general rate function for chemical decay processes (removal) illustrates the approach commonly used in surface flow wetlands design relationships. The general rate function assumes ideal steady-state, plug flow hydraulic conditions.

General decay function: $C_t = C_0 \exp(-k\,t)$

Where:
- C_t = concentration at time, t (e.g. at a point downstream)
- C_0 = initial concentration at time, t = 0 (e.g. at the inlet)
- k = first order reaction rate constant (derived empirically)
- t = reaction time (e.g. hydraulic function HRT or 1/HLR)

In water quality modeling, reactions rates are commonly reported at 20 °C. Reaction rate constants for temperature-dependent relationships (such as BOD) can be adjusted to represent actual temperature.

Temperature adjusted rate: $k_T = k_{20}\,\theta^{(T-20)}$ or $k_{20} = k_T\,\theta^{(20-T)}$

Where:
- k_T = reaction rate constant at temperature, T
- k_{20} = reaction rate constant at 20 °Centigrade
- θ = empirical temperature coefficient
- T = actual (measured) temperature of interest

The ideal plug flow decay function implies a first order decrease in the constituent concentration as water passes through the system. Specific single system models can be developed from data taken at intermediate points along the wetland flow path; however, model relationships are more commonly defined using an input/output mass balance approach. Inflow and outflow data are collected at different depths or different inflow rates that represent reaction time (t) as a function of volumetric detention time (t ~ HRT) or the areal load rate (t ~ 1/HLR).

In a single system wetland inflow-outflow function, C_t is defined as the outflow concentration, C_o (or C_e for effluent concentration), and inflow concentration, C_i is used to represent C_0 (for t = 0 in generic formula). Rate constants are derived for either the volumetric or areal hydraulic characterization.

Current wetland design model rate constants were derived based on inflow-outflow data from multiple systems and/or operating conditions that encompass a range of time samples used to define empirical relationships. Volumetric and areal functions have been derived for wastewater constituents based on data compiled in database sources such as NADB Version 2.0 (EPA, 1999c). Actual performance may depend on both functions; however, the areal approach offers practical advantages in dealing with large data sets where the effective depth and volume are not known.

For these purposes, rate coefficients calculated using Tres Rios data were compared against literature values. The evaluation included both a volumetric expression and an areal load rate function reported (EPA 1999b). Water budget effects were not incorporated although the Hayfield site data were used to avoid

complicating factors caused by seepage effects and operational problems at the Cobble site.

Reed et al. (1995): $C_o / C_i = \exp(- k_{VT}\, t)$

Kadlec and Knight (1996): $(C_o - C^*) / (C_i - C^*) = \exp(- k_{AT} / q)$

Where:	C_o	=	outflow concentration
	C_i	=	inflow concentration
	C^*	=	background concentration
	k_{VT}	=	volumetric temperature-dependent rate constant
	t	=	theoretical hydraulic detention time (~HRT)
	k_{AT}	=	areal temperature corrected reaction rate constant
	q	=	nominal hydraulic loading rate (~HLR)

The background concentration (C^*) was estimated for the Tres Rios data to compare with reported values (Kadlec and Knight, 1996). Volumetric rate constants for BOD, NH_4–N, and NO_3–N were adjusted for site temperature data. No temperature correction was applied in calculating areal rate constants.

The comparison recognized that reported rate constants reflect the aggregate tendency of the data set, which may include widely variable systems, climate conditions, and operations. The water quality evaluation did not attempt to explore the original data sources to adjust or compensate for these factors.

Data Analysis Methods

The water quality monitoring data were analyzed using a variety of classical statistical analysis methods that were appropriate for each evaluation topic. Raw data sets were first reviewed to apply conversions, assign ranking codes, and develop extrapolated data sets necessary for the respective analyses. Data pre-screening, manipulation, and statistical analysis methods are briefly summarized for reference.

Statistical Analysis Methods

The data analysis involved step-wise iteration of statistical methods and calculations that were applied to focus on water quality topics of interest. The variables or basis of comparison for analysis and the types of statistical methods applied are indicated in table 3-9. Further explanations of the sequence of data analysis and interpretation of intermediate products are also illustrated by example in the results.

Table 3-9. Data analysis methods applied by topic.

Water Quality Topics	Variable / Comparison	Statistical Methods
Data review and general performance evaluations (Hayfield, Cobble)	inflow / outflow concentration change mass removal % change % removal all data, all cells	descriptive statistics skewness, kurtosis Lilliefors normality test regression analysis cumulative frequency paired t-test Wilcoxon signed-ranks
Load rate functions (Hayfield)	% change % reduction load rate depth wetland cells cross-comparison	descriptive statistics Mann-Whitney Kruskal-Wallis ANOVA 2-way ANOVA Spearman correlation
Internal configuration (Hayfield)	inflow / outflow % change % reduction load rate depth wetland cell	descriptive statistics regression analysis Wilcoxon test cumulative frequency 2-way ANOVA
Seepage loss effects (Cobble)	inflow / outflow % removal wetland cell	descriptive statistics time series plots paired t-test
Combined site effects (Hayfield, Cobble)	% change % reduction site comparison water budget	descriptive statistics Mann-Whitney
Removal rate comparison (Hayfield)	model rate constants predicted concentrations	direct comparison of empirical model results

Note: ANOVA = Analysis of Variance

The analysis of data were performed using commercially available computer software including Lotus® millennium edition (version 9) spreadsheet and SYSTAT®, versions 7 and 8 (SPSS, 1998). Appendix B includes a description for the statistical methods excerpted from the SYSTAT® version 10 documentation.

The type of analysis applied depends on the nature of the data set and the topic of interest. For example, the evaluation of general water quality characteristics was based on *all* data for the entire first phase monitoring. In other cases, the data were segregated into subsets according to the evaluation matrix described previously.

Both parametric and nonparametric analytical techniques were used to analyze the water quality monitoring data sets. For example, in a paired analysis (inflow *vs.*

outflow concentrations), the parametric technique such as a t-test compares the magnitude of inflow and outflow concentration differences to evaluate statistical significance. In other words, a paired t-test tests whether the magnitude of the outflow concentration differences is significantly different from zero.

A nonparametric test, such as the Wilcoxon signed ranks test, evaluates the frequency of positive *vs.* the frequency of negative differences against an expected split of 50 percent each based on X^2 (chi square) distribution. Consequently, the Wilcoxon test would evaluate whether the outflow concentration is *consistently* higher or lower than the inflow concentration.

Unpaired t-test and nonparametric Mann-Whitney tests were used to compare the performance between cells at the Hayfield and Cobble sites. The nonparametric Mann-Whitney test ranks all of the data. This transforms the data into a uniform distribution, which can be statistically treated like a normal distribution. Although large outliers were discarded before the analysis was run, there are still distributional problems in performing parametric analyses. These problems arise from laboratory detection limits (or more accurately, reporting limits). The nonparametric test also compensates for data that are reported as "<" for a specific analytically "censored" result. Consequently the nonparametric results are considered more definitive for laboratory measurements where censored data are present.

Larger comparisons, using three or four categories such as HLR and HRT, were compared using analysis of variance (ANOVA), or the nonparametric Kruskal-Wallis one-way ANOVA. The parametric ANOVAs, individual categories were compared using the *post-hoc* Fisher's least significant difference technique. These statistical methods were used to compare inflow and outflow concentrations and mass loads, percent reduction in concentrations, and percent removal of mass loads. Infiltration was evaluated by calculating the mass load lost to seepage by averaging the inflow and outflow concentrations and calculating the load in the seepage flow.

In most cases the comparative evaluations were based on either the percent change or percent reduction in concentration from inflow to outflow; however, evaluations of seepage loss effects were based on the mass removal. Percent removal was calculated based on the total inflow and outflow mass loads to include any loss to groundwater infiltration as part of the treatment removal. To evaluate the significance of the loss to groundwater, the estimated infiltration load was added back to the outflow load data and the removal was then recalculated. The mass removal for seepage corrected and uncorrected loads were then compared using paired t-tests and Wilcoxon tests to evaluate the significance of any differences.

Data Review and Preprocessing

Complete data sets for all first phase monitoring were compiled into spreadsheet files by the city of Phoenix. The data categories shown in table 3-6 indicate the sources and type of data collected. These data sets were reviewed and conversions made as necessary to convert data into a form suitable for the statistical analysis and water quality interpretation.

Water quality data were generally converted into weekly form. The field data—water temperature, pH, DO, and EC, were collected daily during the early monitoring and then more sporadic two to three times weekly. All field data were examined first to evaluate distribution characteristics and then converted to weekly values. Residual chlorine data were only collected during the early monitoring (35 total samples).

A large body of laboratory analysis data includes a set of chemically conservative water quality constituents (TDS, alkalinity, chloride) and performance measures for the wetlands (TSS, BOD, COD, TOC, nitrogen, and phosphorus forms). The nitrogen data include ammonia (NH_4–N), nitrite (NO_2–N), nitrate (NO_3–N), NO_2+NO_3–N, TKN (total Kjeldahl nitrogen—a measure of organic plus ammonia nitrogen), and total nitrogen (TN) calculated as the sum of the components. Phosphorus measurements included dissolved P and orthophosphate (PO_4–P). Total phosphorus was not analyzed. Sulfate analysis was done on samples collected later in the study, but those data are not included in this analysis.

Laboratory data were collected weekly early in the study and later monitoring was reduced to monthly samples. The change was handled in two ways in the data review. For summary purposes, the raw data were used without modification other than to discard obvious outliers. Treatment performance evaluations based on the experimental design described earlier were accomplished by expanding the monthly data to weekly by interpolating between samples using the weekly water budget or field parameter measurement dates to time-weight intermediate data points. Monthly water samples were assumed to represent the water quality for the entire month and interpolation was considered appropriate to unweight the sample frequency for the respective operational study phases.

Water quality data below the minimum analytical detection level were reported as less than (denoted <) the detection level concentration. These non-numeric values were converted to equal one-half the minimum detection level for the statistical processes. The effects of having numerous censored values on the data distribution characteristics are discussed in the result.

Hydraulic operations data included daily measurements of inflow rate, outflow rate, and water depth. These daily operations data were converted to weekly values to coincide with the water sampling data. Water volumes were calculated

simply as the surface area times depth, disregarding effects of bank slope or volume occupied by emergent wetland vegetation. Consequently, the cell surface area was fixed and calculated water volume and HRT were proportional to water depth at constant flow rate, and HLR was only a function of inflow rate.

Wetland surface areas determined by aerial survey in 1996 (Reclamation, 1997) were used throughout this study. Another aerial survey conducted in 1997 (Wass, 1997) indicated an increase in area as depth increased. It should be noted that these effects do not affect the statistical results because statistical analyses are based on relative changes rather than absolute values (e.g. in depth, area, volume, porosity, HRT).

Precipitation and pan evaporation data were obtained daily during the monitoring from the Arizona Meteorological Network AZMET (2001) weather station located about 10 miles from the demonstration wetlands. Evapotranspiration was estimated using the weather-based Penman Equation model based on the reference evapotranspiration values and an assumed "crop coefficient" K_c of 1.0 for the fully saturated wetlands conditions. As a cross-check rule, the evapotranspiration was assumed to be about 0.80 times the pan evaporation values. Wetland surface areas derived from the 1996 aerial survey were also used to calculate changes in water volume for precipitation, evapotranspiration, and infiltration components.

Weekly depth and flow measurements and the aerial survey surface area were used directly in the comparison of areal and volumetric rate functions. The areal HLR and theoretical HRT were used to calculate the rate constants (k-values) associated with the respective empirical design models. Concentrations predicted from the two rate functions were calculated and compared to literature reported values.

Water Budget Data Review

Hydrologic and water budget data were reviewed against the operations plans and converted into a format suitable for statistical analysis. This was accomplished in three steps. Data for the wetlands inflow, outflow, precipitation, ET, and infiltration components were reviewed to evaluate overall water budget effects and differences in the actual measured data versus planned operations. Inflow, outflow, and seepage data for the Hayfield and Cobble sites are plotted in figures 3-3 and 3-4.

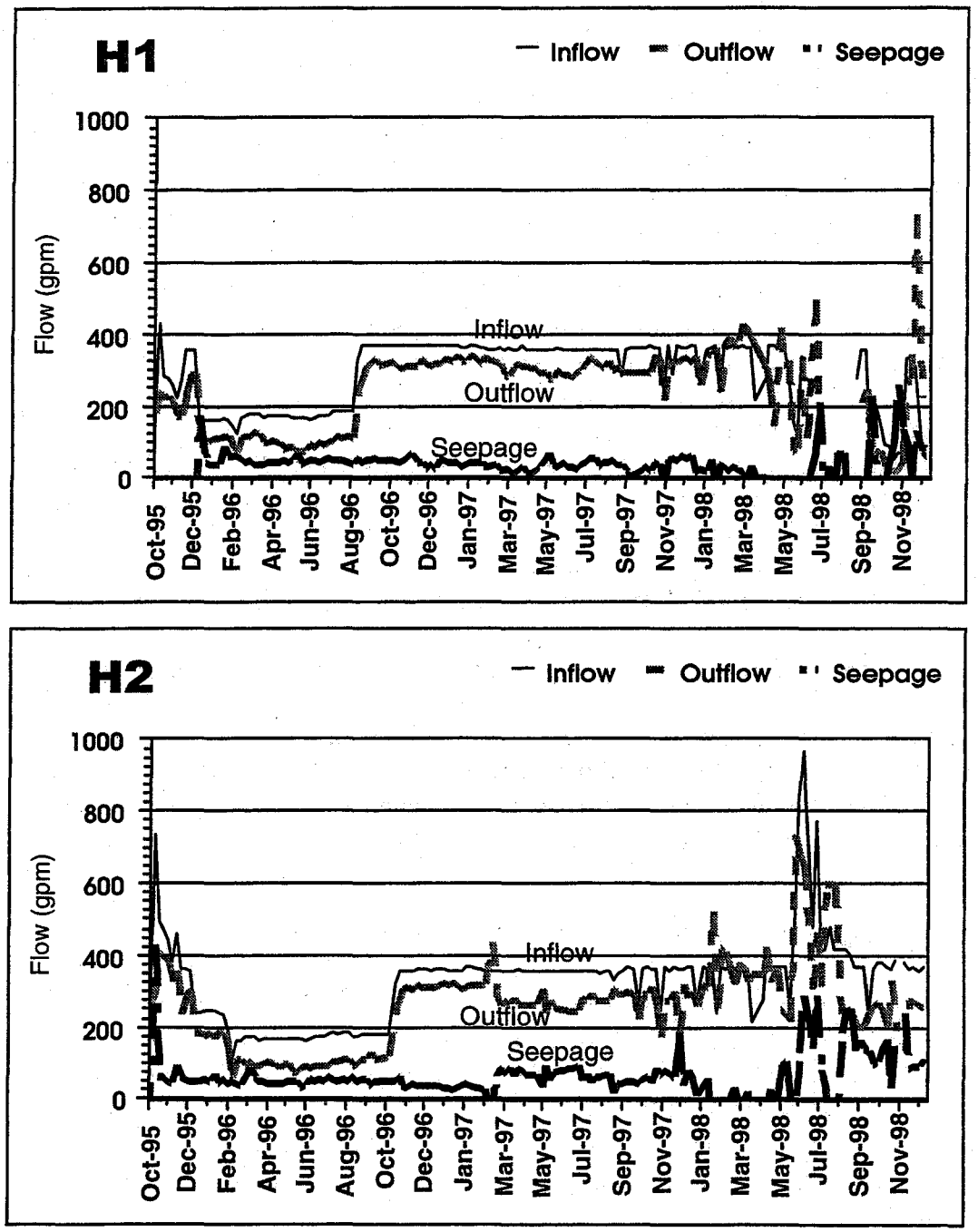


Figure 3-3. Inflow, outflow, and seepage for the Hayfield site H1 and H2 wetland cells.

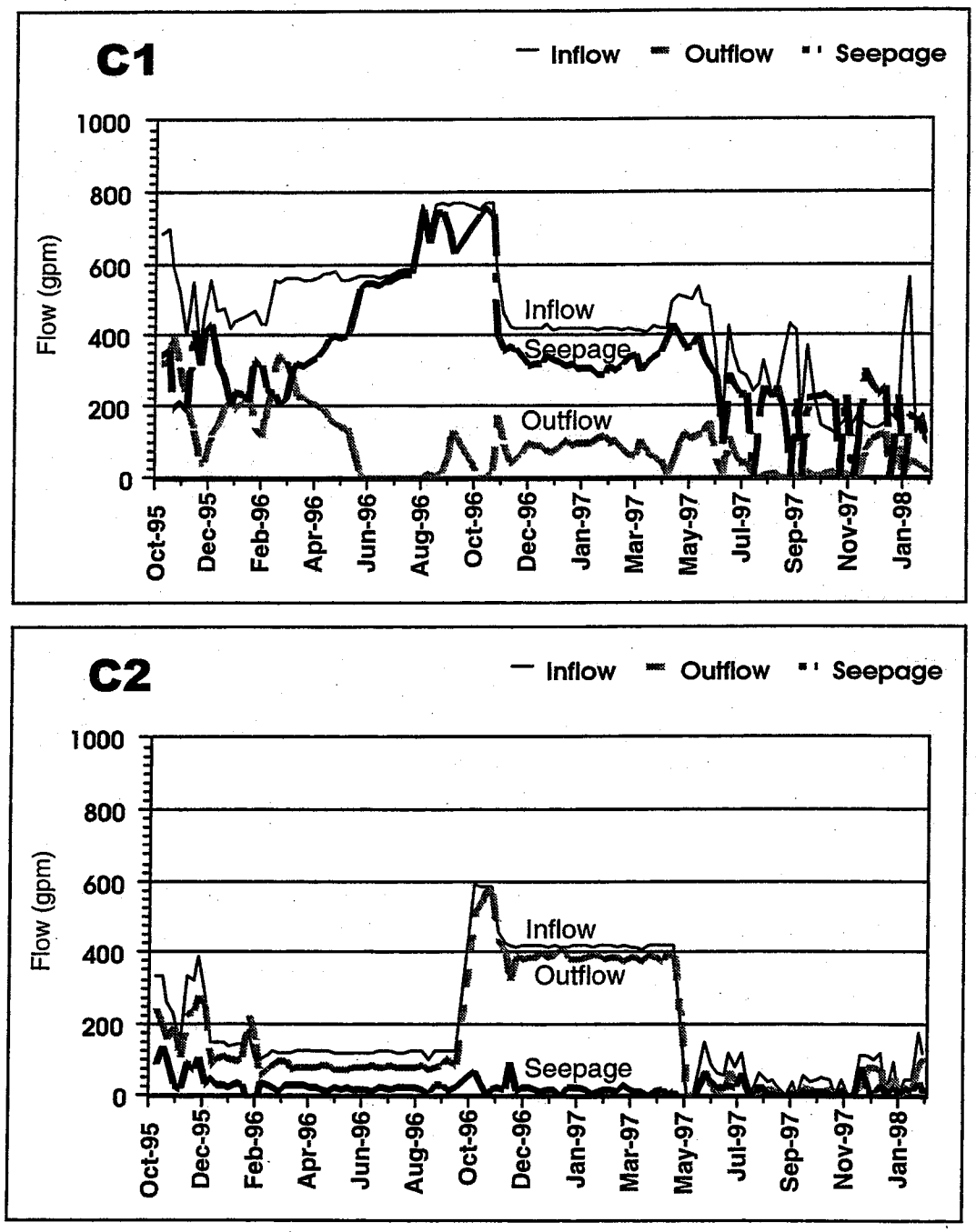


Figure 3-4. Inflow, outflow, and seepage for the Cobble site C1 and C2 wetland cells.

The seepage component shown in these plots is calculated from the monitoring data with corrections for precipitation and ET. Precipitation and ET are minor compared to the three water budget components shown on the plots. Significant seepage losses in the unlined Cobble site cell are evident in the C1 data plot.

The water budget plots also show the erratic data at both the beginning and ending stages of monitoring. Minor fluctuations at the start up are attributed to the initial filling and water control to establish vegetation. A number of factors affected water control in the later stages of operations, including beavers plugging outlets, operations to assist in mosquito control activities, and dewatering to re-plant and recondition the wetlands cells.

Water quality data for the months with highly variable hydraulic control were not included in the data analysis. For the Hayfield site, monitoring data collected from December 1995 to May 1998 were used in analysis. The Cobble site evaluations only included data collected from December 1995 through May 1997, when the wetlands were shut down to restore vegetation and modify the test configuration.

Operations Data Conversion

Planned operations cited in tables 3-3 and 3-4 are roughly apparent in the inflow data plots. The translation of inflows to HLR and water depths measured at the Hayfield and Cobble sites are plotted in figures 3-5 and 3-7. The actual operations phases are evident by the plateaus in the HLR and depth data plots. Actual operations differed somewhat from the planned operations schedule for a variety of reasons.

Monitoring data were divided into subsets corresponding to the actual operations to evaluate relationships between water quality performance and changes in operating conditions. The actual operations were converted into relative test code groups used in statistical data analysis. Hayfield site operational test phases A, B, C, and D shown in figure 3-6 correspond to measured operations plotted in figure 3-5. Similarly the Cobble site operational test phases A, B, and C shown in figure 3-8 correspond to the measured operations data plotted in figure 3-7. Each test phase has a respective depth and HLR ranking codes used in statistical analysis.

To present figures 3-5 and 3-6 on opposite pages and, in turn, 3-7 and 3-8 on opposite pages, most of a blank page has been inserted to allow this presentation.

The data subsets or phases represent a combination of depth and inflow loading rate operating conditions that can be compared against water quality data. For example, an evaluation of load rate effects at the Hayfield site would involve data sets A and B to compare different load rates at constant depth. An evaluation of

depth effects could include water quality data sets B, C, and D which have constant inflow rate for three different changes in depth. Note that a depth evaluation is equivalent to HRT comparison when the inflow load rate and surface area are constant.

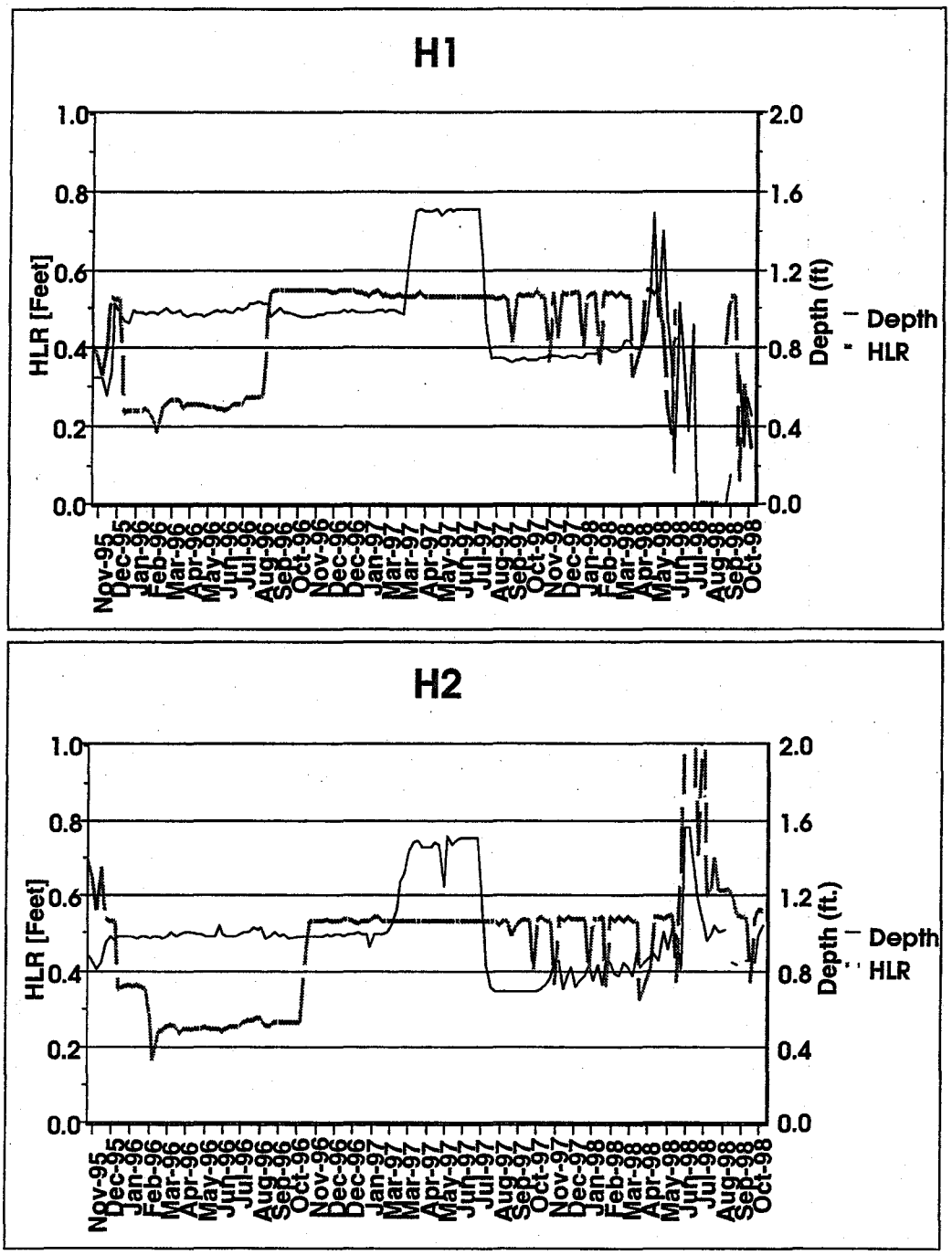


Figure 3-5. Depth and inflow hydraulic load rate (HLR) for the Hayfield site wetlands.

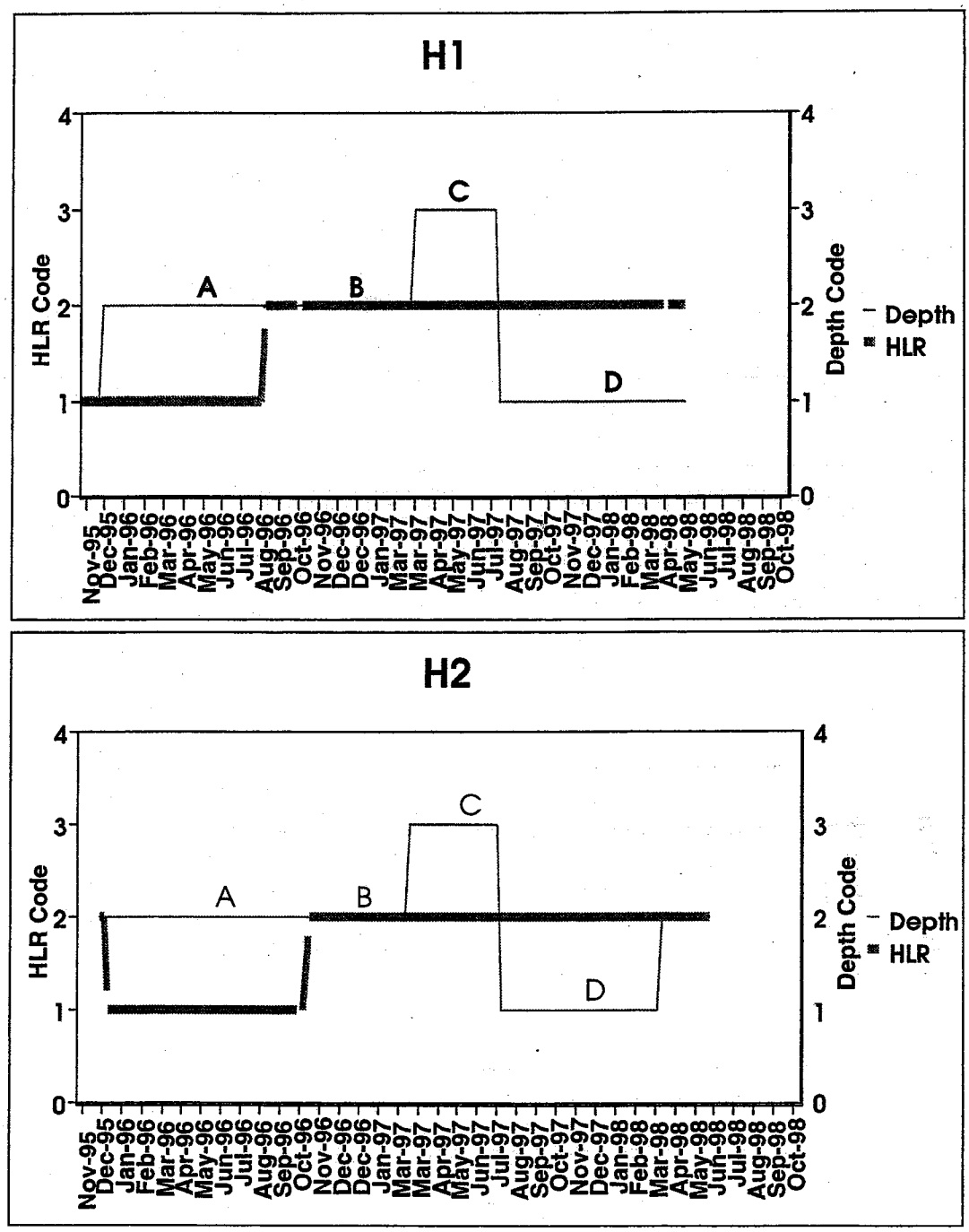


Figure 3-6. Operational test phases for Hayfield site monitoring data.

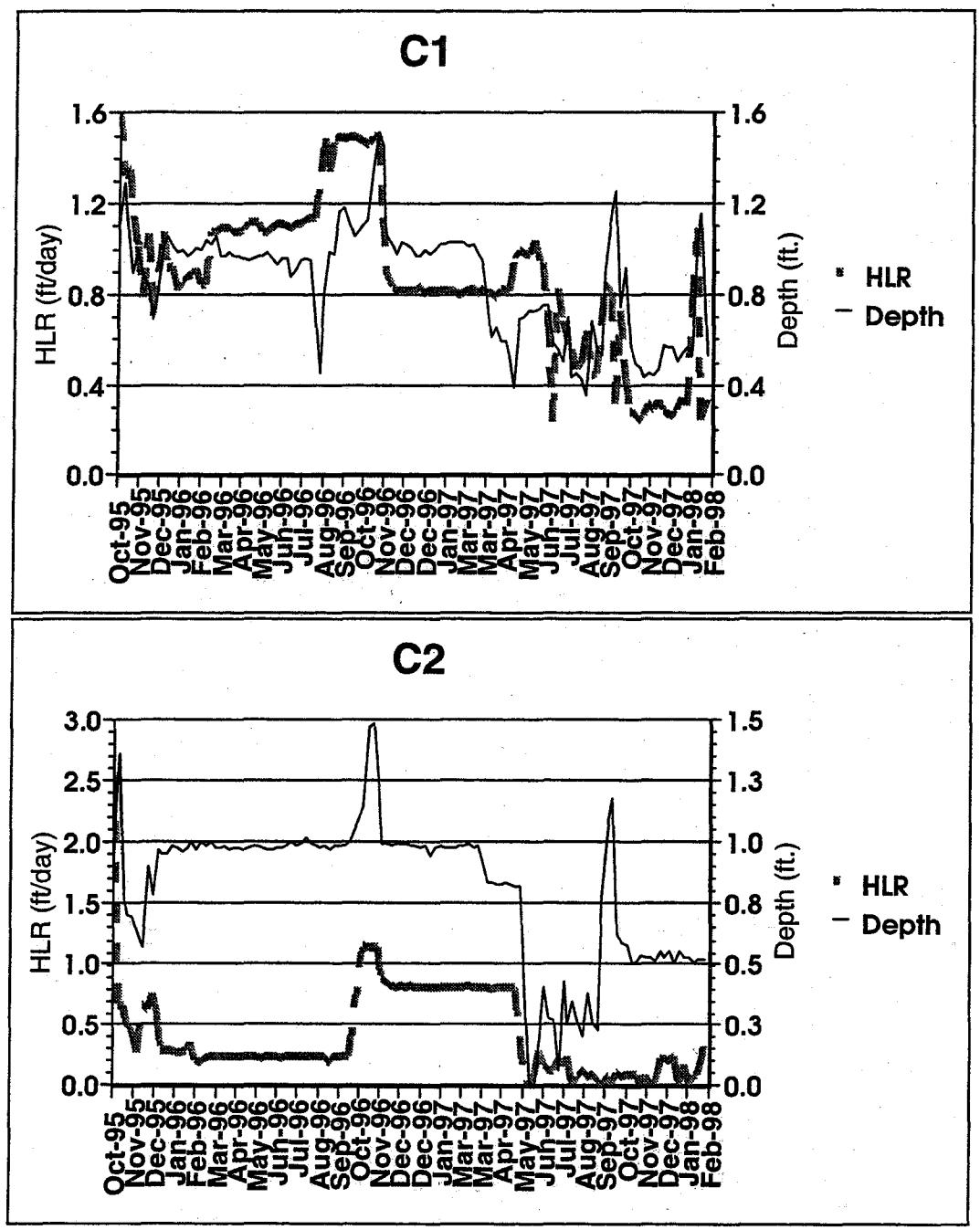


Figure 3-7. Depth and inflow hydraulic load rate (HLR) for the Cobble site wetlands.

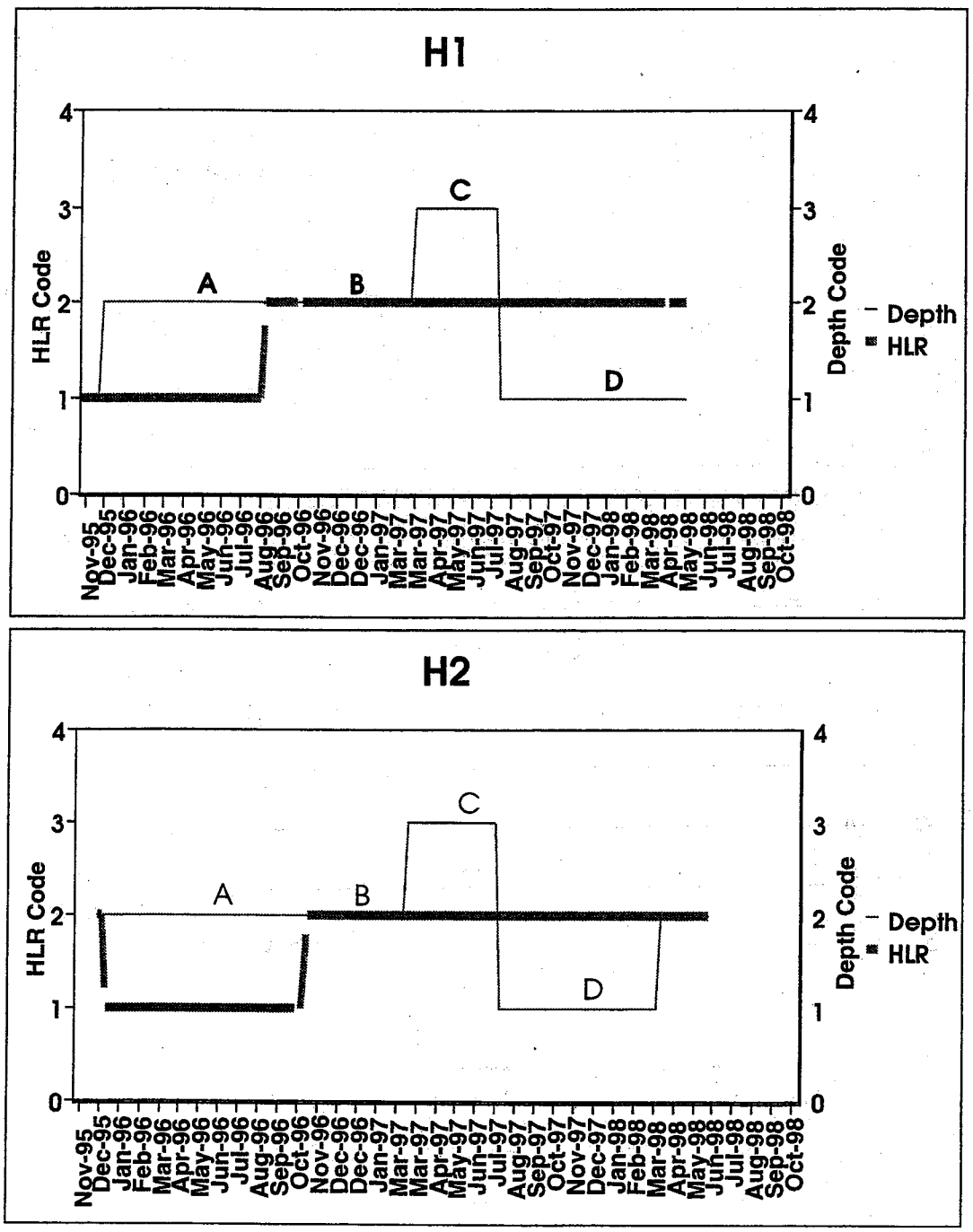


Figure 3-6. Operational test phases for Hayfield site monitoring data.

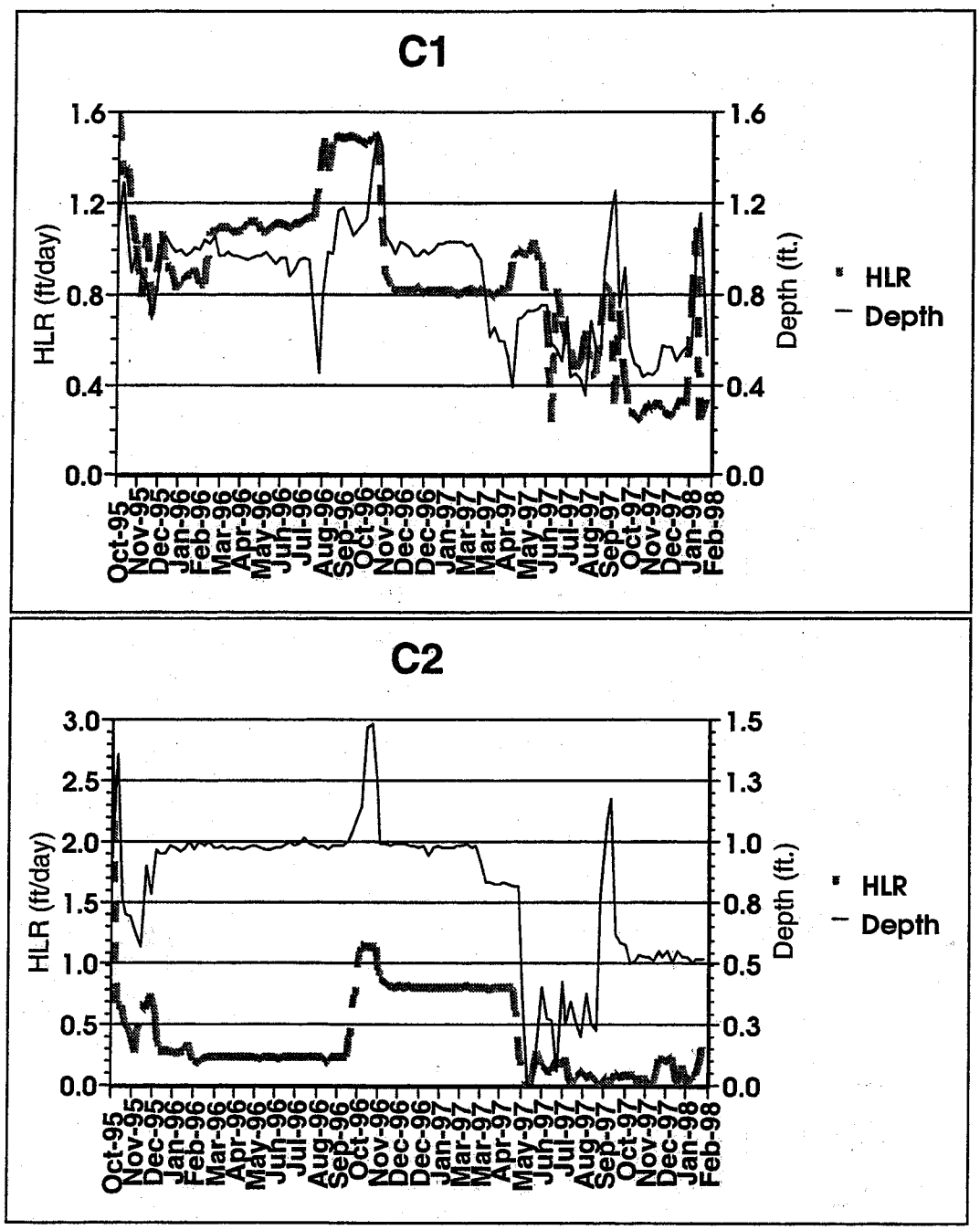


Figure 3-7. Depth and inflow hydraulic load rate (HLR) for the Cobble site wetlands.

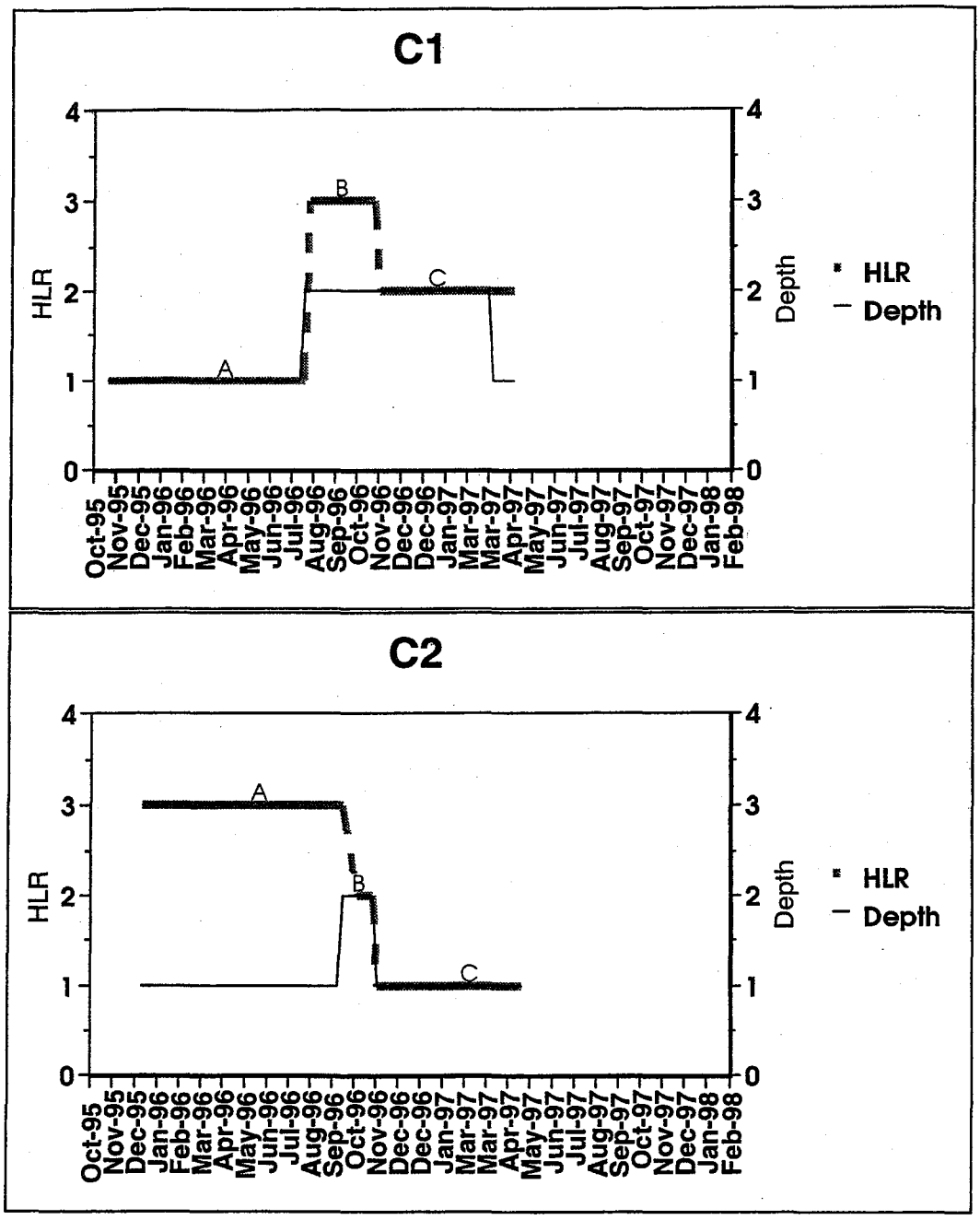


Figure 3-8. Operational test phases for Cobble site monitoring data.

Chapter 4

Water Quality Results and Findings

Technical results and findings from the data analysis investigations are described in this chapter. The initial data review and sequence of analysis are described in the first section, using temperature as an example. The second section presents overall water quality results based on all monitoring data collected at both wetland demonstration sites. This is followed by a series of results from the comparative investigations, including hydraulic rate functions, open water effects, seepage loss effects, site relationships, and comparison of the Tres Rios water quality findings using two empirical design models reported in the literature.

Initial Data Review

A series of computations and statistical procedures were applied in sequence to examine the data and evaluate specific topics. Generally, the different types of analyses were applied to all water quality data sets, although only the significant results are presented. Some intermediate results were only used to examine data characteristics and help define further analysis. The initial data review and results are described using field measurement data for residual chlorine, pH, DO, EC, and temperature data as examples of the analysis process.

Temperature Effects—Example

The effectiveness of the various wetland cells in improving water quality can be evaluated by comparing the inflow and outflow water quality data from each of the wetland cells. A comparison using a parametric statistical procedure (t-tests) for the field data collected at the Hayfield site are shown in table 4-1.

Values shown in the table indicate the t-value and the associated probability of an occurrence of a "t" of that magnitude by chance alone. If the probability is less than 0.05, the difference between inflow and outflow concentration for each cell would be considered significantly different. If the t-values are positive, then the outflow has a lower concentration than the inflow. If the constituent compared is one in which water quality improvement is measured by reduced concentration level, then a positive t-value indicates improvement for that parameter.

Temperature is the first variable shown in table 4-1. The t-values for the H1 and H2 cells show a significant difference (decrease) between the inflow and outflow temperatures because the probability is less than 0.05. The last two columns show a statistical comparison between the cells. This comparison indicates that there is a significant difference in the outflow temperatures of the two cells.

Table 4-1. T-test summary of field measurements at the Hayfield site.

Variable	Comparison to inflow				Cell comparison	
	H1– t	Prob. > t	H2– t	Prob. > t	H1 vs. H2– t	Prob. > t
Temperature	54.95	< 0.001	55.30	< 0.001	-6.86	< 0.001
Residual Cl_2	27.08	< 0.001	25.36	< 0.001	-2.47	0.019
pH	-11.91	< 0.001	-17.18	< 0.001	-4.63	< 0.001
DO	8.07	< 0.001	17.76	< 0.001	6.17	< 0.001
EC	-12.48	< 0.001	-8.31	< 0.001	7.14	< 0.001

Note: Positive t-values indicate a decrease in outflow concentration compared to inflow, or the H2 outflow is less than H1 in the cell comparison. Significant differences are indicated by < 0.05 probability.

Temperature comparisons using the nonparametric Wilcoxon signed-ranks test are shown in table 4-2. These comparisons once again indicate a significant decrease in outflow temperatures and a difference between the two cells.

Table 4-2. Wilcoxon [Z] test summary of field measurements at the Hayfield site.

Variable	Comparison to inflow				Cell comparison	
	H1–Z	Prob. > Z	H2–Z	Prob. > Z	H1 vs. H2– Z	Prob. > Z
Temperature	18.33		18.60	< 0.001	-7.08	< 0.001
Residual Cl_2	5.16	< 0.001	5.02	< 0.001	-2.23	0.026
pH	-12.84	< 0.001	-16.14	< 0.001	-7.01	< 0.001
DO	8.94	< 0.001	13.55	< 0.001	4.23	< 0.001
EC	-11.86	< 0.001	-8.31	< 0.001	9.49	< 0.001

Note: Positive Z-values indicate a decrease in outflow concentration compared to inflow, or the H2 outflow is less than H1 in the cell comparison. Significant differences are indicated by < 0.05 probability.

The results of Lilliefors test (SPSS, 1998) indicated the temperature data are not normally distributed, which might raise questions regarding the validity of t-test results. However, both the t-test and Wilcoxon tests are based on comparison of paired data and the validity of these parametric procedures is determined by the distribution of the residuals. Since both the parametric and nonparametric results agree, it is reasonable to conclude the significant differences are valid.

These differences are further illustrated by the inflow and outflow temperature plots in figure 4-1. These time-series plots show the outflow temperatures are significantly lower than the inflow. There is essentially no overlap between the inflow and outflow temperatures; which corresponds to the large t-values shown in table 4-1 (about 55). Additional time-series plots for other monitored water quality constituents are included in Appendix C.

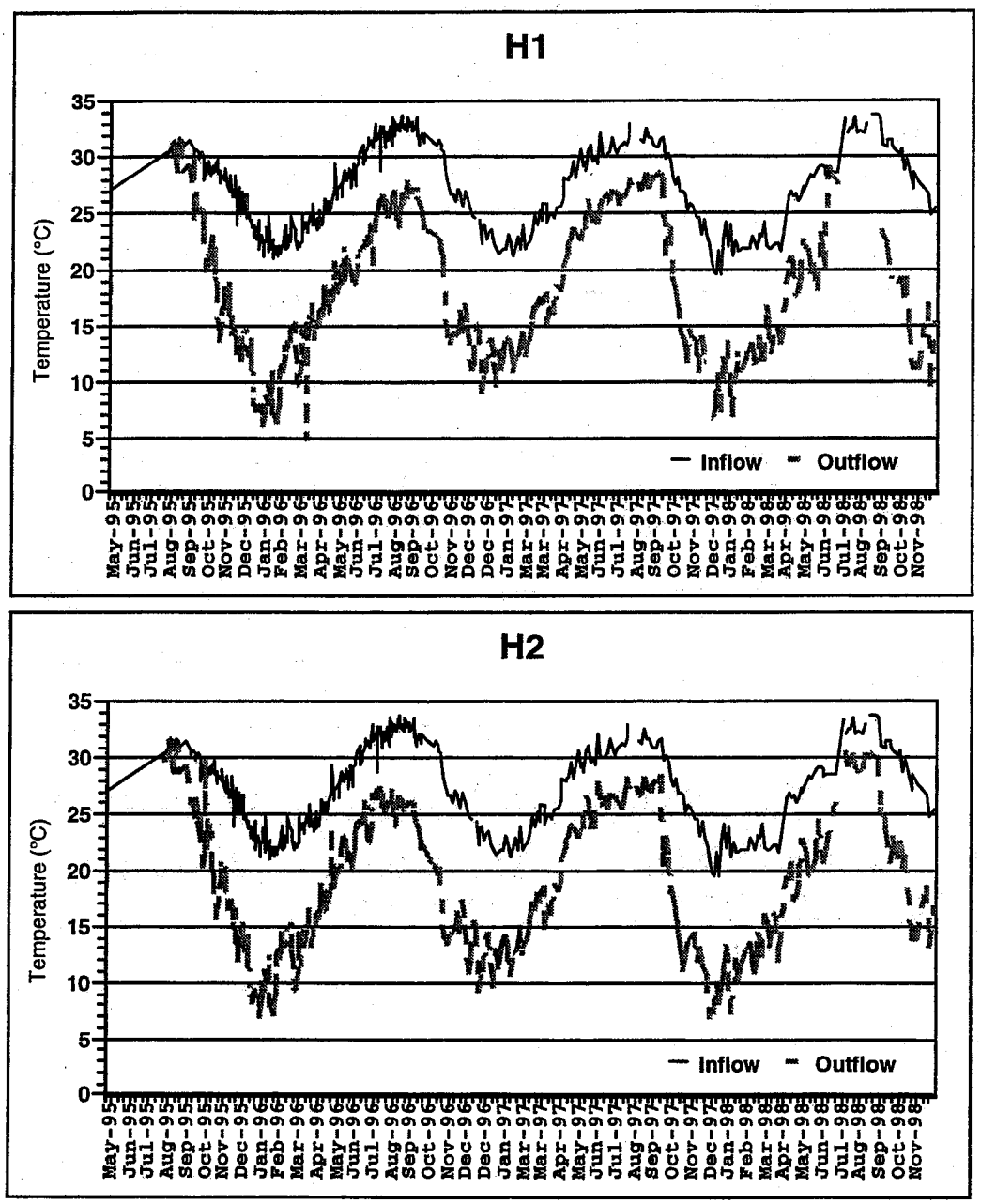


Figure 4-1. Inflow and outflow temperatures of the Hayfield site wetland cells.

Figure 4-2 shows an overlay of the outflow temperatures for the two Hayfield site cells. In this case, it is difficult to see that there is any difference between the two data sets; however, there are numerous spikes in the H2 data that extend above the H1 values. Apparently, these high values are great enough to make the H2 mean temperature (18.8°C) exceed that of H1 (18.4°C). Although the mean difference is relatively small, the number of observations is sufficient to produce the significant difference revealed by the statistical t-test results.

The frequency distribution is another way of looking at the data. A comparison of the cumulative frequency distributions for Hayfield site outflow temperature data are shown on the lower plot in figure 4-2. The outflow temperature distributions are similar in shape, but there is little overlap between the plots. The cumulative frequency reveals differences between the cells that are not evident in time-series plots. The cumulative frequency distributions shown graphically in the figures are the basis for non-parametric statistical comparisons.

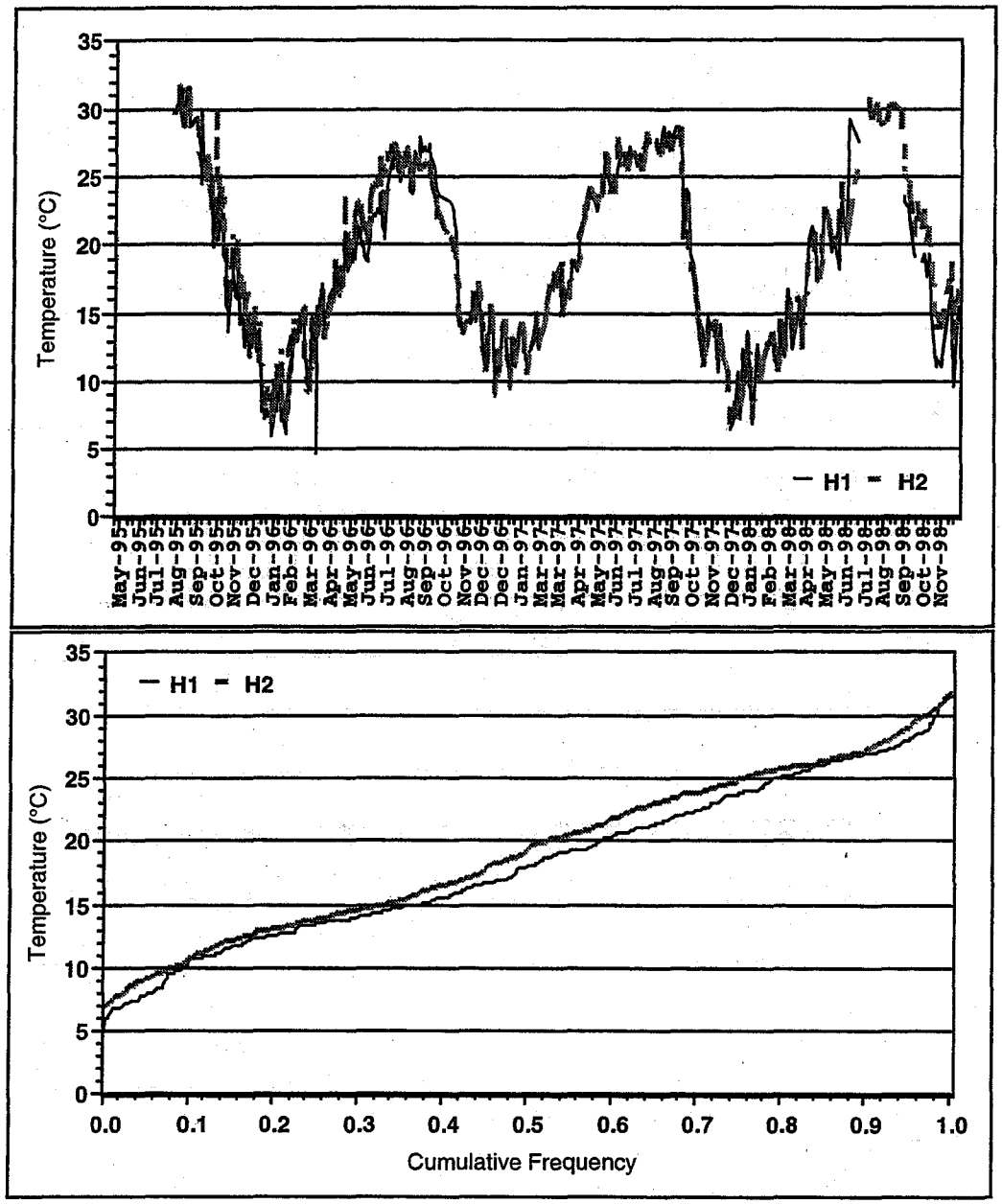


Figure 4-2. Time-series and cumulative frequency distribution for outflow water temperatures at the Hayfield site H1 and H2 wetland cells.

Cumulative frequency plots of temperature data for the Hayfield site cells inflow and outflow are shown in figure 4-3. In this case, the separation in temperatures shown in the time series plots (figure 4-1) are readily apparent in the slope and separation between the inflow and outflow distributions. Similar cumulative frequency distributions for other water quality data are included in Appendix D.

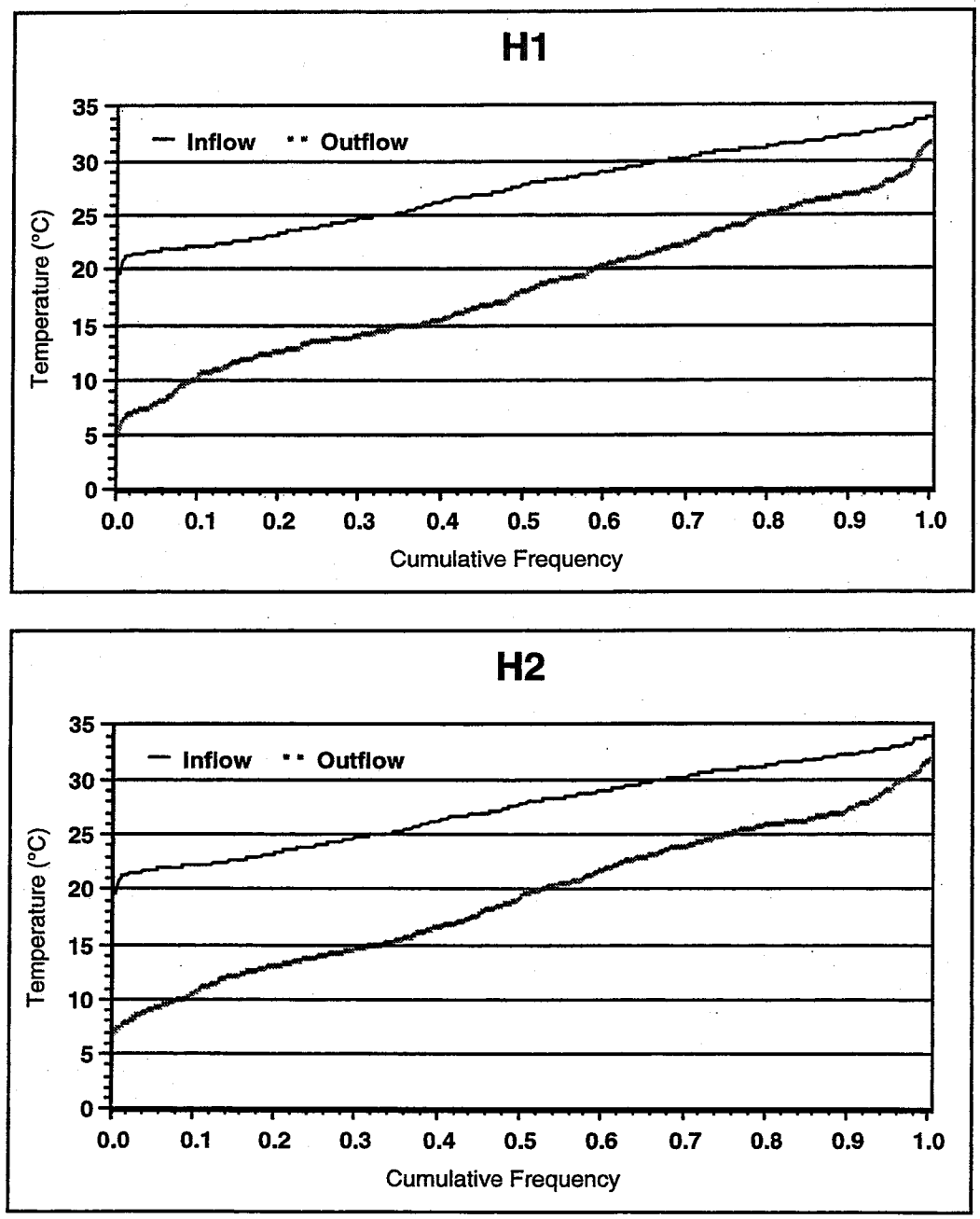


Figure 4-3. Cumulative frequency distributions of inflow and outflow temperature data for the Hayfield site H1 and H2 wetland cells.

Daily Field Data Review

Similar statistical comparisons using the t-test and Wilcoxon test for the other field measurement data are provided in tables 4-1 and 4-2. The field data are particularly useful for evaluating data distribution characteristics because there are more data points for the daily data. The exception is total residual chlorine which was only sampled early in the demonstration project when de-chlorination was applied to the wetlands water supply. Summary statistics, skewness, and kurtosis data distribution characteristics for the daily field measurement data are shown in table 4-3.

Table 4-3. Summary statistics, skewness, and kurtosis for Hayfield site daily field data.

Location	Field data Variable	Number of cases	Minimum	Maximum	Median	Mean	Standard Deviation
HS combined inflow	Temperature	468	19.7	33.9	27.8	27.4	3.77
	Residual Cl_2	43	1.0	3.4	2.7	2.7	0.54
	pH	463	6.03	7.6	7.00	6.97	0.16
	DO	452	0.5	9.5	3.2	3.4	1.12
	EC	425	1125	1990	1486	1490	133.16
H1 cell outflow	Temperature	453	4.7	31.6	18.1	18.4	6.37
	Residual Cl_2	36	0.0	0.2	0.1	0.1	0.07
	pH	451	6.05	9.02	7.10	7.14	0.29
	DO	442	0.1	12.1	1.6	2.6	2.54
	EC	417	1161	1941	1521	1530	144.95
H2 cell outflow	Temperature	469	6.8	31.8	19.1	19.2	6.40
	Residual Cl_2	34	0.0	0.3	0.1	0.1	0.07
	pH	467	6.55	8.77	7.18	7.19	0.25
	DO	456	0.1	8.8	1.6	2.1	1.71
	EC	430	1100	1946	1511	1521	145.53

Location	Field data Variable	Skewness coefficient	Std. error skewness (SES)	Ratio of skew to SES	Kurtosis coefficient	Std. error kurtosis (SEK)	Ratio of kurtosis to SEK
HS combined inflow	Temperature	-0.102	0.113	-0.903	-1.283	0.225	-5.696
	Res. Cl_2	-1.275	0.361	-3.529	1.789	0.709	2.523
	pH	-1.502	0.114	13.231	8.365	0.227	36.930
	DO	1.638	0.115	14.270	3.985	0.229	17.386
	EC	0.644	0.118	5.439	1.187	0.236	5.022
H1 cell outflow	Temperature	0.038	0.115	0.333	-1.013	0.229	-4.424
	Residual Cl_2	0.180	0.393	0.458	-0.752	0.768	-0.978
	pH	2.308	0.115	20.070	10.500	0.229	45.769
	DO	1.374	0.116	11.834	1.233	0.232	5.322
	EC	0.368	0.120	3.081	0.578	0.239	2.422
H2 cell outflow	Temperature	-0.011	0.113	-0.093	-1.142	0.225	-5.074
	Residual Cl_2	0.346	0.403	0.858	0.401	0.788	0.509
	pH	1.991	0.113	17.618	8.588	0.226	38.083
	DO	1.045	0.114	9.143	0.456	0.228	1.998
	EC	0.228	0.118	1.939	0.655	0.235	2.788

Note: Units: Temperature = °C, Residual Cl_2 and DO = mg/L, pH = -log activity, and EC = µS/cm

A nonnormal distribution is characterized by skewness (a measure of the distribution symmetry) and / or kurtosis (a measure of the length of the tails relative to the height of a distribution). According to SYSTAT (SPSS, 1998), a large nonzero skew indicates asymmetry. A positive skew indicates that the distribution has a long right tail, while a negative skew indicates a long left tail.

With kurtosis, a large positive value indicates that the distribution has longer tails than a normal distribution, and a large negative value indicates that a distribution is flatter (more spread out) than a normal distribution. If the ratio of the coefficient of skew or kurtosis to the standard error is greater than 2, the coefficient is considered significantly nonzero, indicating significant skew or kurtosis in the distribution.

Table 4-3 illustrates that the ratios of skew and/or kurtosis of most of the variables have an absolute value (sign ignored) greater than 2 which indicates that most of the data do not meet the criteria for normal distribution. Based on this, nonparametric tests are considered more appropriate to evaluate this data set.

Regression analysis also examined some of the water quality monitoring data. For example, relationships between inflow and outflow dissolved oxygen concentrations were examined by regression to evaluate the difference in DO between the two Hayfield site wetland cells. These results are presented later as part of the comparative evaluation of open water configuration effects.

Laboratory Data Review

Many of the monitored data have numerous values below detectable concentrations in the laboratory. In statistical analysis, such data are known as censored data. When there are numerous censored values in a data set, it is truncated at the lower (left tail) end of the distribution. Such a data set cannot be adequately fit to a distribution on which parametric statistics can be reliably be performed. The laboratory analysis data for water quality parameters indicated in tables 3-7 have numerous non-detect censored values. All of the nitrogen and phosphorus species, TSS, and BOD data are somewhat censored (more than 50 percent NO_2–N and outflow NH_4–N). As a result, cumulative frequency and nonparametric statistical methods were considered more appropriate for most of the subsequent water quality data evaluations.

General Water Quality Results

The first evaluation of overall water quality performance was based on all of the data collected from the four Hayfield and Cobble site wetland cells. All data for each water quality parameter were aggregated to examine any trends evident regardless of the wetland operating conditions, water budget, or physical configuration.

Hayfield Site Summary

Results of the Hayfield site water quality data analysis using the parametric t-test and non-parametric Wilcoxon test are shown in tables 4-4 and 4-5. Descriptive statistics for the Hayfield site inflow (HS) and cell outflow (H1 and H2) data are summarized in table 4-6. Results of these analyses are described by water quality topic.

Table 4-4. Summary of t-test results for the Hayfield site water quality data.

Variable	Comparison to inflow				Cell comparison	
	H1– t	Prob. > t	H2– t	Prob. > t	H1 vs. H2– t	Prob. > t
Temperature	54.95	< 0.001	55.30	< 0.001	-6.86	< 0.001
Residual Cl_2	27.08	< 0.001	25.36	< 0.001	-2.47	0.019
pH	-11.91	< 0.001	-17.18	< 0.001	-4.63	< 0.001
DO	8.07	< 0.001	17.76	< 0.001	6.17	< 0.001
EC	-12.48	< 0.001	-8.31	< 0.001	7.14	< 0.001
Alkalinity	-3.30	0.003	-2.57	0.015	1.45	0.157
TSS	0.21	0.839	-0.10	0.921	0.40	0.692
TDS	-3.33	0.002	-2.61	0.014	0.84	0.410
Chloride	-4.64	< 0.001	-2.61	0.013	2.65	0.012
TKN	9.73	< 0.001	11.82	< 0.001	1.77	0.086
NO_2–N	0.81	0.426	0.67	0.509	-0.54	0.592
NO_3–N	4.26	< 0.001	4.21	< 0.001	-0.41	0.688
NO_2+NO_3–N	5.00	< 0.001	4.83	< 0.001	-0.75	0.457
NH_4–N	5.43	< 0.001	10.48	< 0.001	1.68	0.102
Total N	10.82	< 0.001	9.48	< 0.001	-0.45	0.654
PO_4–P	1.00	0.327	1.04	0.307	0.97	0.339
Diss. P	-1.84	0.074	-2.45	0.019	-1.27	0.213
COD	0.67	0.509	1.71	0.098	-0.03	0.977
BOD	3.31	0.003	3.39	0.002	0.58	0.569
TOC	1.56	0.128	3.68	0.001	1.55	0.131

Note: Positive t-values indicate a decrease in outflow concentration compared to inflow, or the H2 outflow is less than H1 in the wetland cell comparison. Significant differences are indicated by < 0.05 probability.

Table 4-5. Summary of Wilcoxon [Z] test results for the Hayfield site water quality data.

Variable	Comparison to inflow				Cell comparison	
	H1–Z	Prob. > Z	H2–Z	Prob. > Z	H1 vs. H2–Z	Prob. > Z
Temperature	18.33	< 0.001	18.60	< 0.001	-7.08	< 0.001
Residual Cl_2	5.16	< 0.001	5.02	< 0.001	-2.23	0.026
pH	-12.84	< 0.001	-16.14	< 0.001	-7.01	< 0.001
DO	8.94	< 0.001	13.55	< 0.001	4.23	< 0.001
EC	-11.86	< 0.001	-8.31	< 0.001	9.49	< 0.001
Alkalinity	-3.02	0.002	-2.45	0.014	1.93	0.054
TSS	1.35	0.177	1.58	0.114	1.07	0.286
TDS	-2.87	0.004	-2.60	0.009	1.00	0.318
Chloride	-4.23	< 0.001	-2.27	0.023	2.59	0.010
TKN	4.82	< 0.001	5.26	< 0.001	1.42	0.156
NO_2–N	0.60	0.550	0.73	0.463	-1.47	0.141
NO_3–N	3.38	< 0.001	3.40	0.001	-0.53	0.594
NO_2+NO_3–N	3.83	< 0.001	3.76	< 0.001	-0.71	0.480
NH_4–N	4.48	< 0.001	5.37	< 0.001	2.08	0.037
Total N	4.78	< 0.001	4.62	< 0.001	-0.24	0.806
PO_4–P	0.23	0.821	0.88	0.376	0.90	0.367
Diss. P	-1.41	0.158	-2.36	0.018	-0.75	0.453
COD	0.31	0.758	1.37	0.170	0.81	0.417
BOD	2.72	0.006	3.01	0.003	1.41	0.157
TOC	1.99	0.046	3.12	0.002	1.52	0.127

Note: Positive Z-values indicate a decrease in outflow concentration compared to inflow, or the H2 outflow is less than H1 in the wetland cell comparison. Significant differences are indicated by < 0.05 probability.

Table 4-6. Descriptive statistics for the Hayfield site water quality data (all in mg/L).

Monitoring location	Constituent	Minimum	25th Percentile	Median	75th Percentile	Maximum	No. data points	No. < detect
HS combined inflow	Alkalinity	105	170	175	183	198	65	—
	TSS	1	2	3	4	22	65	0
	TDS	706	824	863	886	1050	62	—
	Chloride	158	216	240	269	354	65	—
	Sulfate	112	142	159	176	231	18	—
	TKN	1.7	2.7	3.2	3.7	7.7	73	0
	NO_2–N	< 0.1	< 0.1	< 0.1	0.2	2.6	56	35
	NO_3–N	0.6	1.7	2.2	3.2	6.9	59	0
	NO_2+NO_3–N	0.9	3.6	5.4	6.5	12.9	66	—
	NH_4–N	1	1	2	2	5	71	0
	Total N	3.3	6.5	8.1	10.0	16.4	68	—
	PO_4–P	0.7	2.4	3.3	3.8	6.6	57	—
	Diss. P	1.0	3.0	3.6	4.1	8.0	71	—
	COD	16	28	36	45	717	65	7
	BOD	< 2	2	3	4	8	64	6
	TOC	6.0	7.6	8.6	9.9	12.2	71	—
H1cell effluent	Alkalinity	91	174	182	193	213	63	0
	TSS	1	2	3	5	17	65	7
	TDS	568	826	878	929	1130	61	—
	Chloride	167	222	255	273	378	63	—
	Sulfate	105	145	170	190	280	17	—
	TKN	0.8	1.2	1.5	1.9	5.8	71	0
	NO_2–N	< 0.1	< 0.1	< 0.1	< 0.1	0.6	57	54
	NO_3–N	< 0.1	< 0.1	0.8	3.0	8.1	57	20
	NO_2+NO_3–N	0.1	0.3	0.9	1.4	5.5	12	—
	NH_4–N	< 0.1	< 0.5	< 0.5	0.5	2.4	71	47
	Total N	1.1	1.6	2.8	4.5	9.3	68	—
	PO_4–P	0.9	2.5	3.2	3.8	5.0	57	—
	Diss. P	1.0	3.2	3.8	4.2	6.3	70	—
	COD	7	24	34	50	165	65	6
	BOD	< 1	2	2	3	6	64	19
	TOC	5.3	7.2	8.0	9.6	17.3	70	—
H2 cell effluent	Alkalinity	106	171	179	188	202	65	0
	TSS	1	1	2	3	22	65	2
	TDS	600	831	878	922	1110	62	—
	Chloride	160	215	254	282	363	65	—
	Sulfate	117	143	169	191	230	19	—
	TKN	0.5	1.2	1.5	1.8	4.2	73	1
	NO_2–N	< 0.1	< 0.1	< 0.1	< 0.1	0.7	58	49
	NO_3–N	< 0.1	< 0.1	0.8	3.0	8.2	59	21
	NO_2+NO_3–N	0.1	0.5	2.7	3.4	5.3	12	—
	NH_4–N	< 0.1	< 0.5	< 0.5	0.5	2.1	72	45
	Total N	0.7	1.6	2.8	4.9	9.7	70	—
	PO_4–P	1.2	2.3	3.2	3.9	5.1	59	—
	Diss. P	1.5	3.2	3.9	4.2	8.0	71	—
	COD	7	26	37	46	281	65	7
	BOD	2	2	2	2	20	65	23
	TOC	5.0	7.4	8.0	9.2	13.0	71	—

Residual Chlorine. Hayfield site cells show a highly significant reduction in residual chlorine (tables 4-4 and 4-5) based on few data points measured during the early testing phases. Median inflow residual Cl_2 exceeds 3 mg/L versus 0.1 mg/L for the outflow of each cell (table 4-6). The cell comparison indicates the H1 cell was more effective in reducing residual Cl_2 although the main difference is in the maximum values of 0.2 and 0.3 mg/L for H1 and H2, respectively.

Relative pH. The pH changes in the Hayfield cells follow those of most other variables shown in tables 4-4 and 4-5. There is a small (table 4-3), but significant increase in pH in the outflow of each cell. The increase is slightly greater in H2; the outflow pH in H2 is significantly greater than that of H1, although the difference is only 0.05 based on the respective mean values.

Alkalinity. Alkalinity is affected by pH and the CO_2 concentration, both of which can be affected by photosynthesis. For this reason, alkalinity may increase, decrease, or stay the same depending on the predominant process within the cells. Alkalinity generally increased (tables 4-5 and 4-6). The increases are not large, 7 mg/L in H1 and 4 mg/L in H2; however, this could indicate that the primary factor affecting alkalinity is evaporative concentration. There is no significant difference between the alkalinity of two cell outflows (table 4-5).

Sulfate, Chloride, and TDS. These major anions generally behaved conservatively; as expected (i.e. only affected by dilution or evaporation). Each constituent shows higher median concentrations in the outflow than the inflow. Chloride increased by about 25 mg/L in each cell, while TDS increased by 15 mg/L in each cell (table 4-6). The fact that the increase in TDS was lower than the increase in one of its constituents would indicate that something was lost in the TDS to offset 10 mg/L of the increase due to chloride.

These results were confirmed by the t-test and Wilcoxon results for chloride and TDS. There is a significant increase in the TDS and chloride concentrations in both of the cells (table 4-5). The increase in H1 was significantly greater than that in H2. All of these results are consistent with the results based on EC and indicate that evaporative concentration had a significant effect on each.

Median data values also indicate an increase in outflow sulfate which is consistent with evaporative concentration effects. This was not confirmed by statistical analysis because only a few sulfate measurement data were collected during the later stages of the demonstration monitoring period.

Total Suspended Solids. TSS was also expected to decrease due to physical settling and filtration processes in the wetlands; however, table 4-5 shows no significant overall difference between the inflow TSS and either cell outflow. There is also no significant difference in outflow TSS data between the two Hayfield cells.

Only the outflow from H2 has a median TSS lower than the inflow—2 mg/L as opposed to 3 mg/L in the inflow. Although this is a weak indicator of removal, a number of outflow data were less than the 1 mg/L detection limit, whereas no inflow data were below detection. Low to moderate levels of TSS are also produced by the normal processes in wetland systems. Throughout the monitoring, TSS in the inflow to the wetland cells was low, (i.e. less than 4 mg/L in 75 percent of the samples), which could limit the potential for further net reduction in TSS.

Nitrogen. Inflow and outflow data for the various forms of nitrogen are summarized in table 4-6. There is a significant decrease in all of the nitrogen species for both H1 and H2 outflows with the exception of NO_2–N (tables 4-4 and 4-5). This is not unusual because nitrite is transitional in the presence of oxygen and more than half the inflow NO_2–N samples were below the 0.1 mg/L detection limit. The percentage of data below detection limit increased to about 95 percent in the H1 outflow and 85 percent in the H2 outflow. This cannot be evaluated statistically, but indications are that it is not possible to measure significant differences near detection limit levels.

Ammonium (the ion, NH_4^+) shows a dramatic decrease from a median of 2 mg/L NH_4–N to a median concentration below detection in both cells (table 4-6). The analytical detection limit for NH_4–N changed from 0.1 to 0.5 mg/L during the monitoring. Nevertheless, the median concentration decreased to about 25 percent of the inflow concentration. Table 4-5 shows the NH_4–N in the H2 outflow was significantly lower than that from H1, although the descriptive statistics (table 4-6) indicate the only difference was in the respective maxima.

NO_3–N also decreased significantly from a median inflow concentration of 2.2 mg/L to an identical 0.8 mg/L in the outflow from each of the cells, or a decrease of about 65 percent of the median inflow concentration. TKN (organic plus ammonia nitrogen) has a somewhat lesser percentage decrease than that of nitrate, from a median inflow concentration of 3.2 mg/L to an outflow concentration of 1.5 mg/L or slightly less than 50 percent of the inflow concentration.

The total nitrogen decrease was reflected in the decrease in the individual nitrogen species. The median inflow concentration of 8.1 mg/L decreased to 2.8 mg/L in the outflow, indicating 65 percent TN removed from the water. The decrease among all major forms is consistent with sequential nitrification and denitrification to gaseous N_2 released to the atmosphere. Typically lesser amounts of nitrogen are removed through biomass uptake and disposition of organic sediments.

Phosphorus. The most common P measurements are total phosphorus and dissolved ortho-phosphorus (PO_4–P: orthophosphate or ionic phosphate). In this case, the dissolved P is actually total dissolved P because the samples were filtered and digested. Total phosphorus (unfiltered, digested) was not measured. Moreover, the PO_4–P samples were not filtered; however, since PO_4–P should be predominantly in dissolved form, these data are considered representative of the dissolved PO_4–P.

There was no significant change in the PO_4–P from inflow to outflow in either cell (tables 4-4 and 4-5). The median inflow PO_4–P concentration was 3.3 mg/L while the median outflow concentrations were 3.2 mg/L (table 4-6). An increase in the concentration of total dissolved P in H2 was observed (prob. < 0.05), from a median of 3.6 mg/L in the inflow to 3.9 mg/L in the outflow. The median concentration of the H1 outflow data were 3.8 mg/L, which also represents an increase.

Apparent increases in P are attributed to leaching from soils and wetlands vegetation materials which could bias data collected during the early monitoring. These trends are evident in the time-series plots in Appendix C . Data for the early start up months are erratic and generally higher, followed by steady decrease in P levels through 1996 and 1997. A slight increase evident near the end of 1997 into 1998 coincides with the observed senescence and decomposition of wetlands vegetation, which could release phosphorus from biomass into the overlying water. Inflow P levels are also highly variable which complicates evaluation.

Oxygen Demand and Organic Content. There was no significant change in COD in either cell (tables 4-4 and 4-5). Median inflow COD was 36 mg/L and the median outflows were 34 and 37 mg/L from H1 and H2, respectively (table 4-6). The inflow COD range was more variable than the outflows. The outflow minima and maxima were both lower than the inflow; however, the center of the distribution (between the 25th and the 75th percentiles) were very similar to the inflow.

Inflow BOD levels were quite low (maximum = 8 mg/L). Despite this, there was a statistically significant decrease in BOD in the outflows from each of the cells. The center of the distribution of the outflow BOD in each of the cells is about 1 mg/L lower than the equivalent part of the inflow BOD distribution. The decrease in BOD could account for some of the DO decrease.

TOC showed a highly significant (prob. < 0.01) decrease in the outflow from H2 (table 4-5), but only a barely significant decrease in the H1 outflow (prob.=0.046). This is interesting because the TOC would include both the labile and recalcitrant organic components reflected by the non-specific BOD and COD indicators.

Both TOC and BOD are significantly different between cells, which might suggest a difference in the oxygen status between Hayfield site cells (discussed later as part of open water configuration comparison). Inflow COD is more resistant to degradation and could be offset by biomass production effects.

Cobble Site Summary

Results for t-test and Wilcoxon test comparing inflow and outflow, and differences between Cobble site cells are shown in tables 4-7 and 4-8. The following results are based on all of the monitoring data available regardless of the different operating conditions or infiltration characteristics of the two Cobble site cells.

Seepage could remove water-borne materials through the wetland soils which could affect mass removal results, but should not affect concentrations drastically. Consequently, the overall Cobble site t-test and Wilcoxon test results are based on concentration (seepage loss effects are discussed separately). Descriptive statistics results for the Cobble site laboratory data are summarized in table 4-9.

Table 4-7. Summary of t-test results for the Cobble site water quality data.

Constituent	Comparison to inflow				Cell comparison	
	C1–t	Prob. > t	C2–t	Prob. > t	C1 vs. C2–t	Prob. > t
Temperature	48.67	< 0.001	51.81	< 0.001	7.71	< 0.001
Residual Cl_2	36.26	< 0.001	28.44	< 0.001	1.04	0.310
pH	-17.46	< 0.001	-16.49	< 0.001	-3.46	< 0.001
DO	1.86	0.067	7.72	< 0.001	6.40	< 0.001
EC	-2.29	0.023	-8.31	< 0.001	-7.38	< 0.001
Alkalinity	-0.50	0.622	-2.70	0.012	-2.13	0.043
TSS	0.16	0.872	1.38	0.178	0.33	0.745
TDS	-0.97	0.339	-2.33	0.027	-1.97	0.059
Cl^-	0.26	0.794	-2.75	0.010	-1.90	0.069
TKN	6.71	< 0.001	9.69	< 0.001	1.40	0.173
NO_2–N	-0.57	0.575	0.81	0.426	1.58	0.130
NO_3–N	2.32	0.030	4.00	< 0.001	0.92	0.367
NO_2+NO_3–N	2.28	0.030	3.85	0.001	1.16	0.257
NH_4–N	7.59	< 0.001	7.43	< 0.001	0.21	0.838
Total N	4.94	< 0.001	7.33	< 0.001	1.83	0.078
PO_4–P	-1.03	0.313	-0.69	0.494	0.07	0.945
Diss. P	-1.91	0.066	-1.81	0.081	-0.89	0.379
COD	-0.92	0.368	1.49	0.147	1.31	0.203
BOD	0.42	0.681	3.58	0.001	1.56	0.130
TOC	0.09	0.930	0.11	0.915	-0.28	0.783

Note: Positive t-values indicate a decrease in outflow concentration compared to inflow, or the C2 outflow is less than C1 in the wetland cell comparison. Significant differences are indicated by < 0.05 probability.

Table 4-8. Summary of Wilcoxon [Z] test results for the Cobble site water quality data.

Constituent	Comparison to inflow				Cell comparison	
	C1–Z	Prob. > Z	C2–Z	Prob. > Z	C1 vs. C2–Z	Prob. > Z
Temperature	17.48	< 0.001	17.48	< 0.001	7.12	< 0.001
Residual Cl_2	4.71	< 0.001	3.92	< 0.001	1.23	0.218
pH	-15.50	< 0.001	-16.34	< 0.001	-3.92	< 0.001
Diss. Oxygen	4.34	< 0.001	8.10	< 0.001	6.13	< 0.001
EC	-2.07	0.039	-8.28	< 0.001	-8.64	< 0.001
Alkalinity	-0.51	0.611	-2.48	0.013	-1.93	0.053
TSS	0.86	0.391	1.96	0.050	-0.02	0.984
TDS	-0.57	0.567	-2.52	0.012	-1.41	0.159
Cl^-	0.32	0.750	-2.38	0.017	-1.78	0.075
TKN	4.25	< 0.001	4.82	< 0.001	2.11	0.035
NO_2–N	-0.77	0.443	-0.67	0.505	1.04	0.300
NO_3–N	2.00	0.046	3.29	0.001	1.53	0.126
NO_2+NO_3–N	1.90	0.057	3.15	0.002	1.65	0.098
NH_4–N	4.46	< 0.001	4.50	< 0.001	0.82	0.411
Total N	3.88	< 0.001	4.54	< 0.001	1.91	0.056
PO_4–P	-1.10	0.269	0.01	0.989	0.10	0.920
Diss. P	-2.01	0.045	-1.57	0.116	-0.39	0.699
COD	-0.32	0.746	2.04	0.041	0.93	0.355
BOD	1.18	0.237	2.99	0.003	1.51	0.130
TOC	-0.16	0.876	1.36	0.173	1.07	0.286

Note: Positive Z-values indicate a decrease in outflow concentration compared to inflow, or the C2 outflow is less than C1 in the wetland cell comparison. Significant differences are indicated by < 0.05 probability.

Table 4-9. Descriptive statistics for the Cobble site water quality data.

Monitoring location	Constituent	Minimum	25th Percentile	Median	75th Percentile	Maximum	No. data points	No. < detect
CS Inlet	Alkalinity	121	170	175	182	286	64	—
	TSS	1	2	3	3	18	65	0
	TDS	716	818	851	890	1080	64	—
	Cl^-	174	226	249	269	346	63	—
	Sulfate	135	156	170	185	228	14	—
	TKN	1.8	2.7	3.1	3.8	8.8	67	—
	NO_2–N	< 0.1	< 0.1	< 0.1	0.3	4.9	51	36
	NO_3–N	0.6	1.7	2.6	3.4	7.6	54	0
	NO_2+NO_3–N	0.6	1.5	2.4	3.6	8.1	65	0
	NH_4–N	0.7	1.4	1.8	2.2	3.8	67	0
	Total N	3.4	4.6	5.7	7.4	12.5	65	—
	PO_4–P	0.7	2.5	3.4	3.9	5.5	54	—
	Diss. P	0.9	3.1	3.6	4.1	6.2	67	—
	COD	2	29	38	49	190	65	3
	BOD	< 2	2	3	4	8	63	8
	TOC	6.0	7.8	8.6	9.9	11.6	66	—
C1 Effluent	Alkalinity	138	165	173	185	202	62	—
	TSS	< 1	1	2	4	48	63	4
	TDS	680	810	858	897	1260	63	—
	Cl^-	162	219	242	271	380	62	—
	Sulfate	143	159	184	194	305	14	—
	TKN	1.0	1.4	1.9	2.7	4.6	65	—
	NO_2–N	< 0.1	< 0.1	< 0.2	0.7	4.9	51	30
	NO_3–N	< 0.1	0.6	2.2	3.4	7.1	52	12
	NO_2+NO_3–N	0.1	1.1	2.6	4.0	11.9	61	0
	NH_4–N	< 0.1	< 0.5	0.6	1.6	2.3	65	22
	Total N	0.1	1.1	2.6	4.0	11.9	61	—
	PO_4–P	1.2	2.3	3.2	4.2	5.6	52	—
	Diss. P	1.4	3.1	3.8	4.4	9.1	65	—
	COD	9	31	38	49	212	63	2
	BOD	< 2	2	2	3	9	63	15
	TOC	6.0	7.9	8.6	9.6	11.8	64	—
C2 Effluent	Alkalinity	129	168	154	191	204	60	—
	TSS	< 1	1	2	3	15	62	5
	TDS	714	826	866	914	1050	61	—
	Cl^-	170	220	249	272	418	59	—
	Sulfate	140	168	185	192	259	12	—
	TKN	0.7	1.2	1.7	2.2	3.4	64	—
	NO_2–N	< 0.1	< 0.1	< 0.1	0.4	0.9	50	2
	NO_3–N	< 0.1	< 0.1	1.4	2.8	9.4	50	15
	NO_2+NO_3–N	< 0.1	0.2	1.6	3.3	9.9	61	1
	NH_4–N	< 0.1	< 0.5	< 0.5	0.6	2.6	64	38
	Total N	0.1	0.2	1.6	5.6	9.9	61	—
	PO_4–P	1.0	2.4	3.6	4.0	5.3	50	—
	Diss. P	2.0	3.7	3.8	4.2	11.0	64	—
	COD	< 7	26	35	45	228	62	6
	BOD	< 2	< 2	2	2	7	62	18
	TOC	5.8	7.5	8.3	9.4	53.7	63	—

Field Measurements. Results for the Cobble site field measurements are similar to the Hayfield site results. Highly significant differences (prob. < 0.001) are evident between the inflow and outflow temperatures, residual Cl_2, and pH in both cells. Only in C2 is there a significant difference from inlet to outlet for DO and EC based on the parametric t-test. The parametric t-test results are generally consistent with the nonparametric Wilcoxon results. Significant differences between the two cell outflows are apparent for DO and temperature.

The difference in the DO results appears to be due to changing relationships in the distributions. At frequencies below 75th percentile, outflow DO is lower than inflow, but above the 75th percentile this reverses and the outflow is higher. Dissolved oxygen is also higher in C1 than C2. This could indicate the increased inflow rate to C1 (to compensate for seepage losses) which reduces the hydraulic retention time and the effective time for oxygen depleting process mechanisms to occur.

There are also significant differences between the two cells for the other field parameters except residual Cl_2. The pH and EC are higher in the C2 outflow, while water temperature and DO are lower.

Major Anions, TDS, and TSS. There are no significant differences between any of the C1 inflow and outflow concentrations indicated in tables 4-7 or 4-8. In the C2 cell, there is a significant increase for the conservative parameters TDS and major anions based on either the parametric t-test or nonparametric Wilcoxon test. TSS does not show a significant difference in C2 on the basis of the t-test, but shows a significant (prob. = 0.05) decrease based on the Wilcoxon test; however, the descriptive statistics (table 4-9) indicate any differences are relatively small.

Nitrogen. The Cobble site results for nitrogen are consistent with the Hayfield site where nitrogen changes were among the most obvious effects. Again, significant reduction in each of the nitrogen species is evident with the exception of the NO_2–N data which included many samples below detectable concentration. The decrease in NO_3–N and NO_2+NO_3–N in cell C1 was not as significant as C2, and there was no significant difference between outflow concentrations of the two cells.

Based on median concentrations (table 4-9), TKN was reduced by nearly 50 percent in each cell, and the changes in both cells are significant. The difference between TKN in the C1 and C2 outflows was significant based on the Wilcoxon test, but not the t-test (tables 4-7 and 4-8). The differences across their respective distributions are less than 1 mg/L at all points except the maxima, which show a difference of 1.2 mg/L between the C1 and C2 outlets.

Both cells show a significant NH_4–N decrease. Inflow NH_4–N levels were all above the detection limit, while about ⅓ and ½ of the outflow samples were below detection for C1 and C2, respectively.

Phosphorus, Oxygen Demand and TOC. In most cases, no significant changes were evident for these water quality constituents at the Cobble site. A significant decrease in BOD concentrations in the C2 cell was indicated by both the t-test and Wilcoxon tests; however, the C2 outflow BOD concentrations were either close to, or below the detection limit of 2 mg/L in over 75 percent of the samples. The Wilcoxon test results also indicated a decrease in COD in C2 and a increase in total dissolved phosphorus in C1 both at a minimally significant probability level near 0.05.

Hydraulic Function Results

Hayfield site data were used in this analysis because of better experimental control conditions during the monitoring period. The water quality and water operations data were separated into subsets to evaluate relationships between hydraulic properties and water quality performance—accomplished in three main steps.

First, data were analyzed that correspond to inflow hydraulic load rate and hydraulic retention time properties. Then a cross comparison analysis was applied to determine whether the apparent effects of HLR or HRT were related to hydraulic properties or differences between individual cells. The third analysis involved a multivariate correlation analysis to several physical factors including HLR, HRT, depth, inflow water temperature, and inflow constituent concentration.

Hydraulic Load Rate Effects

The hydraulic load rate (HLR) evaluation was based on data compiled for two inflow load rates indicated as test phases A and B (figure 3-6) conducted at a constant 1-foot (30 cm) pool depth (or constant HRT of approximately 7 days). The initial HLR in both Hayfield cells was 0.25 ft/day, (7.6 cm/d) during phase A, which was increased to 0.5 ft/day (15.2 cm/d) for phase B (figure 3-5).

Statistical evaluations of the effects of HLR on the percent change for various water quality components at the Hayfield cells are summarized in table 4-10. The percent change was calculated as a positive value for removal or net change as appropriate for each component. A chi-square (X^2) with an associated probability of less than 0.05 (shown as prob. > X^2) translates to a statistically significant effect.

Table 4-10. Mann-Whitney test of hydraulic load rates 0.25 ft/day (7.6 cm/day) versus 0.5 ft/day (15.2 cm/day) on inflow-outflow water quality changes at the Hayfield site.

Water quality component (dependent variable)	Hayfield cell H1		Hayfield cell H2	
	Chi-square (X^2)	Prob. > X^2	Chi-square (X^2)	Prob. > X^2
% Change Alkalinity	1.363	0.242978	3.413	0.064700
% Reduction TSS	30.284	<0.000001	16.317	0.000054
% Change TDS	4.026	0.044793	5.255	0.021890
% Change Cl^-	0.026	0.871746	2.048	0.152423
% Reduction TKN	30.107	<0.000001	17.417	0.000030
% Reduction NO_2–N	1.311	0.252276	4.107	0.042718
% Reduction NO_3–N	9.368	0.002208	14.685	0.000127
% Reduction NO_2+NO_3–N	10.414	0.001251	15.604	0.000078
% Reduction NH_4–N	16.683	0.000044	5.710	0.016867
% Reduction Total N	4.786	0.028699	15.191	0.000097
% Reduction PO_4–P	0.553	0.457174	1.135	0.286743
% Reduction Diss. P	0.583	0.445193	1.274	0.259067
% Reduction COD	23.556	0.000001	29.237	<0.000001
% Reduction BOD	2.519	0.112483	0.976	0.323292
% Reduction TOC	34.746	<0.000001	31.407	<0.000001

Most of the water quality measures shown on table 4-10 show a significant effect on the percent change between the inflow and outflow due to varying the HLR. Two that do not show a significant effect include alkalinity and chloride, both of which show an increase attributed to evaporative concentration. This means the alkalinity is behaving conservatively, without transformation in the wetland cells.

Chloride always behaves conservatively because of its high solubility. Nearly all Cl^- salts are evaporites. The increases in the median Cl^- are from 5 to 7 percent and from 2 to 8 percent in H1 and H2, respectively, when the HLR is decreased from 0.5 ft/day to 0.25 ft/day. Alternatively, TDS does not show significant evaporative concentration effects with the change in HLR (table 4-10).

Although HLR effects on the percent change in TDS is not much different from that of Cl^- (or alkalinity), the significance determination is based on the frequency of the differences, where more of the percentage changes at the 0.25 ft/day HLR are higher than those of the 0.5 ft/day HLR. In other words, when the data are ranked from low to high, there are significantly more of the higher ranks in the low HLR group.

Mann-Whitney tests (table 4-10) typically give a U statistic; however, the SYSTAT package (SPSS, 1998) converts U to the Chi-square X^2 values. The X^2 statistic (sum of squared deviations between observed and expected values) does not have a sign to indicate the direction of change. Direction trends can be seen in the descriptive statistics for cells H1 and H2 in tables 4-11 and 4-12, respectively.

A highly significant effect of HLR on the percent reduction in TSS was evident in both wetland cells (table 4-10). TSS removal by physical settling is generally more effective at a lower HLR; however, the results did not confirm this trend. For the H1 cell, a median decrease in TSS of 15 percent at the 0.25 ft/day HLR and 55 percent for the higher 0.5 ft/day HLR are indicated in table 4-11. H2 had similar results with a decrease of 36 percent and 61 percent for the low and higher HLR rates shown in table 4-12. This indicates that simple settling processes were not the controlling factor that affected TSS reduction under these test conditions.

The effects of HLR were statistically significant for all nitrogen forms except nitrite; however, the trends were not consistent among different forms. Total N and NO_3–N followed the expected trend of decreased removal efficiency with increasing inflow load rate (attributed to reduced reaction time). The median NO_3–N percent removal declined with increasing HLR, from 82 to 28 percent in H1 and 92 to 29 percent in H2 (tables 4-11 and 4-12). Alternatively, the median percent reduction in TKN was the opposite, with greater removal at the higher HLR. Moreover, although NH_4–N is a component of TKN, it followed the pattern of total and NO_3–N, which suggests that organic nitrogen is responsible for the trend of TKN. For example, this could be attributed to seasonal uptake, decay, and release of organic nitrogen from emergent plants. Nitrogen fixing algae could also produce organic nitrogen which would offset the TKN removal efficiency of the wetland system.

Table 4-11. Descriptive statistics by Hydraulic Load Rate (HLR) for the Hayfield site H1 cell.

	HLR (ft/day)	N of cases	Minimum	Maximum	Median	Mean	95% confidence Upper	95% confidence Lower
% change Alkalinity	0.25	32	-31.29	13.71	-5.51	-7.07	-3.04	-11.10
	0.5	34	-17.87	13.33	-3.16	-3.18	-0.39	-5.96
% reduction TSS	0.25	33	-250.00	86.36	15.00	-6.66	17.13	-30.46
	0.5	34	33.33	66.67	55.10	53.11	57.03	49.18
% change TDS	0.25	33	-13.72	11.49	-4.24	-4.30	-2.03	-6.57
	0.5	34	-9.86	6.48	-1.83	-1.25	0.19	-2.69
% change Cl^-	0.25	30	-29.47	13.62	-7.25	-7.53	-3.84	-11.22
	0.5	34	-38.89	6.91	-5.07	-7.89	-4.52	-11.25
% reduction TKN	0.25	33	24.00	72.34	54.00	52.49	56.28	48.70
	0.5	34	22.58	73.68	67.18	66.01	69.12	62.90
% Reduction NO_2-N	0.25	29	-200.00	96.15	0.00	10.65	30.54	-9.24
	0.5	34	-100.00	68.75	0.00	21.05	33.57	8.52
% Reduction NO_3-N	0.25	30	-97.56	97.50	81.65	50.23	72.95	27.51
	0.5	34	-533.33	94.12	28.10	2.23	40.40	-35.94
% Reduction NO_2+NO_3-N	0.25	32	-100.00	96.00	79.94	50.23	71.08	29.37
	0.5	34	-471.43	88.89	24.67	5.47	39.78	-28.84
% Reduction NH_4-N	0.25	33	37.50	85.29	76.19	72.11	75.89	68.34
	0.5	34	44.44	75.00	65.15	63.14	66.21	60.07
% Reduction Total N	0.25	32	-37.14	80.00	60.80	52.80	63.08	42.51
	0.5	34	-68.42	71.64	44.26	41.81	51.78	31.83
% Reduction PO_4-P	0.25	30	-77.78	98.09	0.00	-2.62	9.35	-14.60
	0.5	33	-142.86	37.50	7.32	-4.78	8.73	-18.29
% Reduction Diss. P	0.25	32	-45.16	34.00	0.00	-2.84	3.55	-9.22
	0.5	34	-105.26	32.50	-2.05	-10.78	-0.26	-21.31
% Reduction COD	0.25	33	-193.62	45.45	-15.56	-29.01	-7.06	-50.96
	0.5	34	-62.08	95.96	39.46	30.81	42.59	19.03
% Reduction BOD	0.25	33	-66.67	75.00	33.33	23.61	35.09	12.12
	0.5	31	0.00	66.67	40.17	36.82	44.06	29.58
% Reduction TOC	0.25	33	-46.48	33.03	0.00	-0.83	4.15	-5.81
	0.5	34	0.00	39.32	29.19	24.48	28.26	20.69

Nitrite nitrogen is a good example of how data near the detection limit can influence statistical results. Nitrite is very transient in the presence of oxygen and as expected, there was no measurable effect on NO_2–N in any of the analyses. The difference in the NO_2–N percent change is significant in H2 (table 4-10), even though the median percent change is 0.0 for both cells at either load rate (tables 4-11 and 4-12).

The median percent change of zero indicated for NO_2–N reflects the large number of values that are below the detection limit, and are, therefore, equal in inflow and outflow. In other words, when a constituent is not measurable, it is impossible to determine whether the concentration has increased or decreased. Nevertheless, there are apparently enough measurable data points greater than zero to yield statistical differences in H2 (prob. < 0.05 - table 4-10).

Table 4-12. Descriptive statistics by Hydraulic Load Rate (HLR) for the Hayfield site H2 cell.

	HLR (ft/day)	N of cases	Minimum	Maximum	Median	Mean	95% confidence Upper	95% confidence Lower
% change Alkalinity	0.25	40	-69.72	14.72	-7.11	-6.80	-2.45	-11.14
	0.5	25	-17.31	12.71	-2.34	-1.76	1.46	-4.98
% reduction TSS	0.25	40	-250.00	90.91	35.96	13.73	36.02	-8.57
	0.5	25	9.68	75.00	61.11	59.07	64.06	54.07
% change TDS	0.25	40	-12.19	5.40	-3.53	-3.76	-2.27	-5.25
	0.5	25	-5.45	4.97	-1.32	-1.08	0.03	-2.19
% change CL	0.25	37	-28.99	6.47	-7.59	-6.86	-4.36	-9.35
	0.5	26	-33.33	70.32	-2.39	-1.20	7.10	-9.50
% reduction TKN	0.25	40	13.04	70.18	56.07	53.44	56.99	49.89
	0.5	26	45.16	67.65	64.03	62.15	64.39	59.92
% reduction NO_2-N	0.25	38	-300.00	96.15	0.00	4.85	24.13	-14.42
	0.5	25	-20.69	68.75	0.00	25.09	37.81	12.37
% reduction NO_3-N	0.25	40	-106.67	97.67	92.03	59.02	77.40	40.64
	0.5	26	-633.33	84.14	29.45	-4.54	50.46	-59.54
% reduction NO_2+NO_3-N	0.25	40	-104.76	96.00	86.51	57.16	75.20	39.13
	0.5	26	-528.57	79.35	28.83	-2.93	43.63	-49.49
% reduction NH_4-N	0.25	40	12.50	84.85	74.34	69.49	73.92	65.06
	0.5	26	44.44	80.77	66.67	64.66	68.85	60.47
% reduction Total N	0.25	40	-41.43	82.35	64.14	55.89	64.96	46.82
	0.5	26	-60.53	64.20	42.91	38.30	48.41	28.18
% reduction PO_4-P	0.25	40	-90.91	98.09	-3.30	-6.91	2.26	-16.08
	0.5	25	-304.88	35.00	-12.79	-47.06	-12.05	-82.07
% reduction Diss. P	0.25	40	-46.67	30.00	-2.41	-5.20	0.18	-10.59
	0.5	26	-147.37	37.50	-6.32	-20.52	-3.38	-37.65
% reduction COD	0.25	40	-275.00	39.19	-3.83	-13.46	2.75	-29.68
	0.5	25	-95.45	60.81	47.84	36.10	49.40	22.79
% reduction BOD	0.25	40	-100.00	75.00	33.33	31.84	42.01	21.68
	0.5	25	0.00	66.67	46.56	40.75	48.40	33.10
% reduction TOC	0.25	40	-28.17	30.28	2.10	2.76	6.90	-1.38
	0.5	26	0.00	35.90	26.81	24.59	28.26	20.92

There was no statistically significant effect of HLR on the removal of either form of phosphorus measured (table 4-10). This may be attributed in part to the fact that the particulate fraction of total phosphorus was not measured and this component could correlate more strongly to changes in inflow HLR.

There also is no significant difference in the BOD decrease due to HLR in either cell; however, there are highly significant effects of HLR on the percent change in COD in each of the cells, with the more significant effect in H2. COD increases (negative percent reduction) in both cells at the lower HLR, but decreases at the higher HLR based on the median (or mean) values. This trend might suggest net conversion and production of resistant organic matter from vegetation biomass (internal loading) that accumulates at the lower HLR (greater HRT). TOC also shows a highly significant difference in the rate of change with HLR, with the greater reduction at the higher HLR, again suggesting possible effects of primary production.

Operational Depth Effects

Evaluation of water depth effects was based on data subsets collected during test phases B, C, and D (figure 3-6) that correspond to three operating depths tested with a constant inflow rate. The test water depths were 0.5, 1.0, and 1.5 feet (15.2, 30.5, and 45.7 cm) in both Hayfield wetland cells. Depth is proportional to the theoretical hydraulic retention time (HRT) with constant area and inflow rate. Consequently, the three depths tested correspond to HRT values of about 5, 7, and 10 days.

Statistical results of depth data based on the Kruskal-Wallis one-way ANOVA are summarized in table 4-13. These results indicate the effects of water depth changes on the percent change in concentration for water quality constituents measured at the Hayfield site. The percent change was calculated as a positive value for a net decrease (reduction) for each water quality constituent. A chi-square (X^2) with an associated probability of less than 0.05 (shown as prob. > X^2) indicates a statistically significant water quality effect with changing water depth.

Table 4-13. Kruskal-Wallis one-way ANOVA of water depth effects for 0.5, 1.0, and 1.5 feet (15.2, 30.5, and 45.7 cm) on inflow-outflow water quality changes at the Hayfield site.

Constituent	Hayfield cell H1		Hayfield cell H2	
	Chi-square	Prob. > X^2	Chi-square	Prob. > X^2
% Change Alkalinity	26.79	0.000002	16.62	0.000246
% Reduction TSS	18.70	0.000087	19.92	0.000047
% Change TDS	31.08	<0.000001	17.55	0.000154
% Change Cl^-	8.44	0.014726	6.00	0.049831
% Reduction TKN	29.36	<0.000001	33.18	<0.000001
% Reduction NO_2-N	7.10	0.028680	12.18	0.002262
% Reduction NO_3-N	37.75	<0.000001	21.34	0.000023
% Reduction NO_2+NO_3-N	36.93	<0.000001	34.81	<0.000001
% Reduction NH_4-N	16.50	0.000261	44.06	<0.000001
% Reduction Total N	11.18	0.003730	31.34	<0.000001
% Reduction PO_4-P	1.11	0.574478	4.41	0.110196
% Reduction Diss. P	8.71	0.012865	2.14	0.343688
% Reduction COD	24.94	0.000004	30.42	<0.000001
% Reduction BOD	31.36	<0.000001	26.19	0.000002
% Reduction TOC	45.13	<0.000001	41.16	<0.000001

In this case, the Kruskal-Wallis test was used instead of the Mann-Whitney test to handle the three data groups for depth test phases. In the Kruskal-Wallis test data values are transformed into ranks (ignoring group membership) to test that there is no shift in the distribution centers (that is, the centers do not differ). This is a nonparametric analog of a one-way analysis of variance (ANOVA). This procedure reduces to the Mann-Whitney nonparametric analog of the two-sample t-test, when there are only two groups such as the previous comparison of HLR differences.

Most of the water quality constituents show significant effects for the depth intervals evaluated (table 4-13). Note that the operating plans called for a minimum test depth of 0.5 feet, the actual test operation was 0.75 feet for practical reasons; however, this did not alter the statistical results based on relative ranks.

Trends for depth effects are illustrated graphically by the median data plots for nine water quality components in figure 4-4. Descriptive statistics by depth intervals for the H1 and H2 cells are summarized in tables 4-14 and 4-15. For most constituents there was an inflection point associated with the 1-foot

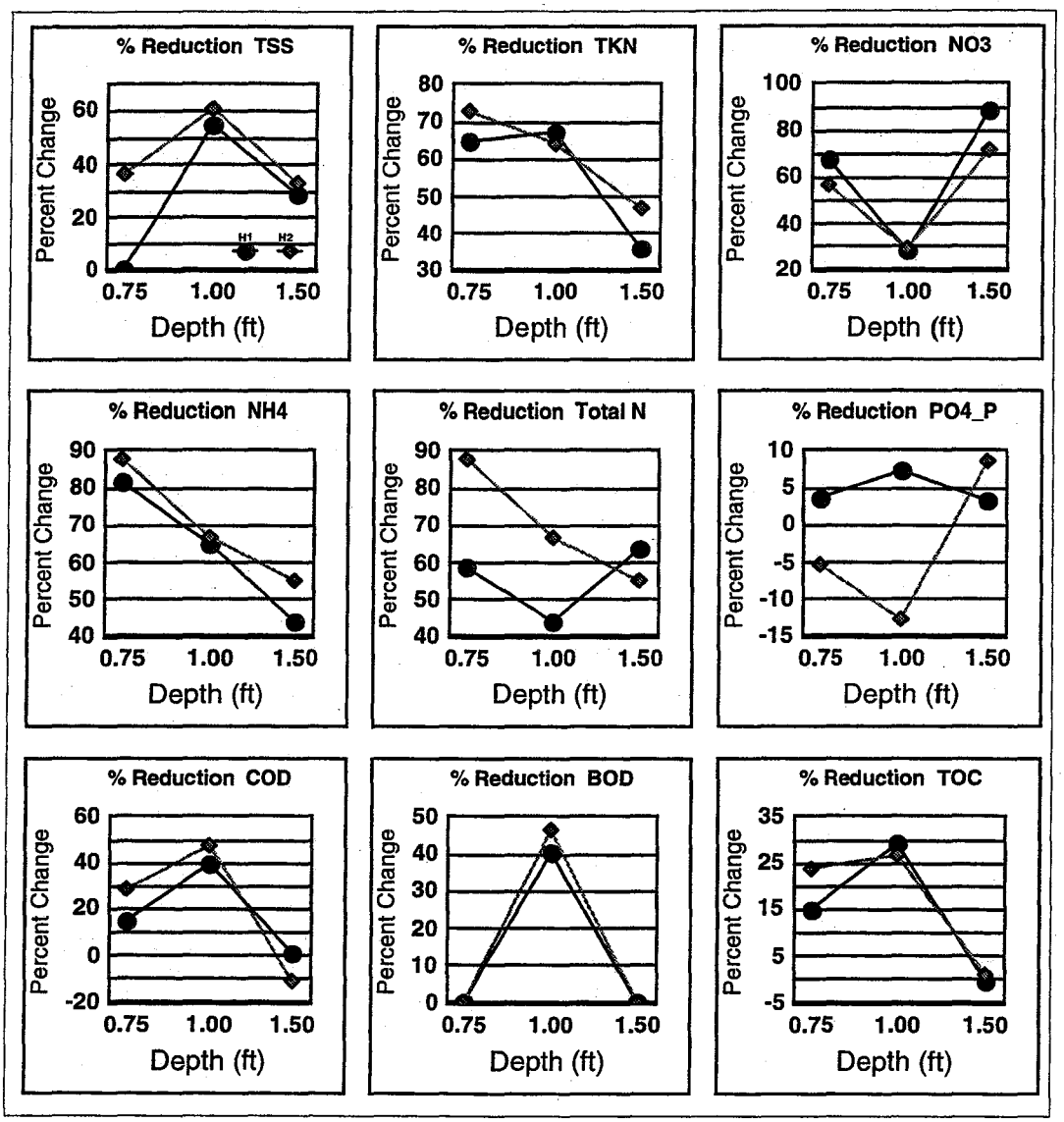


Figure 4-4. Median percent change in selected water quality constituents by water depth for the Hayfield site H1 and H2 wetland cells.

depth shown in figure 4-4. The intermediate depth produced peak reductions for TSS, COD, BOD, and TOC, and the opposite trend of minimum percent removal was indicated for Cl^-, NO_3–N, and NO_2–N. Ammonia and TKN had declining removal with depth whereas phosphorus and total N had mixed trends. At a minimum, these results indicate that the depth change effects do not have to be a linear increase or decrease to produce a statistically significant result.

Table 4-14. Descriptive statistics by depth for the Hayfield site H1 cell.

	Depth (ft)	N of cases	Minimum	Maximum	Median	Mean	95% Confidence Upper	95% Confidence Lower
% change Alkalinity	0.75	23	-8.92	1.06	-2.32	-3.39	-2.16	-4.62
	1.00	34	-17.87	13.33	-3.16	-3.18	-0.39	-5.96
	1.50	18	-20.78	-7.22	-13.08	-13.41	-10.81	-16.01
% reduction TSS	0.75	23	-266.67	66.67	0.00	-43.28	4.55	-91.12
	1.00	34	33.33	66.67	55.10	53.11	57.03	49.18
	1.50	18	-500.00	66.67	28.61	-46.08	35.14	-127.30
% change TDS	0.75	23	-4.87	3.20	-0.84	-1.01	0.03	-2.06
	1.00	34	-9.86	6.48	-1.83	-1.25	0.19	-2.69
	1.50	18	-8.60	-3.54	-6.42	-6.36	-5.72	-6.99
% change Cl^-	0.75	34	-7.11	8.24	-3.13	-2.46	-1.26	-3.67
	1.00	34	-38.89	6.91	-5.07	-7.89	-4.52	-11.25
	1.50	18	-6.78	-1.58	-4.02	-4.10	-3.38	-4.82
% reduction TKN	0.75	34	16.22	77.14	64.89	58.62	64.54	52.71
	1.00	34	22.58	73.68	67.18	66.01	69.12	62.90
	1.50	18	11.76	59.69	36.09	35.77	43.35	28.19
% reduction NO_2-N	0.75	34	-400.00	75.00	0.00	-14.57	21.64	-50.78
	1.00	34	-100.00	68.75	0.00	21.05	33.57	8.52
	1.50	18	-400.00	80.00	-51.94	-97.05	-23.33	-170.77
% reduction NO_3-N	0.75	34	-10.00	96.15	67.50	62.05	69.91	54.19
	1.00	34	-533.33	94.12	28.10	2.23	40.40	-35.94
	1.50	18	72.89	96.55	88.23	87.45	90.70	84.20
% reduction NO_2+NO_3-N	.75	34	-9.09	92.59	58.55	57.19	64.40	49.98
	1.00	34	-471.43	88.89	24.67	5.47	39.78	-28.84
	1.50	18	56.52	97.69	88.01	84.33	90.13	78.53
% reduction NH_4-N	0.75	34	-7.53	94.44	81.46	66.99	77.81	56.18
	1.00	34	44.44	75.00	65.15	63.14	66.21	60.07
	1.50	18	12.00	78.00	44.10	41.41	52.82	30.00
% reduction Total N	0.75	34	46.15	76.96	58.80	58.94	62.03	55.84
	1.00	34	-68.42	71.64	44.26	41.81	51.78	31.83
	1.50	18	37.50	75.81	63.88	61.08	66.48	55.67
% reduction PO_4-P	0.75	33	-342.86	36.76	3.80	-42.34	-9.92	-74.77
	1.00	33	-142.86	37.50	7.32	-4.78	8.73	-18.29
	1.50	18	-75.20	21.88	3.33	-7.32	7.36	-21.99
% reduction Diss. P	0.75	34	-135.71	17.65	-17.34	-39.10	-22.96	-55.24
	1.00	34	-105.26	32.50	-2.05	-10.78	-0.26	-21.31
	1.50	18	-91.30	26.47	-23.22	-26.20	-9.78	-42.63
% reduction COD	0.75	23	-21.21	40.00	15.36	17.22	25.84	8.60
	1.00	34	-62.08	95.96	39.46	30.81	42.59	19.03
	1.50	18	-242.11	17.50	1.46	-42.60	-3.94	-81.27
% reduction BOD	0.75	23	0.00	50.00	0.00	17.60	26.52	8.68
	1.00	31	0.00	66.67	40.17	36.82	44.06	29.58
	1.50	18	0.00	0.00	0.00	0.00	0.00	0.00
% reduction TOC	0.75	34	3.53	33.70	15.15	16.82	20.04	13.59
	1.00	34	0.00	39.32	29.19	24.48	28.26	20.69
	1.50	18	-3.75	6.53	-0.31	-0.02	1.26	-1.30

Table 4-15. Descriptive statistics by depth for the Hayfield site H2 cell.

	Depth (ft)	N of cases	Minimum	Maximum	Median	Mean	95% Confidence Upper	95% Confidence Lower
% change Alkalinity	0.75	24	-6.94	4.62	-2.63	-1.63	-0.14	-3.11
	1.00	25	-17.31	12.71	-2.34	-1.76	1.46	-4.98
	1.50	19	-19.48	-1.11	-8.93	-10.02	-6.87	-13.17
% reduction TSS	0.75	24	-1000.00	66.67	36.90	-76.13	35.38	-187.64
	1.00	25	9.68	75.00	61.11	59.07	64.06	54.07
	1.50	19	0.00	66.67	33.33	26.48	36.91	16.04
% change TDS	0.75	24	-5.13	1.03	-1.22	-1.30	-0.67	-1.93
	1.00	25	-5.45	4.97	-1.32	-1.08	0.03	-2.19
	1.50	19	-8.60	2.10	-5.13	-4.54	-3.17	-5.91
% change Cl^-	0.75	34	-3.70	7.69	-1.88	-1.44	-0.72	-2.16
	1.00	26	-33.33	70.32	-2.39	-1.20	7.10	-9.50
	1.50	18	-3.00	78.35	-0.14	8.93	20.23	-2.36
% reduction TKN	0.75	34	47.37	83.33	73.02	69.57	73.07	66.07
	1.00	26	45.16	67.65	64.03	62.15	64.39	59.92
	1.50	19	29.41	65.79	46.89	47.83	52.73	42.93
% reduction NO_2-N	0.75	34	-400.00	75.00	0.00	-17.96	18.79	-54.71
	1.00	25	-20.69	68.75	0.00	25.09	37.81	12.37
	1.50	7	-400.00	0.00	-52.17	-110.33	24.17	-244.83
% reduction NO_3-N	0.75	34	-10.00	92.31	57.41	53.77	63.35	44.20
	1.00	26	-633.33	84.14	29.45	-4.54	50.46	-59.54
	1.50	19	48.27	82.76	71.70	70.31	75.28	65.34
% reduction NO_2+NO_3-N	0.75	34	-9.09	88.89	53.78	48.97	56.85	41.10
	1.00	26	-528.57	79.35	28.83	-2.93	43.63	-49.49
	1.50	19	56.52	97.69	77.54	77.52	83.62	71.43
% reduction NH_4-N	0.75	34	65.00	95.24	87.69	85.44	88.53	82.35
	1.00	26	44.44	80.77	66.67	64.66	68.85	60.47
	1.50	19	16.00	79.33	55.07	51.18	62.35	40.00
% reduction Total N	0.75	34	48.04	80.35	57.64	60.35	63.50	57.20
	1.00	26	-60.53	64.20	42.91	38.30	48.41	28.18
	1.50	19	45.00	69.26	64.41	61.47	64.75	58.20
% reduction PO_4-P	0.75	33	-335.29	27.90	-5.33	-48.14	-15.57	-80.71
	1.00	25	-304.88	35.00	-12.79	-47.06	-12.05	-82.07
	1.50	19	-14.29	18.75	8.51	3.39	9.82	-3.04
% reduction Diss. P	0.75	34	-128.57	17.65	-14.08	-36.61	-20.50	-52.72
	1.00	26	-147.37	37.50	-6.32	-20.52	-3.38	-37.65
	1.50	19	-82.61	32.35	-17.54	-19.25	-5.40	-33.09
% reduction COD	0.75	24	-15.00	54.55	29.35	25.43	33.51	17.36
	1.00	25	-95.45	60.81	47.84	36.10	49.40	22.79
	1.50	19	-110.53	40.00	-10.89	-20.15	-2.54	-37.76
% reduction BOD	0.75	25	-322.79	50.00	0.00	3.05	32.25	-26.15
	1.00	25	0.00	66.67	46.56	40.75	48.40	33.10
	1.50	19	0.00	33.33	0.00	8.21	13.94	2.48
% reduction TOC	0.75	34	8.86	38.04	23.97	24.31	27.12	21.49
	1.00	26	0.00	35.90	26.81	24.59	28.26	20.92
	1.50	19	-5.00	6.98	1.10	1.02	2.78	-0.75

It should also be noted that the data observations are not equally divided among the various depth intervals. There are about equal numbers of measurements for the 0.75 and 1-foot depth samples, but there was much less data available at the 1.5-foot depth for most of the water quality constituents examined.

The apparent trend reversal among oxygen demand indicators BOD and COD, and the nitrogen species is interesting. This could indicate secondary effects of depth changes on the wetland mixing properties and the status of associated aerobic and anaerobic conditions that influence removal.

Retention Time Effects

The previous evaluation of three depth intervals also reflects HRT effects because the depth is directly proportional to retention time since the surface area and inflow HLR were constant for the test phases B, C, and D data examined. This evaluation extends the analysis of potential retention time effects further to consider the data for all four test phases at the Hayfield site.

To accomplish this, a hydraulic retention time index (HRT_i) was applied to group the data according to the combined depth and HLR effects. The HRT_i was derived by taking the inverse of HLR divided by the depth (i.e. $HRT_i = 1 / [HLR/d]$. As a result the HRT_i is not a calculated HRT (based on actual flow rates and water volume), but it represents the relative HRT for the operating conditions tested that could influence water quality performance.

Data plots of the median percent changes for selected water quality constituents by the HRT_i for the Hayfield wetland cells are shown in figure 4-5. The relative HRT_i values of 1.5, 2, 3, and 4 indicated correspond in order to the data sets for test phases D, B, C and A, respectively. Associated data tables are included in appendix E.

Overall, the downward trend for each of the conservative constituents (alkalinity, TDS, chloride) verifies the expected effects of increased retention time on greater evaporative losses, resulting in concentration increases (negative reduction). Trends for the two wetland cells appear similar for all constituents, although in some cases the position of the H2 line above that for the H1 cell data may reflect the difference in evaporation and oxygen effects for the two cell configurations.

Water quality parameters that are influenced by oxygen (e.g. BOD, COD, NH_4–N, and NO_3–N) have trends that could indicate the aerobic or anaerobic conditions in the wetlands. The downtrend for COD and NH_4–N with increasing retention may reflect oxygen depletion with extended retention, although internal production and evaporative concentration could also contribute to this trend. The reverse trend for NO_3–N provides some confirmation of oxygen effects since removal depends on denitrifying bacteria under anaerobic conditions. Unfortunately, the BOD data are contorted by detection limit effects and cannot be used to verify these trends.

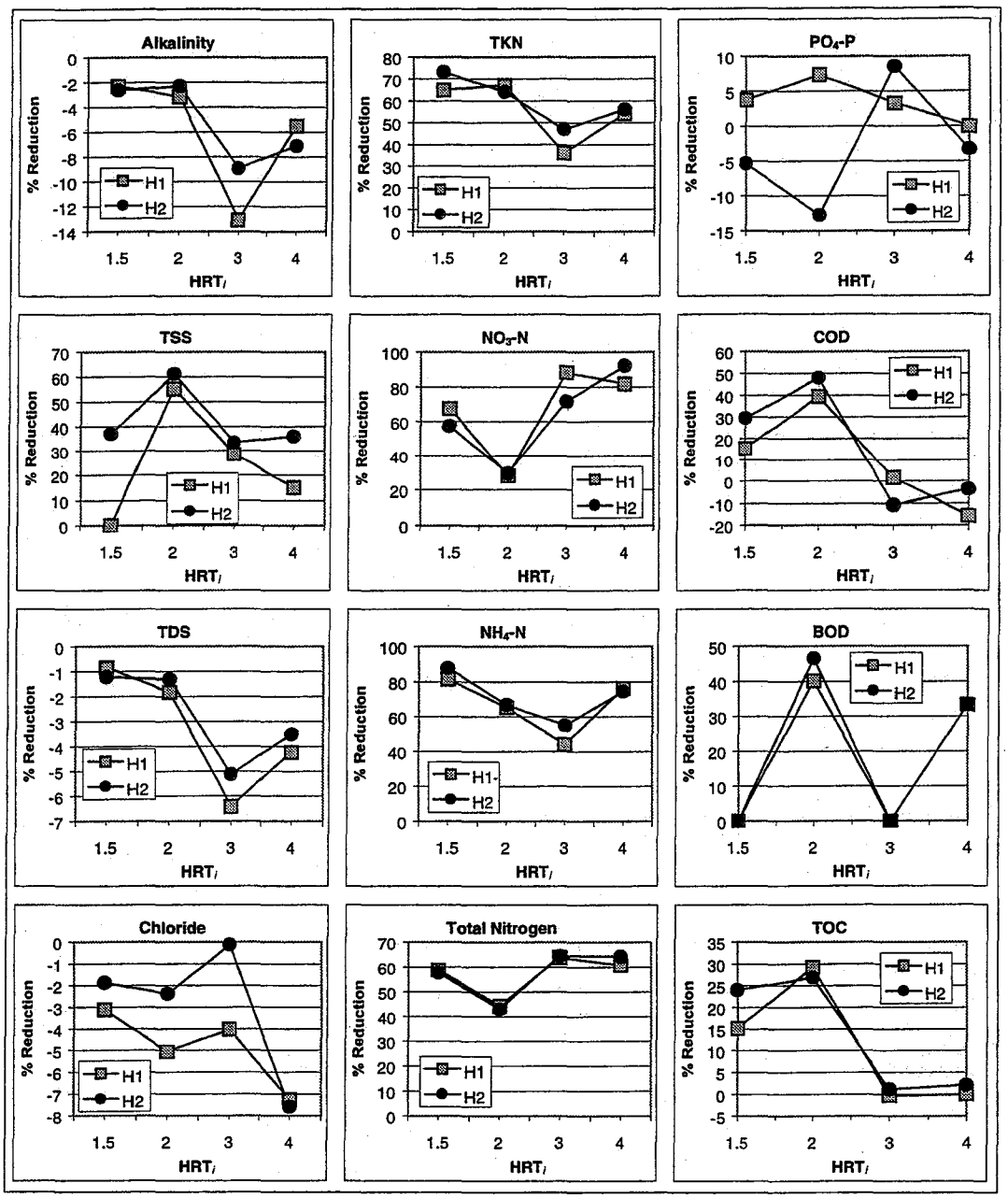


Figure 4-5. Median percent change in selected water quality constituents by hydraulic retention time index (HRT_i) for the Hayfield site H1 and H2 wetland cells.

Decreased removal performance for TSS with increased retention time corresponds with the results for HLR effects. In either case, these trends are not consistent with removal by settling and filtration mechanisms and may indicate the net results are affected by particulate matter from phytoplankton growth, vegetation biomass decay, or other factors that cause resuspension of particulate materials. Evaporative concentration effects could also affect TSS that remain in the water column.

Generally, it appears that the operating conditions for test phase B provide the best compromise for removal of degradable water quality constituents while minimizing the evaporation effects. Seasonal effects on temperature and oxygen conditions could also be important. Figures 3-6 and 4-1 show that test phase B corresponds to cooling trends, whereas test phases A, C, and D coincided with more warming or mixed conditions. It appears that minor changes in the operating conditions can influence temperatures and oxygen shifts substantially.

Hydraulics Cross-Comparison

The initial evaluation of hydraulic conditions indicated possible differences between the Hayfield site cells based on either HLR or HRT (depth). This cross comparison focused on evaluating whether the significant effects of HLR or HRT are due solely to the hydraulic conditions, cell configuration, or combined effects. Implications of the different Hayfield site open water characteristics are evaluated separately.

These cross comparisons were done using a two-way analysis of variance (ANOVA) method. Results can be used to evaluate the cells or HLR effects individually (i.e. similar to t-tests) or interactions between the two. Interactions are manifested when the effects of one independent variable are different at different levels of the other variable. Results for the HLR cross comparison are shown in table 4-16. Probability values (Prob. > F in right columns) less than 0.05 are considered significant.

Table 4-16. Two-way ANOVA comparing Hayfield site cells and HLR effects.

Water quality variable	Cell		HLR		Cell x HLR	
	F-ratio	Prob. > F	F-ratio	Prob. > F	F-ratio	Prob. > F
% change TSS	1.238	0.267966	11.359	0.001004	0.058	0.809916
% change TDS	0.419	0.518850	355.806	< 0.000001	0.092	0.762670
% change TKN	2.324	0.129941	1.084	0.299825	2.909	0.090621
% change NO_3-N	0.005	0.943658	19.787	0.000019	0.002	0.961230
% change NO_2+NO_3-N	0.034	0.854334	24.848	0.000002	0.103	0.748517
% change NH_4-N	0.979	0.324405	114.507	< 0.000001	0.055	0.815157
% change Total N	0.110	0.741102	29.258	< 0.000001	0.470	0.494156
% change PO_4-P	11.461	0.000966	36.507	< 0.000001	6.699	0.010861
% change Diss. P	1.291	0.258104	66.849	< 0.000001	0.395	0.530601
% change COD	1.871	0.173911	10.918	0.001248	0.007	0.931904
% change BOD	1.754	0.187859	7.263	0.008047	0.015	0.902479
% change TOC	0.146	0.703496	8.994	0.003279	0.264	0.608428

The change in PO_4–P is the only variable with significant cell effects and interactions between cells and HLR. Mean PO_4–P increased by 3 to 5 percent in H1 and by 7 to 47 in H2 for the low and high HLR, respectively. However, these results may be subject to anomalies in the PO_4–P data, because ANOVA is a parametric (i.e., compares means) analytical technique. When two outliers in the H2 data set are deleted, the PO_4–P interaction effect disappears, but then two new outliers appear in the H1 data. This illustrates the hazards of parametric analyses where the results are greatly affected by outliers. Phosphorus results are also difficult to interpret due to the loading sources, transformations, and analytical factors.

Results of the two-way ANOVA cross comparison of Hayfield cells and HRT (depth) effects are summarized in table 4-17. Again, probability values (Prob. > F in right columns) less than 0.05 are considered significant interactions.

Table 4-17. Two-way ANOVA comparing Hayfield site cells and depth effects.

Water quality variable	Cell		Depth		Cell x Depth	
	F-ratio	Prob. > F	F-ratio	Prob. > F	F-ratio	Prob. > F
% change TSS	3.287	0.072175	6.030	0.003143	0.879	0.417677
% change TDS	38.092	< 0.000001	8.919	0.000236	15.155	0.000001
% change TKN	13.861	0.000278	20.672	< 0.000001	9.337	0.000151
% change NO_3-N	1.052	0.306680	34.439	< 0.000001	1.209	0.301192
% change NO_2+NO_3-N	0.195	0.659240	45.920	< 0.000001	0.076	0.927307
% change NH_4-N	10.699	0.001330	11.451	0.000024	3.454	0.034159
% change Total N	1.232	0.268857	25.883	< 0.000001	1.259	0.286834
% change PO4_P	0.124	0.724940	5.841	0.003638	3.638	0.028738
% change Diss. P	0.631	0.428408	13.691	0.000003	1.751	0.177214
% change BOD	8.432	0.004359	28.422	< 0.000001	2.304	0.104058
% change COD	9.533	0.002475	27.951	< 0.000001	1.802	0.169208
% change TOC	18.767	0.000027	24.682	< 0.000001	6.391	0.002169

Unlike the cell—HLR cross comparison, there are several variables with significant interaction between cell and depth effects. Several variables including TDS, TKN, NH_4—N, COD, BOD, and TOC show a significant relationship between the percent change and cell effects alone, and all of the water quality variables indicated significant relationships solely with depth. Significant interactions are evident between cell and depth for TDS, TKN, NH_4—N, PO_4—P, and TOC. Except for the percent reduction in TDS, these interactions appear rather subtle.

Possible interactions with depth and cell differences are also illustrated by the median data plots in figure 4-4. These plots show the median percent reduction at each depth for the two Hayfield site cells. In the H1 cell TKN percent reduction was about the same at 0.75 and 1-foot depths with a large decline at the 1.5-foot depth whereas H2 had a more linear decrease as the depth increased.

For NH_4—N there was a very linear decrease with increasing depth in H1, while H2 shows a slightly bowed decrease that was not as prominent at the 1.5-foot depth. TOC shows an increase in the percent reduction in H1 between the 0.75 and 1-foot depths, while they show little difference in H2; the decrease in the percent reduction between the 1 and 1.5-foot depths is virtually identical between the two sites.

Correlation of Physical Factors

Interactions were also examined using correlation analysis. Spearman correlations are a type of nonparametric correlation based on the rank of one variable and as it relates to the order of a second variable. Data are sorted by the first variable, assigned a rank, sorted by the second variable, and each of the resulting values are ordered. This effectively transforms data to a uniform distribution which can then be examined using correlation analysis based on the ranks and orders.

A matrix of Spearman correlation coefficients for the percent change in concentration of each dependent water quality variable and the correlations with HLR, HRT, water depth, inflow temperature, and inflow concentration are shown in table 4-18.

Table 4-18. Spearman (r–rank-order) correlations between percent change in inflow-outflow concentration and selected physical factors and initial inflow concentration.

H1	HLR		HRT		Water Depth		Inflow Temperature		Inflow Concentration	
DO	-0.105	NS	0.105	NS	-0.339	**	-0.831	**	0.320	**
TSS	0.358	**	-0.358	**	0.155	NS	-0.146	NS	0.265	**
TDS	0.171	NS	-0.172	NS	-0.419	**	-0.521	**	-0.018	NS
Cl^-	-0.021	NS	0.022	NS	-0.177	NS	-0.051	NS	0.031	NS
TKN	0.417	**	-0.417	**	-0.420	**	-0.150	NS	0.616	**
NO_2-N	0.066	NS	-0.067	NS	-0.140	NS	-0.450	**	0.750	**
NO_3-N	-0.256	**	0.256	**	0.259	**	0.512	**	-0.081	NS
NO_2+NO_3-N	-0.253	*	0.253	*	0.263	**	0.433	**	0.026	NS
NH_4-N	-0.127	NS	0.127	NS	-0.473	**	-0.127	NS	0.546	**
Total N	-0.096	NS	0.096	NS	0.017	NS	0.428	**	0.015	NS
PO_4-P	0.133	NS	-0.134	NS	0.120	NS	-0.211	*	0.540	**
Diss. P	0.028	NS	-0.028	NS	0.148	NS	-0.140	NS	0.732	**
COD	0.494	**	-0.495	**	-0.256	**	-0.364	**	0.135	NS
BOD	0.139	NS	-0.139	NS	-0.183	NS	-0.456	**	0.802	**
TOC	0.654	**	-0.655	**	-0.404	**	-0.363	**	0.294	**
H2	HLR		HRT		Depth		Inflow Temperature		Inflow Concentration	
DO	0.256	**	-0.256	**	-0.365	**	-0.835	**	0.208	*
TSS	0.055	NS	-0.056	NS	-0.105	NS	0.071	NS	0.436	**
TDS	0.135	NS	-0.135	NS	-0.398	**	-0.357	**	0.096	NS
Cl^-	0.263	**	-0.263	**	-0.102	NS	-0.194	NS	-0.084	NS
TKN	0.373	**	-0.374	**	-0.539	**	-0.286	**	0.391	**
NO_2-N	0.150	NS	-0.150	NS	0.007	NS	-0.486	**	0.515	**
NO_3-N	-0.463	**	0.463	**	0.177	NS	0.622	**	-0.157	NS
NO_2+NO_3-N	-0.445	**	0.445	**	0.313	**	0.531	**	-0.133	NS
NH_4-N	0.200	*	-0.201	*	-0.650	**	-0.282	**	0.317	**
Total N	-0.383	**	0.383	**	0.017	NS	0.469	**	-0.282	**
PO_4-P	0.014	NS	-0.014	NS	0.105	NS	-0.132	NS	0.656	**
Diss. P	-0.123	NS	0.123	NS	0.119	NS	-0.208	*	0.718	**
COD	0.466	**	-0.466	**	-0.310	**	-0.277	**	0.120	NS
BOD	-0.074	NS	0.073	NS	-0.073	NS	-0.268	**	0.918	**
TOC	0.585	**	-0.586	**	-0.516	**	-0.355	**	0.143	NS

Note: NS = Not Significant (prob. > 0.05); * = significant (prob. ≤ 0.05); ** = highly significant (prob. ≤ 0.01); indicates the probability of an "r" of equal or greater magnitude occurring by change alone, based on the absolute value of the r–coefficients shown. Sign indicates a direct (+) or inverse (-) relationship.

The first row in table 4-18 shows the best correlation in H1 for the percent change in DO with inflow temperature. The negative sign indicates an inverse correlation (i.e. higher temperatures produce less change in DO). This does not necessarily indicate the mechanisms involved. A number of factors could affect DO, including direct mechanisms (e.g. DO solubility correlates inversely with inflow temperature and concentration), or indirect processes (e.g. microbial activity or seasonal changes where inflow-outflow differences are greater in the winter).

There is also a significant inverse relationship between DO and depth (i.e. the greater the depth the smaller the percent change in DO). Depth effects are complicated because of the related effects on water volume which can influence the total amount of DO present and the HRT, which independently does not exhibit a significant correlation. The percent change in DO in H1 also correlates positively with the increased inflow DO concentration. In comparison to the H2 cell, the change in DO correlates with all five variables, with the best relationship being with temperature and the poorest with the inflow concentration.

In the H1 cell, the TSS correlates best to the HLR or the HRT, which have the same magnitude, but differ in sign. Again, these relationships are counterintuitive because the greatest difference (decrease) with higher HLR and lower HRT, is the opposite of what is expected for pure settling processes. However, the percent change TSS correlates positively with the inflow concentration, which is expected if settling is the primary removal factor. In the H2 cell, the only significant correlation is between the TSS percent change and inflow TSS concentration. It should be noted that while the correlations are statistically significant, the r-values are comparatively small. Under these circumstances, many different mechanisms can be shown to be significant, but none are mutually exclusive of the others. This may also provide further support to simultaneous TSS removal, resuspension, and production inputs.

The main reason for looking at the correlations was to evaluate temperature and the inflow concentration as possible factors that could influence the various water quality constituents. In H1, temperature correlates significantly with the percent change of NO_2–N, NO_3–N, NO_2+NO_3–N, total N, PO_4–P, COD, BOD, and TOC. In the H2 cell, significant correlations include all the N-species, COD, BOD, and TOC. In both cells, the correlations for the percent change of NO_3–N, NO_2+NO_3–N, and total N with temperature are positive, while the others are inverse.

Also in both cells, there is no correlation between percent removal of NO_3–N, NO_2+NO_3–N, and COD and the respective inflow concentrations. In H1 there is no significant correlation for total N or TOC change and inflow concentration; however, in H2 there is a significant inverse correlation between total N change and inflow concentration. A number of factors and counteracting mechanisms could influence different forms of nitrogen and non-specific oxygen demand indicators.

All of the other correlations between the percent change and the inflow concentration are positive. In other words the percent change (removal) is greater when the inflow concentration is greater. This expected trend may reflect the difficulty in reducing low inflow concentrations further. An extreme example would be NO_2–N, which was below detectable concentrations most of the time in the inflow. Reductions, if any, would be immeasurable. However, when there is measurable NO_2–N in the inflow, reduction to a concentration below the detection limit is measurable, but impossible to quantify.

A very consistent inverse relationship between HLR and HRT for every parameter is also evident in table 4-18. The underlying HLR values are calculated based on a fixed surface area for each wetland cell; however, the HLR and HRT correlations were based on actual inflow and depth measurements using all data for test phases A, B, C, and D. Nevertheless, this really just further supports the inherent inverse relationship between HLR and HRT for a given wetlands system.

Open Water Comparison

The open water comparison was designed into the two Hayfield site cells to allow evaluation of the effects of different open water zones (figure 3-1) on mixing, oxygen transfer, and associated water quality characteristics. Consequently, this data analysis focused on the differences in temperatures (described previously) that can produce evaporative concentration effects for conservative components, and water quality performance parameters including DO, BOD, COD, and various nitrogen forms that are frequently influenced by the oxygen status of the wetlands system.

Dissolved Oxygen

Dissolved oxygen data were included the daily field monitoring results presented in tables 4-1, 4-2, and 4-3. These results indicated a significant difference between the inflow and outflow DO concentrations. The outflow DO levels are frequently lower than the inflow, which indicates net oxygen depletion through the system.

Differences between the inflow and outflow DO concentration levels are illustrated by the cumulative frequency distribution plots in figure 4-6. The inflow DO in both cells is between 2 and 4 mg/L in about 0.8 (80 percent) of the samples and outflow DO levels are less than 2 mg/L in about 0.6 (60 percent) of the samples.

Overall, the statistical analysis shows the outflow DO concentrations are significantly different between the two Hayfield cells (tables 4-1 and 4-2). Although the median outflow DO concentration of the two cells is identical, the mean outflow levels differ by 0.5 mg/L. About 25 percent of the H1 outflow DO measurements exceed the inflow with a maximum concentration of 12.1 mg/L (table 4-3). This is also evident in the upper 25 percent of the cumulative distribution for H1 (figure 4-6).

The greatest difference between the two Hayfield site cells occurs at the higher range of measured DO concentrations. In the H1 cell, the trend reverses to have outflow DO concentrations that exceed the inflow for about 25 percent of the upper range of measurements. In the H2 cell, inflow and outflow DO levels converge for the upper 20 percent of samples. The H2 outflow levels nearly

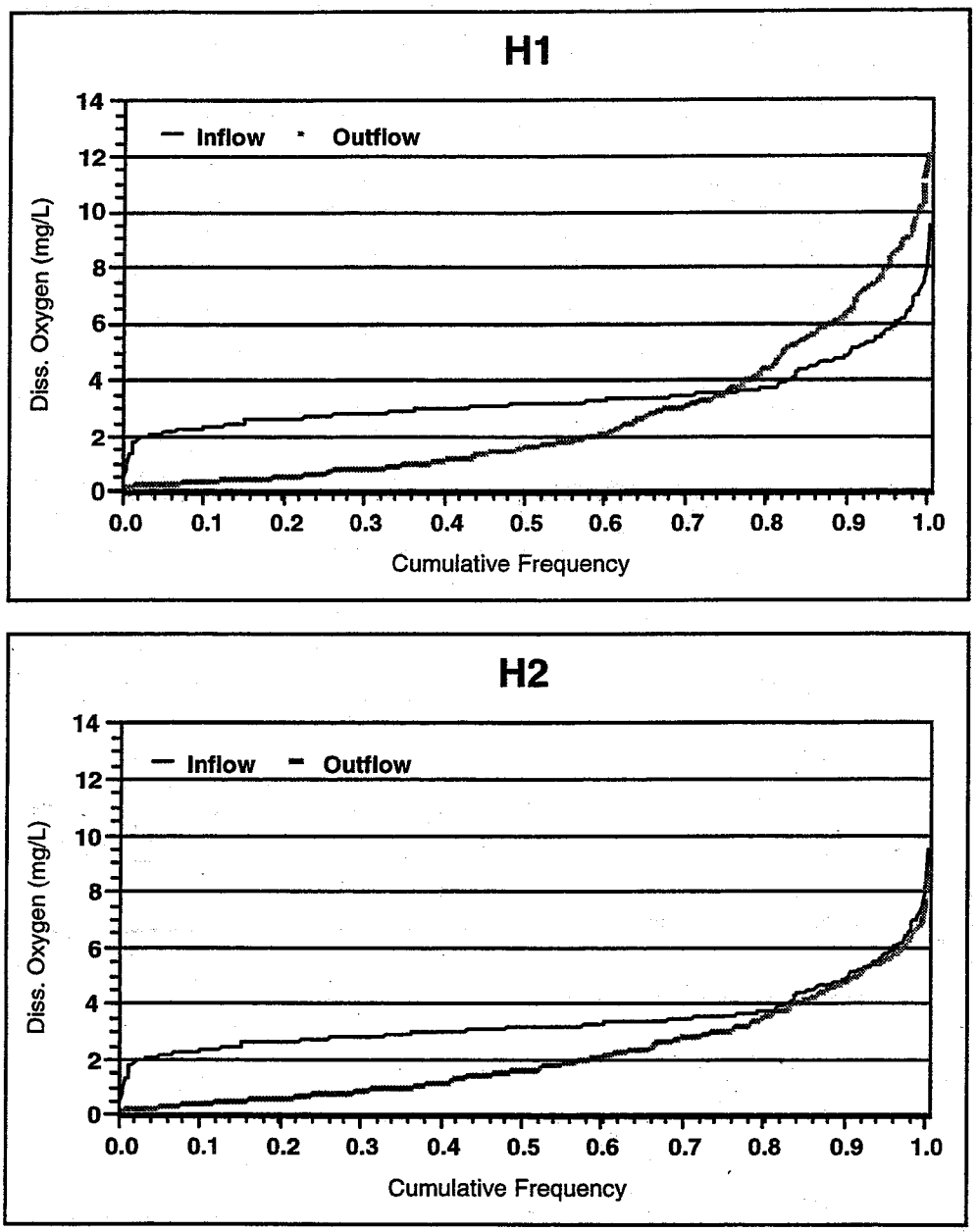


Figure 4-6. Cumulative frequency distributions of inflow and outflow dissolved oxygen (DO) for the Hayfield site wetland cells.

overlay the inflow, but do not exceed the inflow DO at any point in the distribution.

Regression relationships are also helpful to examine trends. Regressions of inflow and outflow DO concentrations are plotted on figure 4-7. The regressions for the two cells have nearly identical r-values (correlation coefficients),

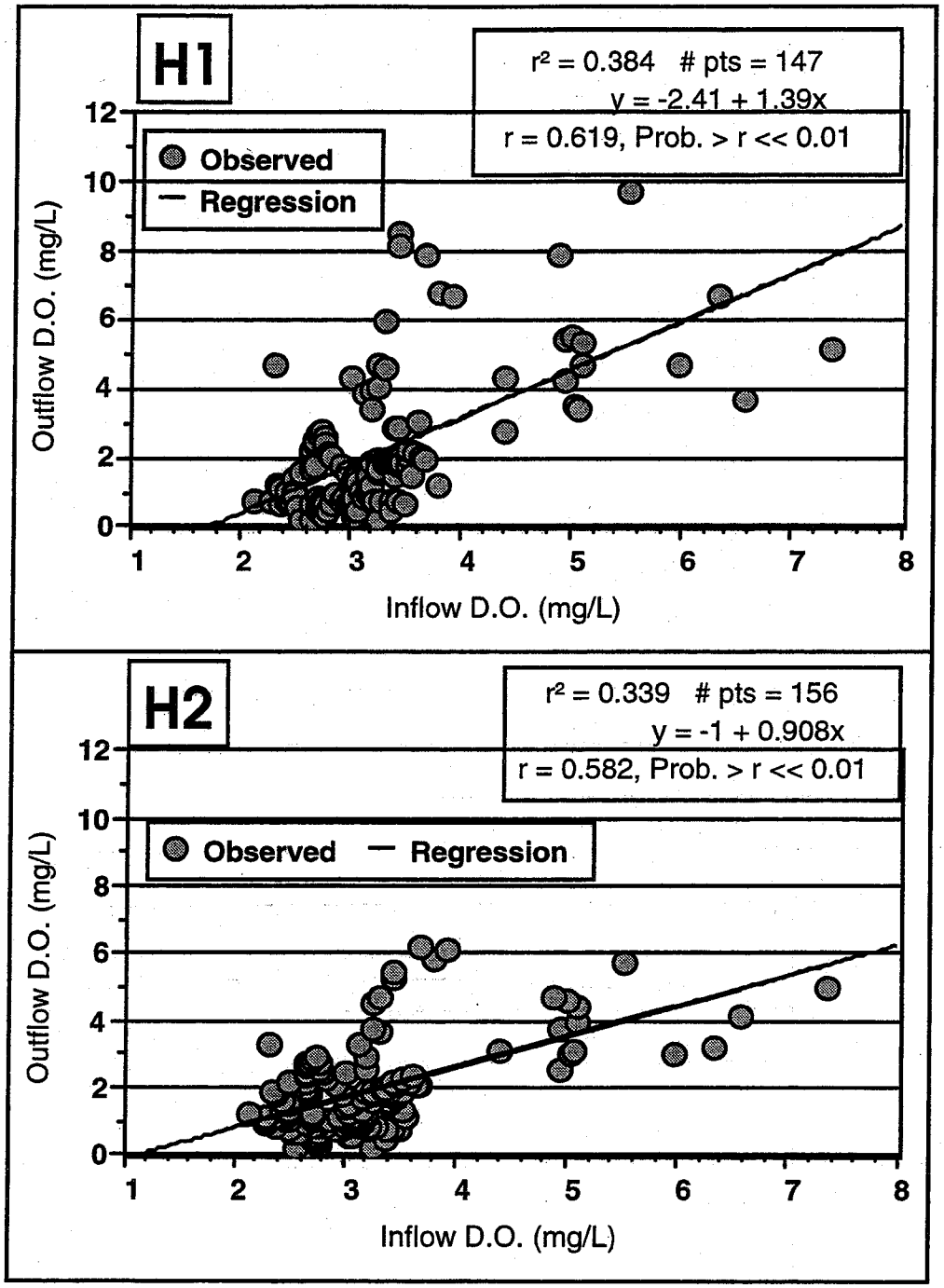


Figure 4-7. Regression of outflow dissolved oxygen (DO) on inflow DO daily measurements for the Hayfield site H1 and H2 wetland cells.

indicating the influence of inflow DO concentration on the outflow DO concentration is similar; however, the different slope of the two regression lines is obvious. Similar regressions for other water quality constituents are provided for reference in Appendix E.

The slope of the H1 regression is 1.16 ± 0.18, versus the H2 regression slope of 0.79 ± 0.12 (based on twice the standard error of the slope). Within the respective confidence intervals, there is no overlap in the inflow/outflow relationships (slopes) and consequently, they are considered significantly different.

These results based on DO alone indicate there are substantial differences in the conditions between the two open water configurations evaluated. The outflow DO in H1 is significantly greater than H2 and the slope of the DO regression for H1 is consistent with a greater reaeration or lower (or slower rate) DO depletion.

Factors causing oxygen depletion include respiration due to biomass decay, organic loading, higher temperatures, and poor reaeration. Conversely, dissolved oxygen levels can be raised with sufficient air exposure, reaeration, circulation, saturation capacity, and reduced organic loading (either internal or external).

The H1 cell has five narrow open water bands versus two larger open water zones in the H2 cell (table 3-1). The results could suggest that more open water zones can provide better mixing, air exchange, or algal productivity, which could increase reaeration and help to overcome the oxygen demands in the systems. It should be noted that the aerial survey found H1 actually has slightly greater surface area than the H2 cell (table 3-2). Although greater surface area could contribute to improved atmospheric exchange, the difference in total area is only about 4 percent, and the difference in the effective open water area is even less.

It is difficult to determine exactly what mechanisms regulate the difference in oxygen status in the two wetland cells. Local wind exposure is another factor that could influence reaeration. Overall, both cells had similar dimensions and test operating conditions. Consequently, the effects of the open water configuration on mixing, flow redistribution, and air exchange appear to be the most reasonable explanation for the resulting differences in oxygen status.

Other Cell Differences

The time series and cumulative distributions for water temperatures (figure 4-2) show the H2 temperatures are generally higher than the H1 wetland cell. This suggests that there could be some difference in either local climate (wind exposure) or surface area exchange that influence the evaporative cooling effects. This is a matter of degree, since both wetland cells exhibited significant cooling effects. Greater surface area might imply more evaporation and evapotranspiration; however, other factors such as shading, wind exposure, and local position effects are uncertain.

Electrical conductivity (EC) data were used to evaluate differences in the evaporative concentration effects. The H1 cell outflow EC was significantly higher than that of H2 (table 4-2, and 4-3). This indicates a greater degree of evaporative concentration in H1, which coincides with greater cooling and higher DO capacity.

A few differences between the two cells for the other water quality constituents are evident in the two-way ANOVA results in tables 4-16 and 4-17. In the comparison of HLR and cell effects (table 4-16) only PO_4–P had a significant relationship for cell effects only (i.e. difference between cells). In contrast, the comparison of depth and cell effects (table 4-17), indicated significant differences for TDS, TKN, NH_4–N, BOD, COD, and TOC based solely on cell effects. Although both tables present results for cell effects, the first table is based on data from test phases A and B, whereas the second table includes phases B, C, and D that were later in the monitoring program. The results for PO4–P could be influenced by soil leaching during the early wetland startup period in test phase A.

The differences between wetland cells for the nitrogen species and oxygen demand parameters coincide with the results for DO. Microbial transformations of TKN and NH_4–N will consume oxygen (nitrogenous oxygen demand), whereas BOD and COD are indicators of the oxygen consumption potential attributed to the labile and more resistant organic matter in the water. Total organic carbon (TOC) provides further evidence of the differences in organic assimilation between the cells.

Differences in the water quality performance of the two Hayfield wetland cells are also illustrated graphically by the median data plots in figures 4-4 and 4-5, although the trends apparent in the data plots are not necessarily statistically significant. This effect can be caused by trend reversals between the two cells at different operating conditions, which effectively narrows the overall difference in the data sets. In other cases, trends between lines may appear small, but the differential is large enough and consistent over the data set to produce a statistical difference.

These results suggest that the open water configuration can produce a subtle, but significant difference in the oxygen characteristics of the wetlands cells, and may be manifested in the removal performance for water quality constituents that require oxygen for removal. Differences in the evaporative effects between the cells are also evident by the differences in evaporative concentration for conservative parameters. The differences give further support to air circulation, water mixing, and reaeration as primary mechanisms associated with the open water configuration effects.

Seepage Loss Effects

Infiltration and seepage loss effects were evaluated using data collected from the Cobble site. The Cobble site has one wetland cell constructed using native alluvial materials in the river floodplain and the other cell received an impervious layer of clay to reduce seepage. These cells are referred to as the unlined (C1), and lined (C2) wetland cells. This evaluation of water quality effects related to seepage losses is based on total mass loads (removal) rather than concentration changes.

Seepage Adjusted Removal

The time-series plot of flows and losses (figure 3-4) shows a significant difference in the seepage rate of the two Cobble cells. The seepage adjusted and non-adjusted percent removals are compared for various water quality constituents in both Cobble site cells in table 4-19. For each constituent, the first line of the comparison is not adjusted for seepage and the second line shows the adjusted results.

The first three constituents—alkalinity, TDS, and chloride—are known to behave conservatively (i.e., only affected by evaporation or dilution). Evaporation results in an increase in concentration, but generally does not affect the mass load because the water depleted offsets the concentration increase in computing loads. Consequently, these conservative constituents are useful to evaluate seepage effects.

In cell C1, the conservative constituents show 78 to 79 percent removal, whereas the removal in cell C2 is about 23 to 27 percent. When the percent removal is adjusted for the estimated seepage loss, removal drops to slightly negative percentage (an increase), while C2 still shows a net removal of 5 to 10 percent. These minimal values could represent the error in calculating estimated loads, including the inflows outflows, and seepage components. For example, travel time through the wetlands was not taken into account. Another possible source of error is in the estimated concentrations of seepage. The percent removal is calculated as the difference in the mass balance between the inflow and outflow loads. Errors in estimating the mass balance can have significant effects on the calculated percent removal.

The comparison of percent removal (table 4-19) also shows a highly significant difference (prob. < 0.01) between cells C1 and C2 for all three conservative constituents based on the unadjusted loads. When the loads are adjusted for seepage, the comparison of the percent removal between the two cells only shows a significant difference (prob. ≤ 0.05) for TDS, which indicates the mass balance is fairly close disregarding the uncertainty in calculations or unknown effects of TDS components. There is no significant difference between the cells based on alkalinity and chloride, although the t-values approach significance. These results provide a point of reference for less conservative water quality components.

For TSS there is an unadjusted removal of about 75 percent that shifts to net increase with the seepage adjustment. This may reflect a filtration effect for the particulate suspended matter, which are not transported during seepage infiltration unless the sediment pores are very large. Deposition of the solids at the sediment water interface is more likely, and resuspension of some particulate matter would explain the net gain in TSS based on surface outflow measurements. Although there may be a net gain, the amount removed by seepage in C1 could also be overestimated based on the simplistic calculation method. Ignoring shortcomings in the methodology, there are significant differences in the removal of TSS. Removal is greater in C1 without seepage adjustment and is greater in C2 with the adjustment.

Table 4-19. Comparison of percent mass load removal with and without seepage adjustment for various water quality constituents in the Cobble site C1 and C2 wetland cells.

Constituent	Seepage Adjusted ?	Mean percent removal		t	Prob. > t
		C1	C2		
Alkalinity	No	78.46	22.70	20.24	< 0.01
	Yes	-1.40	5.75	-1.68	0.09
TDS	No	78.18	24.58	20.52	< 0.01
	Yes	-1.02	7.68	-2.11	0.04
Chloride	No	79.15	26.92	18.90	< 0.01
	Yes	-0.13	8.62	-1.92	0.06
TSS	No	75.27	45.38	4.84	< 0.01
	Yes	-27.57	29.43	-3.97	< 0.01
TKN	No	87.25	66.16	11.69	< 0.01
	Yes	25.79	53.36	-8.39	< 0.01
NO_2-N	No	48.92	-3.98	2.84	0.01
	Yes	-53.75	-24.29	-1.37	0.17
NO_3-N	No	80.27	54.72	3.76	< 0.01
	Yes	15.45	40.22	-2.70	0.01
NO_2+NO_3-N	No	78.94	53.69	3.46	< 0.01
	Yes	15.57	39.86	-2.55	0.01
NH_4-N	No	89.44	70.06	9.57	< 0.01
	Yes	33.36	58.21	-8.39	< 0.01
Total N	No	85.29	63.09	7.61	< 0.01
	Yes	24.35	50.19	-6.00	< 0.01
PO_4-P	No	78.42	20.21	11.49	< 0.01
	Yes	-6.49	0.83	-1.07	0.29
Diss. P	No	76.90	12.69	14.18	< 0.01
	Yes	-8.36	-6.02	-0.39	0.70
COD	No	78.02	38.24	10.89	< 0.01
	Yes	-8.69	21.03	-4.60	< 0.01
BOD	No	80.37	37.66	8.11	< 0.01
	Yes	-4.44	22.26	-3.54	< 0.01
TOC	No	79.29	29.65	12.63	< 0.01
	Yes	0.56	12.52	-2.25	0.03

Similar results are evident for other water quality components, although filtration effects cited for TSS are not likely because dissolved constituents are exported with seepage water. As a result, the percent removal expected for these constituents is not evident in surface outflow measurements, but every constituent

shows some degree of net mass removal when seepage losses are accounted (table 4-19).

It was anticipated that there would be a significant difference between the seepage adjusted and the unadjusted percent removal for water quality constituents in the unlined C1 wetland cell. However, the difference in percent removal in the lined C2 cell was unexpectedly large (table 4-19). To further evaluate this, the differences in seepage adjusted and unadjusted percent removals are indicated by the t-test results shown in table 4-20. The results indicate the adjusted and unadjusted percent removals are significantly different for all constituents in both cells. This means that the seepage losses account for a significant amount of removal even in the lined cell. The significant seepage effects in the lined Cobble site cell raised questions regarding whether seepage is also a significant factor at the Hayfield site.

Table 4-20. Comparison of mean percent mass load removal for the Cobble site C1 and C2 cells with and without adjustments for seepage infiltration losses.

Variable	Cell	Mean percent removal		t	Prob > t
		no seepage adjustment	with seepage adjustment		
TSS	C1	75.27	-27.57	8.86	< 0.01
	C2	45.38	29.43	8.78	< 0.01
TDS	C1	78.18	-1.02	24.30	< 0.01
	C2	24.58	7.68	10.64	< 0.01
TKN	C1	87.25	25.79	23.87	< 0.01
	C2	66.16	53.36	10.52	< 0.01
NO_3-N	C1	80.27	15.45	15.02	< 0.01
	C2	54.72	40.22	8.26	< 0.01
NO_2+NO_3-N	C1	78.94	15.57	15.06	< 0.01
	C2	53.69	39.86	8.05	< 0.01
NH_4-N	C1	89.44	33.36	25.84	< 0.01
	C2	70.06	58.21	11.02	< 0.01
Total N	C1	85.29	24.35	23.30	< 0.01
	C2	63.09	50.19	9.94	< 0.01
PO_4-P	C1	78.42	-6.49	18.86	< 0.01
	C2	20.21	0.83	9.58	< 0.01
Diss. P	C1	76.90	-8.36	22.78	< 0.01
	C2	12.69	-6.02	9.91	< 0.01
COD	C1	78.02	-8.69	19.24	< 0.01
	C2	38.24	21.03	9.17	< 0.01
BOD	C1	80.37	-4.44	17.94	< 0.01
	C2	38.02	22.26	10.44	< 0.01
TOC	C1	79.28	0.56	23.68	< 0.01
	C2	29.65	12.52	10.45	< 0.01

Hayfield Site Seepage

The Hayfield cells were constructed without a liner, but the site soils are naturally more impervious than the Cobble site. The water budget plots (figure 3-3) indicate low seepage at the Hayfield site and little difference between cells. A comparison of hydrologic factors that could influence seepage is shown in table 4-21.

Table 4-21. Comparison of hydrologic factors in the Cobble site C2 cell and the H1 and H2 wetland cells of the Hayfield site.

Hydrologic factor	Cobble site C2 mean	Hayfield site cell	Hayfield cells mean values	t	Probability > t
Infiltration (gpm)	25.21	H1	33.25	-2.18	0.0304
		H2	45.44	-4.46	< 0.0001
HLR (ft/day)	0.41	H1	0.45	-1.35	0.1789
		H2	0.44	-1.02	0.3115

The infiltration rate at C2 average 25 gpm, while seepage at H1 and H2 averaged 33 and 45 gpm, respectively. The infiltration rates of the cells at the Hayfield site are significantly higher than C2, although the inflow HLR was similar. This implies the mass losses at the Hayfield site could be greater; however, the Hayfield cells are also larger than the Cobble cells, so the actual significance is uncertain.

Seepage Changes Over Time

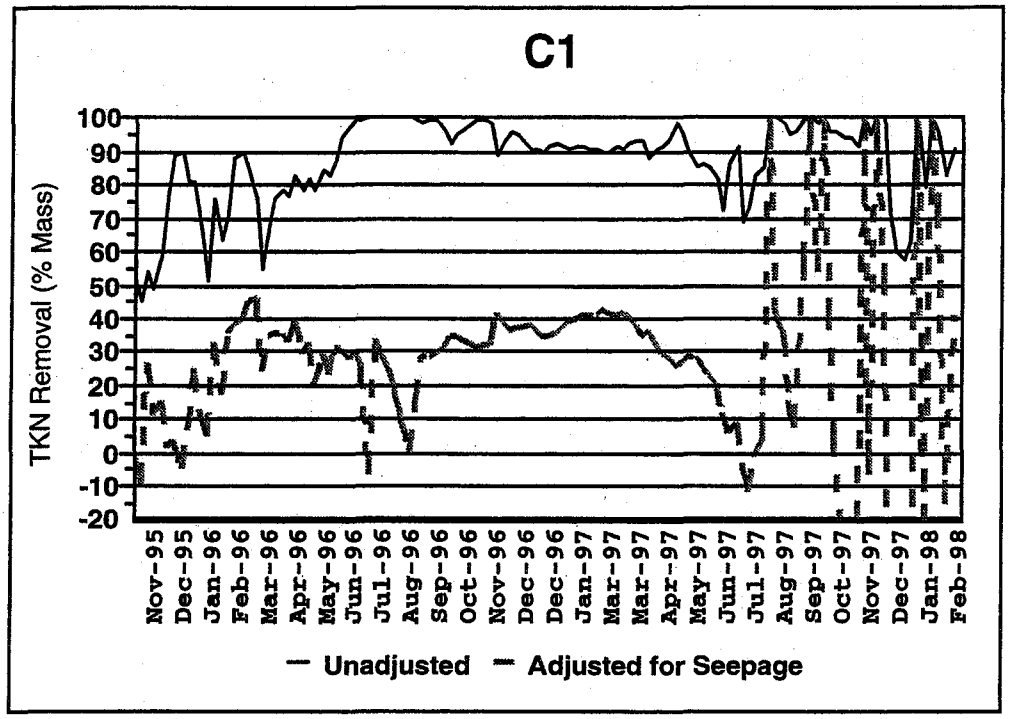
It was noted in previous analyses that the nitrogen species (except NO_2-N), provide the most definitive removal results. Table 4-19 indicates that the unadjusted percent removal of TKN was about 87 percent in cell C1 and 66 percent in the C2 cell. The statistical results confirm that the difference in removal percentage is significant, with C1 removal significantly higher than C2. This trend reverses with the seepage adjustment and the percent removal becomes significantly greater in C2.

The seepage adjusted and unadjusted loads for TKN over time in the Cobble site cells are illustrated in figure 4-8. The plot shows that the unadjusted percent removal of TKN in cell C1 was 100 percent during part of the study. At the time, however, there was no outflow measured because seepage exceeded the inflow. With no outflow there is also no discharge load, resulting in 100 percent calculated removal. Most of the time the percent removal is reduced to less than 40 percent when adjusted for seepage. At the same time, in C2 the percent removal remained between 60 and 80 percent with or without adjustment. As a result, it appears possible that seepage losses may be overestimated somewhat in the C1 unlined cell.

Similar time-series plots for Cobble site NO_3–N, NH_4–N, and total N data are shown in figures 4-9, 4-10, and 4-11. Results for these parameters also indicate the seepage adjusted percent removals are generally lower in C1 than C2. The percent removal of NO_3–N in C2 is nearly 90 percent most of the time, whereas the removal in C1 is generally less than 50 percent. Equivalent results for NH_4–N are between 60 and 80 percent in C2 and less than 50 percent in C1. For total N, the results range from 50 up to 90 percent in C2, but are less than 50 percent in C1. Significant differences between cells are also apparent in the t-test results in table 4-19.

The inflow loading rates were reviewed to further evaluate differences in removal performance between the Cobble site cells. Reference back to figures 3-4 and 3-7 show the inflow HLR was generally much higher in C1 than C2. The mean HLR was 0.89 ft/day in C1 and 0.41 ft/day in C2. The previous evaluation of HLR effects at the Hayfield site indicated greater reduction for NO_3–N, NH_4–N, and total N at a lower HLR, whereas TKN had the opposite trend (tables 4-11 and 4-12). On this basis, the lower seepage adjusted percent removal in C1 could be attributed in part to the higher inflow load rate in C1 during most of the test period.

The seepage adjusted and unadjusted percent removal of total dissolved phosphorus over time is shown in figure 4-12. In this case, there is a large difference in adjusted and unadjusted percent removal in C1, but little difference is apparent between the seepage adjusted removal in C1 compared to C2. Total dissolved phosphorus had no significant change in removal with the change in HLR (table 4-10). This result adds further support to the hypothesis concerning the effects of HLR on the effective removal of various forms of nitrogen.



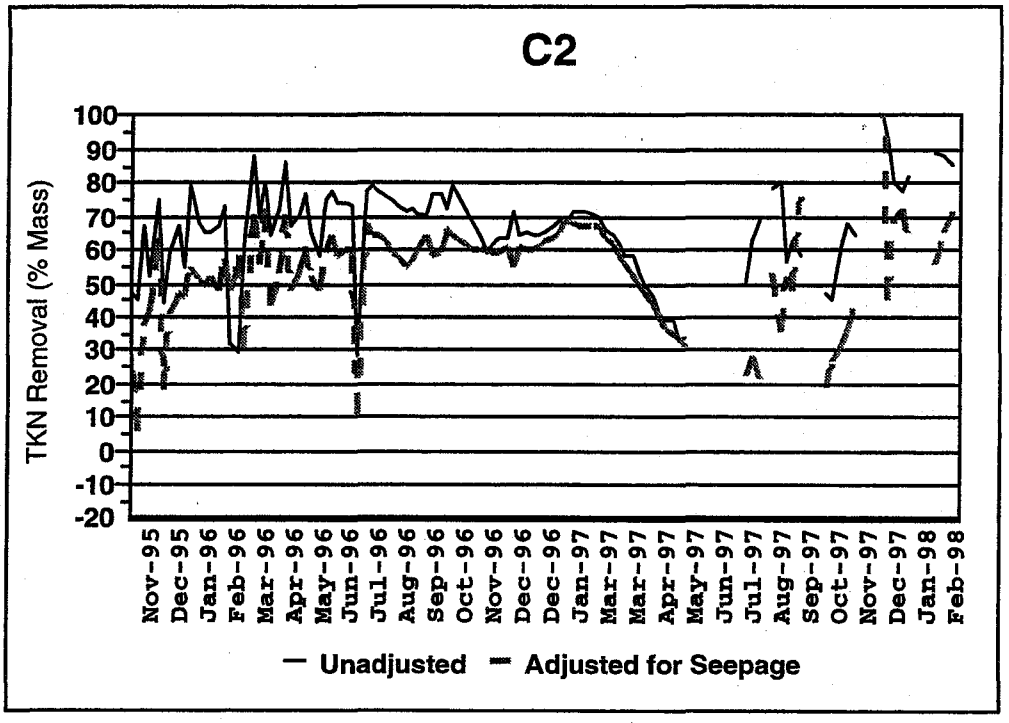
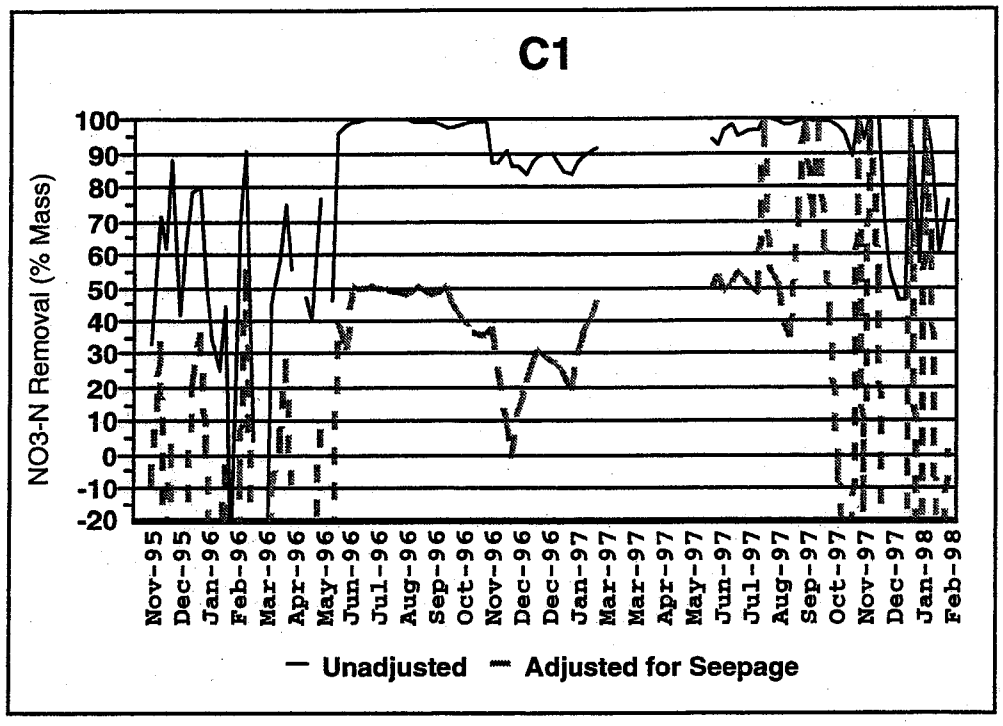


Figure 4-8. Comparison of seepage adjusted and unadjusted percent removal of Total Kjeldahl Nitrogen (TKN) in the Cobble site C1 and C2 wetland cells.



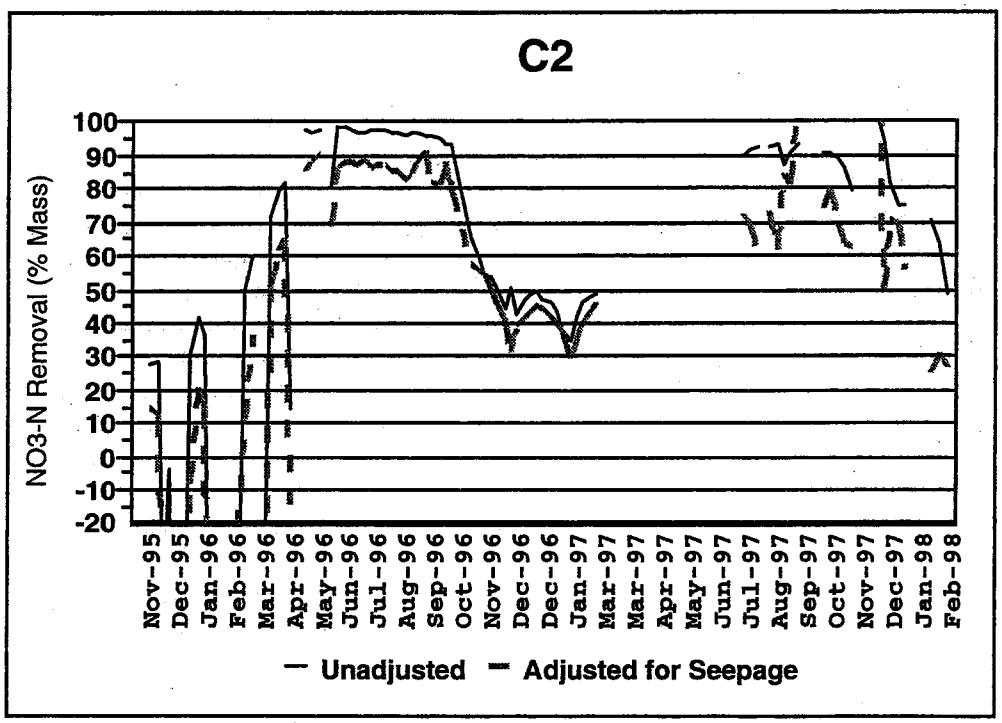
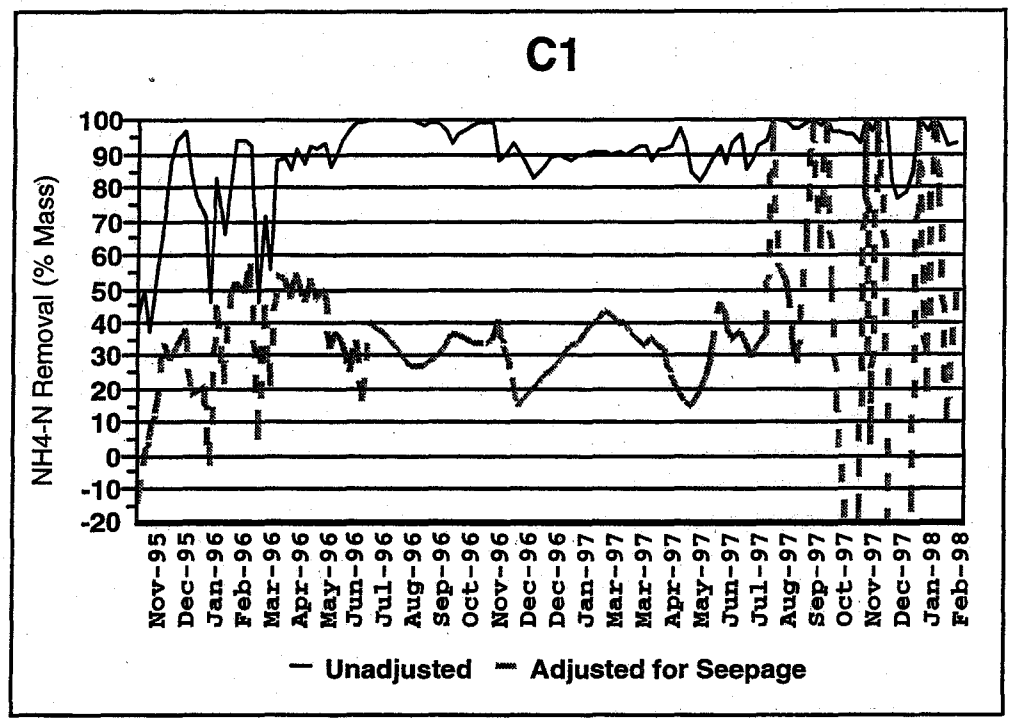


Figure 4-9. Comparison of seepage adjusted and unadjusted percent removal of Nitrate Nitrogen (NO_3–N) in the Cobble site C1 and C2 wetland cells.



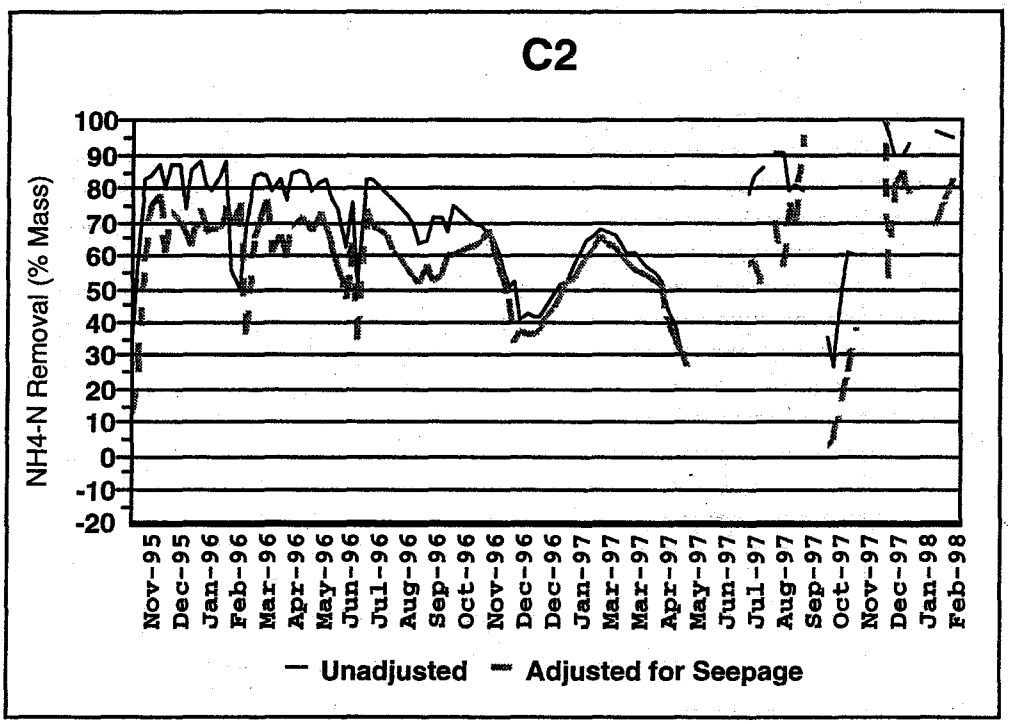
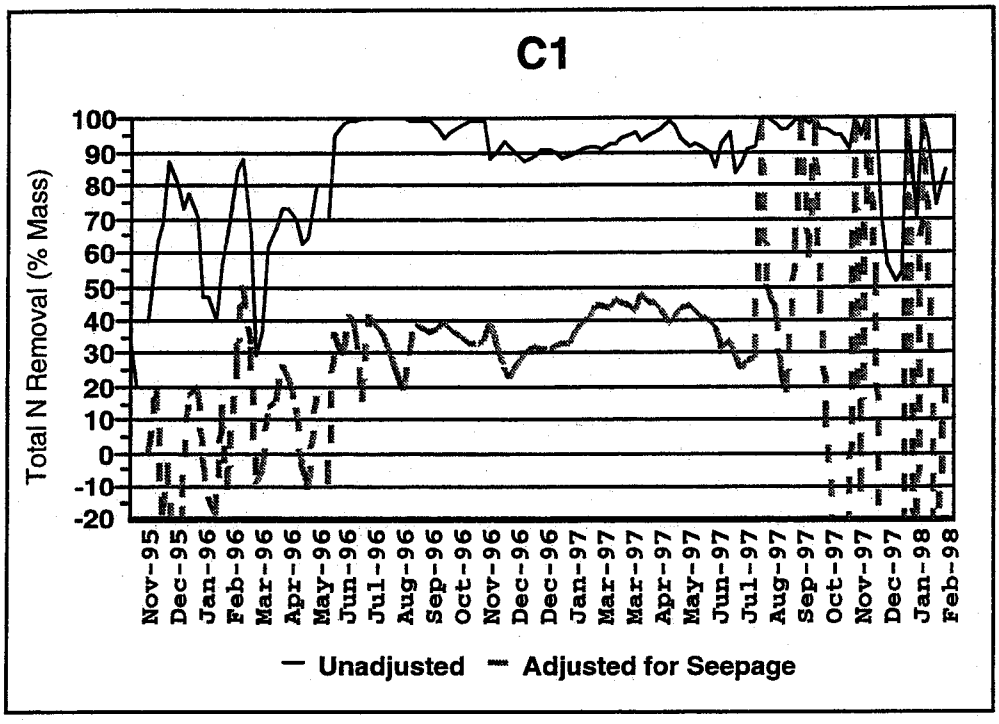


Figure 4-10. Comparison of seepage adjusted and unadjusted percent removal of Ammonia Nitrogen (NH_4–N) in the Cobble site C1 and C2 wetland cells.



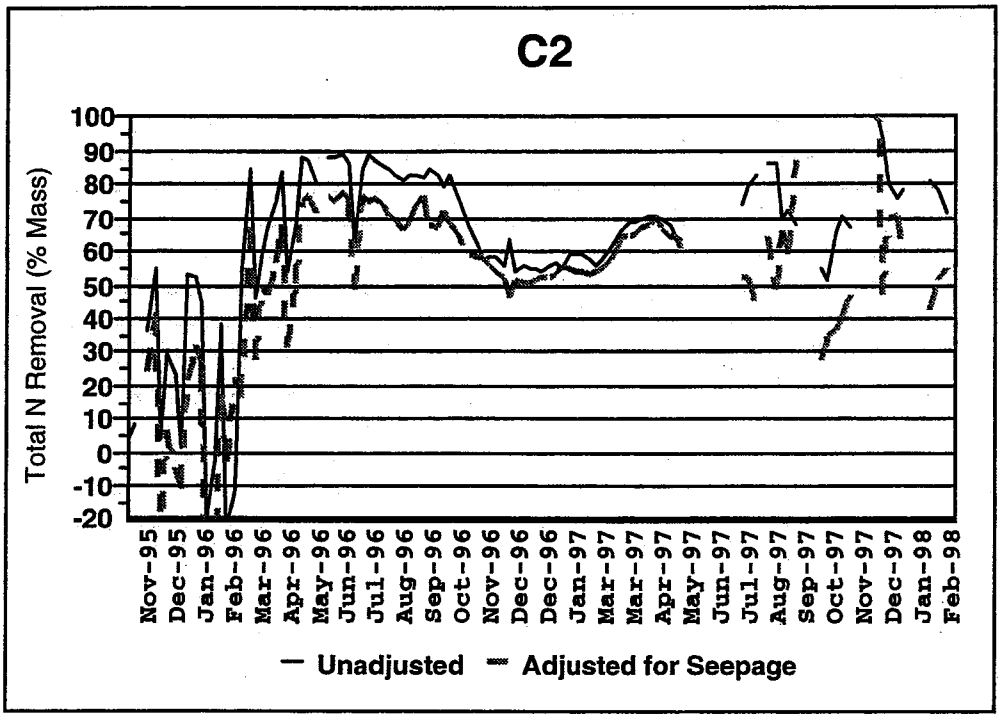
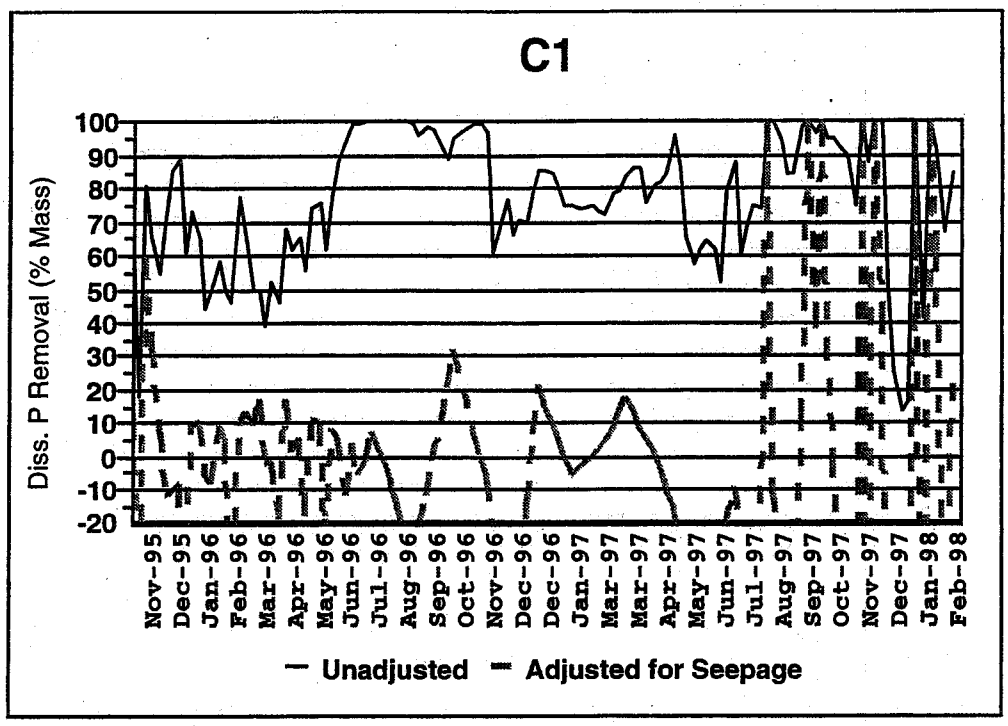


Figure 4-11. Comparison of seepage adjusted and unadjusted percent removal of Total Nitrogen (Total N) in the Cobble site C1 and C2 wetland cells.



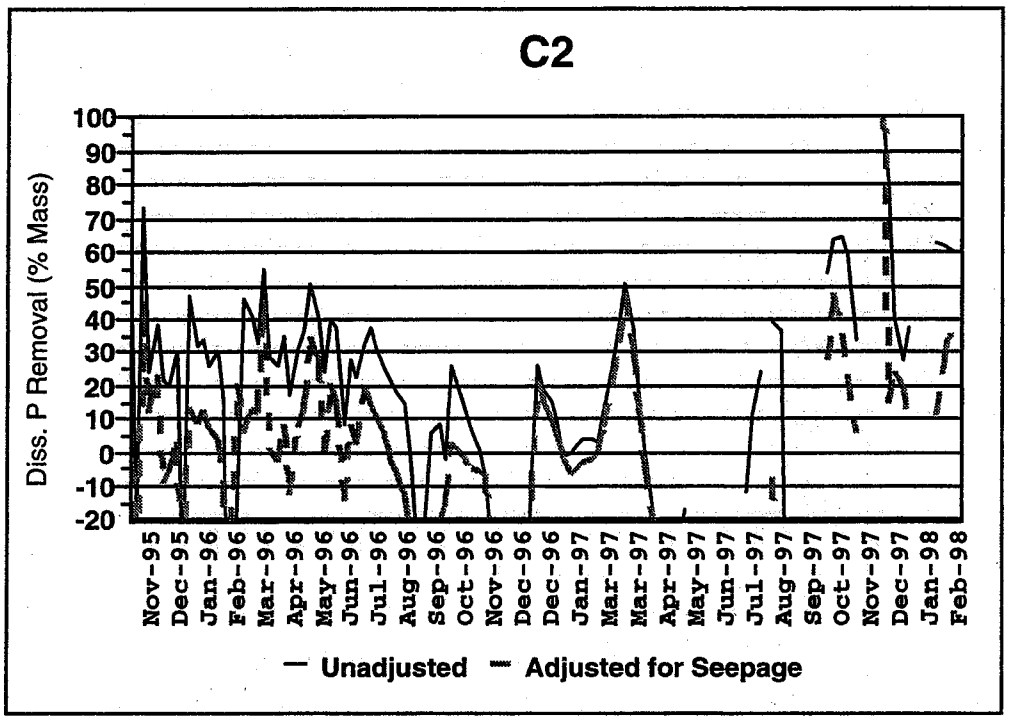


Figure 4-12. Comparison of seepage adjusted and unadjusted percent removal of Dissolved Phosphorus (Diss. P) in the Cobble site C1 and C2 wetland cells.

Combined Site Comparison

This evaluation is a cross comparison of the water quality data results between the wetland cells at the Hayfield site and Cobble site. Design features and operating conditions for the demonstration wetland facilities were summarized previously in tables 3-1 through 3-5. This comparison was based on all data encompassing the study period from December 1995 through May 1998 at the Hayfield site and from October 1995 through February 1998 at the Cobble site.

Water Budget Comparison

Water Quality effects between the Hayfield and Cobble sites were further evaluated by reviewing the wetland operations and climate conditions. A comparison of the operations and water budget factors (mean and median) for each of the four wetland cells are shown in table 4-22.

Table 4-22. Comparison of mean and median water budget factors for Hayfield and Cobble cells.

	Cell	Inflow [gpm]	Outflow [gpm]	Depth [ft]	Volume [ft³]	ET [gpm]	Infiltration [gpm]	Precip [gpm]	HLR [ft/day]	HRT [days]
Mean by cell	H1	304.4	258.4	0.99	142,692	13.18	33.25	1.34	0.45	7.7
	H2	297.1	239.3	0.99	136,743	12.69	45.44	1.18	0.44	7.4
	C1	442.8	92.6	0.86	141,004	6.35	334.01	0.44	0.89	1.9
	C2	201.8	167.1	0.80	130,197	6.28	25.21	0.44	0.41	5.1
Median by cell	H1	359.2	301.2	0.98	140,874	10.60	41.87	0.00	0.53	7.6
	H2	359.2	271.5	0.99	135,585	10.15	52.37	0.00	0.53	7.3
	C1	429.2	77.8	0.96	158,007	5.47	316.36	0.00	0.86	1.6
	C2	125.4	88.0	0.97	157,745	5.47	23.75	0.00	0.25	4.5

The HLR was much greater in C1 than that in the other cells. This reduced the net evaporative concentration by reducing the HRT. Although the estimated ET loss rate in C1 is not much different from C2, it is much smaller relative to the inflow rate, which is proportional to the concentration effect. The concentration of constituents that behave conservatively increases in proportion to the ratio of the evaporative concentration factor (i.e., Q_i to $Q_i - Q_{et}$ = effective concentration factor).

The C2 cell was expected to have operating conditions similar to the Hayfield cells because of reduced seepage effects in the lined cell. The comparison of mean values (table 4-21), indicated infiltration was actually lower in C2 than either Hayfield cell. The median values in table 4-22 verify that the infiltration was much less in C2, and in addition, the median precipitation rate was also lower. It should be noted that the monitoring periods at the two sites are somewhat different which could affect conditions such as precipitation that can vary depending on the storm events included in the data. Although the mean inflow HLR in C2 was similar to the H1 and H2, the median was much lower. The mean and median HRT in C2 were also lower than for the Hayfield cells due to the difference in cell surface area.

Discrepancies between the mean and median values for several other hydrologic variables are also evident. The mean precipitation at the Hayfield cells is more than twice that of the Cobble cells, but the median precipitation rate was zero in all four cells. Although the mean volume of the cells (calculated from hydrologic data) is comparable, the median volumes for the Cobble cells are much greater than that of the Hayfield cells. The greater the difference between the mean and the median, the greater the skew in the distribution. The inference verifies that operating conditions at the Hayfield site were less variable than those of the Cobble cells.

Water Quality Comparison

The maximum and median values for all data showing the percent difference in concentration of various water quality constituents in the Hayfield and Cobble sites are summarized in table 4-23. The first three conservative constituents are affected only by evapoconcentration and thus show a negative reduction (concentration increase), with median increases of about 5 percent or less. Although the largest cell, H1, also has the greatest concentration increase, surface area effects are otherwise inconsistent. In general, there are no obvious patterns with respect to the magnitude for either the maximum or median changes among these constituents.

Table 4-23. Summary statistics of maximum and median percent difference in the concentration of various constituents in each of the Hayfield and Cobble site wetland cells.

Constituent	H1 (5 zone)		H2 (2 zone)		C1 (unlined)		C2 (lined)	
	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median
Alkalinity	-31.3	-5.6	-69.7	-3.8	-47.1	-1.2	-57.0	-5.2
TDS	-13.7	-2.9	-12.2	-2.4	-24.8	0.0	-33.7	-1.4
Cl^-	-38.9	-4.2	-33.3	-2.3	-11.7	-2.7	-20.8	-1.4
TSS	86.4	33.3	90.9	46.2	88.9	33.3	94.4	36.4
TKN	77.1	58.3	83.3	60.0	64.9	47.1	81.8	60.0
NO_2-N	96.2	0.0	96.2	0.0	68.8	0.0	98.0	0.0
NO_3-N	97.5	64.6	97.7	63.4	97.2	48.3	97.7	63.0
NO_2+NO_3-N	97.7	60.7	97.7	60.7	97.7	58.7	98.2	61.7
NH_4-N	94.4	68.8	95.2	74.3	94.1	58.3	94.1	64.3
Total N	80.0	58.0	82.4	58.7	79.7	49.1	84.1	55.1
PO_4-P	98.1	3.8	98.1	-2.9	59.5	0.0	48.6	3.0
Diss. P	34.0	-8.6	37.5	-7.8	71.4	-5.5	55.1	-6.6
COD	96.0	7.3	60.8	8.1	85.8	-0.8	88.4	18.4
BOD	75.0	24.5	75.0	30.0	75.0	13.4	75.0	25.0
TOC	39.3	10.2	38.0	15.1	28.9	2.9	35.1	10.6

NOTE - Negative maximum values for Alkalinity, TDS, and Cl, indicate largest increase, or minimum reduction.

Mann-Whitney test evaluations of the statistical significance of the differences shown in table 4-23 are summarized in table 4-24. The comparison of the H1 and H2 cells with C1 shows significant differences (< .05) for several constituents. Alternatively, comparison of the Hayfield cells to C2 shows very few constituents had significant differences between cells. Overall, this might suggest that seepage loss is the most significant factor that influences the percent removal results.

Table 4-24. Mann-Whitney comparison of percent changes between cells across sites.

WQ Constituent	H1 versus C1			H2 versus C1		
	X^2	Prob > X^2	< .05	X^2	Prob > X^2	< .05
Alkalinity	11.283	0.0008	*	4.921	0.0265	*
TDS	12.521	0.0004	*	14.441	0.0001	*
Cl^-	17.361	< 0.0001	*	1.186	0.2761	
TSS	0.093	0.7603		4.688	0.0304	*
TKN	31.053	< 0.0001	*	46.713	< 0.0001	*
NO_2-N	10.195	0.0014	*	8.217	0.0041	*
NO_3-N	2.627	0.1051		1.334	0.2480	
NO_2+NO_3-N	0.001	0.9733		0.094	0.7590	
NH_4-N	15.726	0.0001	*	43.434	< 0.0001	*
Total N	8.383	0.0038	*	11.589	0.0007	*
PO_4-P	1.435	0.2309		0.016	0.8991	
Diss. P	0.432	0.5109		0.663	0.4156	
COD	5.880	0.0153	*	9.302	0.0023	*
BOD	5.883	0.0153	*	10.480	0.0012	*
TOC	22.220	< 0.0001	*	33.167	< 0.0001	*
WQ Constituent	**H1 versus C2**			**H2 versus C2**		
	X^2	Prob > X^2	< .05	X^2	Prob > X^2	< .05
Alkalinity	0.215	0.6428		0.539	0.4629	
TDS	1.658	0.1979		1.512	0.2189	
Cl^-	5.325	0.0210	*	0.281	0.5962	
TSS	0.524	0.4690		1.892	0.1690	
TKN	1.473	0.2248		3.770	0.0522	
NO_2-N	2.485	0.1149		1.837	0.1753	
NO_3-N	0.046	0.8298		0.092	0.7620	
NO_2+NO_3-N	0.579	0.4468		1.411	0.2348	
NH_4-N	3.129	0.0769		18.510	< 0.0001	*
Total N	0.003	0.9555		0.678	0.4104	
PO_4-P	0.124	0.7249		3.327	0.0681	
Diss. P	0.455	0.5000		0.786	0.3754	
COD	3.752	0.0527		1.923	0.1655	
BOD	0.104	0.7467		1.891	0.1691	
TOC	2.901	0.0885		8.900	0.0029	*

The maximum difference in the inflow and outflow concentration of the various nitrogen species is similar in the four cells (table 4-23). Notable exceptions include NO_2–N and TKN as indicated previously. Although there is a lower maximum difference in both NO_2–N and TKN in C1 than the other cells, the median percent NO_2-N difference in all of the cells is zero, while the median TKN difference is about 60 percent in each cell except C1, where it is 47 percent. As a result, the percent difference of both NO_2–N and TKN in the Hayfield cells are significantly different from C1, but not C2 (table 4-24). In the case of NO_2–N, the differences are in values greater than the median, while the differences in TKN occur across the distribution. Because of this difference, the probability level for TKN is lower than that for NO_2–N when comparing Hayfield cells with C1.

There is no significant difference in the percent change NO_3–N among the cells, although the median change in NO_3–N in C1 is only 48 percent. The percent difference in NH_4–N is significantly less in the Cobble cells than the Hayfield cells, except for H1 versus C2, where the probability is slightly greater than 0.05. Total N shows the pattern of TKN with the percent difference significantly lower in C1 than in the Hayfield cells, but not between C2 and the Hayfield cells.

Percent differences in the maxima and medians of the two measures of phosphorus are quite variable among the cells. Values range between positive and negative and the differences among them appear large. None of the differences are statistically significant, most likely because the Mann-Whitney data analysis does not indicate significance for inconsistent data. As long as the ranks of the data are intermingled, there will be no significant difference in the input variables.

The percent change in median COD, BOD, and TOC is significantly lower in C1 than in either Hayfield cell (tables 4-23 and 4-24); however, the median values are not significantly different between C2 and the Hayfield cells, except for TOC between H2 and C2. The comparison of TOC removal follows the pattern for NH_4–N, while those for COD and BOD appear similar to TKN and total N. The median percent change in all three constituents is relatively low. The BOD reduction is greatest at 25 to 30 percent in H1, H2, and C2, and only 13 percent in C1. The median COD reduction is 7 or 8 percent in the Hayfield cells, 18 percent in C2, and the percent change increases in C1. The median decrease in TOC is 10 and 15 percent in the H1 and H2, respectively; and 10 percent in C2 (significantly lower than H2).

These results are, for the most part, consistent with the differences in HLR and HRT of the various cells indicated by the operational properties in table 4-22 and the water quality results in table 4-23. The site cross-comparison (table 4-24) indicates that without correction for seepage losses, the data for unlined C1 cell is significantly different than the other three cells. The mixed results for nitrogen may be attributed to transformations between various forms, making different nitrogen species sensitive to operational changes. Phosphorus and TSS results are inconsistent, perhaps due to the inability to differentiate filtration-resuspension effects induced by infiltration, and conversions between particulate and dissolved forms.

Overall, it appears that in spite of the wide variations in the operating conditions, climate factors, and the different period of data record for the two sites, the seepage effects in C1 are an overriding factor for many constituents. This may reflect some stability in wetland systems (the ability to dampen short-term variations), but it also indicates that water budget and hydraulic operations are key factors in the overall wetland system process characteristics.

Rate Function Comparison

Empirical rate models have been developed to aid in the design planning of treatment wetlands. The decay coefficients (k-values) for these models provide a point of reference to assess performance by comparing the Tres Rios demonstration results against values reported in literature. This evaluation compared the decay coefficients for a volumetric model (Reed et al., 1995) and an areal model (Kadlec and Knight, 1996) using the water quality data from the Hayfield site.

Expressions for the two rate functions evaluated are as follows:

Volumetric rate function: $C_o / C_i = \exp(- k_{VT}\, t)$

Areal basis rate function: $(C_o - C^*) / (C_i - C^*) = \exp(- k_{AT} / q)$

Where:

C_o	=	outflow concentration
C_i	=	inflow concentration
C^*	=	background concentration
k_{VT}	=	volumetric temperature-dependent rate constant
t	=	theoretical hydraulic detention time (~HRT)
k_{AT}	=	areal temperature corrected reaction rate constant
q	=	nominal hydraulic loading rate (~HLR)

Median inflow and outflow concentrations and the ratio of C_o/C_i for selected water quality constituents are shown in table 4-25. These data sets are separated by test phases A, B, and C used in the volumetric and areal rate function evaluations.

Table 4-25. Median concentrations under different operating conditions at the Hayfield site.

	Test phase	HLR (cm/day)	Depth (ft)	BOD [mg/L]	TSS [mg/L]	NH_4-N [mg/L]	NO_3-N [mg/L]	PO4-P [mg/L]
H1 Inflow	A	7.5	1.0	3.8	4.1	2.0	3.0	8.5
	B	15.0	1.0	3.7	2.6	1.5	3.0	2.9
	C	15.0	1.5	2.3	2.2	1.4	2.5	2.1
H2 Inflow	A	7.5	1.0	3.8	4.1	2.0	3.0	8.5
	B	15.0	1.0	3.9	2.6	1.4	3.6	2.6
	C	15.0	1.5	2.2	2.3	1.4	2.6	2.3
H1 Outflow	A	7.5	1.0	2.6	3.5	0.5	1.5	3.5
	B	15.0	1.0	2.2	1.3	0.5	2.6	2.9
	C	15.0	1.5	2.3	2.4	0.9	0.3	2.0
H2 Outflow	A	7.5	1.0	2.4	2.9	0.5	1.5	3.7
	B	15.0	1.0	2.0	1.0	0.5	2.7	3.4
	C	15.0	1.5	2.0	1.7	0.8	0.7	2.1
H1 1- (C_o/C_i)	A	7.5	1.0	0.7	0.9	0.3	0.5	0.4
	B	15.0	1.0	0.6	0.5	0.4	0.9	1.0
	C	15.0	1.5	1.0	1.1	0.6	0.1	1.0
H2 1- (C_o/C_i)	A	7.5	1.0	0.6	0.7	0.3	0.5	0.4
	B	15.0	1.0	0.5	0.4	0.4	0.7	1.3
	C	15.0	1.5	0.9	0.7	0.6	0.3	0.9

Volumetric Rate Model

Hydraulic residence times (t) used to calculate volumetric rate coefficients (k_{VT}) were derived from two Hayfield site tracer studies (Wass, 1997). Water quality data for test phases B and C (figure 3-6, table 4-25) were used to coincide with the conditions during the tracer studies conducted at 1.0 and 1.5 feet water depths. The resulting volumetric K_{VT} values for the Tres Rios data and typical values reported for other wetland systems (Reed et al., 1995) are shown in table 4-26.

Temperature dependent rate coefficients derived for the volumetric model were corrected to 20 °C using the formulas presented in Reed, et al. (1995). For example, the BOD correction is $k_{VT} = k_{20}\ (1.06^{(T-20)})$, where T is the ambient temperature taken from the site field monitoring data. Volumetric k_{VT} values shown in table 4-25 are corrected to 20 °C for comparison with the typical k_{20} values indicated.

Table 4-26. Volumetric model k_{VT} rate constants for the Hayfield site and typical reported values.

Cell	Depth (ft)	Res. time t [days]	Temperature [° C]	Volumetric rate coefficients K_{VT} in days^{-1}		
				BOD	NH_4-N	NO_3-N
H1	1.0	2.50	21.5	0.194	0.385	0.054
	1.5	3.16	25.4	0.000	0.101	0.503
H2	1.0	2.13	19.1	0.332	0.515	0.144
	1.5	3.17	24.7	0.028	0.137	0.309
Typical k_{20}	0.5-2.0	---	20.0	0.678	0.411	1.000

Note: Hydraulic residence times based on tracer studies (Wass, 1997). Calculated rate coefficients k_{VT} are based on inflow hydraulic load rate HLR = 0.5 ft (15 cm)/day. Typical k_{20} values from Reed, et al. (1995).

The results indicate BOD and NO_3–N rate coefficients for the Tres Rios wetlands are somewhat lower than typical values, whereas the Tres Rios NH_4–N values bracket the typical values reported for NH_4–N removal (Reed, et al., 1995). The decay coefficients for BOD and NH_4–N are greater at the 1-foot depth, while those for NO_3–N decay are higher at the 1.5-foot depth.

It should be noted, however, the monitoring period at 1.5-foot water depth was rather short and encompassed the spring and early summer. The period on which the 1-foot depth data is based included the late summer through the winter. These differences could affect the median temperatures and temperature-dependent results. The time period of test phases B and C in the H1 and H2 cells does not coincide exactly, which could also produce minor differences in climate data affecting the results.

The comparison of volumetric K_{VT} values did not account for inflow HLR effects because the residence time, t was derived from tracer studies that were conducted during test phases B and C, at a consistent HLR of 0.5 ft (15cm)/day. The previous correlation analysis (table 4-18) indicated the percent change in BOD and NH_4–N correlates positively with the inflow concentration in both H1 and H2, whereas the change in NO_3–N does not in either cell. However, all three constituents have a significant decrease in inflow concentration over time (table 4-25). Consequently, the data for the 1.5-foot depth has relatively lower inflow concentrations than those at the 1-foot depth interval.

Changes in the inflow concentration might be expected to affect the removal of BOD and NH_4–N but not NO_3–N. NO_3–N may not correlate with inflow concentration because it is a product of TKN and NH_4–N nitrification. Based on this, more efficient removal of BOD and NH_4–N would occur earlier in the study, and coincide with the 1.0-foot operating depths as indicated in table 4-25.

Areal Rate Model

The areal rate model evaluated incorporates a factor (C*) to account for irreducible minimum concentrations attributed to natural background levels for certain water quality components in wetlands. Background C* values calculated for the Hayfield site data are summarized in table 4-27. Values shown for Kadlec and Knight (1996) are based on data examined for constructed wetlands in the NADB.

Table 4-27. Background C* minimum concentrations for Hayfield cells and reported values.

C* reference	C* minimum concentration values (mg/l)				
	TSS	BOD	NH_4-N	NO_3-N	PO_4-P
Tres Rios H1cell	0.5	1.0	0.33	0.10	0.57
Tres Rios H2 cell	0.5	1.0	0.19	0.50	1.60
Kadlec and Knight (1996)	5.1	6.2	0	0	0.02 (TP)

Note: Tres Rios C* set to ½ det. limit for TSS to calculate K_A rate constants. Tres Rios values are for PO_4–P data as opposed to reported the value 0.02 mg/L for total phosphorus (TP).

The minimum values derived for the Hayfield site data are all close to the minimum detection levels. In the case of NH_4–N and NO_3–N, both the calculated and reported C* values are near zero. Calculated C* values for TSS and BOD are well below the reported 5.1 mg/L and 6.2 mg/L values. In the case of TSS, the C* was set to 0.5 mg/L (½ the detection limit) to calculate k_{AT} rate constants (i.e., due to mathematical error when C_o - C* = 0). For BOD, the minimum of 1 mg/L is equal to the detection limit and is below the range of 1.1 mg/L to 13.9 mg/L reported for different systems (Kadlec and Knight, 1996). The reported C* for TP (0.02 mg/L) is considered a better indication of background than the minimum PO_4–P outflow values.

The median concentration data (table 4-25) and the respective background C* values (table 4-27) were used to calculate areal rate coefficients (k_{AT}). The resulting k_{AT} values for the Hayfield site under the operating conditions for test phases A, B, and C (table 4-25), and areal rate constants reported based on wetlands systems in the NADB (Kadlec and Knight, 1996) are shown in table 4-28.

Table 4-28. Areal model k_{AT} rate constants for the Hayfield site data and reported values.

Cell	HLR (cm/day)	Depth (ft)	HRT (days)	Areal rate coefficients k_{AT} in meters / year				
				BOD	TSS	NH_4-N	NO_3-N	PO_4-P
H1	7.5	1.0	7.70	114	35	443	153	214
	15.0	1.0	3.52	175	221	351	32	-4
	15.0	1.5	5.47	0	-43	147	826	9
H2	7.5	1.0	6.60	140	83	301	183	243
	15.0	1.0	3.59	227	304	308	73	-110
	15.0	1.5	5.35	69	135	169	710	78
reported values	---	---	—	34	1000	18	35	TP=12

Note: Reported values from Kadlec and Knight (1996). All k_A values are in m/yr, assumed at 20 °C.

The areal k_{AT} values, like the volumetric k_{VT} values, show a large variation with differences in depth and HLR. With the exception of TSS, the Tres Rios values were generally greater than values reported by Kadlec and Knight (1996). This indicates good treatment, even though the inflow concentrations were relatively low.

Near detection level operations can complicate the performance evaluations. For example, both the areal and volumetric reaction rate coefficients for BOD are zero at the 1.5-foot depth in the H1 cell. The data simply indicate the inflow and outflow BOD concentrations are nearly equal during that study period, indicating no removal; however, the problem is the inflow and outflow BOD concentrations are close to the detection limit (i.e. inflow to outflow ratio is 1, and logarithm if 1 is 0). There are also other factors that could confound the BOD removal. For example, there was a significant correlation between the difference in BOD and inflow temperature, which could be considered surrogate measure of seasonal effects.

Aside from the detection limit problems, the BOD K_{AT}-values are greater than the reported mean and maximum (94 m/year) of the data used to calculate the mean (Kadlec and Knight, 1996). At the Hayfield site, all of the K_{AT} values for NH_4–N and five of six NO_3–N values were greater than the reported areal rate values.

The areal k_{AT} results also indicate that the worst performance for BOD and NH_4–N removal and the best removal rates for NO_3–N were produced at the 1.5-foot water depth of test phase C (summer of 1997). This might indicate oxygen depletion which would tend to limit the capacity to reduce BOD and NH_4–N (nitrification) and would also explain improved NO3–N removal through anaerobic nitrification.

The pattern for TSS is similar to BOD, although all conditions produced removal rates that are worse than the reported value (1,000 m/yr). The TSS removal rates are worse with lower HLR and increased HRT, and in one case the k_{AT} is negative. This may indicate the effects of wind mixing, resuspension, or algae growth are effectively counteracting any reduction attributed to particulate settling. Again, the generally low concentrations and detection level effects could influence variability. Results for PO_4–P provide further evidence of variability and trend shifts that could reflect changes in the effective mechanisms with operations or seasonal effects.

Tres Rios Predicted Results

To further evaluate the predictive capability of the areal k–C* rate model, a set of predictive outflow concentrations were calculated based on inputs from the Tres Rios Hayfield site wetland data. These results are summarized in table 4-29. The first series of predicted concentrations are based on the median inflow values for all data and the areal rate coefficients derived for the Hayfield site at the two HLR operations tested. The lower portion of the table shows the median of measured concentrations at each Hayfield site cell and for each HLR tested. Percent removal values are also provided for comparison.

Table 4-29. Measured and predicted concentrations using areal rate model for Hayfield site data.

	Cell	HLR (cm/day)	BOD (mg/L)	TSS (mg/L)	NO_3-N (mg/L)	PO_4-P (mg/L)
Predictions using areal rate coefficients derived from Hayfield site data						
Tres Rios median inflow		all 7.5-15	3.0	3.0	2.20	3.60
Predicted outflow concentration		7.5	1.58	1.00	1.70	2.33
Percent removal			47.4%	66.7%	23.0%	35.3%
Predicted outflow concentration		15	2.08	1.00	1.87	2.90
Percent removal			30.8%	66.7%	15.0%	19.6%
Median concentrations for Hayfield site H1 and H2 cells measured data						
Tres Rios inflow (HS)		7.5	3.8	4.1	3.0	8.5
Tres Rios outflow	H1	7.5	2.6	3.5	0.5	1.5
	H2	7.5	2.4	2.9	0.5	1.5
Percent removal	H1	7.5	12.1%	-17.5%	77.1%	57.6%
	H2	7.5	20.6%	4.9%	77.1%	58.3%
Tres Rios inflow (HS)		15	2.3	2.2	2.5	2.1
Tres Rios outflow	H1	15	2.3	2.4	0.3	2.0
	H2	15	2.0	1.7	0.7	2.1
Percent removal	H1	15	24.7%	18.5%	86.9%	43.8%
	H2	15	33.3%	44.3%	67.2%	41.2%

In many instances the predicted values do not differ in terms of concentration units, but the percent removal trends shows greater difference. To a certain extent this just shows the effects of the relatively small (low) concentrations in producing large percentage changes.

The BOD and TSS removal tends to be overestimated, while NO_3–N and PO_4–P are underestimated. The model also predicts that the percent removal of all four water quality constituents would decline with higher HLR; however, greater BOD and TSS percent removal with the higher HLR was observed in the monitoring data for both cells (tables 4-11 and 4-12). The NO_3–N removal increased in H1 and decreased in H2 at greater HLR and there was a decline in the percent removal for PO_4–P in both cells with the increased HLR.

Overall, it appears that both the volumetric and areal-based rate constants are highly variable and subject to a number of simultaneous conditions. The resulting models are also somewhat in conflict because the conditions best for treating one water quality component may not be optimal for others. A number of these issues are related to the generally low, near detection limit concentrations for several of the water quality constituents evaluated. Nevertheless, both the volumetric and areal relationships are worth consideration and provide some reference to other constructed wetlands systems operating nationwide.

Chapter 5

Discussion and Conclusions

The initial Tres Rios wetlands demonstration monitoring investigations produced interesting results concerning the water quality characteristics, operational functions, and planing considerations. Prominent results and findings of the water quality data analysis are discussed in this chapter along with interpretation regarding future wetland project considerations, water management planning in the Phoenix area, and additional research needs. Finally, the last section summarizes major conclusions and considerations drawn from this part of the demonstration project.

Discussion of Water Quality Results

This section summarizes the major water quality results and briefly discusses the significance and uncertainties evident in the interpretation. The following topics are described in roughly the same order as results in the previous chapter.

Initial Data Review

1. Actual operations of the demonstration wetlands varied substantially from the original or revised plans (tables 3-3 and 3-4, Appendix A). At the Hayfield site, the inflow load rate during test phase A was slightly higher (7.6 vs. 5.0 cm/day) and the depth during test phase D was greater than planned (22.9 vs. 15.2 cm). Operations at the Cobble site were much more variable and the unlined C1 cell required much greater inflow loading to compensate for seepage. Although these variations could alter water quality transformation properties, they did not compromise the data analysis for comparisons based on the relative test phase codes. The breakdown of hydraulic functions and cell configuration differences were based on the better Hayfield site data sets. The Cobble site served the primary purpose of evaluating seepage effects and mass loads were used effectively to examine seepage components.

2. Water quality data included a fairly extensive suite of constituents and inflow and outflow samples were collected at regular intervals throughout the monitoring program. Using a lower detection limit method for BOD and replacing the dissolved phosphorus with total phosphorus are suggested for future

monitoring. Nevertheless, the resulting data constitute one of the better data sets available for a constructed wetland and proved essential to complete the demonstration evaluations.

3. The operating variations and events that occurred (e.g., table 3-5) that altered operations are not uncommon in wetland systems and may be a good indicator of the practical considerations for full-scale wetlands planning. Operating fluctuations may decrease somewhat over time with experience and system stabilization; however, the requirements to manage a complicated wetlands system comprised of larger cells has important practical implications concerning the commitment of resources, on-site staff expertise, and wetlands performance expectations.

4. The statistical analysis clearly revealed some trends and results that were not evident in simple averages or review of data plots. The below or near-detection limit concentration levels for several monitored water quality components influenced the data analysis and limited the ability to quantify certain results. This was particularly true for BOD and NO_2–N; however, in some instances even when percent removal could not be calculated, net removal was evident by an increased number of outflow data points below the detection level. Although percent removal is not the most sensitive or useful measurement in comparing different wetland systems, in this case, inflow water quality was relatively stable over time and the percent removal was a convenient approach to aggregate the data (without factoring time step) for use in the various cross-comparison performance evaluations.

Field Measurement Results

5. Outflow temperatures were consistently lower than the inflow with a uniform seasonal pattern. In addition, the outflow temperatures in the H1 cell (five open zones) were slightly lower (1-2 degrees) than in the H2 cell (two open zones). The decrease in temperature indicates effective evaporative cooling and the difference between cells suggests the cooling effect is tied to the extent of open water or possible mixing effects. In any case, the temperature shift has important implications for seasonal evaporative losses and associated properties including oxygen transfer and the upper limits for DO saturation concentration.

6. Dissolved oxygen levels decreased from inflow to outflow for about 75 percent of the data at the lower end of the DO concentration range. This indicates the consumption of oxygen to satisfy the inflow (and internal) demands. At the upper end of the DO range above 3 mg/L, the inflow and outflow data converged, and the outflow DO levels in the H1 cell are 1-2 mg/L higher than the inflow or H2 outflow (figure 4-6). This may reflect sufficient oxygen is available to overcome minor demands imparted by low levels of readily assimilated organic

load (e.g., BOD), whereas more resistant organic matter (e.g., COD) is passed through the system at the operating conditions tested. Oxygen depletion was evident during test phase C during the hotter summer months and higher water depth. These results indicate the wetlands oxygen status is easily shifted by changes in organic loading, temperatures, or inflow rates. It also appears that under conditions with light inflow loading, moderately elevated HLR operations may be advantageous to minimize internal loading (i.e., from production) and associated oxygen demands in proportion to the flow rates.

Overall Water Quality Results

7. At the Hayfield site, all parameters monitored except TSS, phosphorus, and COD exhibited significant differences in concentration between the inflow and outflow. The reactive components (e.g., nitrogen, BOD) had a net decrease while conservative indicators (e.g. TDS, EC, Cl^-) increased. The consistently opposite trends for these groups provides confirmation of the operative assimilation and evapoconcentration mechanisms. It also indicates that any processes that reduce concentrations were sufficient to overcome evaporative concentration effects and result in a net decrease. This is an important result given that this analysis was based on the entire data set including all operating conditions and that several water quality constituents were very low or near detection limits in the inflow.

8. The overall analysis of the Cobble site data indicated similar trends as the Hayfield site. Many reactive components including total N, NH_4–N, NO_3–N, and TKN decreased significantly in the unlined C1 cell, and these nitrogen components plus BOD, COD, and TSS were all reduced in the lined C2 cell. The conservative constituents also increased in both Cobble site cells. This again was based on the entire data set without correction for seepage. In this case, operations were variable, but the higher inflow loading would tend to reduce the retention time for removal processes to occur and also reduce evaporation effects.

9. The results for TSS are somewhat unusual, although the inflow concentrations were very low (median 3 mg/L at both sites). Slight net gains for TSS and COD could also indicate a degree of internal production (particularly algal production). Phosphorus results were variable and could have been influenced by additional inputs leached from soils during the early start-up of the wetland operations.

10. Net removal of BOD and sequential breakdown of nitrogen indicates there was sufficient oxygen to overcome both carbonaceous and nitrogenous oxygen demands and conditions to support both aerobic nitrification and anaerobic denitrification processes. This could reflect spatially mixed conditions within the wetland cells or fluctuating conditions (i.e., daily, seasonal) over time during the

3-year monitoring period. In either case, the long-term monitoring trends are a more accurate indicator of the overall water quality performance characteristics.

Hydraulic Operations

11. The analysis of HLR and depth effects indicated statistically significant changes in the percent removal for the different HLR and depth conditions tested. Significant effects of HLR were noted for several water quality parameters, and significant effects of depth were evident for every parameter monitored except phosphorus. Moreover, the relative Chi-square values were generally greater, indicating greater probability, for depth versus HLR effects. Significant depth effects were also confirmed by the ANOVA cross-comparison of HLR, depth, and differences between cells.

12. Evaluations of HLR and HRT effects indicated the percent reduction decreased for Total N, NH_4–N, and NO_3–N and increased for TKN, COD, and TOC at the higher HLR test phase. With increased HRT (depth), the percent reduction decreased for TKN and NH_4–N, whereas BOD, COD, and TOC had peak performance at the intermediate depth tested, and NO_3–N had the worst reduction at the intermediate depth. This suggests wetland operations can easily shift the balance between the oxygen dynamics and loading characteristics (both internal and external).

13. Decreasing removal performance with increased inflow loading is the expected trend for assimilation of residuals in the water supply (external loading). Organic indicators, TKN, COD, and TOC are common products of primary production within the wetlands (internal loading), whereas NH_4–N, and NO_3–N are breakdown products of organic nitrogen (a part of TKN) which could be derived from either internal or external sources. Total N includes all species and could shift with loading sources, assimilation rates, and secondary breakdown products. The water supply at Tres Rios is highly treated so the wetlands receive relatively light mass loading in proportion to the hydraulic loading. Consequently, one possible explanation for the mixed trends is that the wetland system operations are close to a balance between internal and external loading and the effective dilution, flushing, and assimilation processes. For example, increased HLR could effectively dilute and transport more of the resistant internal products (e.g., COD, TKN) through the system, while the net concentration of breakdown products (e.g., NH_4–N, and NO_3–N) are not affected as much because of the stability imparted by various loading sources and fluctuations in the effective aerobic and anaerobic assimilation processes.

14. Seasonal changes were not evaluated directly, but may have a significant influence on the wetland transformation properties. For example, when the test phase data sets were arranged in order of increasing HRT (figure 4-5), no

prominent trends were evident other than the general reversal between the oxygen demand parameters and anaerobic processes (e.g. NO_3–N versus BOD and NH_4–N). However, the performance varies widely (e.g. 30-90 percent for NO_3–N) for the different test phases. Review of the temperature time series plots shows the four test phases were conducted under different temperature conditions as indicated in table 5-1.

Table 5-1. Climate trends during first three years Tres Rios demonstration wetlands monitoring.

Test phase	Approximate duration	General seasonal trend
test phase A	Dec. 1995 to Aug. 1996	cool to warming trend
test phase B	Sept. 1996 to Feb. 1997	cooling to winter lows
test phase C	Mar. 1997 to Jul. 1997	overall warming trend
test phase D	Aug. 1997 to Apr. 1998	cooling, warming cycle

15. The Spearman rank-order analysis showed highly significant correlation for temperature and the percent changes in DO, most forms of nitrogen, and oxygen demand parameters. Both operational control and climate conditions appear to have significant influences on the transformation properties for these common water quality parameters. A weighted or composite performance index that incorporates both seasonal factors (e.g. temperature, internal loading) and operating conditions (e.g. depth, hydraulic loading) was not evaluated.

16. The hydraulic load rates during these demonstration evaluations were higher than typical for other constructed wetland systems, although the concentrations of many constituents monitored were relatively low. Although this could influence the transformation processes, the actual loading rate values were not used in comparative analyses and did not affect the statistical results based on relative performance changes and test phase categories. Moreover, the opposite direction for changes in conservative and non-conservative parameters is consistent throughout all of the test phases, which provides some confirmation that the operative mechanisms were functioning as expected under the conditions tested.

Open Water Configuration

17. The two different configurations established in the Hayfield site wetland cells were primarily intended to evaluate possible impacts on air exchange or mixing effects on the water quality performance. The significant differences between the H1 and H2 cells for dissolved oxygen and temperature may have important implications for future wetland planning and operations. Temperature only differed by about 1-2 degrees between the cells (figure 4-2); however, the difference was reflected in the evaporative concentration effects of conservative

constituents with greater losses for the H1 cell with five open water zones, versus two open zones in the H2 cell.

18. Outflow dissolved oxygen in H1 was significantly higher than the H2 cell data at the upper 25 percent of the DO range (figures 4-6, 4-7). Although the specific mechanisms were not examined, more open water bands could result in better mixing, oxygen transfer at the air/ water interface, increased oxygen production from algal growth, or reduced biomass production and decomposition (internal loading). Moreover, the last emergent zone (closest to the outlet) is much bigger in H2 than in H1, which could further influence DO in the outlet. In addition, the significant differences between cells for the percent changes in TKN, NH_4–N, BOD, COD, and TOC (table 4-17) may indicate the DO effects are manifested by the assimilation properties of these oxygen-dependent parameters.

19. Perhaps the most important result of the cell configuration comparison is that in spite of statistically significant differences between the Hayfield site cells, these effects are relatively subtle. In fact, the performance trends of the two cells are remarkably similar, and the differences between cells are small in comparison to the changes evident under different operating conditions (figure 4-5). It should be noted; however, that these cells had similar total open surface area, and more prominent configuration differences could produce different performance results.

Seepage Loss Effects

20. As expected, seepage losses were a major factor in the total mass removal (or concentration) characteristics at the Cobble site. The conservative water quality constituents were particularly useful in evaluating seepage effects. The unadjusted percent removal in the unlined C1 was 78-79 percent versus 23-27 percent for the lined C2 cell. With seepage adjustment, removal of the three conservative parameters was zero to slightly negative in C1 and 5-10 percent in the C2 cell. The mass balance for both cells was good with seepage adjustment, although the seepage in C1 could have been overestimated somewhat due to brief periods when seepage exceeded the inflow rate (no outflow results in 100 percent calculated removal). The reduced evaporative concentration effects at the Cobble site are attributed in part to the higher inflow (shorter retention) operations required to compensate for seepage.

21. Comparison of the Hayfield and Cobble site seepage indicated that the seepage rate from the lined C2 cell (25 gpm) was less than either the H1 cell (33 gpm) or H2 cell (33 gpm); however, this difference is proportional to the difference in surface area. Although the seepage rate at both sites appears significant, seepage could depend on a number of factors including local soils and water table conditions that would require specific site and operational evaluations.

22. Seepage at the Cobble site required continuous monitoring and adjustment; however, short-term factors including the initial filling at start-up, the permeability of newly turned alluvial soils, and local dewatering activities could have added to the seepage problems. Over the longer term, it is difficult to determine whether other factors such as self-sealing of the wetlands and equilibration with local groundwater could effectively counteract these problems and stabilize seepage to an acceptable, sustainable condition. Overall, these results indicate that seepage is an important practical consideration for planning wetlands in the area, but this does not mean that impervious liners are necessarily the best means to address these concerns.

Combined Site Comparison

23. The combined site evaluation compared the characteristics of the two Tres Rios wetlands sites and the overall performance of the Tres Rios demonstration wetlands against ranges reported for other wetlands in the United States. The detailed water budget which factors in site measurements and weather data (table 4-22) provides one basis of comparison. The adjusted values indicate median HLR values for both Hayfield cells are .53 ft/d (16cm/d) and about 7.5 days for HRT. Median values for the Cobble site cells were .86 and .25 ft/d (26 and 7.6 cm/d) for HLR, and 1.9 and 4.5 days HRT for the C1 and C2 cells. Tres Rios HLR values are fairly high with respect to the reported 2.5 to 5.0 cm/d (WPCF, 1990) or 1.5 to 6.5 cm/d (Kadlec and Knight, 1996) reported. Tres Rios retention times are closer to typical ranges of 5 to 10 days (WPCF, 1990) or 7 to 10 days (Kadlec and Knight, 1996).

24. The median Tres Rios results (table 4-23) and performance expectations based on data from the NADB (Kadlec and Knight, 1996) are compared in table 5-2. These results are for general reference only. The reported values are based on an assumed secondary treatment quality and rate constants that reflect the overall tendency of the data in the NADB, which includes many systems that are lightly loaded, and is also biased toward systems in areas of more temperate climate conditions. Although the percent removal results for the Tres Rios demonstration are lower than the reported values, the inflow concentration levels at the Tres Rios wetlands are considerably lower than for the typical secondary treated wastewater sources reported.

Table 5-2. Comparison of percent removal expectations for wetlands receiving secondary treated wastewater and Tres Rios demonstration wetlands results for first 3-years monitoring.

	Reported estimates[1]		Tres Rios demonstration wetlands percent removal			
Parameter	Inflow conc. (mg/L)	percent removal	H1	H2	C1	C2
BOD	30	67 %	25 %	30 %	13 %	25 %
TSS	30	67 %	33 %	46 %	33 %	36 %
TN	20	69 %	58 %	59 %	49 %	55 %
NH_3–N	15	62 %	69 %	74 %	58 %	64 %

Note: (1) reference Kadlec and Knight, 1996.

25. Overall, without adjustment for seepage, the H1 and H2 cells were statistically similar to the C2 performance, whereas C1 is very different. Disregarding seepage however, the differences between the four Tres Rios wetland cells are consistent with the operating conditions. In spite of the fact that the Tres Rios wetlands received much higher hydraulic loading and lower concentrations for these wastewater parameters, positive treatment is indicated for almost all parameters including BOD, which was influenced by below detection limit data.

Rate Function Comparison

26. Tres Rios characteristics are unusual compared to other wetlands nationwide (e.g. NADB cases) because of the relatively high hydraulic load rates, low constituent concentrations, and arid climate conditions. The resulting rate constants are mixed and trend reversals are evident for different conditions (e.g., NH_4–N, and NO_3–N). The inflow and background levels for BOD and TSS are much lower than values derived from the NADB, which can produce high percentage differences for small measured changes. Consequently, the predictive value of the Tres Rios rate functions is uncertain. From a practical standpoint, the areal basis has apparent advantages in deriving rates from multiple systems (of unknown depth) for use in initial sizing estimates; however, the prominent effects of depth indicate volumetric functions are useful to evaluate wetland operations. Tracer studies may help to better define the hydrodynamics and provide a basis to calibrate these functional properties.

Wetlands Project Planning Considerations

The water quality data analysis results have implications for future wetlands project planning including plans for full-scale wetlands at the Tres Rios site. The

following discussion focuses on the water quality findings presented previously, but also includes related demonstration activities and other considerations associated with constructed wetlands and water reuse plans.

Water Quality Implications

27. No apparent concerns were identified for the common wastewater parameters included in the routine water quality monitoring program. Consistent trends in evapoconcentration, seepage effects, reductions of non-conservative parameters, temperature, and oxygen patterns are useful indicators of the operative mechanisms and wetlands characteristics to consider in future water management plans. The results also provide a good basis to support more specialized investigations, including hydraulic transport properties and biological effects of other residual contaminants.

28. Different parameter groups can provide an indication of the prevalent physical and chemical conditions that regulate certain transformation processes and define the overall wetlands performance characteristics. Temperature, dissolved oxygen, and the effective hydraulic properties are clearly major forcing functions that influence the transport and transformation of many water quality constituents. For example, oxygen demands and nitrogen components may change with temperature, oxygen, inflow loading, and retention time. The shift between NH_4–N and NO_3–N removal with depth indicates how easily the balance between aerobic and anaerobic processes can be altered by subtle changes in loading or oxygen transfer. These BOD-nitrogen characteristics are important when considering seasonal changes or active operations plans. In addition, extended retention that results in greater water losses, internal loading, and higher outflow levels of TDS, chloride, COD, or TOC may not be desirable since these components could influence subsequent water reuse or recharge operations, particularly as organic pre-cursors to disinfection by-products.

29. Operating conditions are key to water quality process functions. Based on these demonstration results, it appears that the optimum water depth is between 1.0 and 1.5 feet. The optimum inflow hydraulic load rate is uncertain because only two rates were tested; however, the relatively high load rates tested did not interfere with the effective removal of non-conservative substances. Moreover, higher inflow rates may be desirable to minimize evapoconcentration, water losses, temperature increase, oxygen depletion, and internal loading effects associated with the longer hydraulic retention time at lower inflow rates. Similar situations with highly treated reclaimed water sources and arid conditions, may emphasize maintaining water quantity and avoiding degradation rather than improving water quality. Operating plans should consider possible short-term, long-term, and secondary use implications.

30. The common approach taken in developing constructed wetlands performance relationships focuses on external loading (inflow water supply) as the primary factor for water quality improvement. These demonstration results provide further evidence that this is not necessarily the case in situations with low mass loading of chemical constituents and conditions that are conducive to robust productivity and evaporation effects. The balance between internal and external loading sources and the hydraulic properties (and other factors) that regulate wetlands production and assimilation rates may be very important in planning wetlands projects that will operate under conditions similar to the Tres Rios demonstration wetlands. In this case, it appears that the inflow chemical loading for most constituents monitored is low enough that raising hydraulic load rates does not affect the mass loading appreciably, and organic matter from internal sources is a greater proportion of the total mass loading to the system. Under these conditions, operations at higher than normal inflow HLR may be advantageous to overcome the oxygen demands from internal sources, provide mixing and circulation, and to minimize water losses, organic accumulation, or evapoconcentration effects. Moreover, steady state conditions may not be the only solution to account for seasonal water budget and loading variations. For example, reduced flows and increased retention may be beneficial at certain times to shift the balance toward anaerobic denitrification. Both depth and flow rate regulation may be useful in developing active short and long-term operating plans. Daily variations, seasonal adaptations, and long-term sustainability or restoration needs are important considerations in developing effective operational strategies.

Transferability to Full-Scale Planning

31. The overall wetlands performance objectives and water budget are key issues in developing full-scale wetlands in the area. Performance objectives include water quality, wildlife habitat, and management considerations. Water budget factors include both the operational constraints imposed by comprehensive water and reuse operations and the wetlands seepage, precipitation, evaporation, and hydroperiod control considerations. These factors are essential in considering the siting, sizing, shape, and layout of specific system features in wetlands planning. The wetlands demonstration effort has addressed a number of technical and practical issues that are directly transferable in evaluating water reuse, environmental impacts, habitat values, and management measures associated with full-scale wetlands. Both the routine monitoring results and the more specialized parallel demonstration components may be relevant in future planning. Other issues that were beyond the scope and scale of the demonstration program may require additional investigation.

32. Seepage, site selection, and construction factors were prominent aspects of the Cobble site investigations. Site seepage can affect the wetlands water budget, site preparation, or operating requirements, and ultimately the practical feasibility

of developing wetlands at a given site. Although the clay layer was used effectively to reduce seepage losses, the use of impervious liners for full-scale wetlands is not recommended given the cost and potential damage from riverine flooding. Selecting wetland sites on the floodplain bench (similar to the Hayfield site) appears to be a more practical alternative. It is also worth noting that a large wetlands complex could alter seepage characteristics by raising local groundwater levels. This could effectively reduce the water loss rates; however, related implications including slope stability, groundwater movement, and water quality interactions might warrant further evaluation.

33. Full-scale wetlands planning should consider the total wetlands areal size and flow rates that will accommodate a nominal operating HLR within the range of the demonstration wetlands. Higher HLR implies smaller overall size of the wetlands; however, any full-scale wetlands design plans should allow a range of operational flexibility. Three considerations are apparent regarding the relatively high inflow rates of the demonstration wetlands. First, positive removal was achieved at higher inflow rates even for low constituent concentrations, which indicates lower inflow loading is not necessary. Second, high flow rate and shorter retention time will reduce the associated evaporation effects and also appears to help maintain adequate oxygen to meet organic demands. Finally, higher flow rates could also help to avoid stagnant water that is conducive to mosquito production and reduce the accumulation of organic detritus by more rapid turnover and transport through the system.

34. The demonstration experience, regarding the shape of individual wetland cells and configuration of hydraulic controls, may also be useful in full-scale wetlands planning. The configuration of wetland cells and hydraulic controls were considered in the early demonstration development plans, but were not directly evaluated. The demonstration cell layout was adapted from the original conceptual design report (Reclamation, 1993). The cells were elongated to minimize the short-circuiting of water flowing through the wetlands, with narrowed shallow zones at each end that mimic the alluvial deposition patterns evident in the river floodplain. An aspect ratio (length to width) of 3:1 to 5:1 (EPA 2000b) is suggested to encourage uniform flow and avoid stagnant areas. Cell inlet zones were modified during final design to utilize a submerged manifold, buried in rock to distribute flows across the width of the cell. A deep water zone at the outlet end collects flows before entering the outlet control box. Although the inlet configuration may have some advantages in reducing maintenance and keeping fish or animals out, it is difficult to monitor the manifold for plugging and the actual flow distribution effects are unknown. Beavers entering the demonstration site (presumably from the river channel) were persistent in attempting to block off the outflow and raise water depths. Alternative controls were not evaluated, although using a deep zone at each end is a practical means to promote flow distribution and avoid emergent vegetation encroaching on the controls. Placing the outlet box farther toward the end near

the bank and narrowing the outlet end would help reduce dead, ineffective flow areas on each side of the outlet zone. Effects of introducing flow near the wetland bottom are uncertain, although any effects are likely to dissipate over the linear extent of large wetland cells. No other prominent issues concerning the demonstration configuration were evident and many different hydraulic controls have been used successfully at other wetland systems.

35. Wetlands vegetation and open water patterns can affect the system hydraulic efficiency and related wetland functions. Direct evaluation of these effects at the demonstration wetlands was limited to comparison of the different configurations at the Hayfield site. The results indicated having several open zones that cross the flow path produced a moderate increase in outflow oxygen conditions that could influence other oxygen dependent processes. It should be noted, however, that the effects of the open water configurations were minor in comparison to the wetland hydraulic operations (depths and flows). The total percentage of open water area was not directly examined, although it appears somewhat less surface area of emergent vegetation may be beneficial to reduce internal loading without changing evaporation effects too much. The demonstration wetlands also experienced significant die-off of the emergent vegetation during the third year of operations. It appears that higher HLR might be beneficial to sustain wetlands vegetation by better flushing of detritas and by-products, gas transfer, and reduced microbial activity around stems. These results are important considerations for full-scale wetlands planning; however, the implications of open water and vegetation patterns on wetland functions, the long term succession of vegetation and stable growth patterns, and requirements to sustain wetland vegetation under these conditions remain an important area of research.

36. The indication that operations had much greater effects than open water ratios may open the door for much more spatial diversity, in keeping with practical considerations for short circuiting or "dead" (stagnant) zones. Other general observations concerning wetlands vegetation planting plans and long-term growth characteristics may also be useful in full-scale planning since a large multi-use wetlands complex is likely to consist of larger components with more spatial diversity. Plans for moderate sized wetland systems often include detailed grading to establish vegetation and open water zones in specified patterns. This may be necessary for sites that are flat or require extensive preparation work before the desired wetland features are established. In other instances, it may be more practical to adapt wetland site plans to the existing features and topography. This approach still requires careful planning to consider wetlands configuration, vegetation, and hydraulic properties. For example, the bottom grades (depth zones) established and areas for specific planting should consider possible impacts on flow distribution and routing. The greater hydraulic resistance of different plant varieties and vegetation zones can be used to direct water flow through and around features within a given wetland compartment. Plans should be reviewed to consider the inherent growth form, anticipated succession, and mechanisms to

sustain desirable vegetation and to reduce maintenance of invasive species. Simple guidelines that can help identify specific problems and are easily adapted to local site variations can be effective to promote desirable conditions and achieve diversity objectives while allowing for uncertainties and avoiding unnecessary "over-design" costs.

37. Operating conditions including HLR and HRT were clearly the most prominent factors affecting water quality. The results have implications for full-scale wetlands planning; however, the demonstration studies only examined the inflow to outflow changes and did not reveal how hydraulic transitions cause shifts in water quality mechanisms. For example, changes in water depth or flow rate can produce different effects on vertical and spatial flow patterns through a wetland system. As a result, full-scale planning should identify all potential influences on the effective hydraulic conditions and provide a range of flexibility in operational controls.

Integrated Planning Issues

38. The wetlands water budget and resulting operational requirements are critical factors in developing full-scale wetland plans under the current water management constraints and conditions at the Tres Rios site. In this case, wide seasonal swings in the demands for reclaimed water from the 91st Avenue WWTP could have severe consequences for full-scale wetland design and operation plans. It was possible to regulate the demonstration wetlands hydraulic operations closely because they utilized only a small proportion of the total reclaimed water supply. This may not be the case for full-scale wetlands planning. If the wetlands are operated at steady-state inflow using a portion of total supply, this implies the stream system and other reuse activities will accept the variable excess supply. If other reuses are maintained at steady rates, the wetlands would have to adsorb the seasonal supply fluctuations. In either case, wetlands operations need to be integrated with comprehensive plans for the Salt River corridor and reclaimed water operations.

39. The wetlands water budget is also a major factor in determining the system layout and how internal features are integrated in planning. For example, a full-scale wetlands system might have to accommodate wide seasonal variations in the water supply from the 91st Avenue WWTP. This issue was described previously for the full-scale wetlands alternative in the Phoenix Wastewater Reclamation and Reuse Study (Reclamation, 1996). The reuse study indicated water reuse contracts could take up to 60 percent of the annual reclaimed water. This is problematic for wetland planning because more reuse occurs during hot months when evaporative losses are greater, and less reuse occurs during the winter when losses are low and most of the annual rain occurs. A cursory water budget review completed for the reuse study wetland alternative examined a range of flows and

evaporation rates to evaluate potential effects on wetland operations (Appendix A). The end result indicated that the operating HRT could vary from about 2 to 15 days seasonally for an 800-acre wetlands system. Wetland design and management plans may have to be adjusted accordingly to address practical and operational issues associated with water supply fluctuations. In particular, long-term water management plans should be evaluated against the wetland functional objectives and performance expectations.

40. Although specific plans for full-scale wetlands in the Phoenix area remain to be determined, the alternative concepts developed in the reuse study provide a point of reference to illustrate some of the operational constraints and considerations that may be important in full-scale wetlands planning. The conceptual layout in the reuse study (Appendix A) shows a system of 34 cells of about 25 acres each, arranged into four functional units along the river bank. Surge ponds and conveyance systems are located at the inlet and outlet ends of each unit. This type of arrangement allows independent operation of each cell or groups of cells in a unit. As a result, the water supply can be rotated between cells during times of less water, or individual wetland cells might be shut down entirely for restoration or to maintain full flow to other cells. The 25-acre cell size was intended to provide internal diversity, effective flow distribution, and maintenance access. Although wetland elements may be adapted to site conditions and the system configuration could change substantially during further planning, these concepts regarding overall system functionality and operational flexibility are key factors to effectively integrate constructed wetlands with ongoing river corridor plans and water management objectives.

41. Relationships between mosquito production, vector control methods, wetland vegetation growth patterns, and vegetation sustainability were evident in the initial demonstration evaluations. Integrated approaches to resolve these issues may be more effective since they are related. For example, dense stands of emergent plant growth can block water flow, producing isolated zones of stagnant water that are conducive to mosquito larvae propagation, reduce access for fish predation, and limit access to apply vector control treatments. Emergent growth in the demonstration wetlands was robust during the first few years, possibly because of the density of planting plans or nutrients available initially from the soils. By the third year, however, extensive vegetation die-off was observed in all of the demonstration wetland cells. Resulting changes in flow patterns and detritus inputs can influence mosquito production, water quality, and other ecosystem functions. Planning might include consideration for natural succession trends and longer term stable growth patterns of desirable vegetation communities. Active operations for hydroperiod manipulation could help to periodically regenerate soils and account for water budget fluctuations. These issues are important topics of research.

42. Multipurpose objectives including ecosystems functions, habitat values, and public access will have to be integrated in full-scale wetland plans. Site management issues were evident in the demonstration evaluations. For example, beavers modified the hydraulics at the Hayfield site and muskrats damaged earth berms and destroyed new vegetation at the Cobble site. Management needs for public access and safety are also apparent. These issues have implications for many important ecosystem functions, including water quality. These issues also present significant challenges when considering the extent of a large wetlands complex. A detailed site masterplan may help to delineate specific features to address these identified issues. Elements such as remote monitoring and operational control systems may also be worthwhile to facilitate management.

43. Multi-use wetlands management often crosses the traditional administrative and institutional provisions. For example, water and wastewater operations are typically accomplished through municipal utilities, whereas site management is often handled by parks and recreation departments. Coordination or integration of these functions may be important to manage a large wetlands facility. Wetland ecosystems can also require some extent of interdisciplinary expertise to address different aspects of water quality, wildlife, and site management. The demonstration project experience may be useful to identify specific needs and develop provisions that meet these needs and help in allocating resources and coordinating between groups.

Additional Research Needs

Several important research topics were identified in discussion of water quality results and other demonstration activities described previously. The following topics represent some of the prominent issues that could influence constructed wetland planning in this area and other locations with similar circumstances.

Water Quality Standards

Appropriate water quality standards for effluent dependent streams is an ongoing area of research interest in arid regions with constrained water resources (University of Arizona, 1993). The issue is relevant to constructed wetlands because, in situations where reclaimed water is the only source of water entering a stream, the distinction between a receiving stream system or a wetlands system is blurred. Both systems could be interpreted as receiving streams and the associated implications for human health and environmental protection are similar. This may argue for adjusting the point of regulatory compliance as appropriate to consider the inherent wetland water quality characteristics. For example, moving the point of compliance for disinfection to the wetlands inlet to

avoid problems associated with the production of naturally derived organic matter in the wetlands, that could create harmful by-products upon disinfection at the outlet. The assimilation capacity of the stream system might be compared more directly to the wetlands system and other alternative water uses in evaluating net environmental benefits. Other issues could be considered similarly in developing appropriate standards and monitoring criteria.

Biological Effects

The potential for bioaccumulation, synergistic toxicity, or chronic biological effects caused by longer term exposure to residual contaminants is a complicated topic of research. Common water quality parameters such as TSS and BOD are non-specific measurements that indicate the overall strength of wastewater, which may be useful to estimate the assimilation capacity and dilution effects in receiving streams, but do not measure specific substances. Better understanding of the nature of wastewater residuals could be used to assess the potential biological effects in open aquatic systems or wetland systems that depend on reclaimed water. This is an important component in assessing the wildlife habitat values and potential risks associated with constructed wetlands development. The size and diversity of the demonstration wetlands was not well suited to evaluate large-scale habitat characteristics; however, the facilities provide an excellent resource to examine water quality aspects that could influence ecosystem productivity, food chain effects, and direct exposure effects. Results of this research could be valuable in developing monitoring objectives and management plans for full-scale wetlands. Results could also contribute toward defining water quality standards and guidelines for all effluent dependent aquatic systems.

Hydraulic Characteristics

Better definition of the hydraulic properties in wetlands could help to understand how hydraulic operations influence water quality transformation mechanisms. Tracer studies have been completed at the demonstration wetlands to provide additional information regarding hydraulic transitions and transport conditions. Further testing and research in this area could be useful in local full-scale wetlands planning and to the understanding of functional characteristics in all wetland systems. Results might also be useful in developing detailed operational strategies to account for seasonal flow variations, vegetation, mosquito control, or other site management issues.

Wetlands Vegetation

The die-off of vegetation in the demonstration wetlands is a significant concern when considering the implications for managing large wetland systems. The ability to establish plants in designated areas and sustain specific types of wetlands vegetation is important for water quality and other wetland functions. Massive die-off and decay could overload a system, deplete oxygen, alter hydraulics, and create isolated mosquito breeding areas. These conditions could require extensive maintenance to remove decaying material and re-establishing new plants. Different theories for the problem were discussed during the demonstration project. For example, planting could produce a dense stand of vegetation of all the same age, leading to die-off as a natural process. Although emergent vegetation roots (tubers) are adapted to thrive in anaerobic soils, excessive accumulation of detritus could cause microbial activity up around the plant stems that are not as resistant. Potential toxicity and physical or structural factors related to the growth rates were also discussed. Hydrologic factors could include the need for periodic draining to oxygenate soils and regenerate plant roots. Research in this area may be of general interest for all constructed and created wetlands to develop better, more effective criteria for selecting appropriate species for different conditions and sustaining desirable vegetation.

Active Operations

Most constructed treatment wetlands are operated under steady state hydraulic conditions even though functions including wildlife values and water quality processes might be enhanced or restored through periodic hydroperiod fluctuations. For example, emergent vegetation might thrive better with periodic regeneration of soils through drying and aeration. Cycles of higher and lower water depth can force water in and out of areas that are otherwise blocked by vegetation. Hydroperiod changes could influence mosquito production or invasive plants. Active operations might also help in handling seasonal changes in the reclaimed water supply. Most natural wetlands experience some degree of hydrologic variation. Daily, seasonal, or longer term operating changes could be considered to address different conditions. Research could help to evaluate hydroperiod relationships and develop design and operating criteria to overlay or coordinate different hydrologic functions.

Mosquitos and Vector Control

Additional research into factors that can influence mosquito production and control methods could be very useful in planning constructed wetlands. These issues are particularly relevant in arid or tropical regions because there is often greater concern for disease vectors with warm year-round climate conditions.

Nuisance conditions and health protection are important aspects to successfully integrate public education and recreation benefits into multipurpose constructed wetland plans. Note that the changes in operations to help control mosquitos affected the monitoring and water quality results significantly. These factors must be integrated in planning. Unfortunately, although a great deal of fundamental entemology research has been completed, relatively little information is available that is directly associataed with constructed wetland systems. Consequently, applied research into practical design, operating, and management considerations could help in planning constructed wetlands projects.

Conclusions

The Tres Rios Demonstration Constructed Wetlands Project became fully operational in the fall of 1995. When considered collectively, the demonstration monitoring program and parallel activities, including the Environmental Technology Initiative, specialized research investigations, and related planning efforts, have provided a wealth of information to advance constructed wetlands technology and insight into practical and institutional considerations to effectively incorporate wetlands in water resource planning. Conclusions and considerations evident from these results and the overall demonstration effort are summarized in this section.

The project activities to date have clearly demonstrated the value of the Tres Rios wetland facilities as an excellent research resource. The cooperative support and research collaboration have been instrumental in accomplishing the studies published in this report and other references cited. Prominent attributes of the Tres Rios demonstration wetlands, which have contributed to successful investigations includes (1) the fully operational and appropriate scale wetland facilities, (2) excellent support personnel available including technically competent and active coordination and field site support, (3) open access from the city of Phoenix so researchers can conduct long duration and multiple day testing, and (4) the synergy produced by the large group of collaborative interests, including Phoenix, COE, Reclamation, USGS, several studies sponsored by state agencies and universities (e.g., ASU, UA, UCR, etc.).

This Demonstration Evaluation Effort

The investigations completed to date have successfully demonstrated a number of issues concerning wetland functions and water quality characteristics, including relevant planning, operations, and management implications. In spite of operational variations and other events, the monitoring program has produced an

exceptional data set for constructed wetlands in these conditions. These results have also answered many questions and demonstration objectives, while additional studies are ongoing to explore specific issues. These results may help to guide further planning in the Phoenix area and provide information useful for other water management activities nationwide. Of particular interest are the net removal for all monitored constituents even at very low concentration levels, the significant effects of hydraulic operations including depths and flow rates, and the transient shifts in temperature, oxygen, and related transformation properties that may indicate the balance between external and internal loading and the net effects of assimilation processes. In spite of statistically significant differences between the Hayfield site cells, these configuration effects are relatively subtle in comparison to the changes evident under different operating conditions. The monitoring program also provided the fundamental chemical characterization data necessary to support the other specialized investigations conducted at the demonstration wetlands. Together, these activities have produced a valuable body of information concerning constructed wetlands in arid regions which was not available previously.

Water Management and Wetlands Planning

Water managers in arid regions of the western states face difficult challenges to meet the growing demands for finite water resources. Agencies such as Phoenix, Reclamation, and SROG have actively explored opportunities to coordinate and integrate water use, conservation, and reuse programs. Constructed wetlands offer the potential to attain water quality objectives and provide additional wildlife and public use benefits in an area where wetland and aquatic habitat are scarce. The experience and insight gained from the demonstration project reflects the relationships between water management and wetland functional characteristics that may be important to incorporate wetland components with the ongoing Salt River corridor plans and future water management activities. Although the optimal conditions to sustain specific wetland objectives is uncertain, it is clear that the wetlands operating criteria must be within the range of hydrologic variations and projected water use constraints. Consequently, operational controls should allow a range of flexibility to accommodate current conditions and allow adjustment to management changes. Staged development could be considered in developing an adaptive approach in wetland planning. A well-defined masterplan is recommended to identify important considerations and uncertainties, ensure staged elements are incorporated in an objective framework, and provide a cost-effective approach to sustain and adapt wetland features as appropriate.

EPA, 1999c. *Treatment Wetland Habitat and Wildlife Use Assessment and North American Treatment Wetland Database—Version 2.0.* Electronic database version updated by CH2M Hill of the database compiled by R. Knight, R. Ruble, R. Kadlec, and S. Reed. U.S. Environmental Protection Agency, Office of Research and Development. Cincinnati, Ohio.

EPA, 2000a. *Guiding Principles for Constructed Treatment Wetlands: Providing Water Quality and Wildlife Habitat.* Environmental Technology Initiative report by Interagency Workgroup on Constructed Wetlands: Environmental Protection Agency, Army Corps of Engineers, Fish and Wildlife Service, Natural Resources Conservation Services, National Marine Fisheries Service, and Bureau of Reclamation. EPA 843-B-00-003.

EPA, 2000b. *Manual: Constructed Wetlands Treatment of Municipal Wastewaters.* U.S. Environmental Protection Agency. EPA/625/R-99/010.

Fox, P. and M. Nellor, 1997. *Soil Aquifer Treatment for Sustainable Water Reuse.* Progress Report 1 for Study Period 7/1/97-10/31/97. A Collaborative Research Project funded by the American Water Works Association Research Foundation. Arizona State University, County Sanitation Districts of Los Angeles County, University of Arizona, University of Colorado, and Stanford University.

Fox, P., H.J.S. Fernando, R.V. Rodriguez, T. Serra, and M Arzabe, 2000. *Evaluation of Flow Fields in Wetlands Using Physical Models.* Report to U.S. Bureau of Reclamation. Arizona State University. Tempe, Arizona.

Gerba, C., and M. Karpiscatz, in progress. Impact of Wildlife on Enteric Pathogens in Constructed Wetlands.

Greeley and Hansen, 1991. *City of Phoenix 91st Avenue Wastewater Treatment Plant Reclaimed Water Study - Phase II.* Greeley and Hansen. Phoenix, Arizona.

Greeley and Hansen, 1994. *City of Phoenix 91st Avenue Wastewater Treatment Plant Reclaimed Water Study - Phase II On-Site Investigation / Facility Plan / Implementation Plan, Element D, Total Reuse Facility Plan.* Greeley and Hansen. Phoenix, Arizona.

Greeley and Hansen, 2000a. *Impact Study of Wastewater Reclamation Plants on the 91st Avenue Wastewater Treatment Plant.* Greeley and Hansen. Phoenix, Arizona.

Greeley and Hansen, 2000b. *91st Avenue Wastewater Treatment Plant Capacity Attainment and Planning Report for Sub-Regional Operating Group.* Greeley and Hansen. Phoenix, Arizona.

Hammer, D. 1992. *Creating Freshwater Wetlands.* Lewis Publishers, Inc. Chelsea, Michigan.

Hammer, D. ed., 1989. *Constructed Wetlands for Wastewater Treatment—Municipal, Industrial, and Agricultural.* Edited by D.A. Hammer. CRC Press, LLC. Boca Raton, Florida.

Kadlec, R.H. and R.L. Knight, 1996. *Treatment Wetlands*, CRC Press, LLC. Lewis Publishers. Boca Raton, Florida.

Keefe, S., 2001. "Modeling Transport and Fate of Organic Compounds in a Constructed Wetland." Masters of Science Thesis. University of Colorado. Boulder, Colorado.

Knight, R.L., R.W. Ruble, R.H. Kadlec, and S. Reed, 1993. "Wetlands for Wastewater Treatment: Performance Database." In: G.A. Moshiri (ed.) *Constructed Wetlands for Water Quality Improvement.* CRC Press LLC, Lewis Publishers. Boca Raton, Florida.

Kubly, D. M., 1998. *Invertebrates of the Tres Rios Constructed Wetland.* U.S. Bureau of Reclamation. Phoenix, Arizona.

Martin, B., 1998. "Effect of a Constructed Wetland on Disinfection By-Products and Their Formation Potential." Masters of Science Thesis. Colorado School of Mines. Golden, Colorado.

Mitsch, W.J. and J.G. Gosselink, 1993. *Wetlands.* 2nd ed. Van Nostrand Reinhold, New York, NY.

Moshiri, 1993. *Constructed Wetlands for Water Quality Improvement.* Edited by G.A. Moshiri. CRC Press, LLC. Lewis Publishers. Boca Raton, Florida.

P.L.102-575, 1992. Reclamation Projects Authorization and Adjustment Act of 1992. Section 1608—Phoenix Metropolitan Water Reclamation Study.

Phoenix, 1996. *Data Summary of Selected Water Quality Parameters and Constituents: August, 1995 Through March, 1996*. Tres Rios Demonstration Constructed Treatment Wetland Project. City of Phoenix Water Services Department. Phoenix, Arizona.

Phoenix, 1997. *Salt-Gila River Baseline Ecological Characterization*, Prepared by CH2M Hill and Logan, Simpson, & Day with EcoPlan Associates. April 1997.

Phoenix, 1997. *Tres Rios Demonstration Constructed Wetland Project, 1996/1997 Operation & Water Quality Report*. City of Phoenix Water Services Department. Phoenix, Arizona.

Phoenix, 1998. *Birds of the Tres Rios Constructed Wetlands Demonstration Project*. Sponsored by the city of Phoenix, Subregional Operating Group, Maricopa Audubon, Arizona Department of Water Resources, Arizona Department of Game and Fish, and Bureau of Reclamation.

Phoenix, 1999. *Mosquito Control Strategy for the Tres Rios Constructed Treatment Wetlands*. City of Phoenix, Water Services Department. Phoenix, Arizona.

Reclamation, 1993. *Phoenix Water Reclamation and Reuse Study—Tres Rios Demonstration Wetlands Conceptual Design*. Bureau of Reclamation and City of Phoenix, in cooperation with the Arizona Department of Game and Fish, Arizona Department of Environmental Quality, Maricopa County Department of Parks and Recreation, Flood Control District of Maricopa County, and U.S. Environmental Protection Agency.

Reclamation, 1996. *Phoenix Wastewater Reclamation and Reuse Study*. Bureau of Reclamation in cooperation with the city of Phoenix. Phoenix, Arizona.

Reclamation, 1997. Unpublished data from aerial surveys of the Tres Rios demonstration wetlands conducted in 1996 and 1997. Bureau of Reclamation, Phoenix, Arizona.

Reclamation, 1998. *Tres Rios Demonstration Constructed Wetlands Project, Construction Report.* Bureau of Reclamation. Phoenix, Arizona.

Reclamation, 1999. *Transformation of Dissolved Organic Carbon in Constructed Wetland Systems.* Project Report. Wetlands and Riparian Habitat Initiative. Bureau of Reclamation and U.S. Geological Survey. Denver, Colorado.

Reclamation, 2000. *Tres Rios Demonstration Constructed Wetland Project—Natural Color and Infrared Color Aerial Photographs 1995-1999.* Bureau of Reclamation. Phoenix, Arizona.

Reed, S.C., R.W. Crites, and E. J. Middlebrooks, 1995. *Natural Systems for Waste Management and Treatment*, 2nd ed. McGraw-Hill, Inc., New York, NY.

Rostad, C.E., B.S. Martin, L.B. Barber, J.A. Leenheer, and S. Danials. 2000. "Effect of a Constructed Wetland on Disinfection Byproducts: Removal Processes and Production Precursors." *Environ. Sci. Technol*, 34, 2703-2710.

SPSS, 1998. SYSTAT Version 8.0. 5 Volumes: Users manual and documentation for statistical analysis software. SPSS, Inc., Chicago, Illinois.

University of Arizona, 1993. *Rationale for a Program of Research to Develop Water Quality Criteria for Effluent-Dependent Ephemeral Stream and Riparian Habitats in the Arid West.* A Report to Pima County Wastewater Management. Dames and Moore, Inc. and University of Arizona. Tucson, Arizona.

Wass, Roland, 1997. Tres Rios Demonstration Wetlands: Hayfield Riparian Site Tracer Testing: Preliminary Results. Unpublished manuscript. Phoenix, Arizona.

Wass, Roland, 1999. What's Going on at the Tres Rios Demonstration Project? Mosquito Connection. Vol. IV. November, 1999.

WPCF, 1990. *Natural Systems for Wastewater Treatment.* Task Force on Natural Systems, Water Pollution Control Federation. Manual of Practice FD-16.

WRCC, 2001. Climate data for Phoenix and Tempe, Arizona. Compiled from Western Regional Climate Center, National Climatic Data Center, Regional Climate Centers, State Climate Offices, and National Weather Service data sources.

Appendix A

This appendix includes background information derived from previous reports associated with the Tres Rios Demonstration Constructed Wetlands Project.

CONTENTS:

TRES RIOS DESIGN VERSUS ACTUAL OPERATING CONDITIONS

- **Working notes summary**

TRES RIOS WETLANDS RESEARCH PLAN (CH2MHill, 1995)

- **Table 4-1** — **Preliminary Operations Schedule for the Tres Rios Demonstration Wetlands**
- **Table 4-2** — **Preliminary Operations Schedule for the Tres Rios Research/Plant Propagation Wetland Cells**
- **Table 4-3** — **Sampling Schedule for the Tres Rios Constructed Wetlands Study**
- **Table 4-4** — **Hydrologic Analyses**
- **Table 4-5** — **Ecological and Public Use Monitoring**

RESEARCH PLAN - FIRST SUPPLEMENT (Draft - CH2MHill, 1997)

- **Aerial View of the Tres Rios Hayfield Site Sampling Stations**
- **Aerial View of the Tres Rios Cobble Site Sampling Stations**

PHOENIX WASTEWATER RECLAMATION AND REUSE STUDY (Reclamation, 1996)

- **Working notes on wetlands water budget for full-scale wetlands alternative**
- **Conceptual wetlands system layout for full-scale wetlands alternative**

Tres Rios design versus actual operating conditions

design sizing, planned and actual operations	depth ft	HLR ft/d	area ft2	volume ft3	HRT days
H1 & H2 planned	1.00	0.16	148104	148104	6.3
	1.00	0.50	148104	148104	2.0
	1.50	0.50	148104	222156	3.0
	0.50	0.50	148104	74052	1.0
H1 & H2 actual	1.00	0.25	148104	148104	4.0
	1.00	0.50	148104	148104	2.0
	1.50	0.50	148104	222156	3.0
	0.75	0.50	148104	111078	1.5
C1 & C2 planned	1.00	0.33	104544	104544	3.0
	1.00	0.82	104544	104544	1.2
	0.50	0.82	104544	52272	0.6
	1.50	0.82	104544	156816	1.8
C1 actual	0.90	1.00	104544	94090	0.9
	1.10	1.50	104544	114998	0.7
	1.10	0.82	104544	114998	1.3
C2 actual	1.00	0.33	104544	104544	3.0
	1.50	1.10	104544	156816	1.4
	1.00	0.82	104544	104544	1.2

actual operations and surface areas	depth ft	HLR ft/d	area ft2	volume ft3	HRT days
H1	1.00	0.25	143748	143748	4.0
	1.00	0.50	143748	143748	2.0
	1.50	0.50	143748	215622	3.0
	0.75	0.50	143748	107811	1.5
H2	1.00	0.25	137650	137650	4.0
	1.00	0.50	137650	137650	2.0
	1.50	0.50	137650	206474	3.0
	0.75	0.50	137650	103237	1.5
C1	0.90	1.00	98881	88993	0.9
	1.10	1.50	98881	108769	0.7
	1.10	0.82	98881	108769	1.3
C2	1.00	0.33	97574	97574	3.0
	1.50	1.10	97574	146362	1.4
	1.00	0.82	97574	97574	1.2

Table 4-1
Preliminary Operations Schedule for the Tres Rios Demonstration Wetlands

Operational Period	Interval (months)	System/ Cell	Average[a] Inflow (m^3/d)	Water Depth[b] (m)	Description
Startup	0-6	Hayfield	~ 600	<0.1	Only enough water to keep soil saturated continuously.
		Cobble	~ 2,000	<0.1	
Phase 1	7-12	H1	700	0.3	Approximately 5 cm/d to both cells in parallel.
		H2	700	0.3	
		C1	900	0.3	Approximately 10 cm/d to both cells.
		C2	900	0.3	
Phase 2	13-18	H1	350	0.45	Approximately 2.5 cm/d to both cells in parallel.
		H2	350	0.45	
		C1	1,800	0.45	Approximately 20 cm/d to both cells.
		C2	1,800	0.45	
Phase 3	19-24	H1	1,400	0.15	Approximately 5 cm/d over both cells operated in series (H1 to H2).
		C1	1,350	0.15	Approximately 15 cm/d to both cells.
		C2	1,350	0.15	

[a]gpd = m^3/d * 264
[b]average water depth in emergent areas: ft = m * 3.3

Table 4-2
Preliminary Operations Schedule for the
Tres Rios Research/Plant Propagation
Wetland Cells

Operational Period	Interval (months)	System/ Cell	Average[a] Inflow (m^3/d)	Average Water Depth[b] (m)	Description
Startup	0-6	All	20	<0.1	Only enough water to keep soil saturated continuously.
Phase 1	7-12	R1, R6, R7, R11	24	0.3	Approximately 2 cm/d.
		R2, R4, R8 R5	72	0.3	Approximately 6 cm/d.
		R3, R12, R10, R9	180	0.3	Approximately 15 cm/d.
Phase 2	13-18	R2, R4, R8, R5	24	0.45	Approximately 2 cm/d.
		R3, R12, R10, R9	72	0.45	Approximately 6 cm/d.
		R1, R6, R7, R11	180	0.45	Approximately 15 cm/d.
Phase 3	19-24	R3, R12, R10, R9	24	0.15	Approximately 2 cm/d.
		R1, R6, R7, R11	72	0.15	Approximately 6 cm/d.
		R2, R4, R8, R5	180	0.15	Approximately 15 cm/d.

[a]gpd = m^3/d * 264
[b]average water depth in emergent areas; ft = m * 3.3

Table 4-3
Sampling Schedule for TRES RIOS Constructed Wetlands Study

		Research Cell Site				Hayfield/Riparian Site				Cobble Site		
			R1-R12									
Parameter	Sampling Frequency	RS Inlet Splitter	INTA	INTB	EFF	HS Inlet Splitter	H1 EFF	H2 EFF	RIP EFF	CS Inlet Splitter	C1 EFF	C2 EFF
Water Temperature (field)	5/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
Flow	5/wk.	X	-	-	X	X	X	X	X	X	X	X
Dissolved Oxygen/ pH Conductivity (field)	5/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
$cBOD_5$, Cl^-, TOC	1/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
TSS, TDS	1/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
Total Ammonia N	1/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
Total Kjeldahl N	1/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
Nitrate + Nitrite N (combined)	1/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
Total Phosphorus	1/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
Alkalinity; E. coli; TRC	1/wk. 1/mo.	X -	- X	- X	X -	X -	X -	X -	X -	X -	X -	X -
Metals (Cu, Zn); Organics (diazinon)	1/qtr.	X			X	X	X	X	X	X	X	X
Chronic Toxicity	1/mo.	-	-	-	-	-	-	X	-	-	-	-

Table 4-4 Hydrologic Analyses				
Parameter	**Sampling Frequency**	**Research and Propagation Cells**	**Hayfield/Riparian Site**	**Cobble Site**
Inflow	Continuous	@ Splitter Box	X	X
Outflow	Daily/Continuous	X	X	X
Water Level	Daily/Continuous	X	X	X
Precipitation	Daily		X	
Lithium Tracer Studies	Semiannual	X[a]	X	X

[a]Four cells only with one of each deep zone configuration.

Table 4-5 Ecological and Public Use Monitoring				
Parameter	**Sampling Frequency**	**Research and Propagation Cells**	**Hayfield/Riparian Site**	**Cobble Site**
Vegetative Cover and Composition	1/qtr.	X	X	X
Bird Populations	1/mo.	-	X	X
Macroinvertebrate Populations	1/qtr.	-	X	X
Mosquito Sampling	1/mo.	-	X	X
Fish Populations	1/qtr.	-	X	X
Tissue Analysis - Sediments - Bulrush - Invertebrates - Fish	1/qtr.	-	X	X
User Log/Questionnaire	Daily	-	X	X

111289.E0.01 8/97 GNV

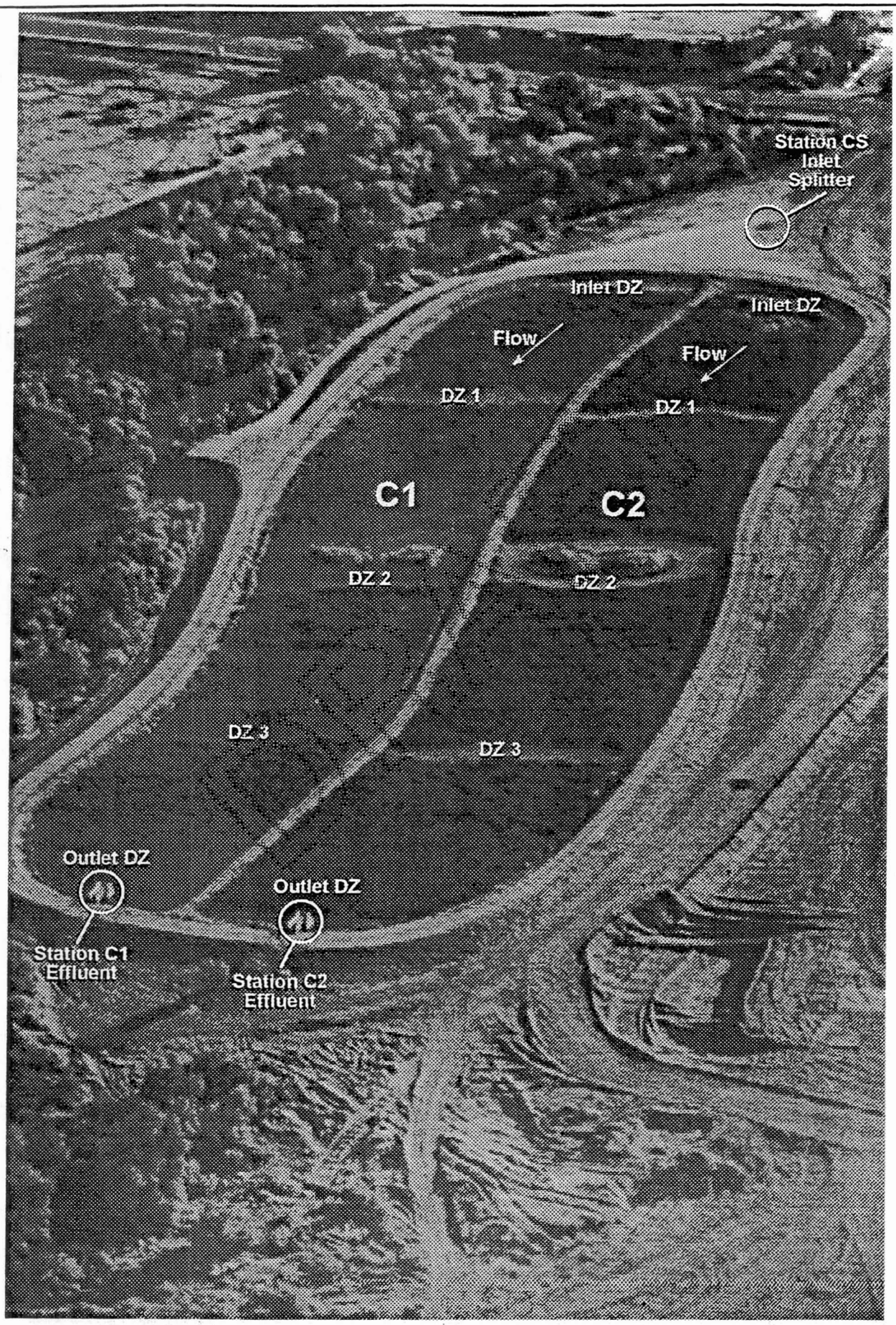


Figure 2-2. Tres Rios - Cobble Site Sampling Stations

CH2MHILL

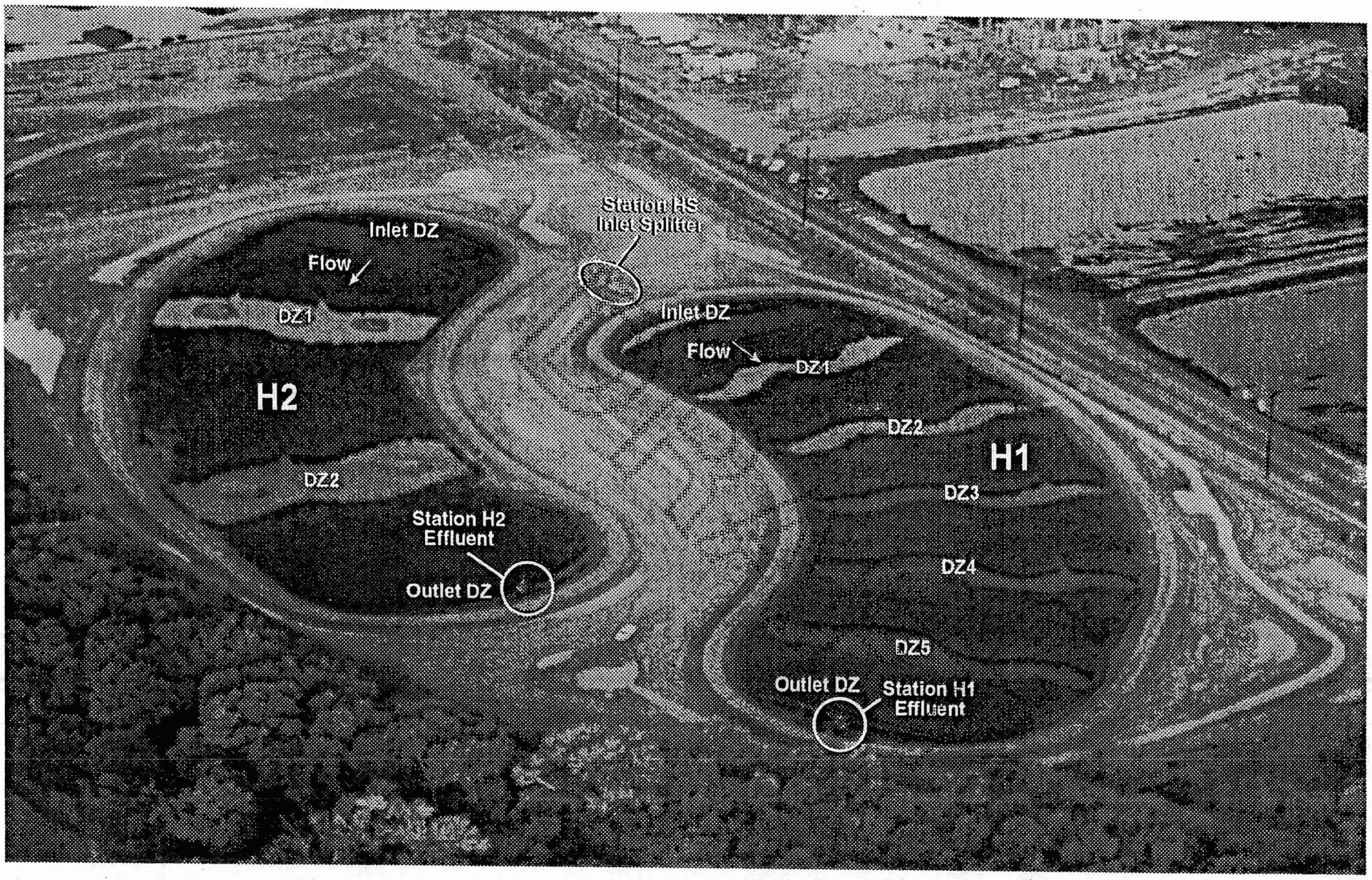


Figure 2-3. Tres Rios - Hayfield Site Sampling Stations

Preliminary Wetland Water Budget

Results of the wetland water budget analyses are summarized in table 5. Wetland water losses were evaluated with respect to a range of inflow rates, net water loss rates, and theoretical retention times. Effects of the assumed net loss rates are indicated by the resulting outflow rates and are also given in terms of an adjusted wetland area requirement. The implications of a net loss range of 0.0 to 0.8 inch (2.0 cm) per day are shown with respect to three flow rates. A moderate flow rate of 60 MGD was evaluated to coincide with the site capacity indicated for typical secondary pretreatment (case #1 of initial wetland size review). The average peak flow rate of 153 MGD and a 40 MGD low-flow condition were also considered.

Table 5. Preliminary wetland water budget evaluation

Wetland Inflow (MGD)	Net Water Loss E+P+S (in/day)	Retention Time (days)	Outflow Rate (cfs)	Corresponding Wetland Area (acres)
40.0	0.0	5.0	62.0	546.6
		7.0	62.0	765.2
		10.0	62.0	1093.1
		15.0	62.0	1639.7
	0.8	5.0	47.8	421.6
		7.0	43.8	540.8
		10.0	38.9	686.4
		15.0	27.8	868.0
60.0	0.0	5.0	93.0	819.8
		7.0	93.0	1147.8
		10.0	93.0	1639.7
		15.0	93.0	2459.5
	0.4	5.0	81.0	714.0
		7.0	77.0	950.6
		10.0	71.7	1264.9
		15.0	64.4	1702.7
	0.8	5.0	71.7	632.4
		7.0	65.7	811.2
		10.0	58.4	1029.6
		15.0	41.8	1302.0
153.0	0.0	2.0	237.2	836.2
		5.0	237.2	2090.6
		7.0	237.2	2926.8
		10.0	237.2	4181.2
	0.8	2.0	212.0	747.6
		5.0	182.9	1612.7
		7.0	167.6	2068.7
		10.0	148.9	2625.4

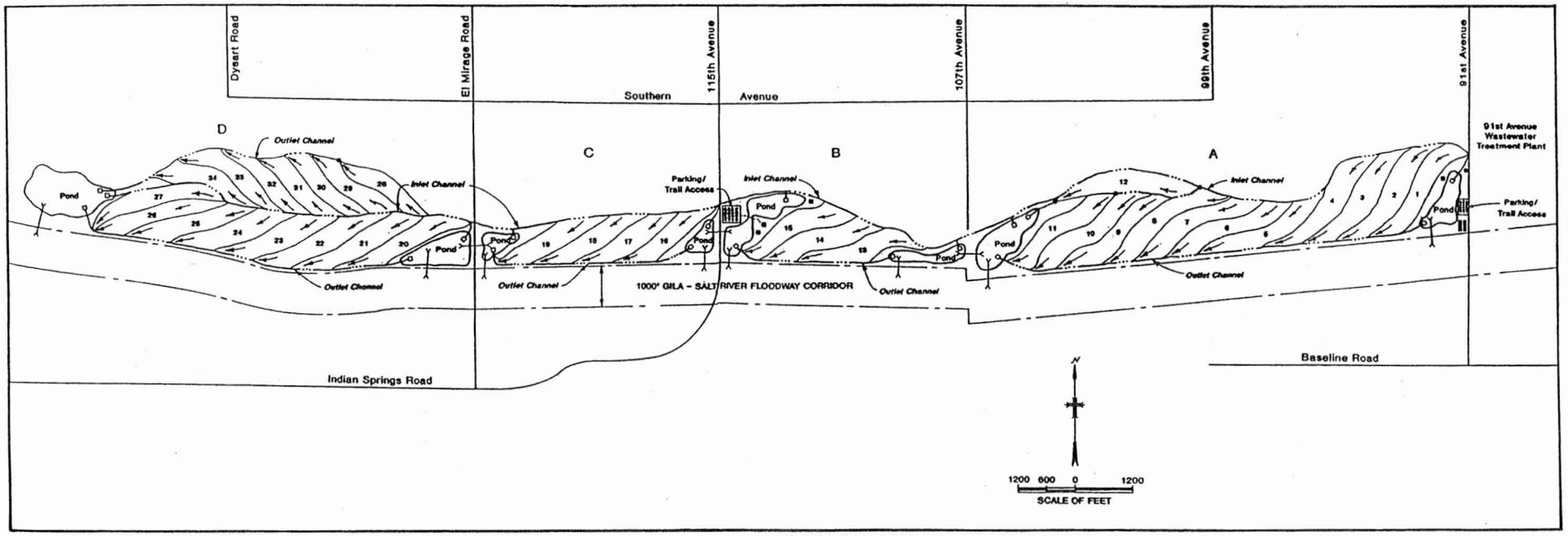


Figure 7.—Schematic site plan showing the conceptual wetland features.

Appendix B

The following pages include basic descriptions for statistical analysis methods excerpted from the SYSTAT software help menus. Only the methods used in the water quality data analysis are included. Further information is available in the complete SYSTAT documentation and product support (SPSS, 1998).

CONTENTS:

DESCRIPTIVE STATISTICS

BASIC STATISTICS

LINEAR MODELS I: LINEAR REGRESSION

T TEST

WILCOXON SIGNED-RANK TEST

KRUSKAL-WALLIS [ONEWAY ANOVA TEST]

KS COMMAND (ONE-SAMPLE)

LINEAR MODELS II: ANALYSIS OF VARIANCE

CORRELATIONS

MEASURES FOR RANK-ORDER DATA

MEASURES FOR CONTINUOUS DATA

DESCRIPTIVE STATISTICS

There are many ways to describe data, although not all descriptors are appropriate for a given sample. Means and standard deviations are useful for data that follow a normal distribution, but are poor descriptors when the distribution is highly skewed or has outliers, subgroups, or other anomalies. Some statistics, such as the mean and median, describe the center of a distribution. These estimates are called measures of location. Others, such as the standard deviation, describe the spread of the distribution.

Before deciding what you want to describe (location, spread, and so on), you should consider what type of variables are present. Are the values of a variable unordered categories, ordered categories, counts, or measurements?

For many statistical purposes, counts are treated as measured variables. Such variables are called quantitative if it makes sense to do arithmetic on their values. Means and standard deviations are appropriate for quantitative variables that follow a normal distribution. Often, however, real data do not meet this assumption of normality. A descriptive statistic is called robust if the calculations are insensitive to violations of the assumption of normality. Robust measures include the median, quartiles, frequency counts, and percentages.

Before requesting descriptive statistics, first scan graphical displays to see if the shape of the distribution is symmetric, if there are outliers, and if the sample has subpopulations. If the latter is true, then the sample is not homogeneous, and the statistics should be calculated for each subgroup separately.

Descriptive Statistics offers the usual mean, standard deviation, and standard error appropriate for data that follow a normal distribution. It also provides the median, minimum, maximum, and range. A confidence interval for the mean and standard errors for skewness and kurtosis can be requested. A stem-and-leaf plot is available for assessing distributional shape and identifying outliers. Moreover, Descriptive Statistics provide stratified analyses--that is, you can request results separately for each level of a grouping variable (such as CELL$) or for each combination of levels of two or more grouping variables.

BASIC STATISTICS

The following statistics are available:

- **N.** The number of nonmissing values for the variable.
- **Minimum.** The smallest nonmissing value.
- **Maximum.** The largest nonmissing value.
- **Sum.** The total of all nonmissing values of a variable.
- **Mean.** The arithmetic mean of a variable -- the sum of the values divided by the number of (nonmissing) values.
- **SEM.** The standard error of the mean is the standard deviation divided by the square root of the sample size. It is the estimation error, or the average deviation of sample means from the expected value of a variable.
- **CI of Mean.** Endpoints for the confidence interval of the mean. You can specify confidence values between 0 and 1.
- **Median.** The median estimates the center of a distribution. If the data are sorted in increasing order, the median is the value above which half of the values fall.
- **SD.** Standard deviation, a measure of spread, is the square root of the sum of the squared deviations of the values from the mean divided by (n-1).
- **CV.** The coefficient of variation is the standard deviation divided by the sample mean.
- **Range.** The difference between the minimum and the maximum values.
- **Variance.** The mean of the squared deviations of values from the mean. (Variance is the standard deviation squared).
- **Skewness.** A measure of the symmetry of a distribution about its mean. If skewness is significantly nonzero, the distribution is asymmetric. A significant positive value indicates a long right tail; a negative value, a long left tail. A skewness coefficient is considered significant if the absolute value of SKEWNESS / SES is greater than 2.
- **SES.** The standard error of skewness (SQR(6/n)).
- **Kurtosis.** A value of kurtosis significantly greater than 0 indicates that the variable has longer tails than those for a normal distribution; less than 0 indicates that the distribution is flatter than a normal distribution. A kurtosis coefficient is considered significant if the absolute value of KURTOSIS / SEK is greater than 2.
- **SEK.** The standard error of kurtosis (SQR(24/n)).
- **Confidence.** Confidence level for the confidence interval of the mean. Enter a value between 0 and 1. (0.95 and 0.99 are typical values).

LINEAR MODELS I: LINEAR REGRESSION

The model for simple linear regression is:

$$y = \beta_0 + \beta_1 x + \varepsilon$$

where y is the dependent variable, x is the independent variable, and the b's are the regression parameters (the intercept and the slope of the line of best fit). The model for multiple linear regression is:

$$y = \beta 0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_p x_p + \varepsilon$$

Both Regression and General Linear Model can estimate and test simple and multiple linear regression models. Regression is easier to use than General Linear Model when you are doing simple regression, multiple regression, or stepwise regression because it has fewer options. To include interaction terms in your model or for mixture models, use General Linear Model. With Regression, all independent variables must be continuous; in General Linear Model, you can identify categorical independent variables and SYSTAT will generate a set of design variables for each. Both General Linear Model and Regression allow you to save residuals. In addition, you can test a variety of hypotheses concerning the regression coefficients using General Linear Model.

The ability to do stepwise regression is available in three ways: use the default values, specify your own selection criteria, or at each step, interactively select a variable to add or remove from the model.

For each model you fit in REGRESS, SESTET reports R^2, adjusted R^2, the standard error of the estimate, and an ANOVA table for assessing the fit of the model. For each variable in the model, the output includes the estimate of the regression coefficient, the standard error of the coefficient, the standardized coefficient, tolerance, and a t statistic for measuring the usefulness of the variable in the model.

T TEST

TTEST provides three types of tests:

- the two-sample t test (independent t test) to compare the mean of one variable for two groups of cases.
- the paired comparison t test (dependent t test) to compare the means of two variables for a single group. The matched pairs t test is a variation of the paired t test.
- the one-sample t test to compare the mean of one variable with a known or hypothesized value.

T Tests [description]

The following t tests are available on the Statistics menu:

Two Groups Two-sample (independent) t test. The values of the variable of interest (for example, INCOME) are stored in a single column and SYSTAT uses codes of a grouping variable (for example, GENDER) to separate the cases into two groups (the codes can be numbers or characters). SYSTAT tests whether the difference between the two means differs from 0.

Paired Paired comparison (dependent) t test. For each case used in a paired t test, SYSTAT computes the differences between values of two variables (columns) and tests whether the average differs from 0.

One-Sample One-sample t test. For the one-sample t test, values of a single variable are compared against a constant that you specify.

WILCOXON SIGNED-RANK TEST

The Wilcoxon test compares the rank values of the variables you select, pair by pair, and displays the count of positive and negative differences. For ties, the average rank is assigned. It then computes the sum of ranks associated with positive differences and the sum of ranks associated with negative differences. The test statistic is the lesser of the two sums of ranks.

KRUSKAL-WALLIS [ONEWAY ANOVA TEST]

For the Kruskal-Wallis test, the values of a variable are transformed to ranks (ignoring group membership) to test that there is no shift in the center of the groups (that is, the centers do not differ). This is the nonparametric analog of a one-way analysis of variance. When there are only two groups, this procedure reduces to the Mann-Whitney test, the nonparametric analog of the two-sample t test.

Variables(s). SYSTAT computes a separate test for each variable in the Variable(s) list.

Grouping Variable. The grouping variable can be string or numeric.

KS COMMAND (ONE-SAMPLE)

Computes a Kolmogorov-Smirnov one-sample test. Specify a distribution to which the variables are compared:

UNIFORM=min,max	uniform distribution (min to max)
NORMAL=mean,SD	standard normal distribution with mean and SD
T=df	t distribution with df degrees of freedom
F=df1,df2	F distribution with df1 and df2 degrees of freedom
CHISQ=df	a chi-square distribution with df degrees of freedom
GAMMA=a	gamma distribution
BETA=a,b	beta distribution
EXP=mean,SD	exponential distribution with location parameter mean and scale parameter SD
LOGISTIC=mean,SD	logistic distribution with location parameter mean and scale parameter SD
RANGE=n,p	Studentized range with parameters n and p
WEIBULL=n,p	Weibull distribution with parameters n and p
BINOMIAL=n,p	binomial distribution with parameters n and p
POISSON=lambda	Poisson distribution with mean=lambda
LILLIEFORS	normal distribution with sample mean and standard deviation

LINEAR MODELS II: ANALYSIS OF VARIANCE

SYSTAT handles a wide variety of balanced and unbalanced analysis of variance designs. The Analysis of Variance (ANOVA) procedure includes all interactions in the model and tests them automatically; it also provides analysis of covariance, and repeated measures designs. After you have estimated your ANOVA model, it is easy to test post hoc pairwise differences in means or to test any contrast across cell means, including simple effects.

For models with fixed and random effects, you can define error terms for specific hypotheses. You can also do stepwise ANOVA (that is, Type I sums of squares). Categorical variables are entered or deleted in blocks, and you can examine interactively or automatically all combinations of interactions and main effects.

The General Linear Model (GLM) procedure is used for randomized block designs, incomplete block designs, fractional factorials, Latin square designs, and analysis of covariance with one or more covariates. GLM also includes repeated measures, split plot, and crossover designs. It includes both univariate and multivariate approaches to repeated measures designs.

Moreover, GLM also features the means model for missing cells designs. Furthermore, the means model allows direct tests of simple hypotheses (for example, within levels of other factors). Finally, the means model allows easier use of population weights to reflect differences in subclass sizes.

For both ANOVA and GLM, group sizes can be unequal for combinations of grouping factors; but for repeated measures designs, each subject must have complete data. You can use numeric or character values to code grouping variables.

You can store results of the analysis (predicted values and residuals) for further study and graphical display. In ANCOVA, you can save adjusted cell means.

ANOVA: Analysis of Variance

SYSTAT provides two procedures for analysis of variance: Analysis of Variance (ANOVA) and General Linear Model (GLM). ANOVA is easier to use, because it includes all interactions in the model and tests them automatically. You can specify covariates, do repeated measures, save residuals, and test post hoc pairwise differences in means.

Group sizes can be unequal for combinations of grouping factors, but each subject must have complete data across repeated measures. You can use numeric or character values to code grouping variables. You can store results of the analysis (predicted values and residuals) for further study and graphical display. In ANCOVA (using COVARIATE), you can save adjusted cell means.

Post Commands [ANOVA post hoc tests]

Performs pairwise mean comparisons. Varlist is an effect without covariates as it appears in the model command with the effects model. With the means model, varlist indicates a set of marginal means.

Fishers Least Significant Difference pairwise comparisons.

[Note: Description of other post hoc procedures not included - not used in this analysis]

CORRELATIONS

Variables. Available only if One is selected for Sets. All selected variables are correlated with all other variables in the list, producing a triangular correlation matrix.

Rows. Available only if Two is selected for Sets. Selected variables are correlated with all column variables, producing a rectangular matrix.

Columns. Available only if Two is selected for Sets. Selected variables are correlated with all row variables, producing a rectangular matrix.

Sets. One set creates a single, triangular correlation matrix of all variables in the Variable(s) list. Two sets creates a rectangular matrix of variables in the Row(s) list correlated with variables in the Column(s) list.

Listwise. Listwise deletion of missing data. Any case with missing data for any variable in the list is excluded.

Pairwise. Pairwise deletion of missing data. Only cases with missing data for one of the variables in the pair being correlated are excluded.

Save file. Saves the correlation matrix to a file.

Types. Type of data or measure. You can select from a variety of distance measures, as well as measures for continuous data (e.g. Pearson), rank-order data (e.g. Spearman), and binary data.\

MEASURES FOR RANK-ORDER DATA

If your data are simply ranks of attributes, or if you want to see how well variables are associated when you pay attention to rank ordering, you should consider the following measures available for ranked data:

- **Spearman.** Produces a matrix of Spearman rank-order correlation coefficients. This measure is a nonparametric version of the Pearson correlation coefficient, based on the ranks of the data rather than the actual values.

[Note: Description of other rank-order procedures deleted - not used in this analysis]

MEASURES FOR CONTINUOUS DATA

The following measures are available for continuous data:

- **Pearson.** Produces a matrix of Pearson product-moment correlation coefficients. Pearson correlations vary between -1 and +1. A value of 0 indicates that neither of two variables can be predicted from the other by using a linear equation. A Pearson correlation of 1 or -1 indicates that one variable can be predicted perfectly by a linear function of the other.

[Note: Description of other continuous data procedures deleted - not used in this analysis]

Appendix C

The following pages include time-series plots of water quality data collected at the Tres Rios Demonstration Constructed Wetlands Hayfield site and Cobble site. Data are included for the first three years of operational monitoring from August 1995 through December 1998.

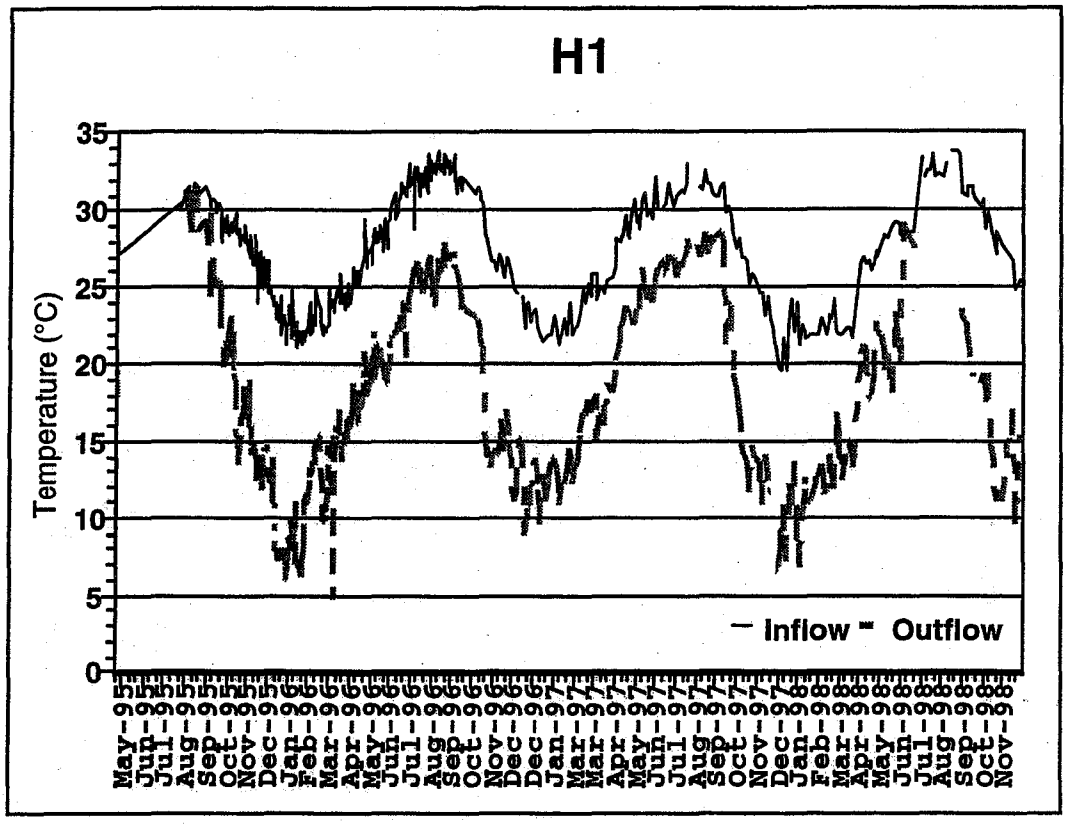
CONTENTS:

HAYFIELD SITE

- Temperature
- pH
- Dissolved Oxygen
- Specific Conductance
- Total Suspended Solids
- Total Dissolved Solids
- Total Kjeldahl Nitrogen
- Nitrate Nitrogen
- Nitrate + Nitrite
- Ammonia Nitrogen
- Total Nitrogen
- Orthophosphate Phosphorus
- Total Dissolved Phosphorus
- Chemical Oxygen Demand
- Biochemical Oxygen Demand
- Total Organic Carbon

COBBLE SITE

- Temperature
- pH
- Dissolved Oxygen
- Specific Conductance
- Total Suspended Solids
- Total Dissolved Solids
- Total Kjeldahl Nitrogen
- Nitrate Nitrogen
- Nitrate + Nitrite
- Ammonia Nitrogen
- Total Nitrogen
- Orthophosphate Phosphorus
- Total Dissolved Phosphorus
- Chemical Oxygen Demand
- Biochemical Oxygen Demand
- Total Organic Carbon



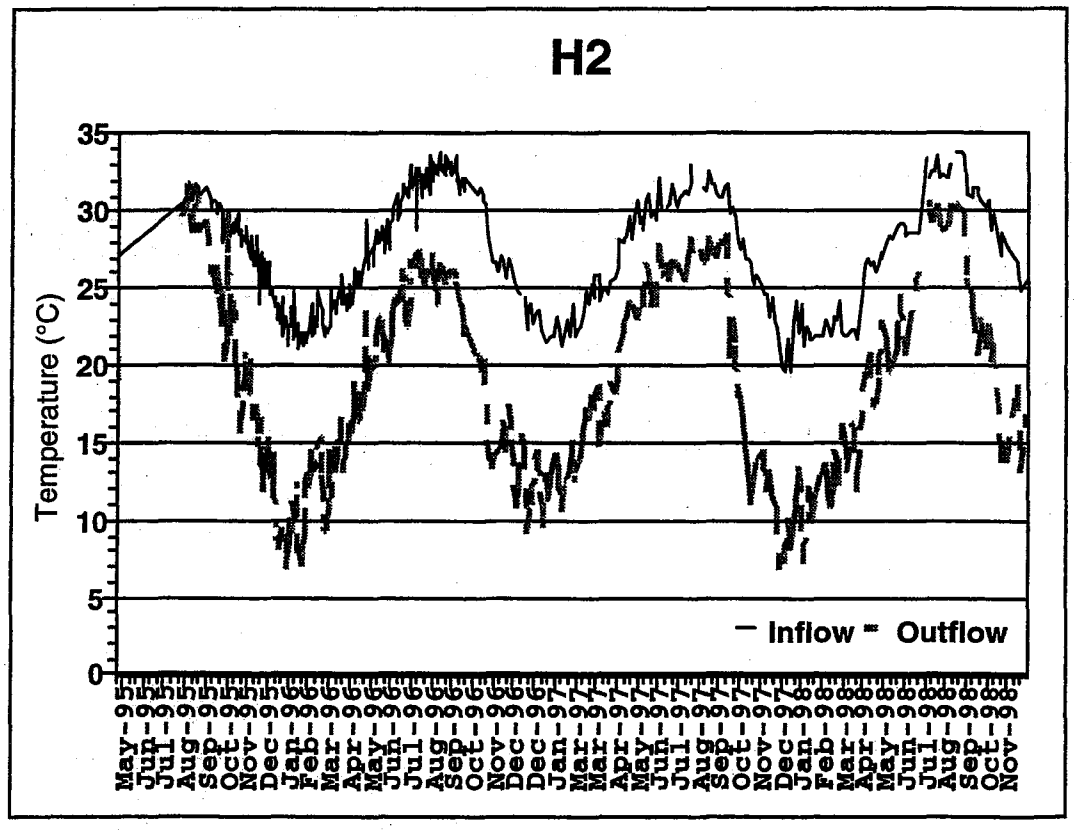
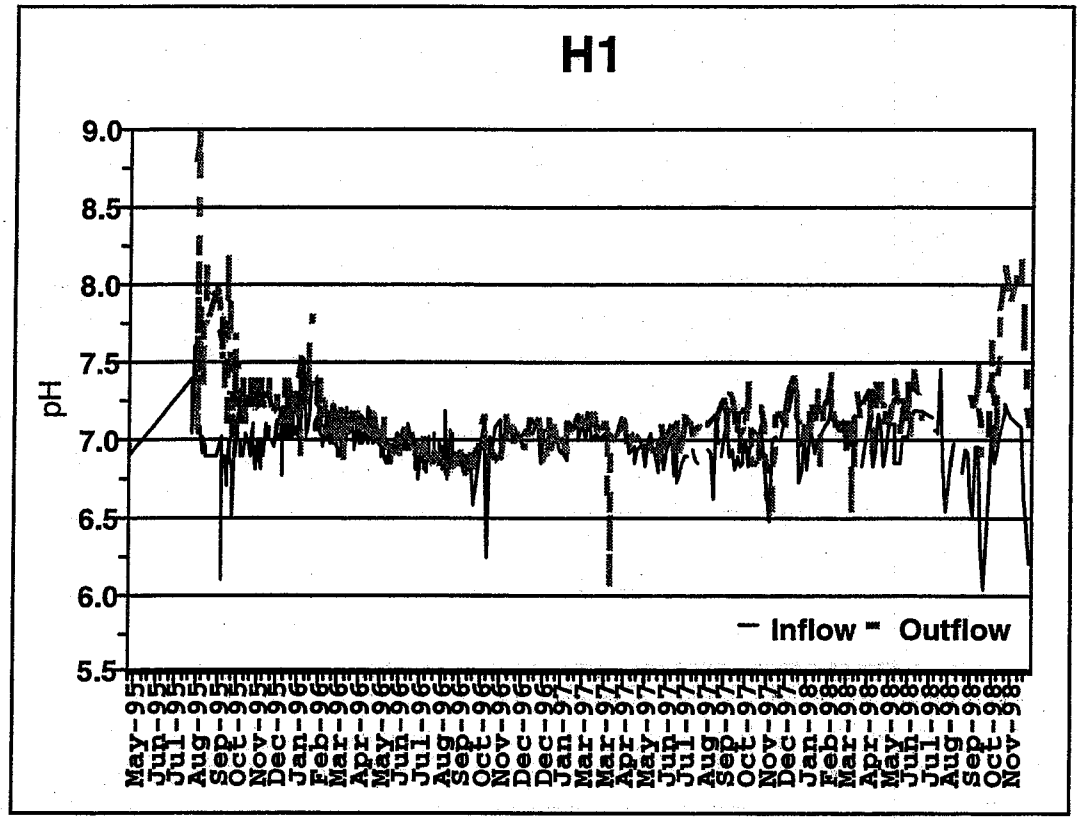


Figure C–1: Temperature data for the Hayfield site



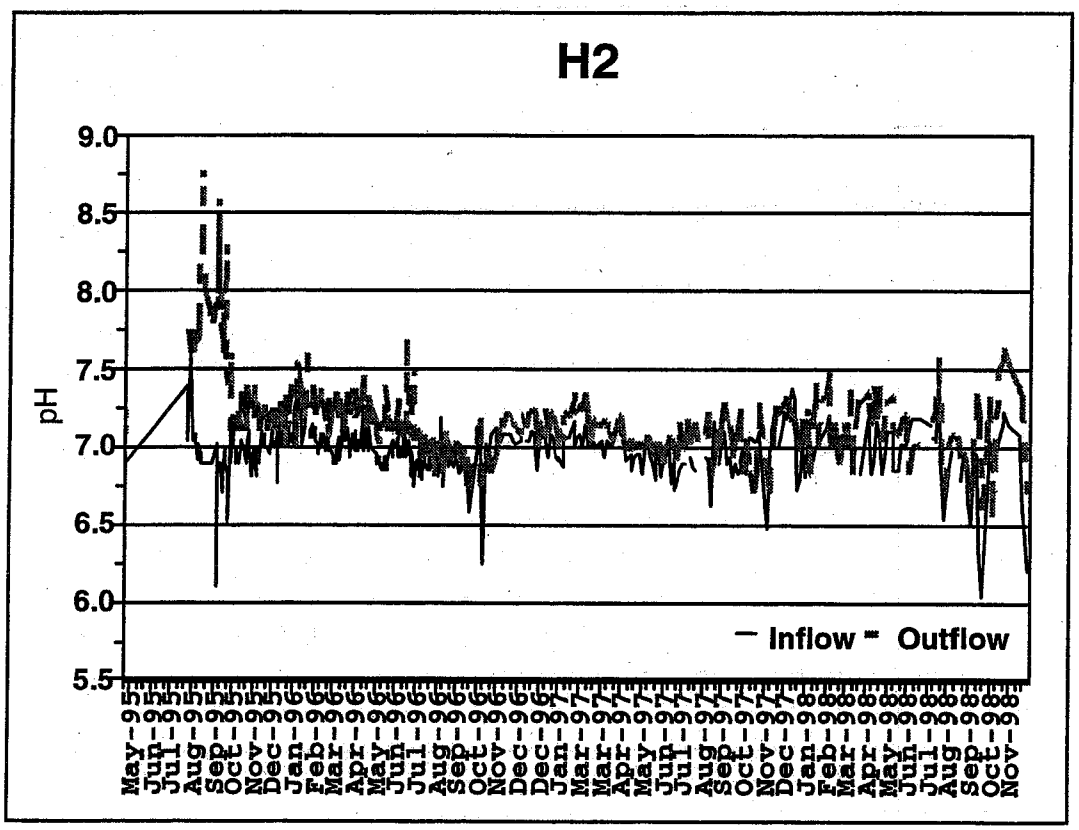
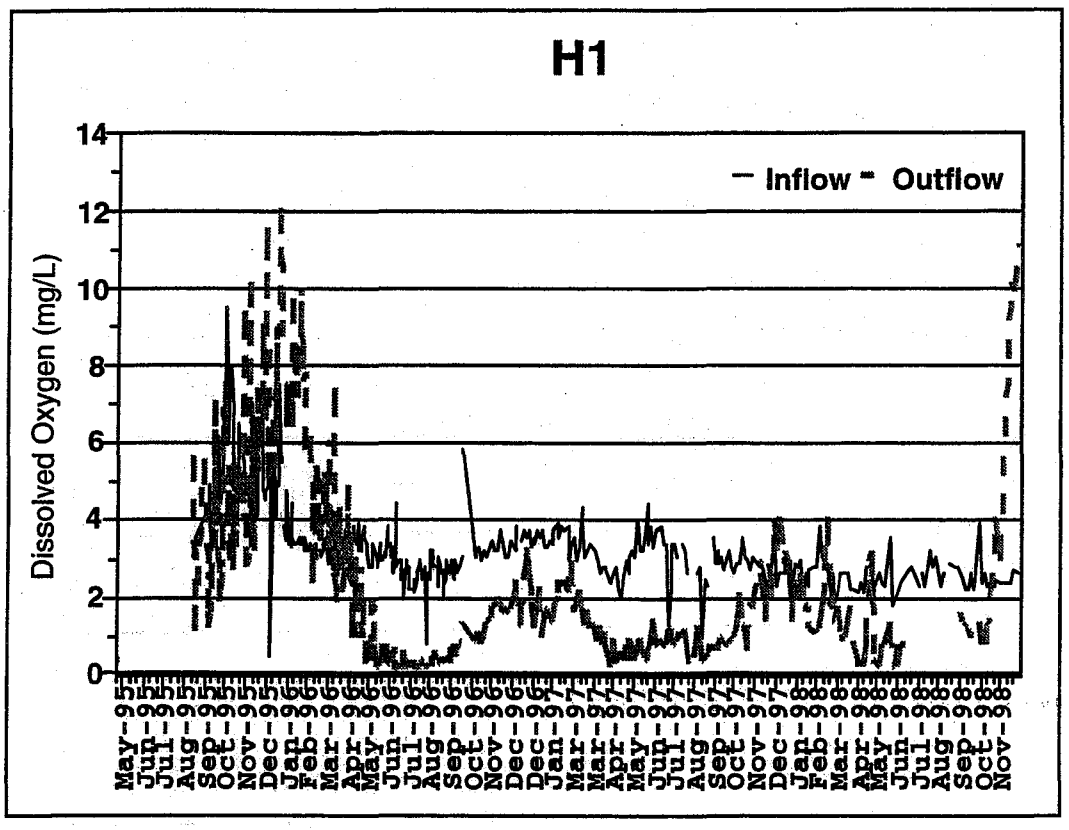


Figure C–2: pH data for the Hayfield site



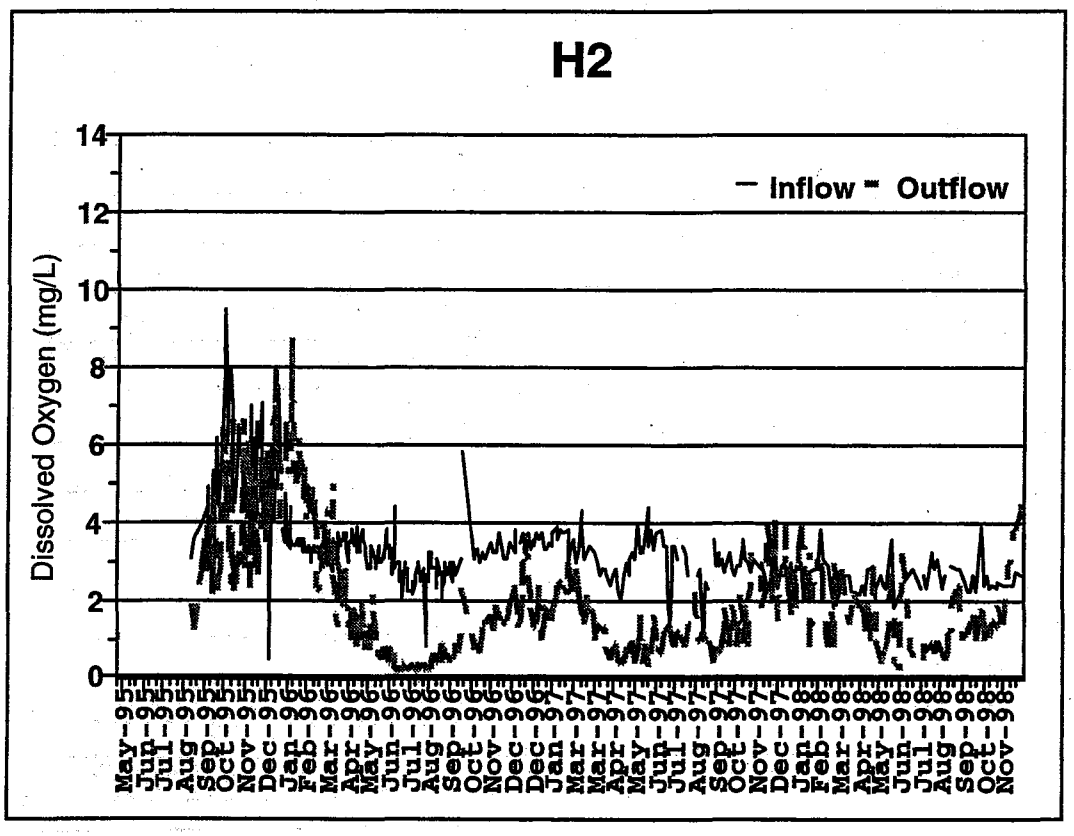


Figure C–3: Dissolved oxygen data for the Hayfield site

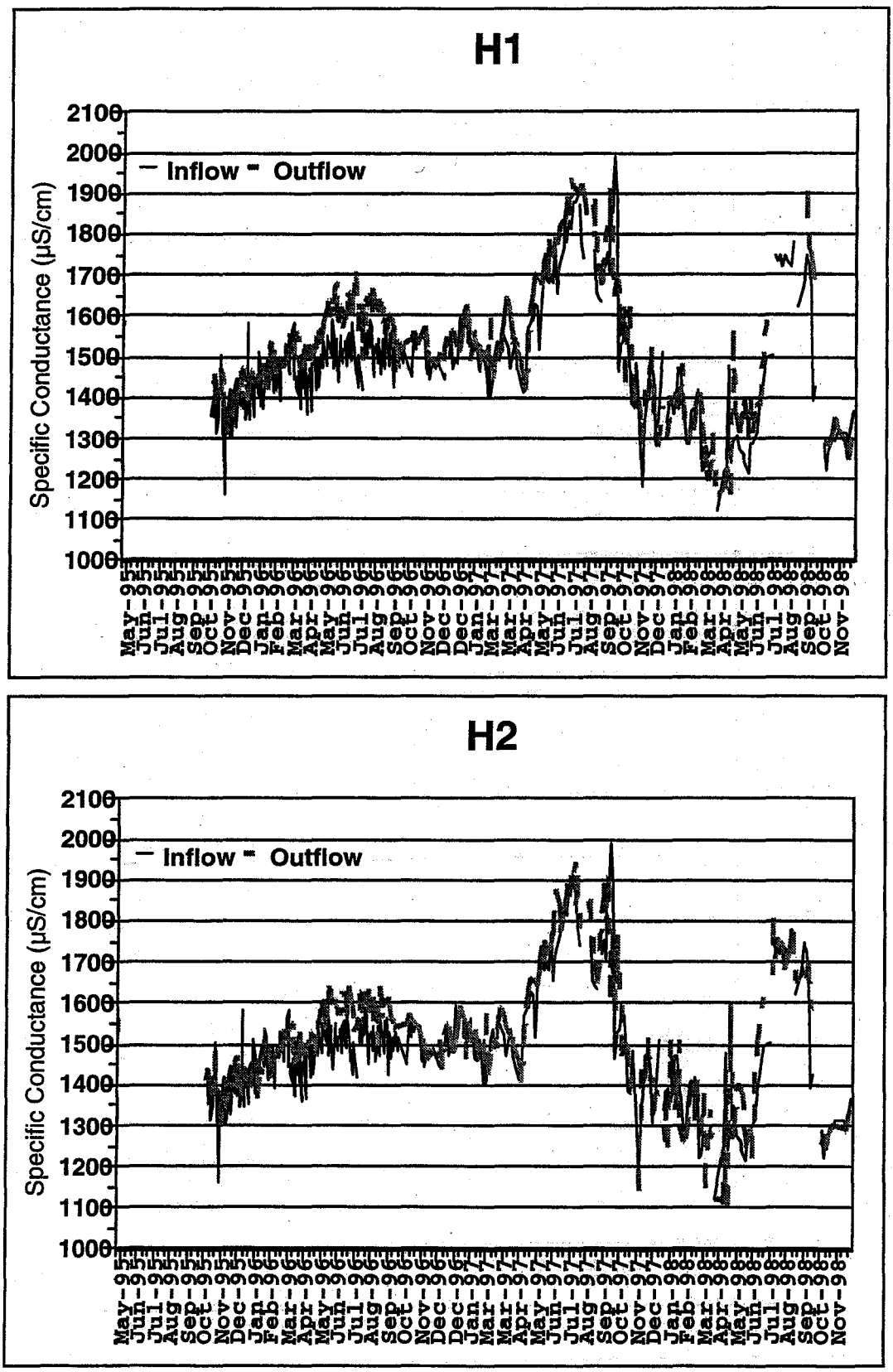
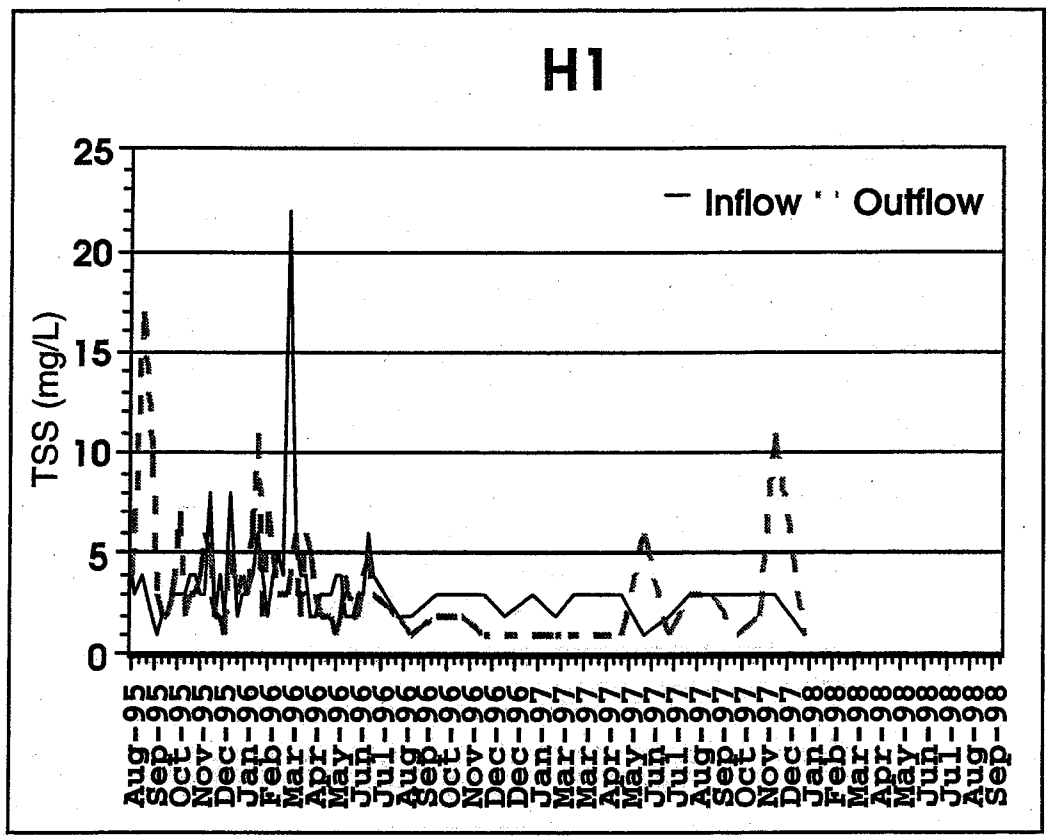


Figure C–4: Specific conductance data for the Hayfield site



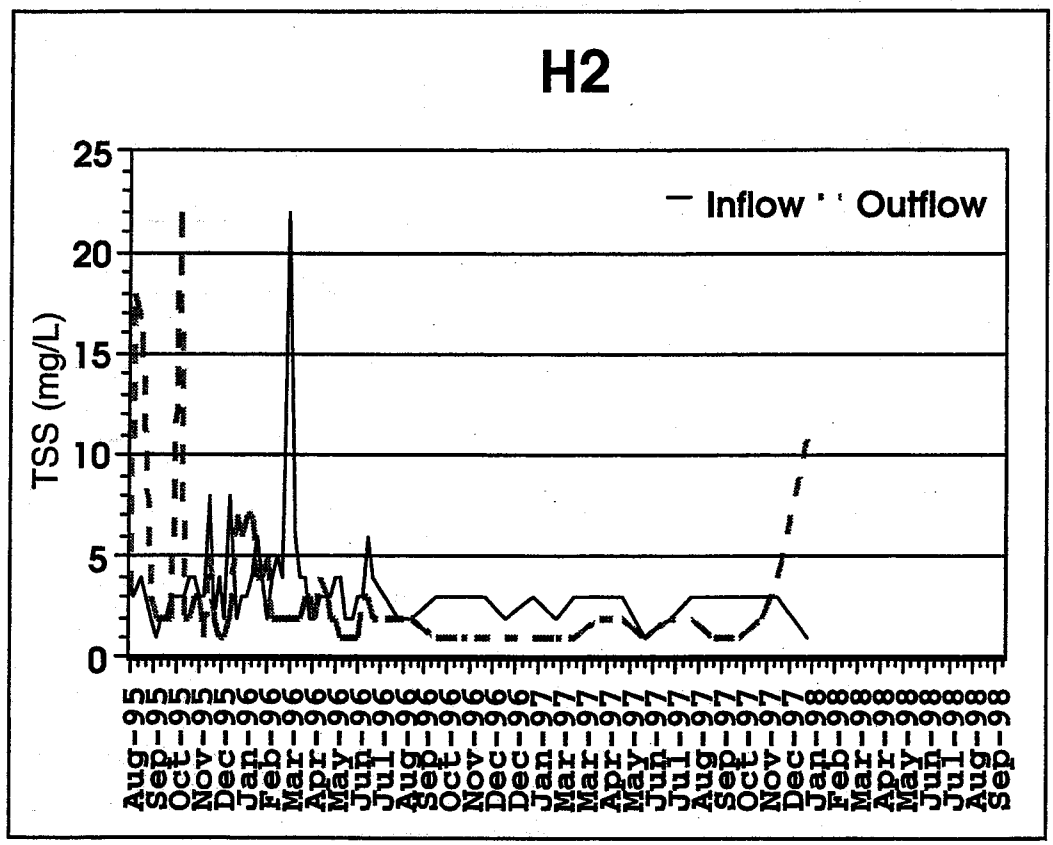
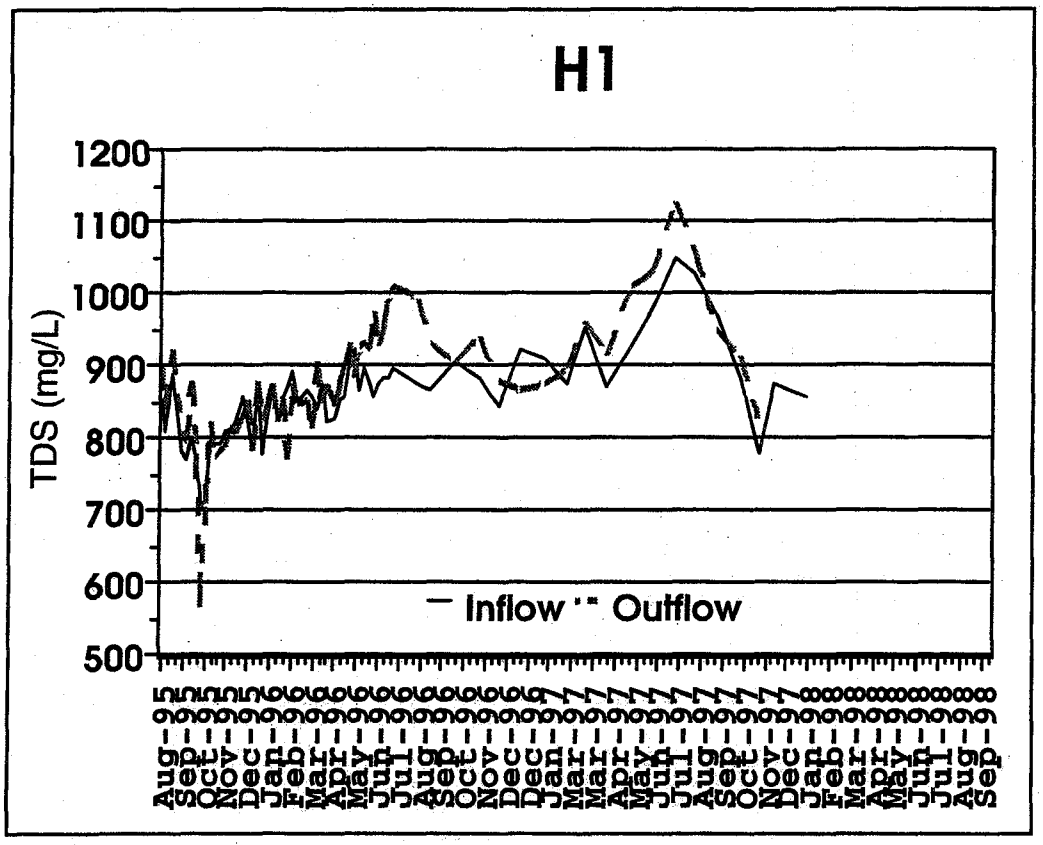


Figure C–5: Total suspended solids (TSS) data for the Hayfield site



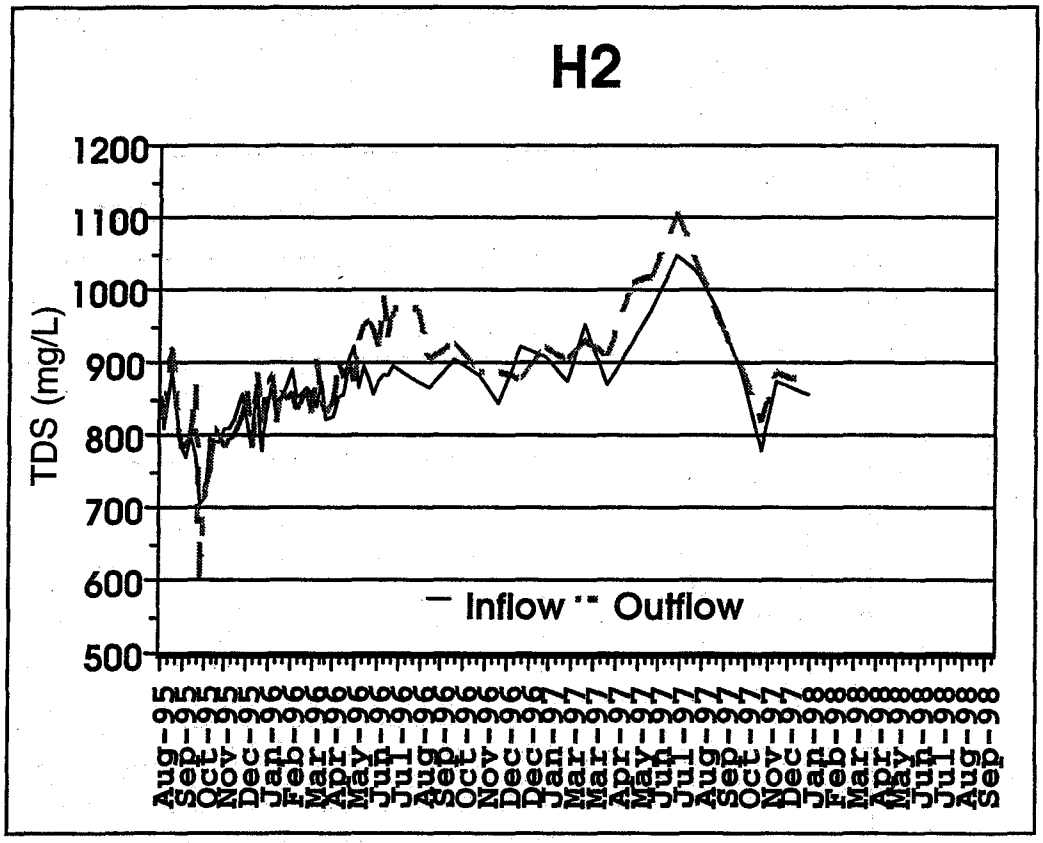
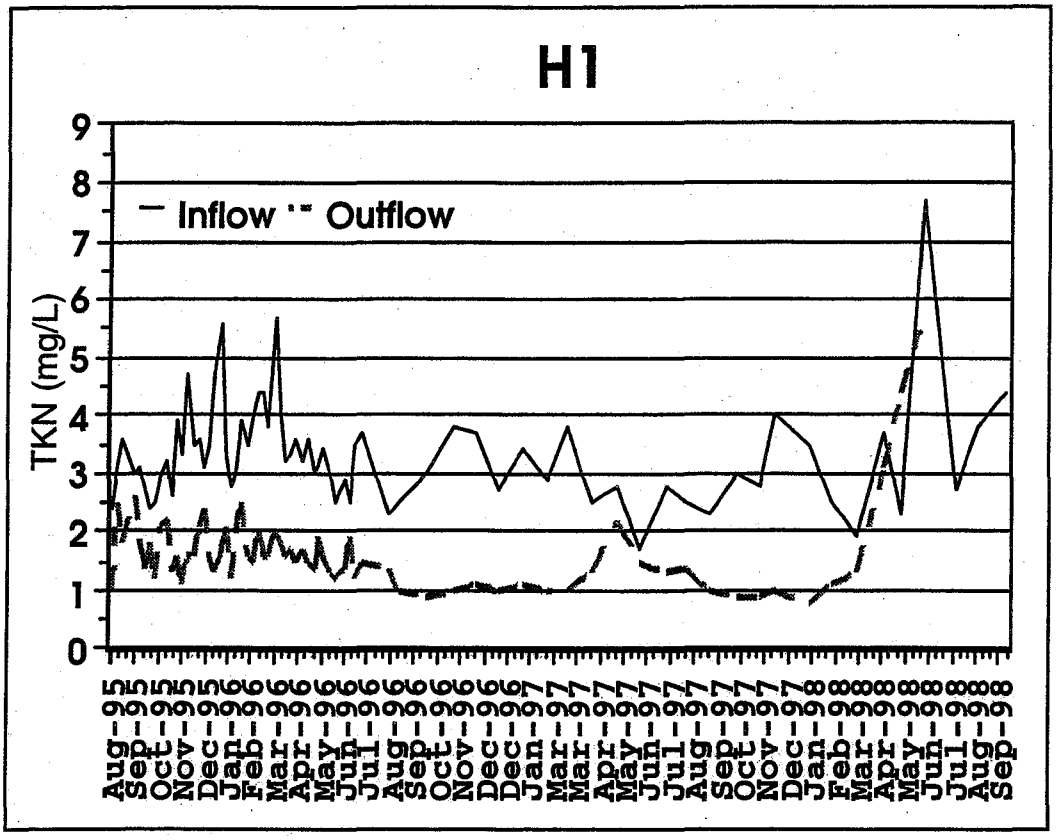


Figure C–6: Total dissolved solids (TDS) data for the Hayfield site



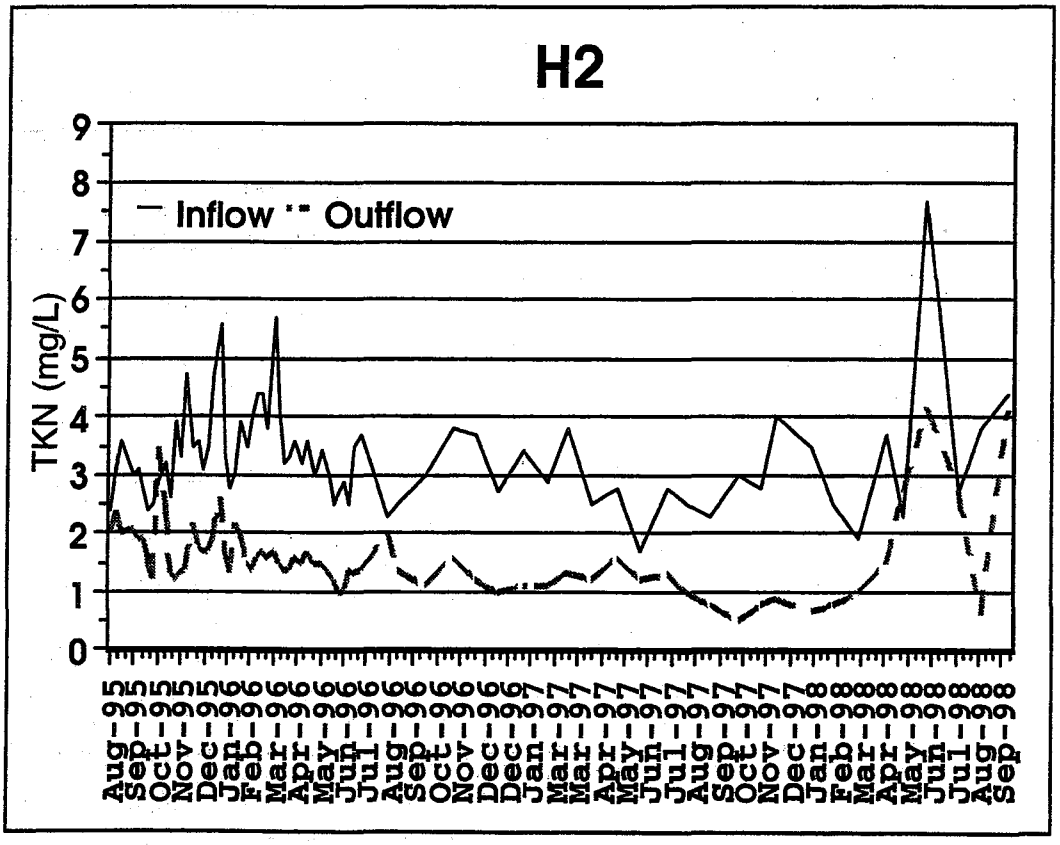


Figure C–7: Total Kjeldahl nitrogen (TKN) data for the Hayfield site

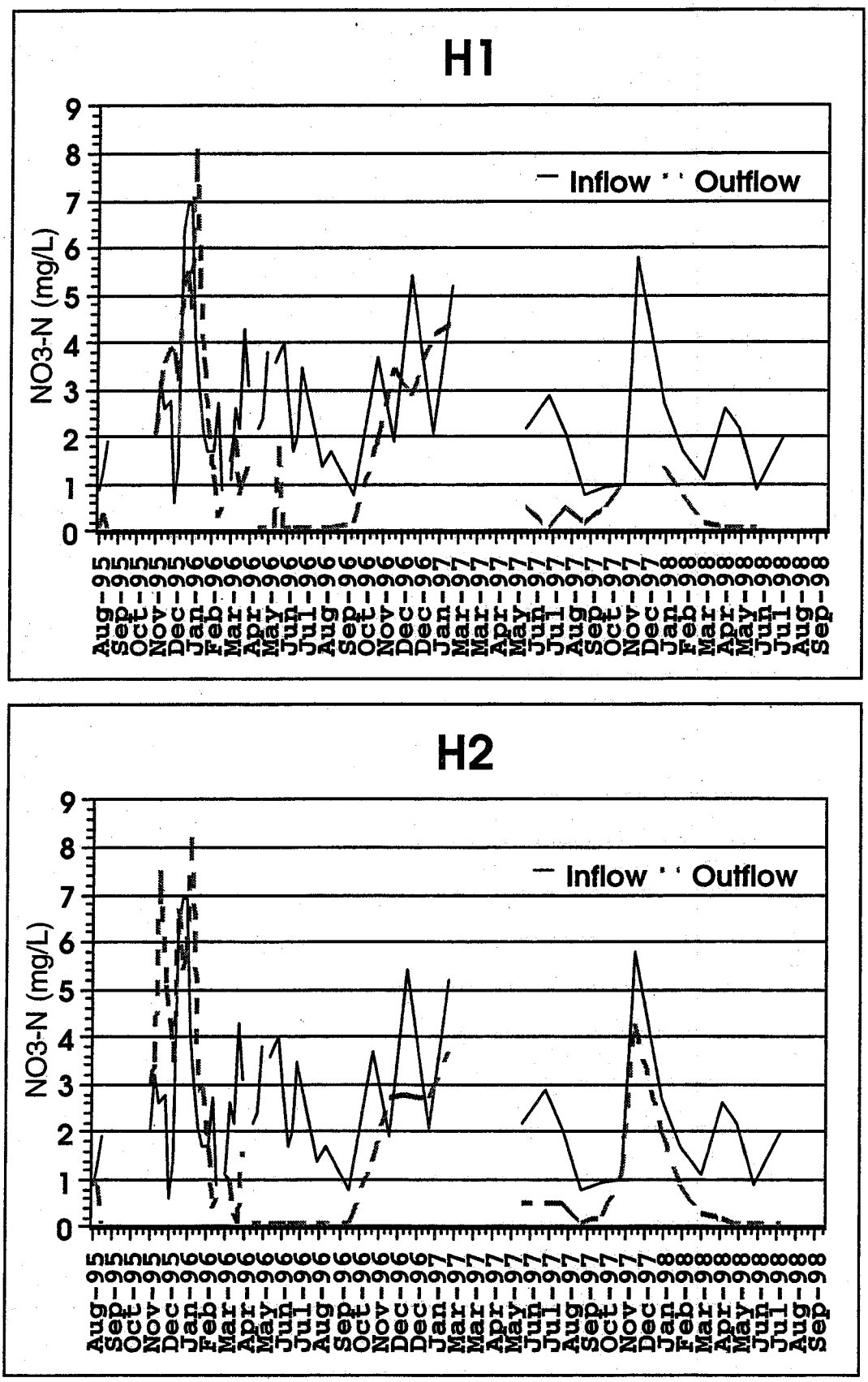
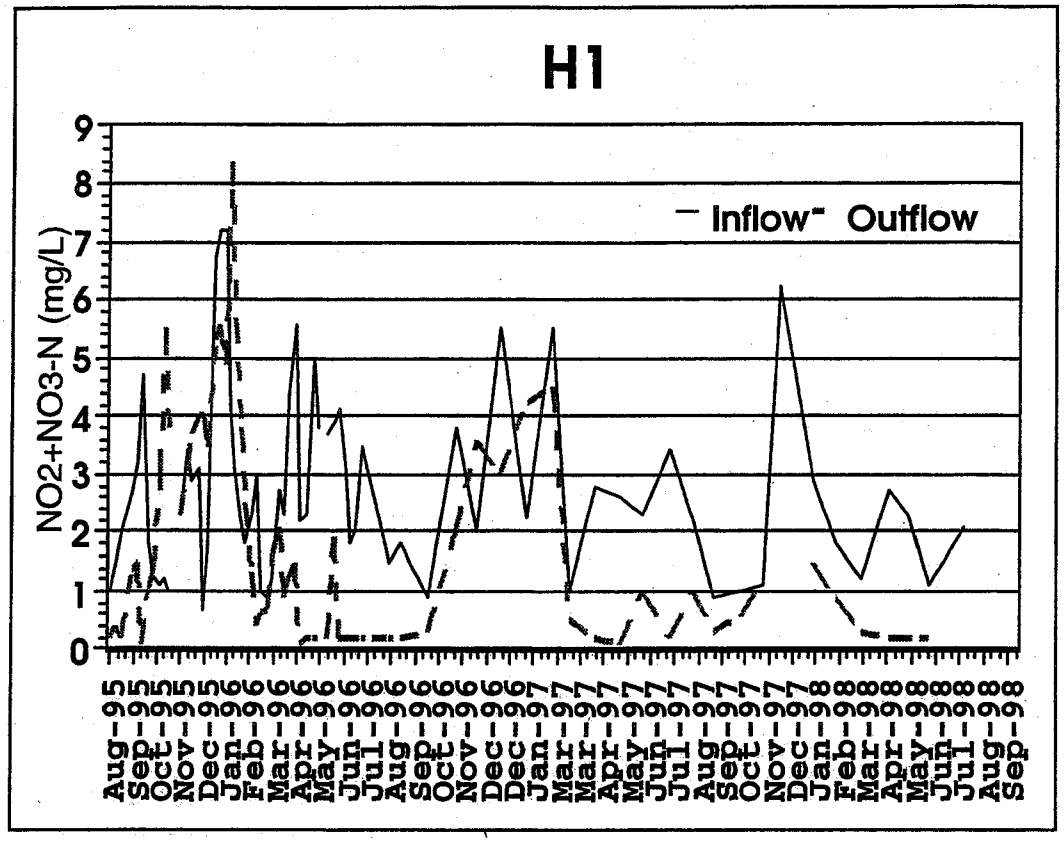


Figure C–8: Nitrate-nitrogen (NO_3-N) data for the Hayfield site



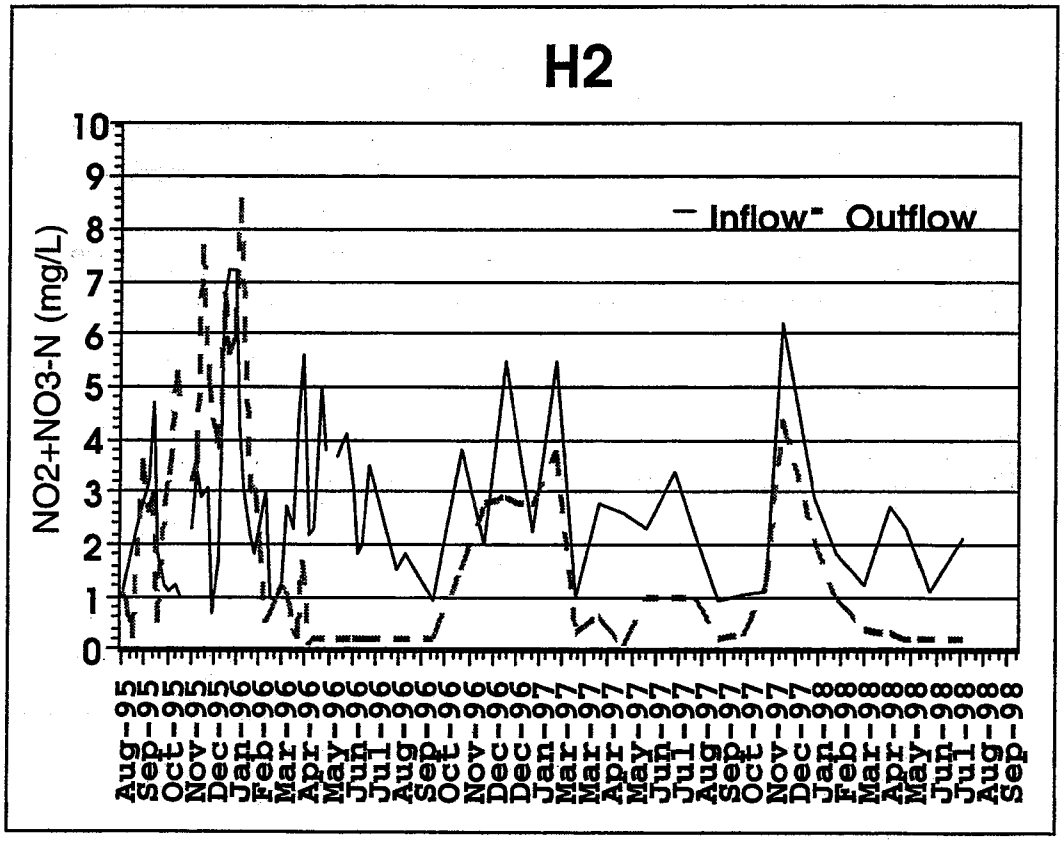


Figure C–9: Nitrate plus nitrite nitrogen (NO_2 + NO_3-N) data for the Hayfield site

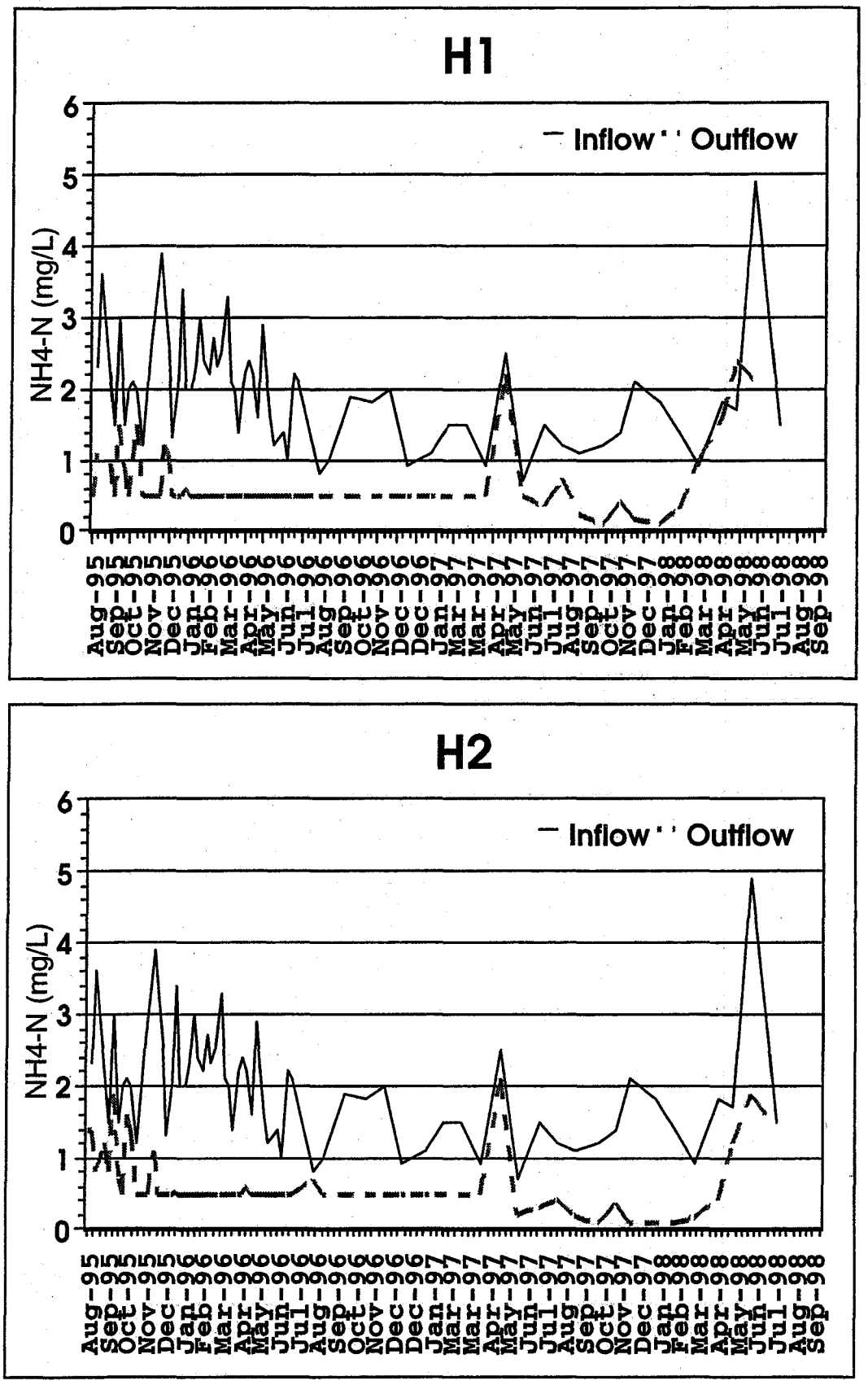


Figure C–10: Ammonia-nitrogen (NH_4-N) data for the Hayfield site

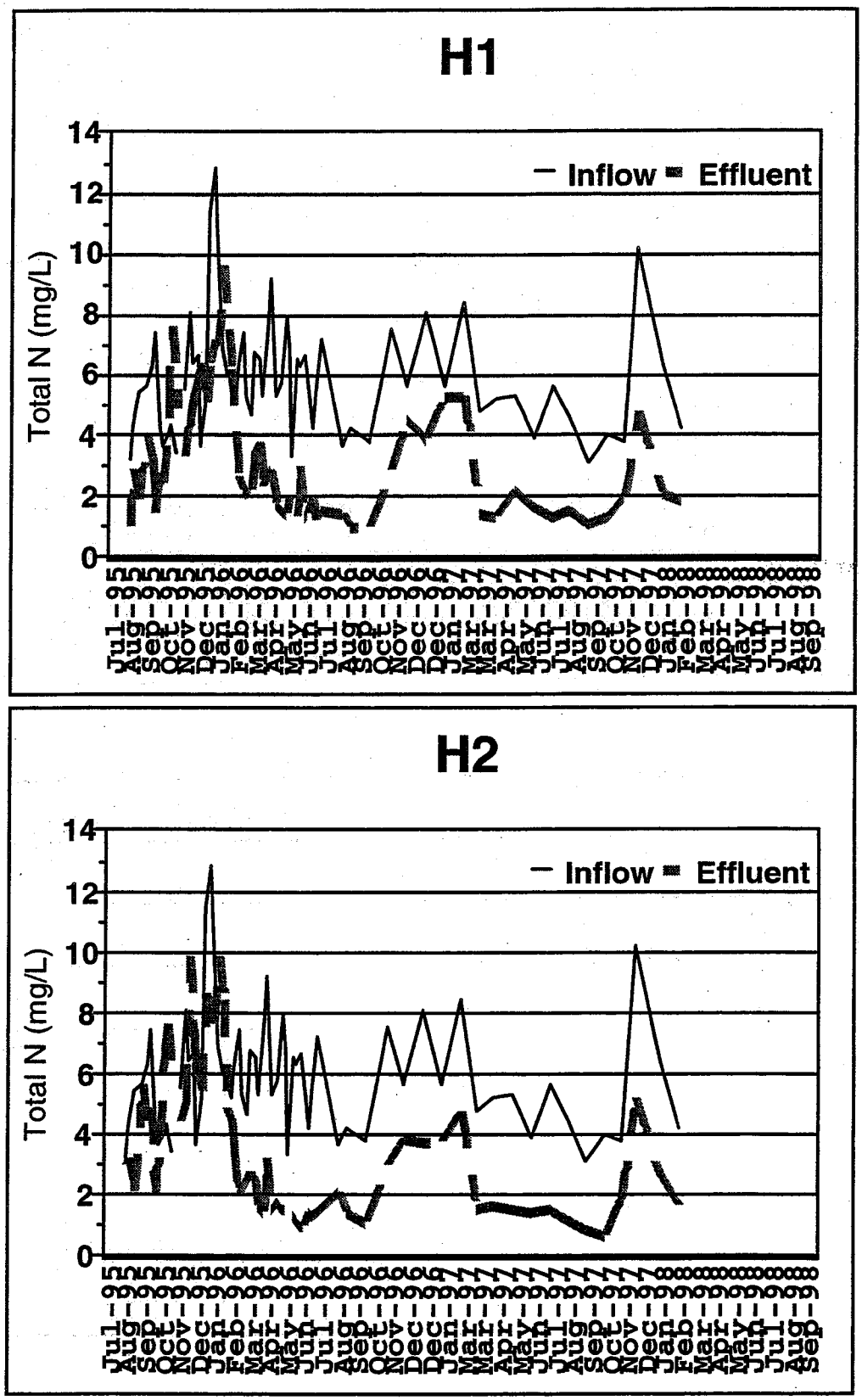
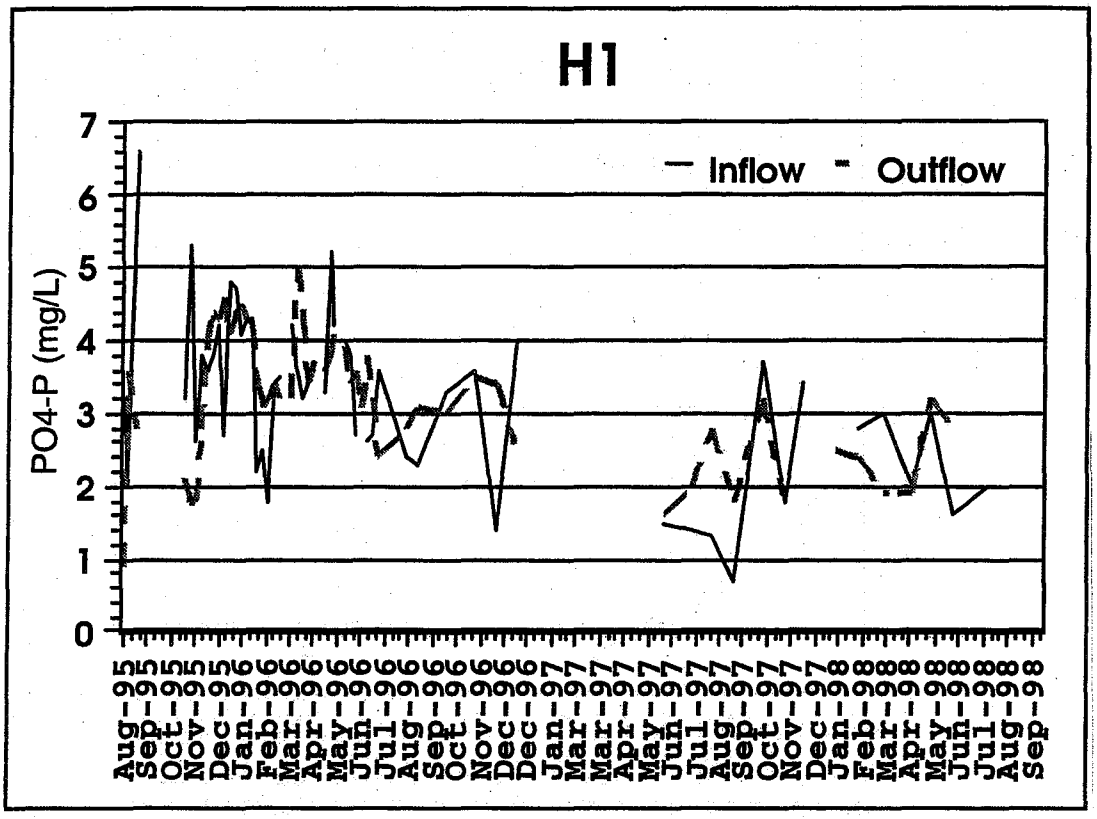


Figure C–11: Total nitrogen data for the Hayfield site



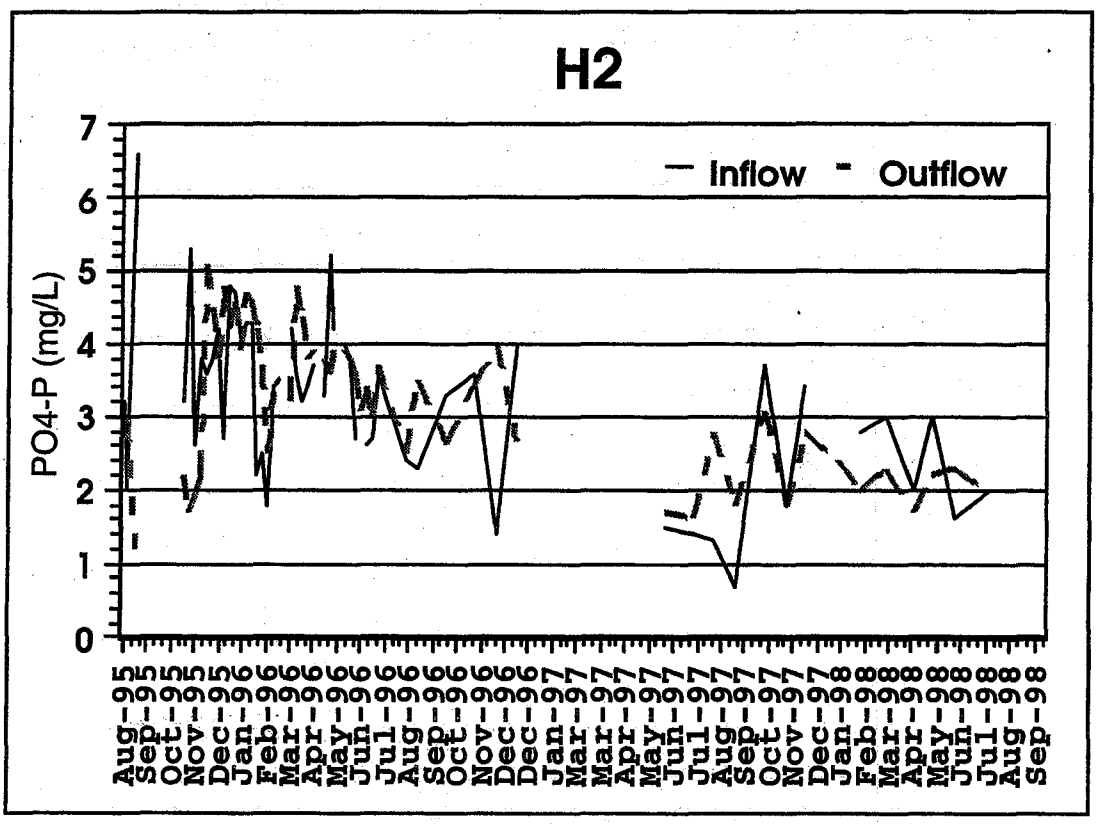
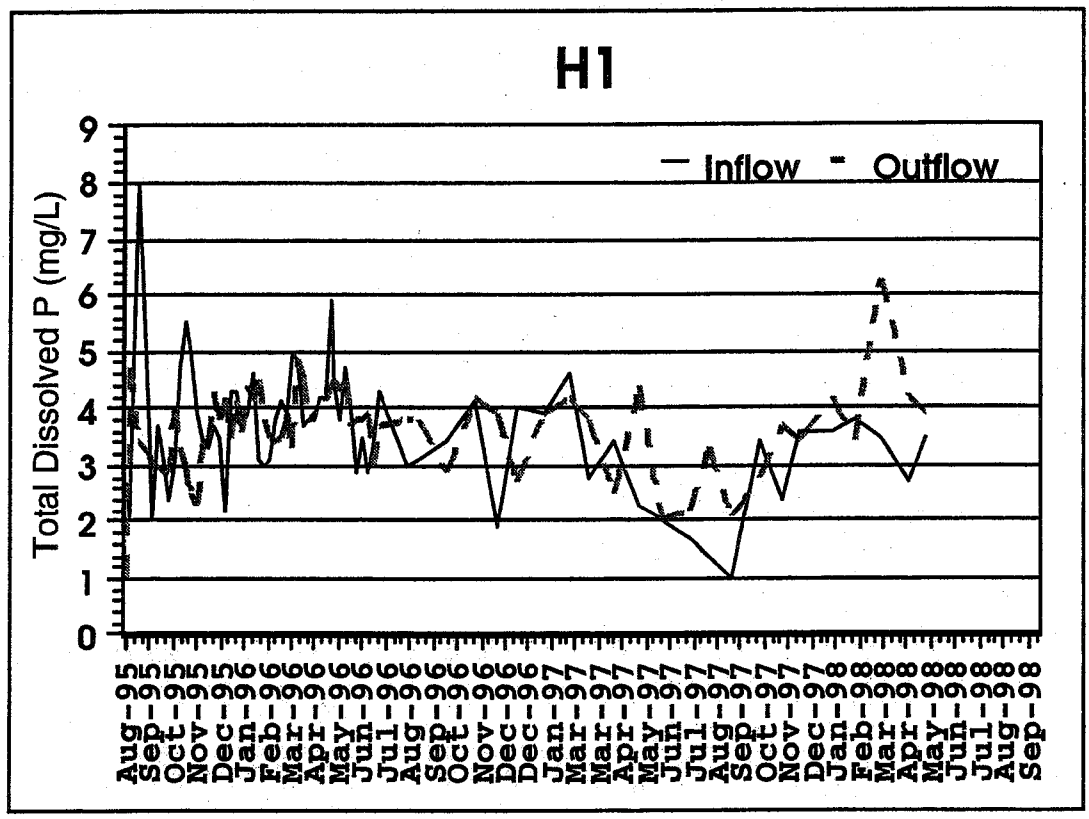


Figure C–12: Orthophosphate-phosphorus (PO_4-P) data for the Hayfield site



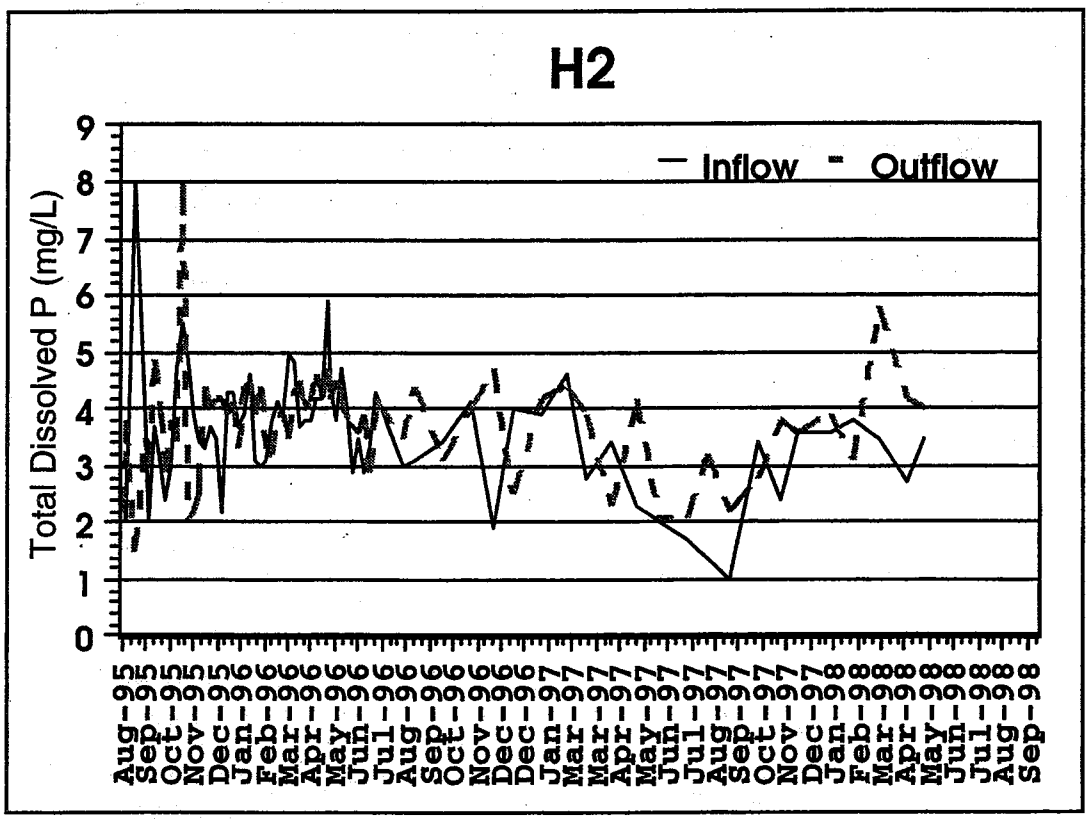
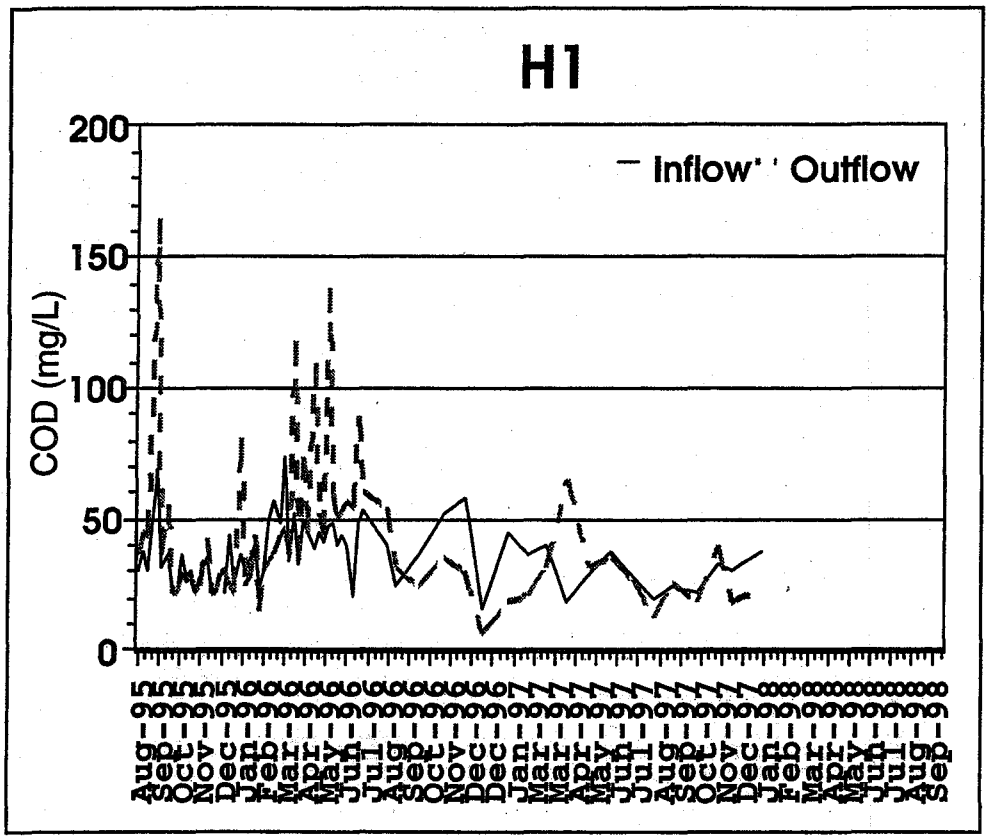


Figure C–13: Total dissolved phosphorus data for the Hayfield site



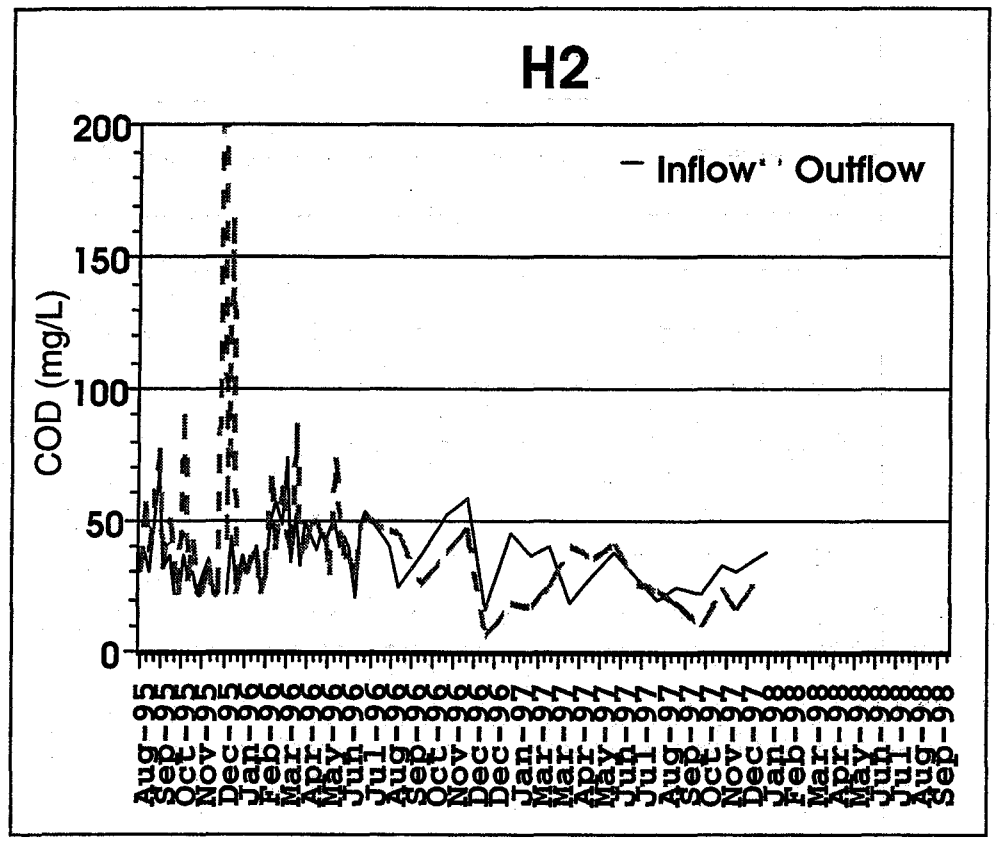
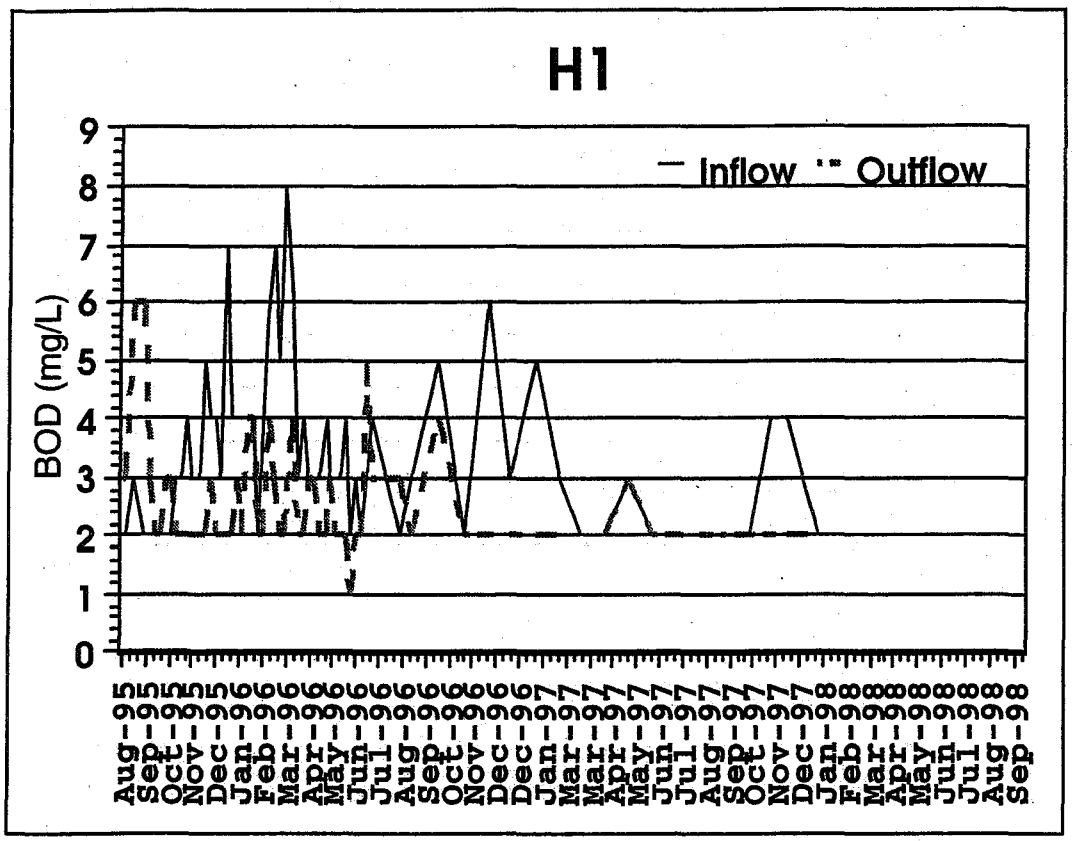


Figure C–14: Chemical oxygen demand (COD) data for the Hayfield site



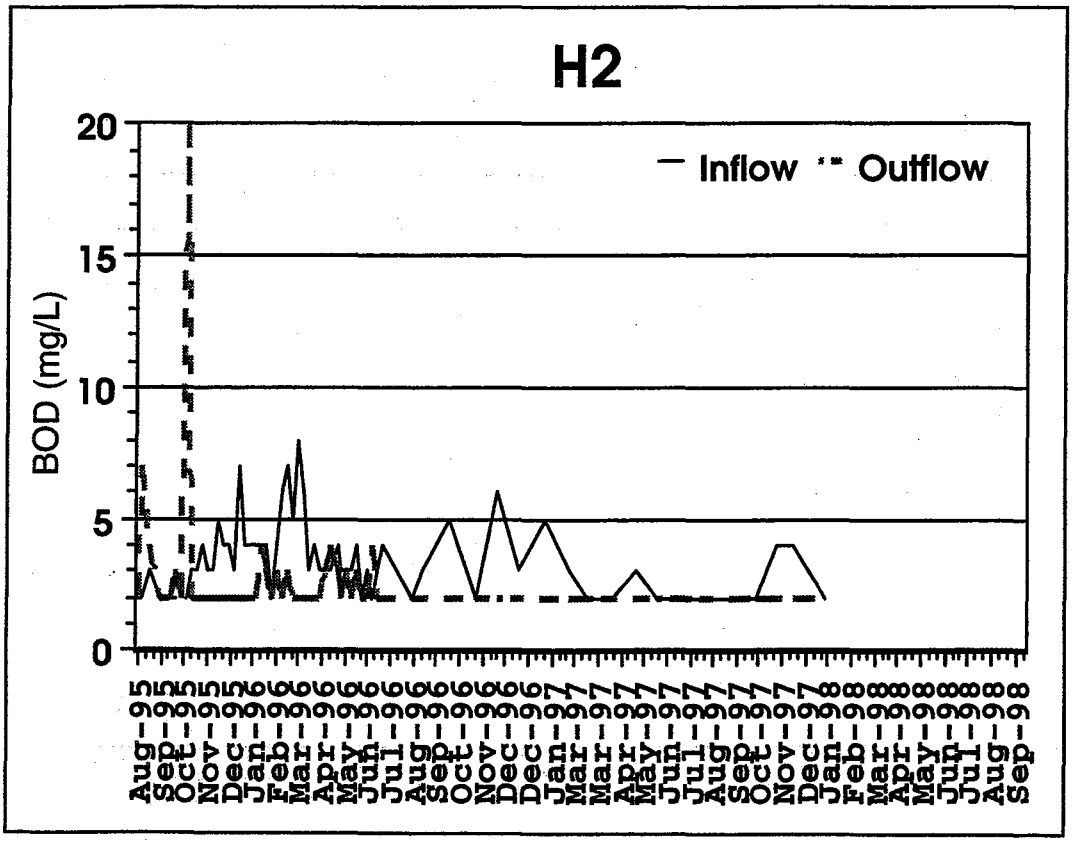
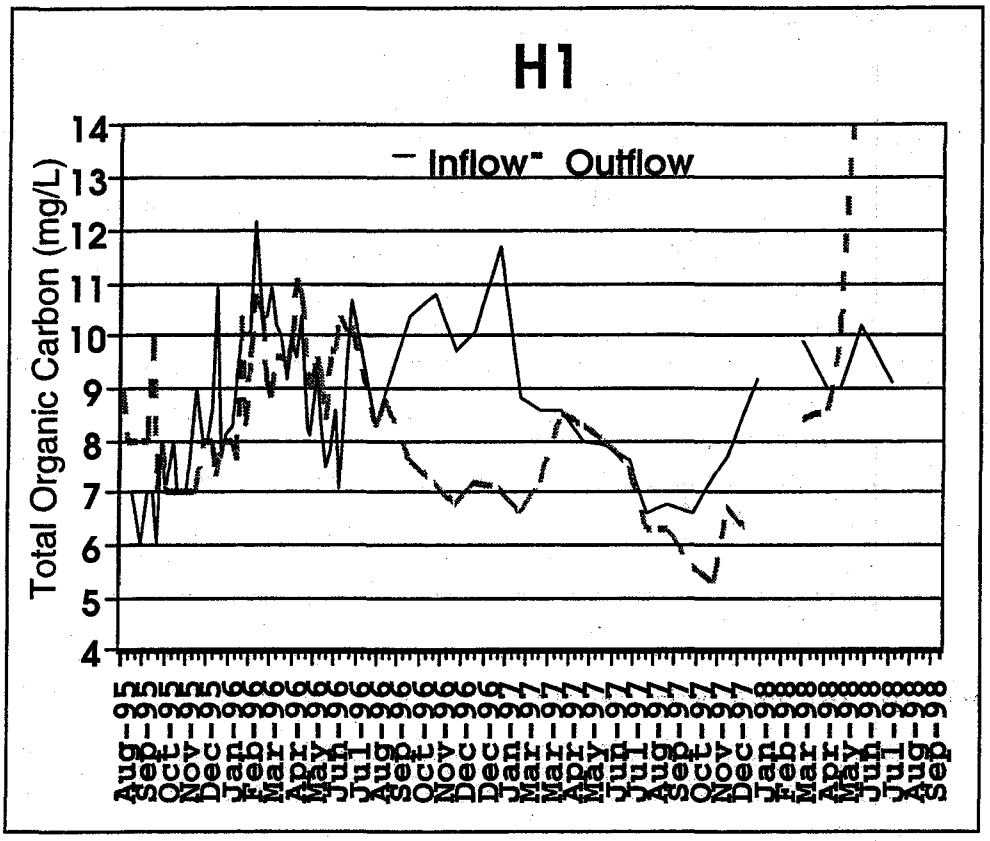


Figure C–15: Biochemical oxygen demand (BOD) data for the Hayfield site



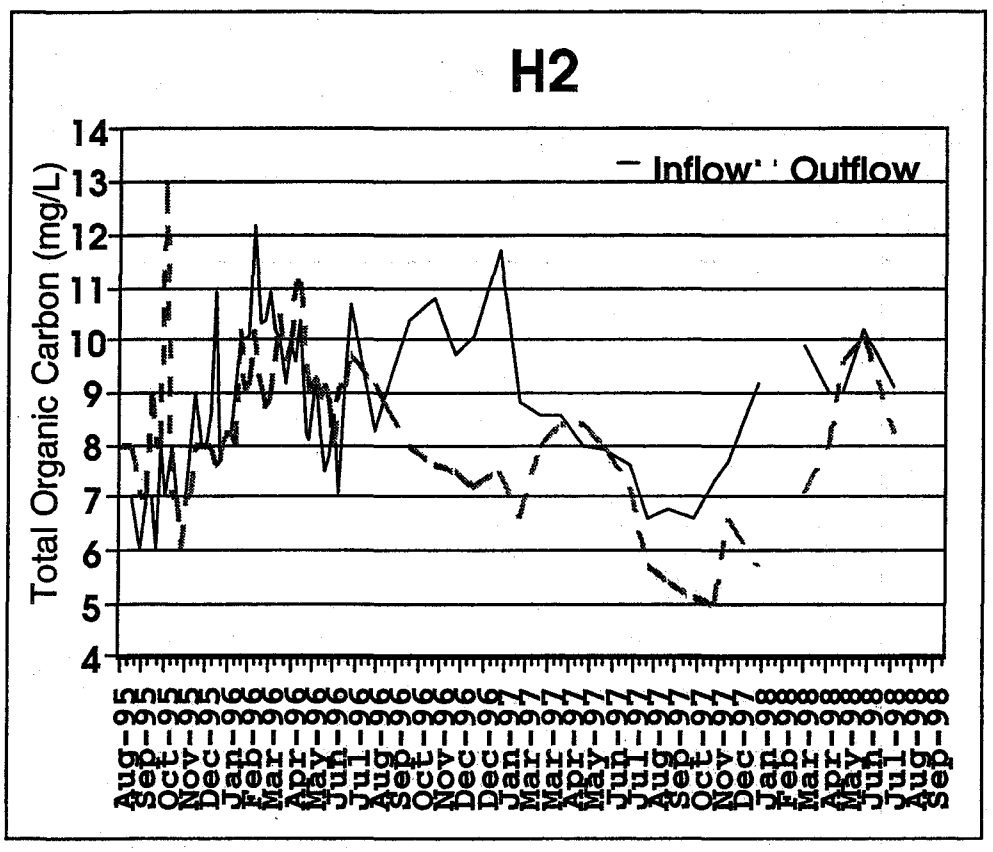
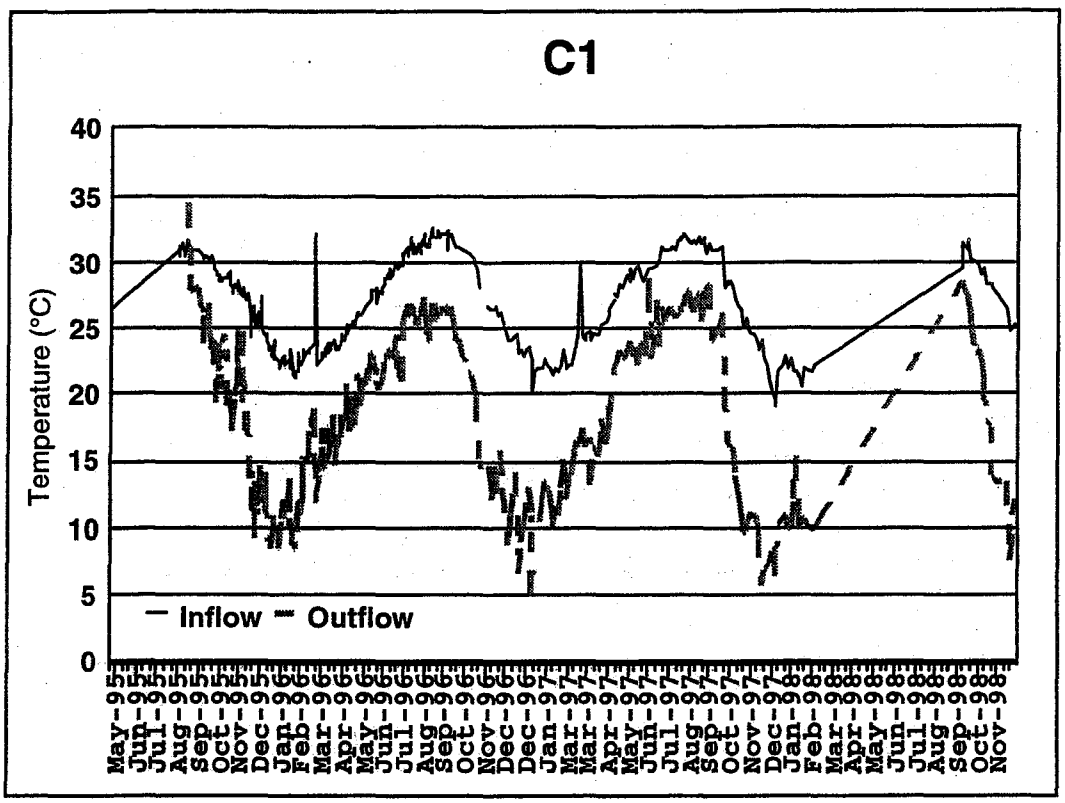


Figure C–16: Total organic carbon (TOC) data for the Hayfield site



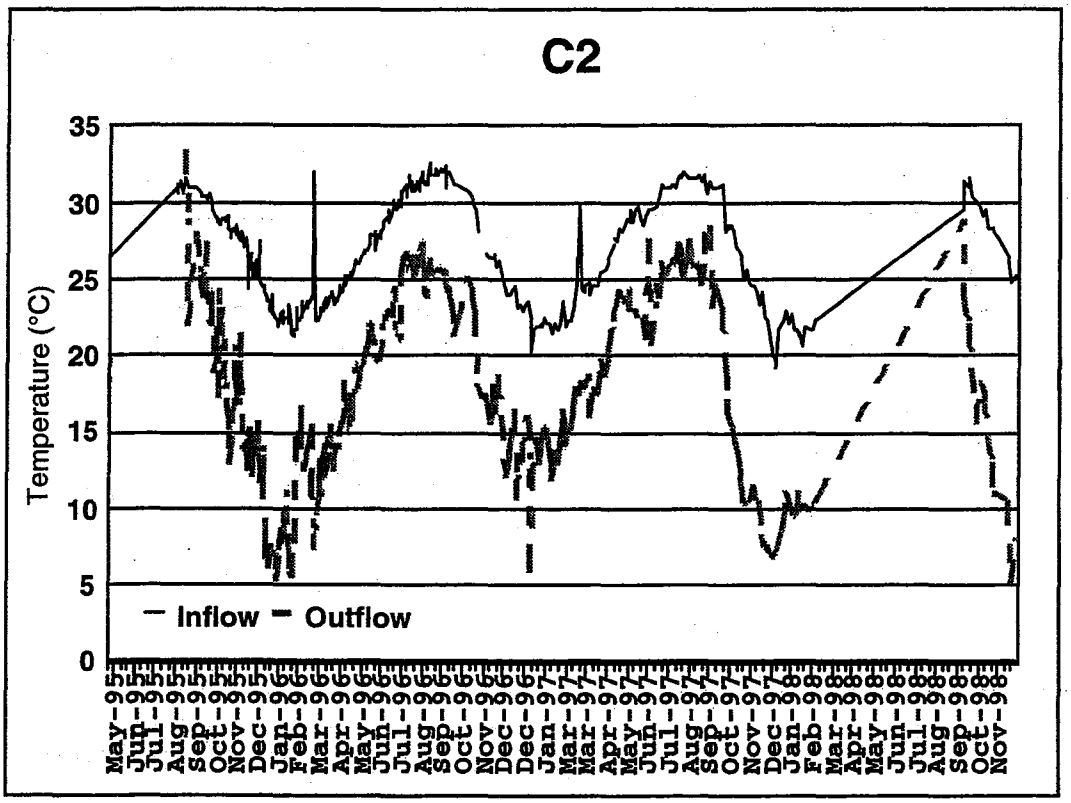
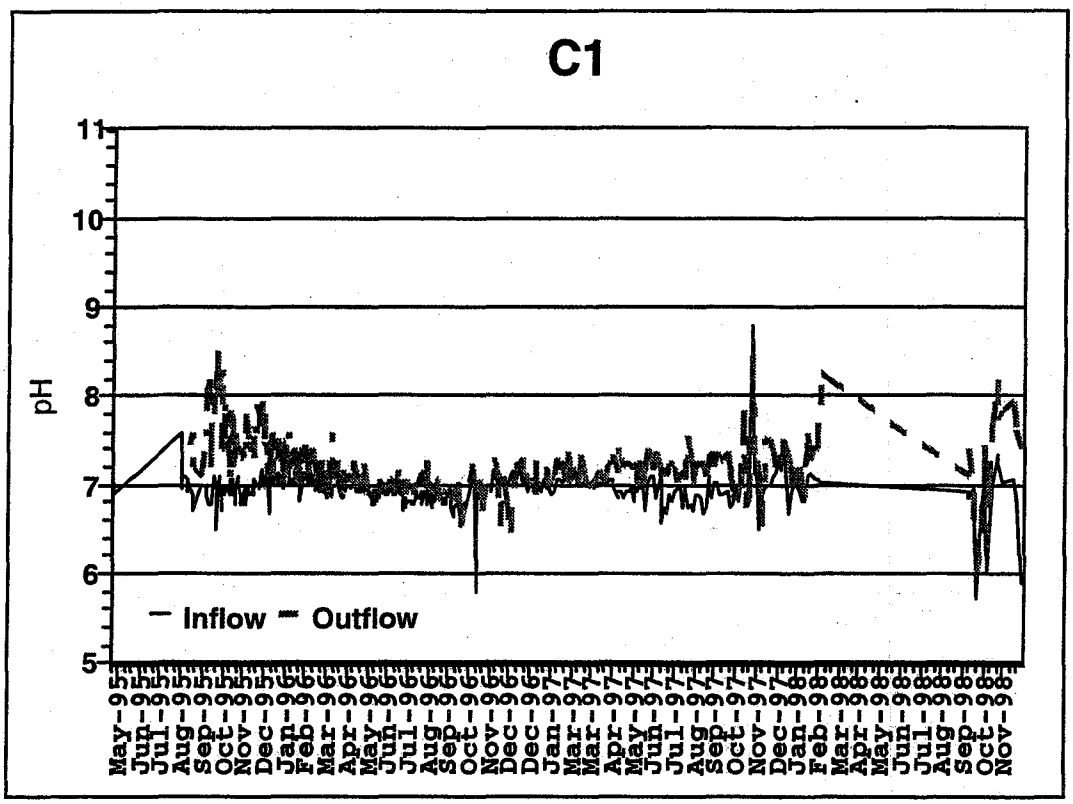


Figure C–17: Temperature data for the Cobble site



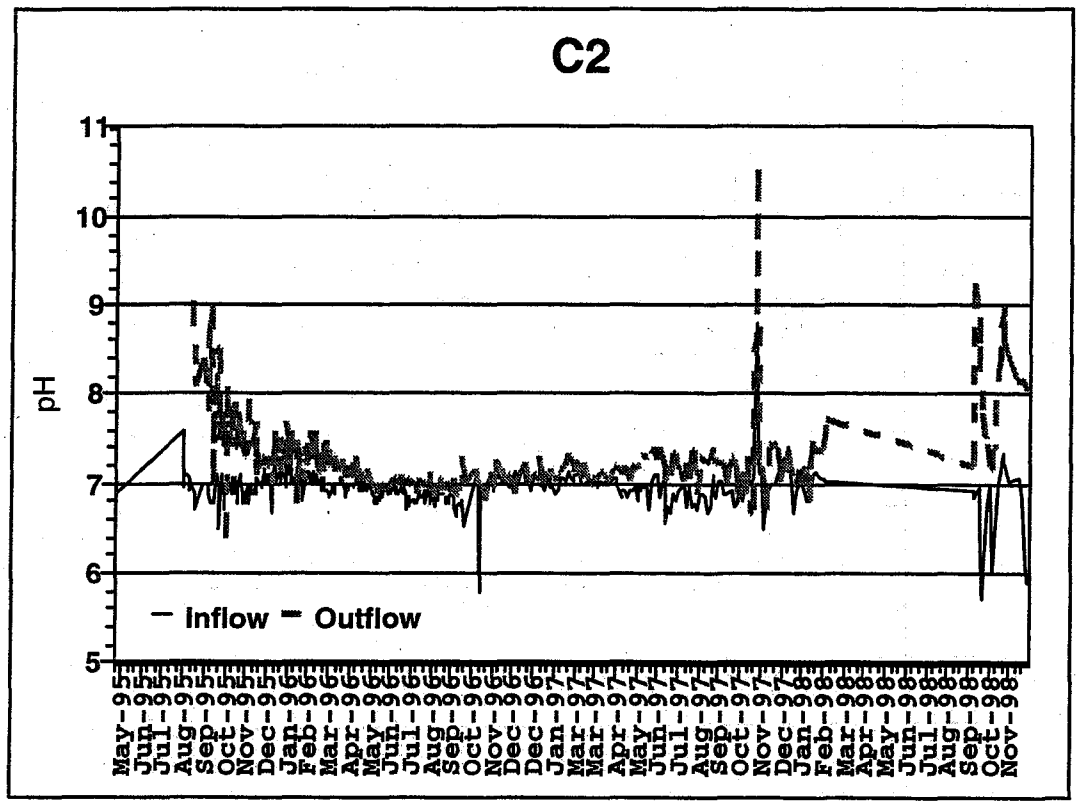
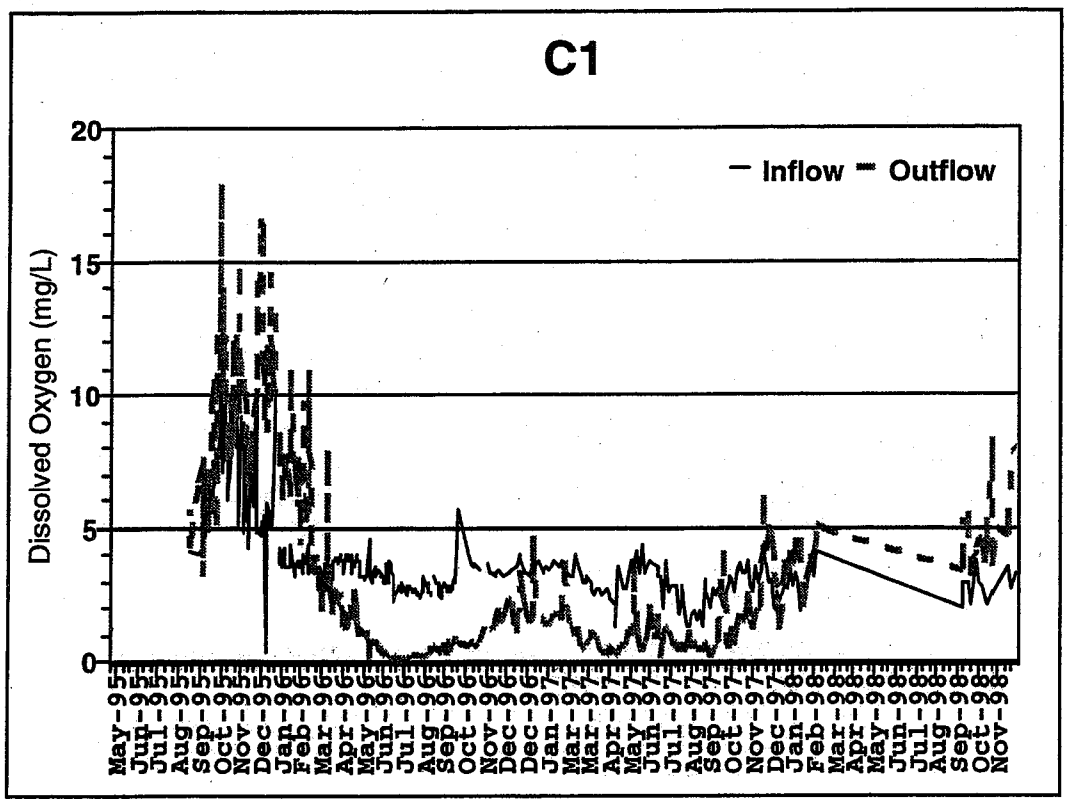


Figure C–18: pH data for the Cobble site



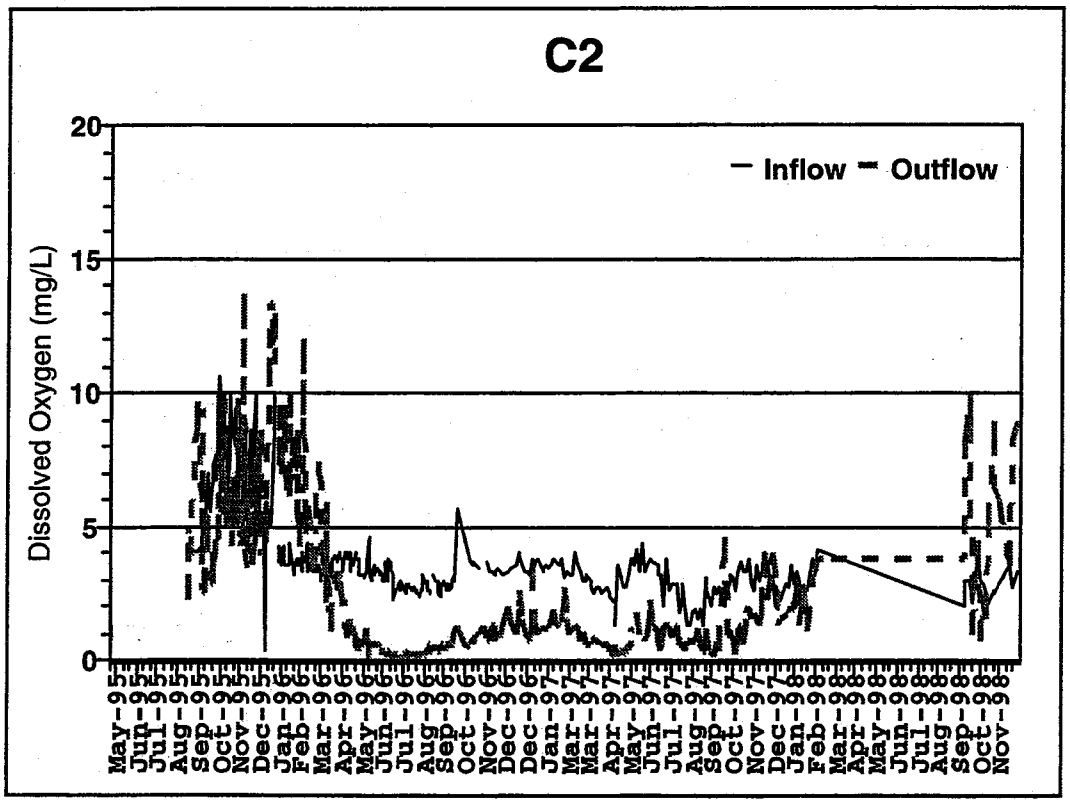
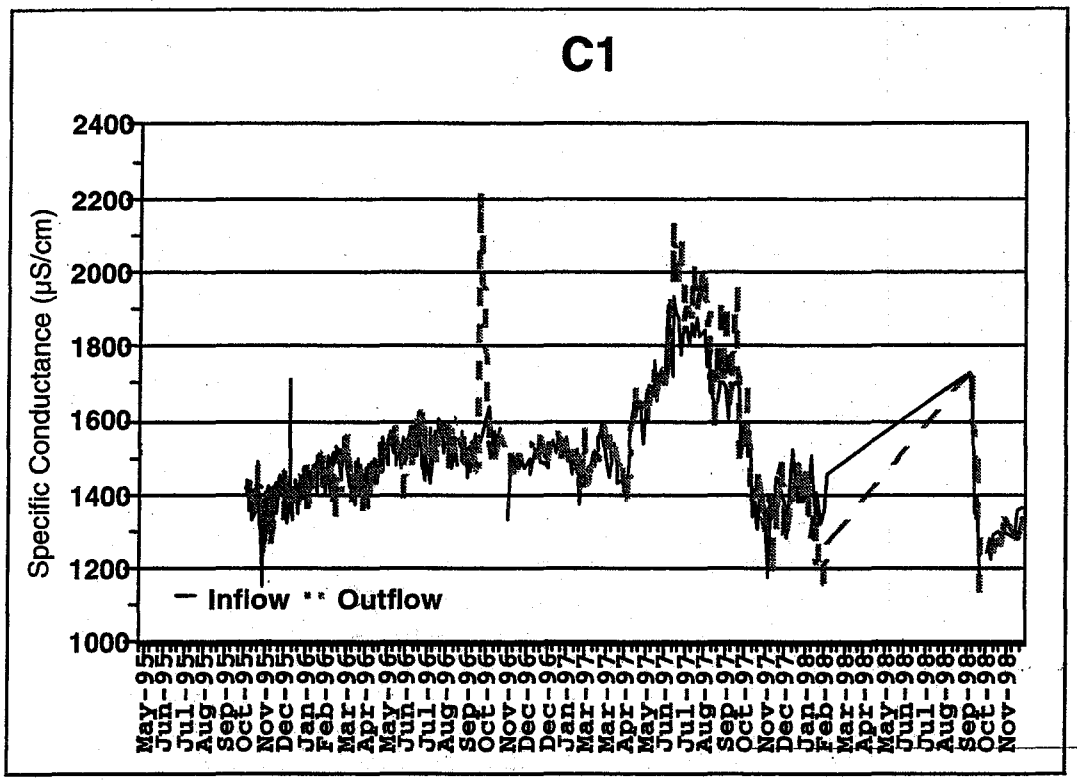


Figure C–19: Dissolved oxygen data for the Cobble site



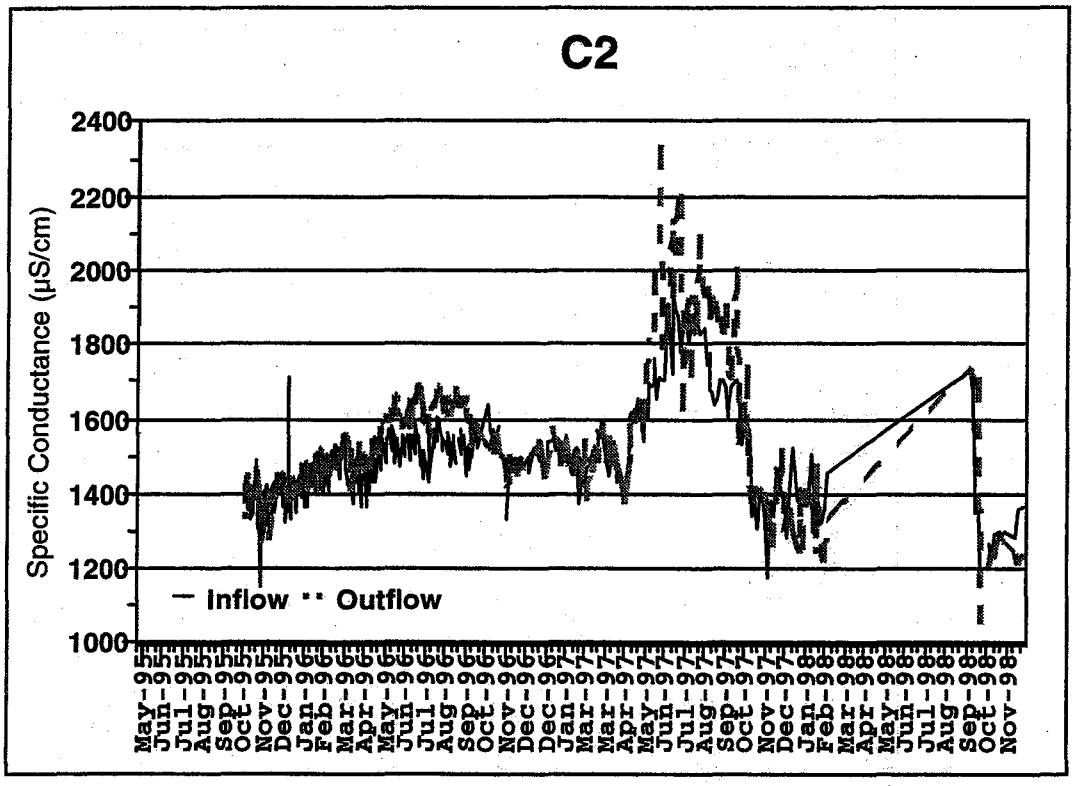
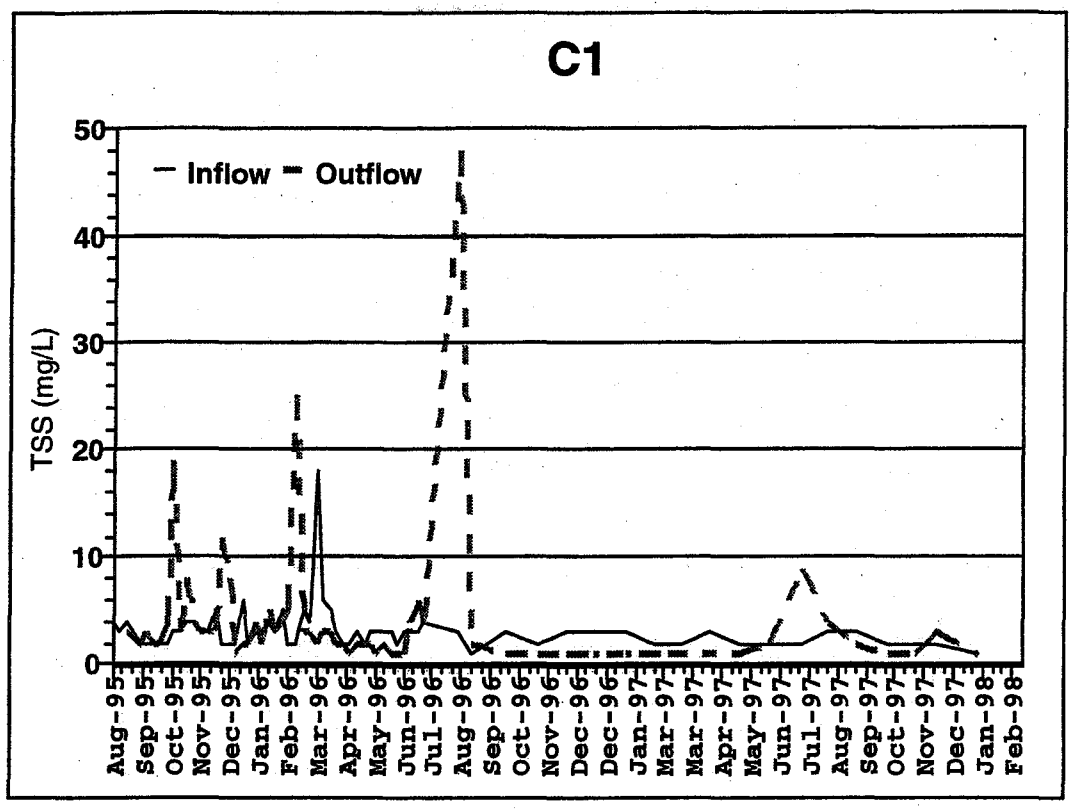


Figure C–20: Specific conductance data for the Cobble site



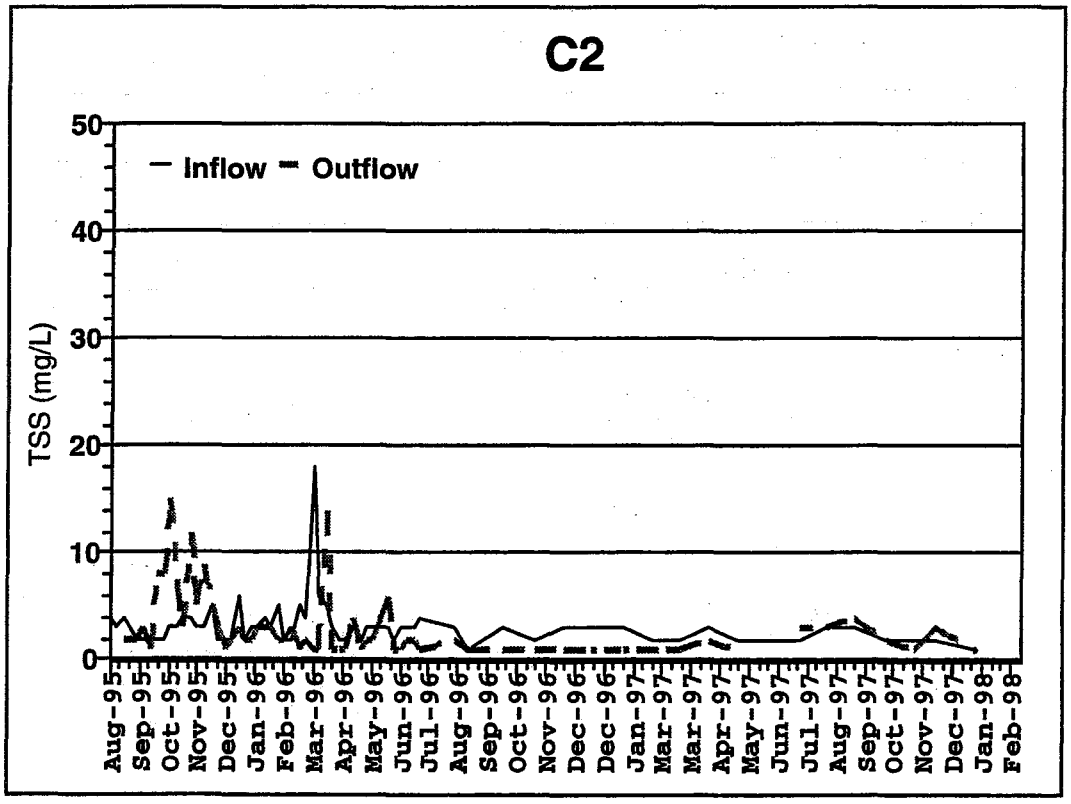
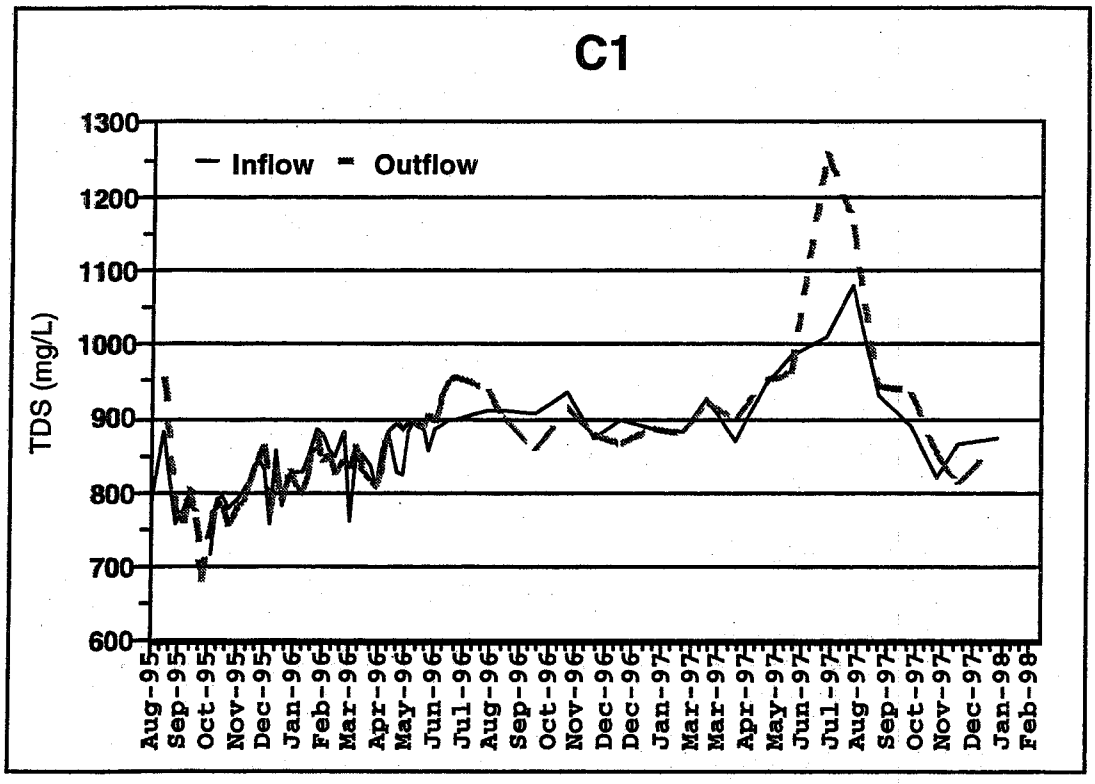


Figure C–21: Total suspended solids (TSS) data for the Cobble site



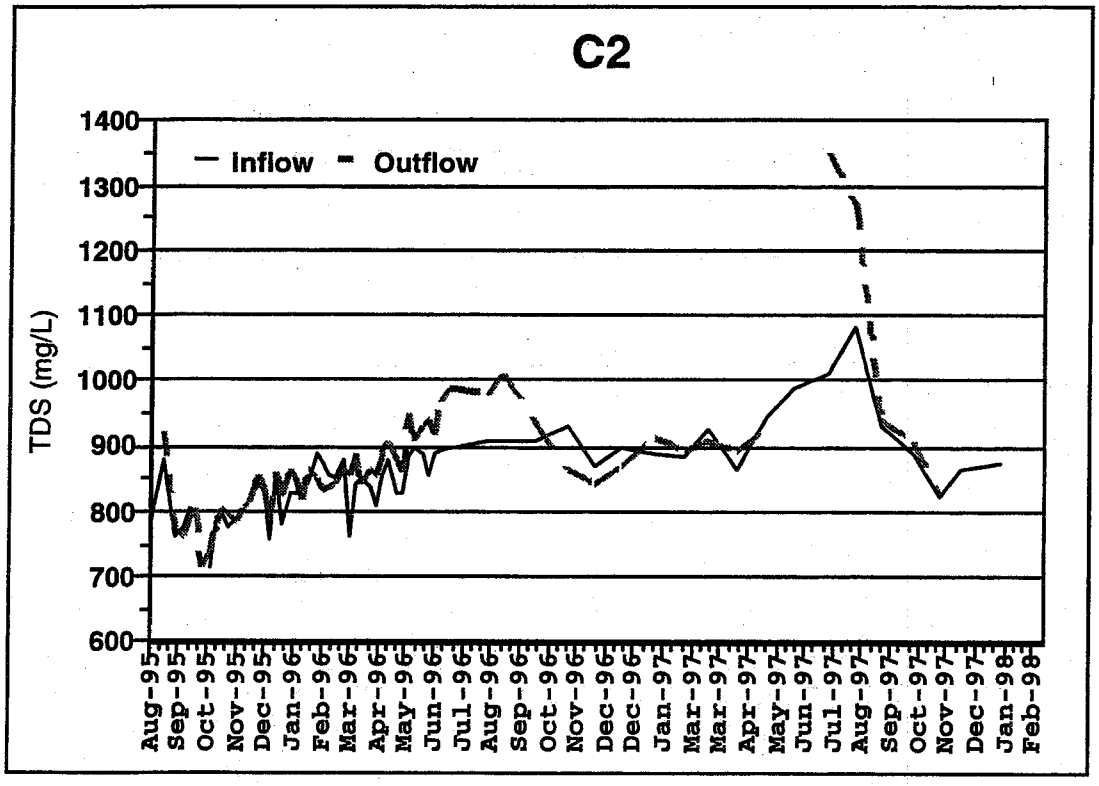
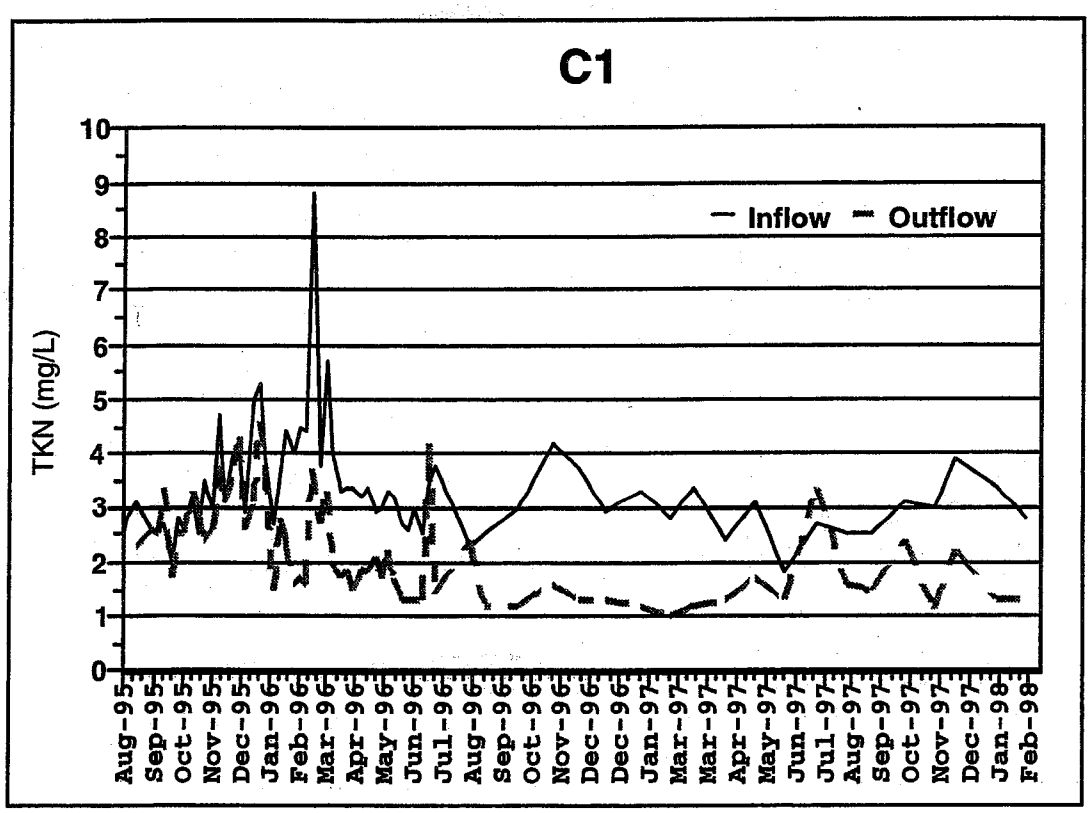


Figure C–22: Total dissolved solids (TDS) data for the Cobble site



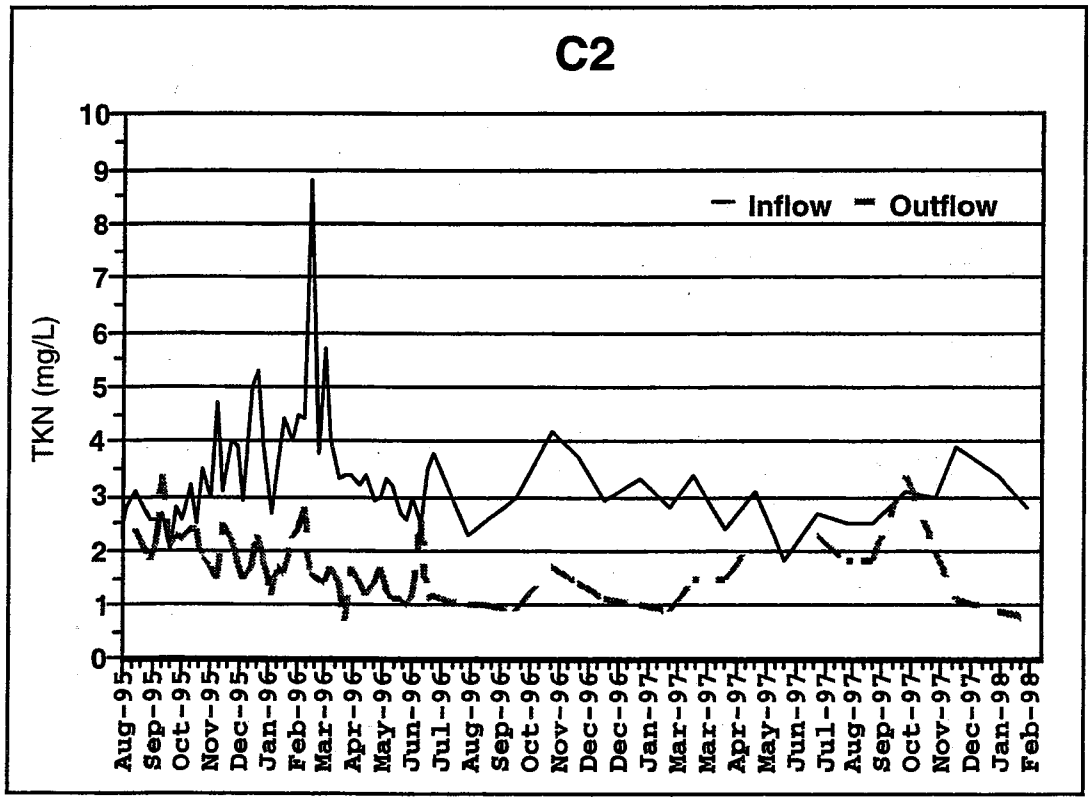
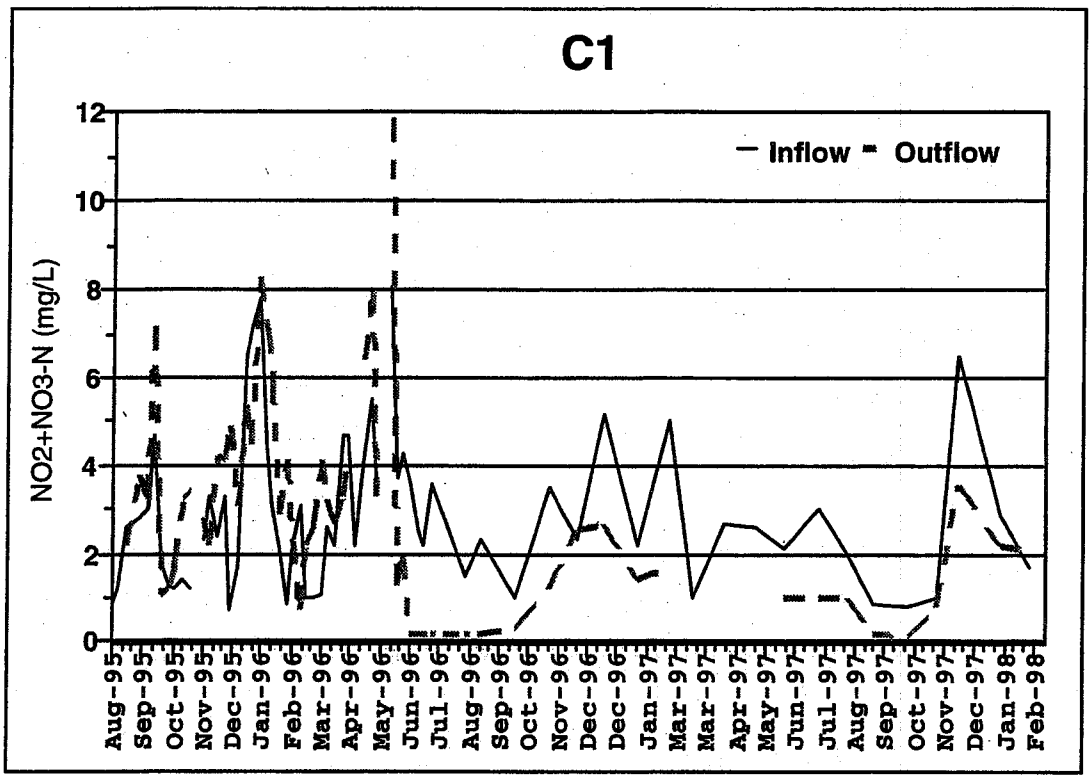


Figure C–23: Total Kjeldahl nitrogen (TKN) data for the Cobble site



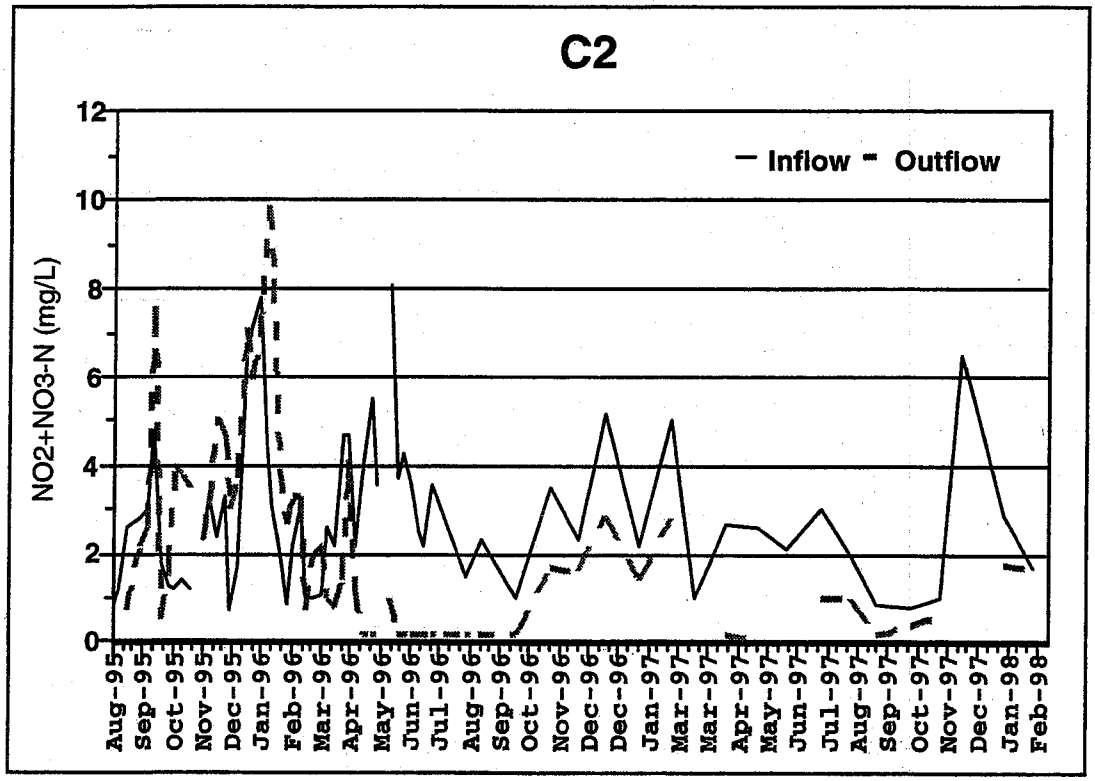
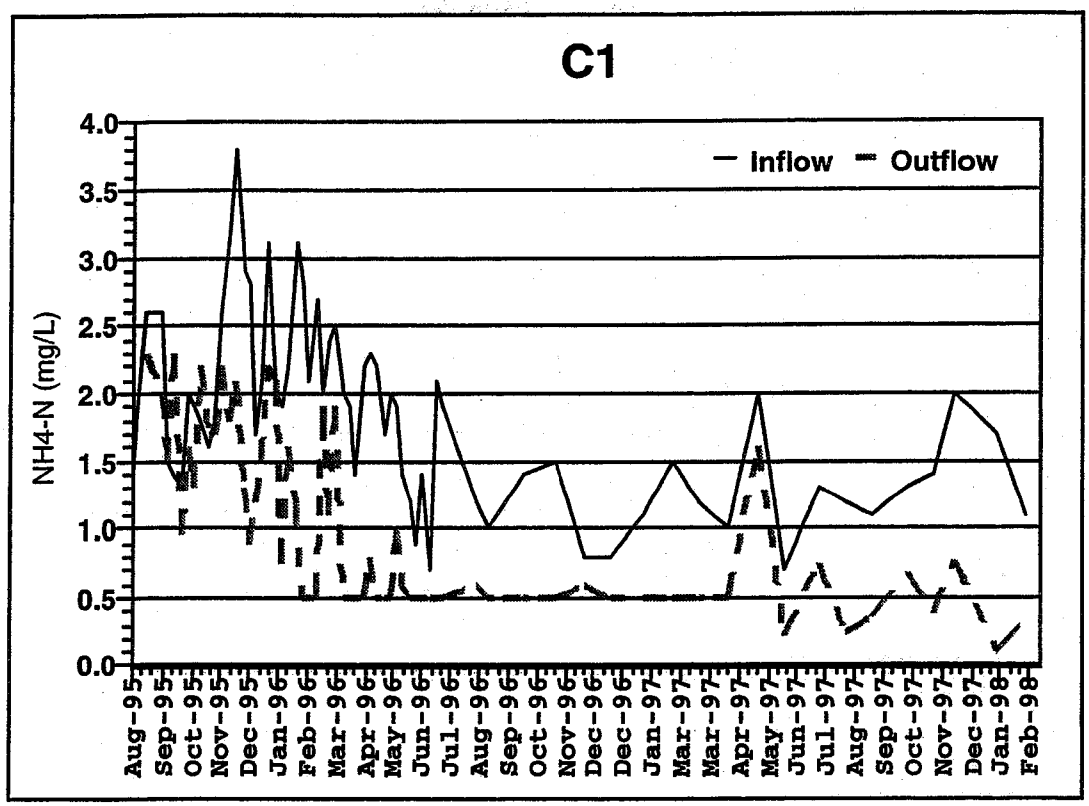


Figure C–24: Nitrite plus nitrate-nitrogen (NO_2 + NO_3) data for the Cobble site



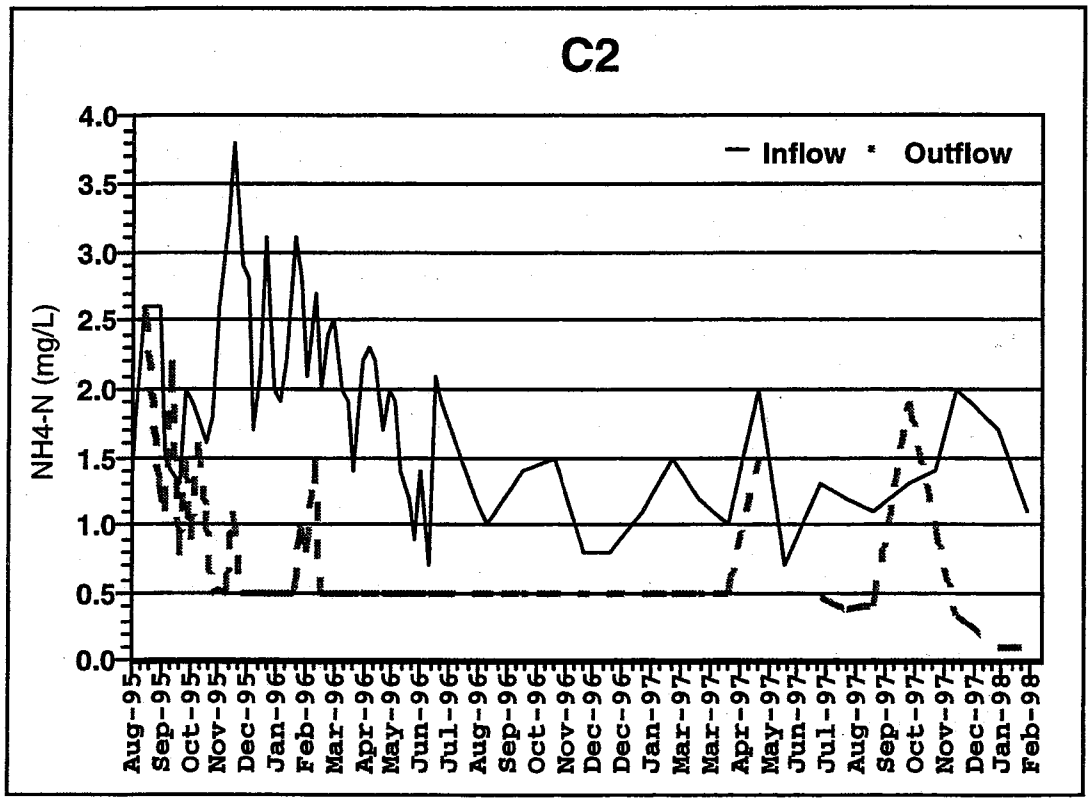
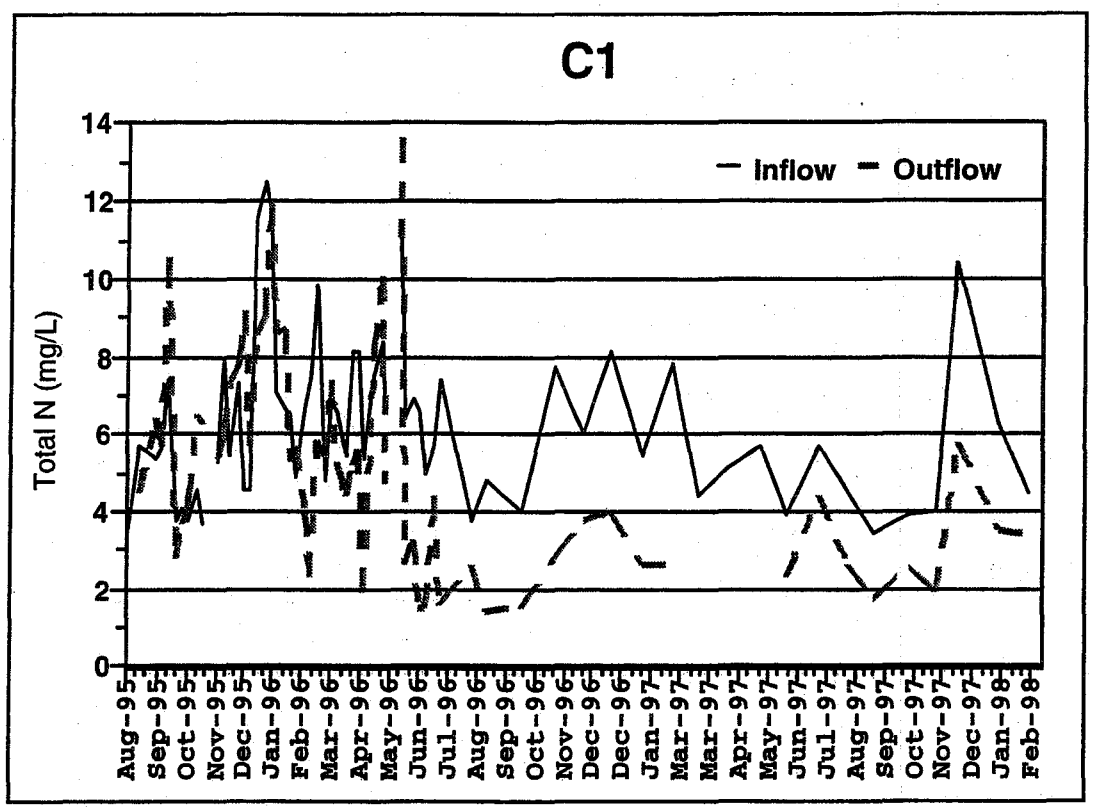


Figure C–25: Ammonia-nitrogen (NH_4-N) data for the Cobble site



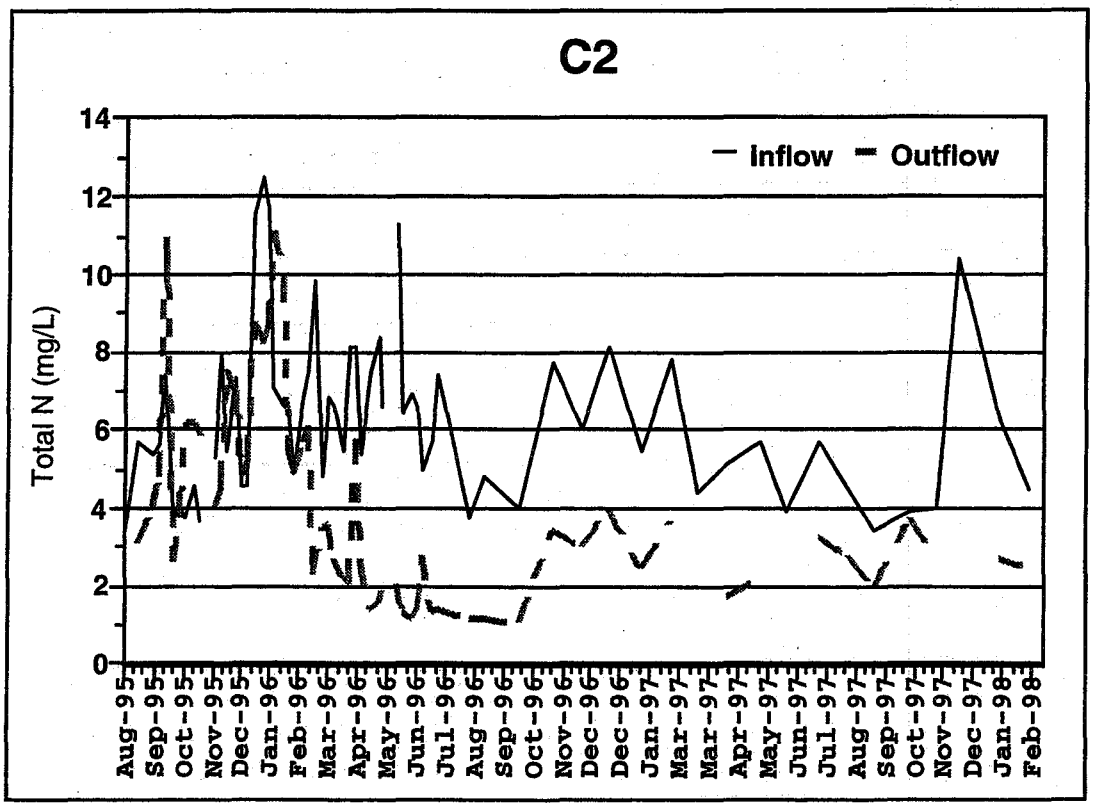
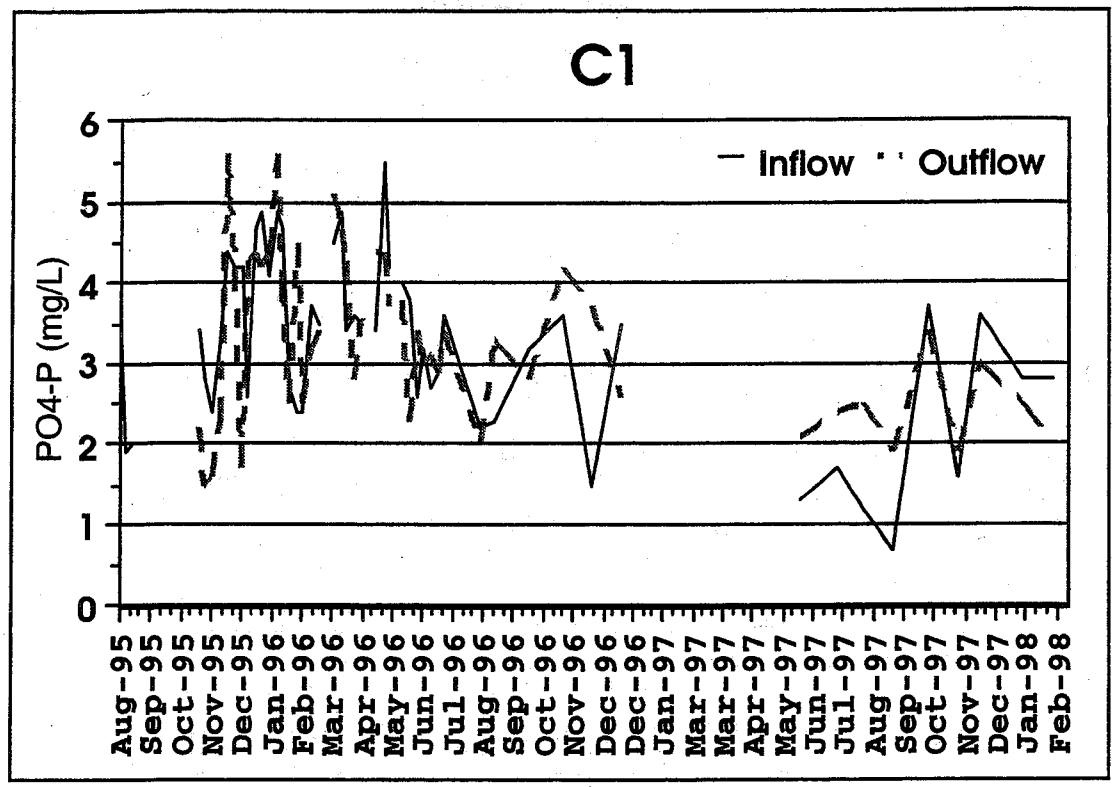


Figure C–26: Total nitrogen data for the Cobble site



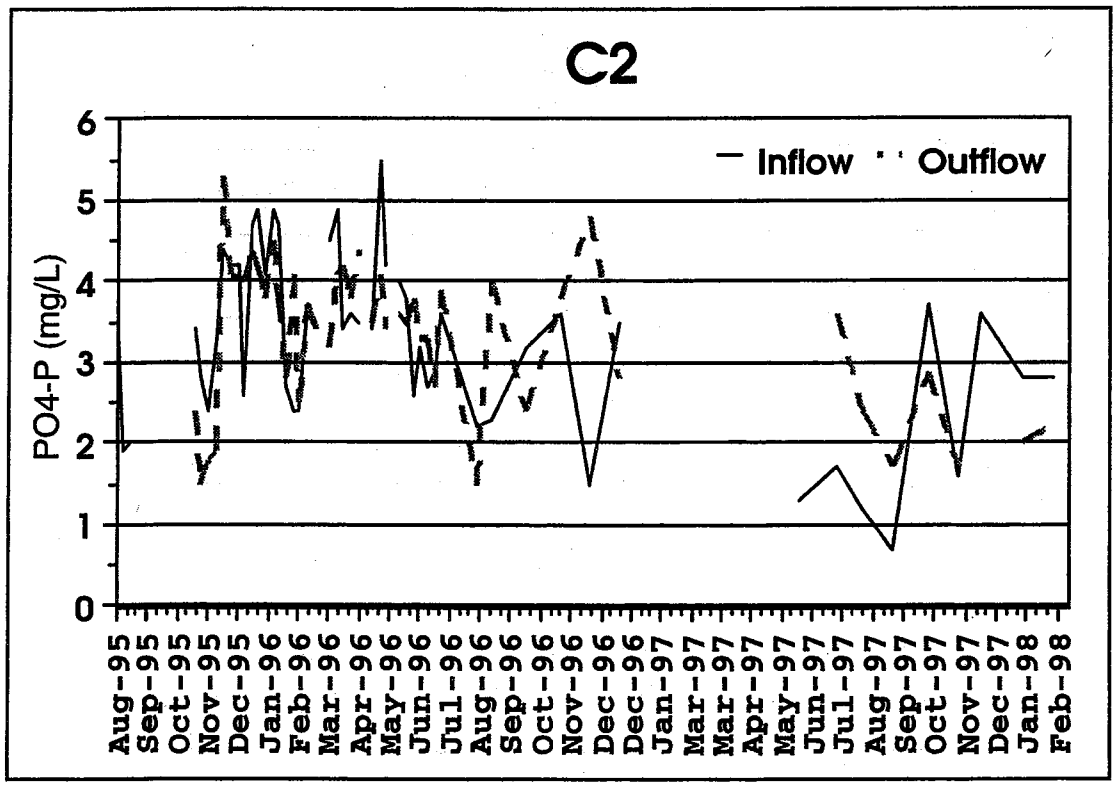
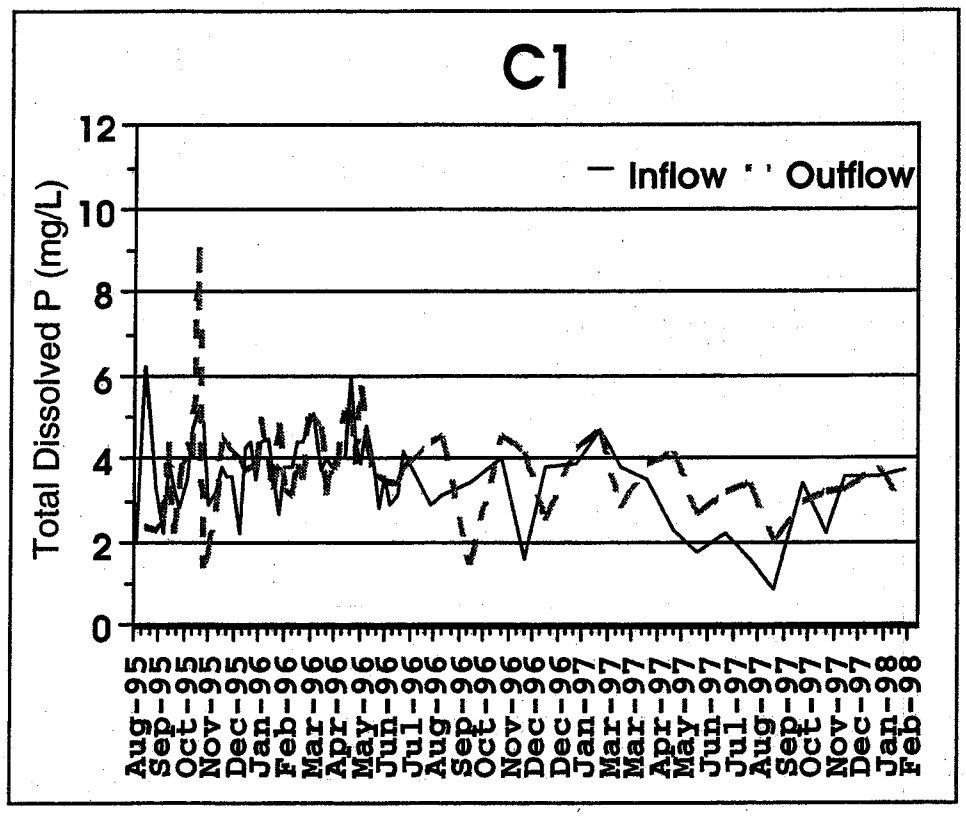


Figure C–27: Orthophosphate-phosphorus (PO_4-P) data for the Cobble site



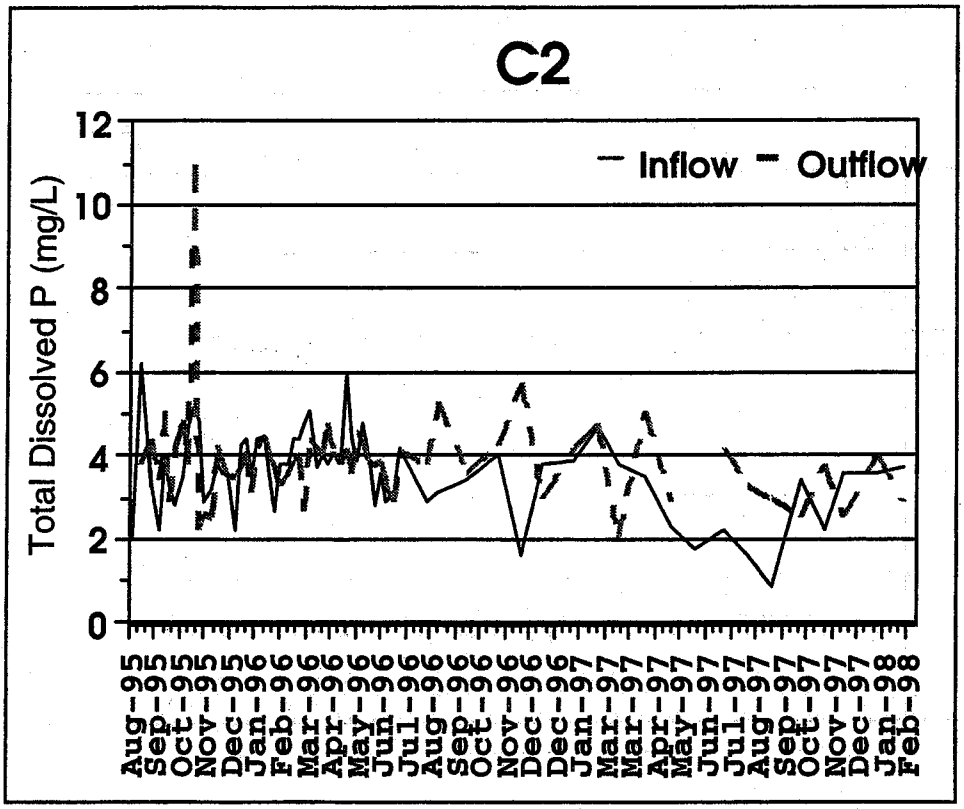
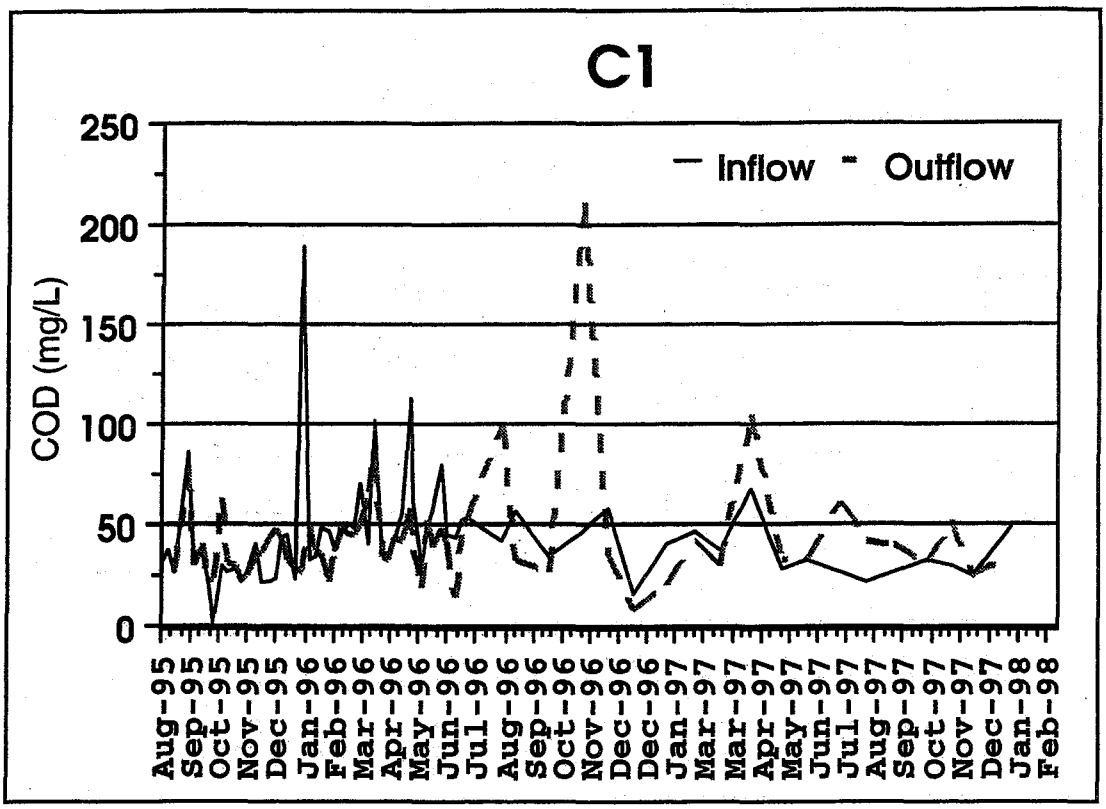


Figure C–28: Total dissolved phosphorus data for the Cobble site



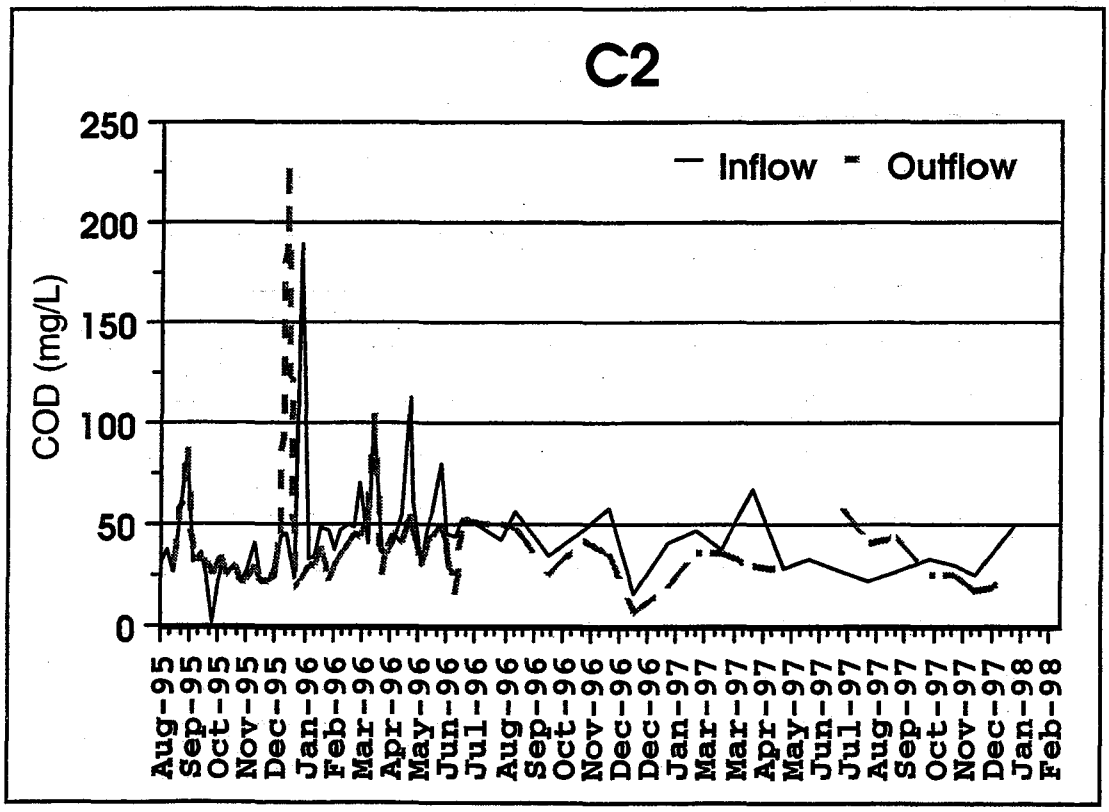
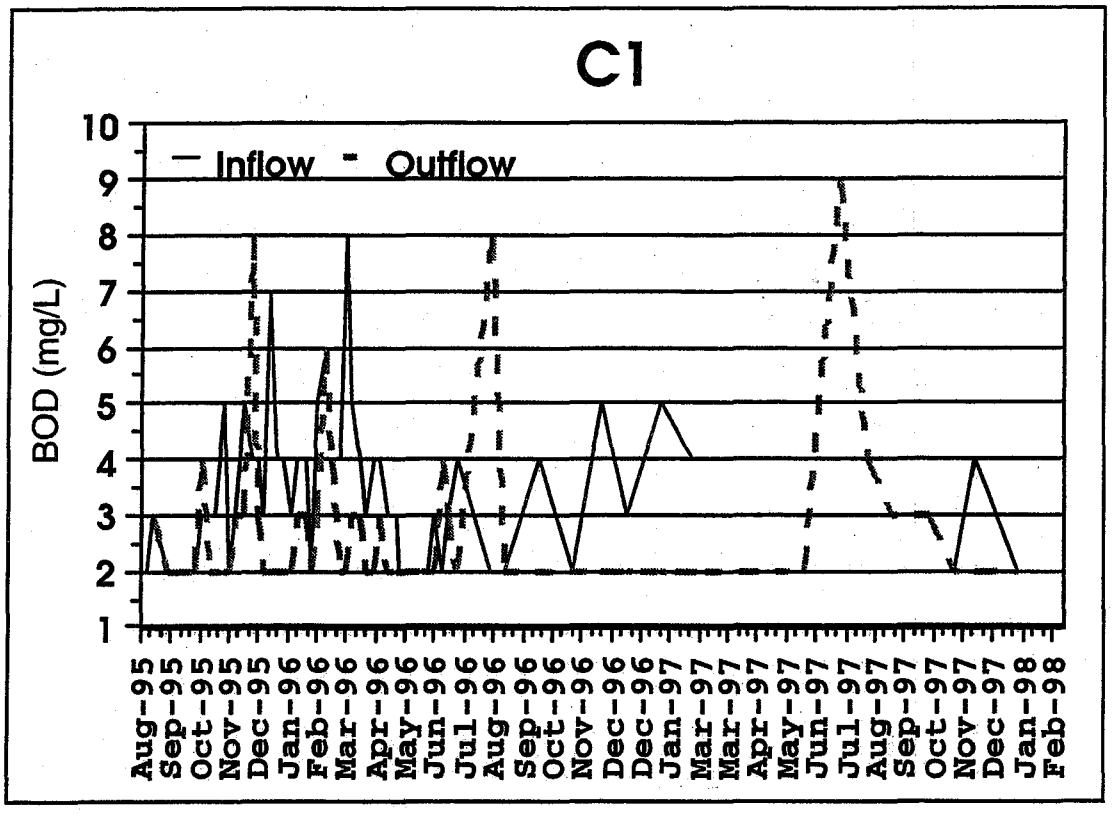


Figure C–29: Chemical oxygen demand (COD) data for the Cobble site



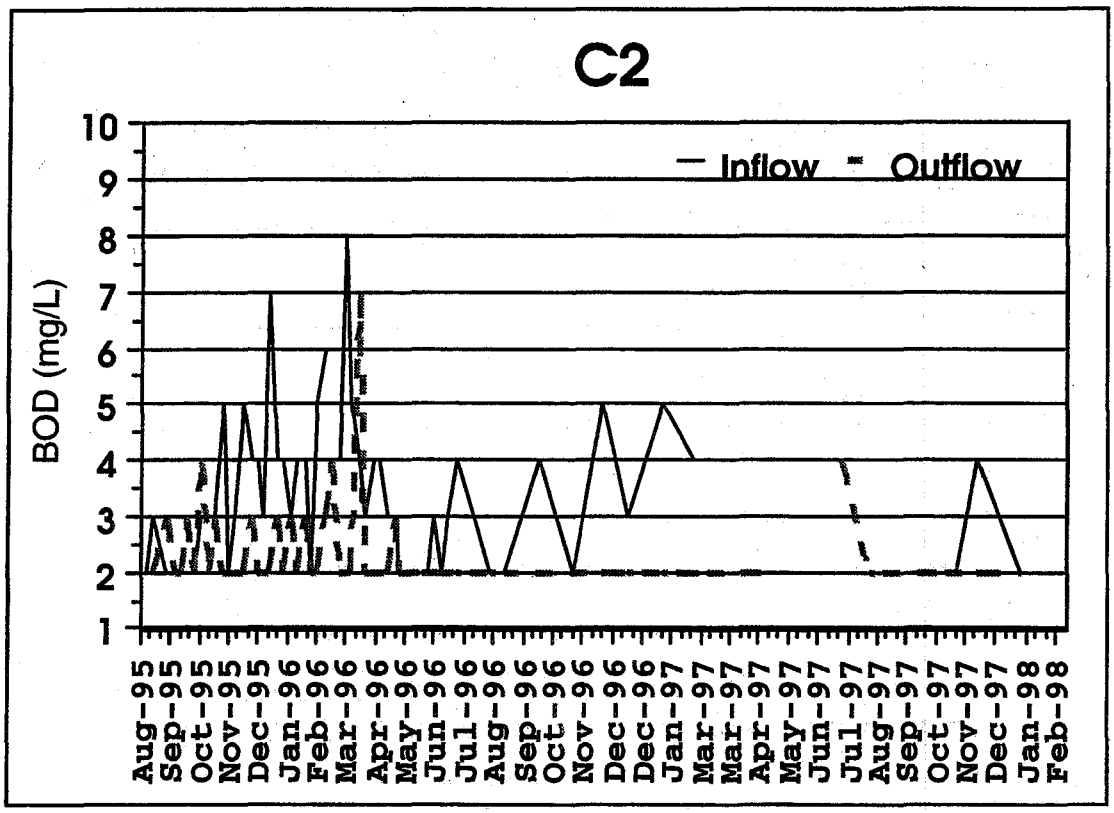
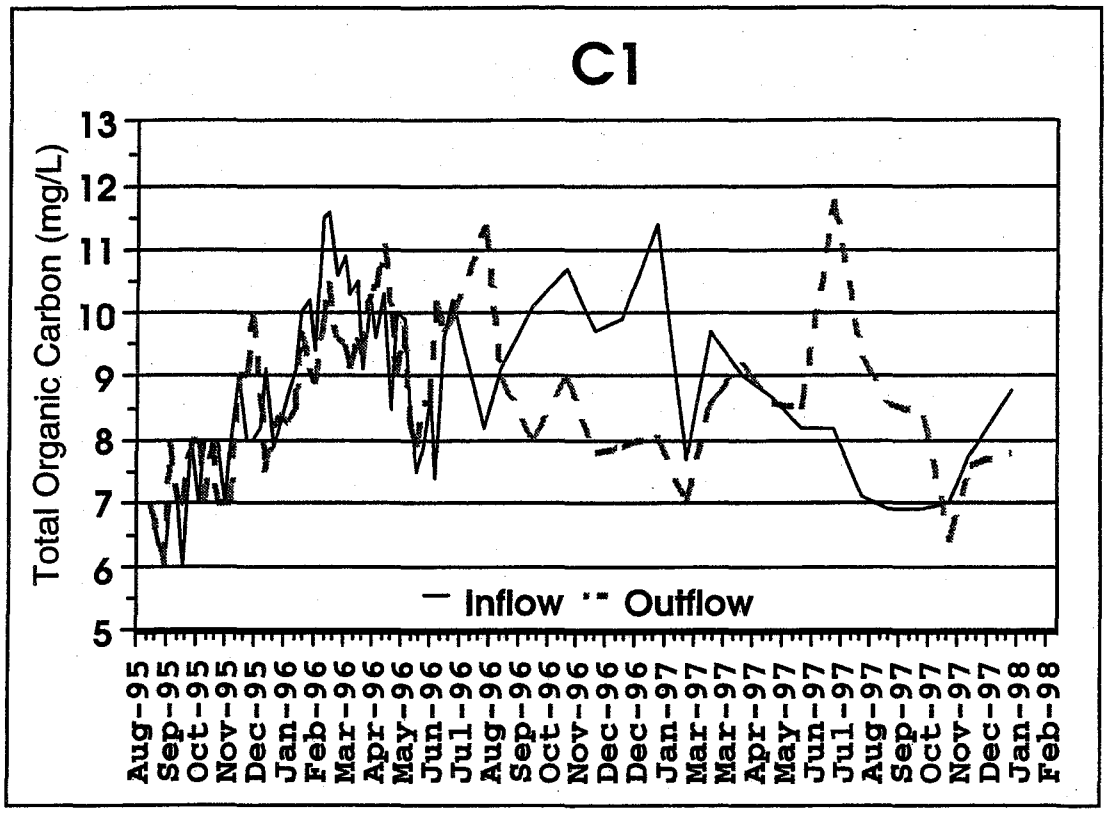


Figure C–30: Biochemical oxygen demand (BOD) data for the Cobble site



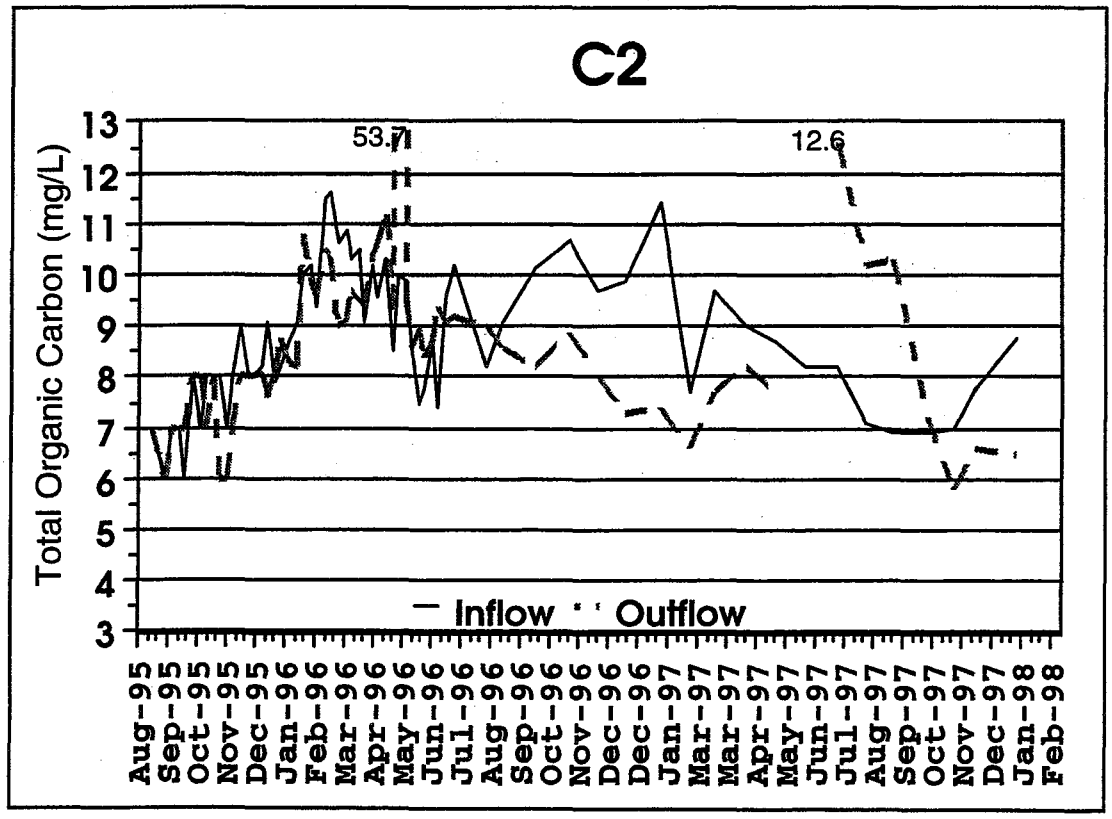


Figure C–31: Total organic carbon data for the Cobble site

Appendix E

The following pages include a summary of descriptive statistics by hydraulic load rate (HLR) and depth, and a series of regression model plots for water quality data collected at the Tres Rios Demonstration Constructed Wetlands Hayfield site.

Data are included for the first three years operational monitoring from August 1995 through December 1998.

CONTENTS:

DESCRIPTIVE STATISTICS BY HYDRAULIC OPERATIONS
- Hayfield site H1 wetland cell
- Hayfield site H2 wetland cell

HAYFIELD SITE REGRESSION PLOTS
- Dissolved Oxygen (DO)
- Electrical Conductivity (EC)
- Total Alkalinity (Alk)
- Total Suspended Solids (TSS)
- Total Dissolved Solids (TDS)
- Total Kjeldahl Nitrogen (TKN)
- Nitrate Nitrogen (NO_3–N)
- Nitrite Nitrogen (NO_2–N)
- Ammonia Nitrogen (NH_4–N)
- Total Nitrogen (Total N)
- Ortho-Phosphate (PO_4-P)
- Chemical Oxygen Demand (COD)
- Biochemical Oxygen Demand (BOD)
- Total Organic Carbon (TOC)

Table E1. Descriptive statistics by HLR and depth for the Hayfield site H1 cell.

	TP	HLR	Depth	HRT_I	# cases	Min	Max	Median	Mean
% change Alkalinity	D	0.50	0.75	1.5	23	-8.92	1.06	-2.32	-3.39
	B	0.50	1.00	2.0	34	-17.87	13.33	-3.16	-3.18
	C	0.50	1.50	3.0	18	-20.78	-7.22	-13.08	-13.41
	A	0.25	1.00	4.0	32	-31.29	13.71	-5.51	-7.07
% reduction TSS	D	0.50	0.75	1.5	23	-266.67	66.67	0.00	-43.28
	B	0.50	1.00	2.0	34	33.33	66.67	55.10	53.11
	C	0.50	1.50	3.0	18	-500.00	66.67	28.61	-46.08
	A	0.25	1.00	4.0	33	-250.00	86.36	15.00	-6.66
% change TDS	D	0.50	0.75	1.5	23	-4.87	3.20	-0.84	-1.01
	B	0.50	1.00	2.0	34	-9.86	6.48	-1.83	-1.25
	C	0.50	1.50	3.0	18	-8.60	-3.54	-6.42	-6.36
	A	0.25	1.00	4.0	33	-13.72	11.49	-4.24	-4.30
% change Cl	D	0.50	0.75	1.5	34	-7.11	8.24	-3.13	-2.46
	B	0.50	1.00	2.0	34	-38.89	6.91	-5.07	-7.89
	C	0.50	1.50	3.0	18	-6.78	-1.58	-4.02	-4.10
	A	0.25	1.00	4.0	30	-29.47	13.62	-7.25	-7.53
% reduction TKN	D	0.50	0.75	1.5	34	16.22	77.14	64.89	58.62
	B	0.50	1.00	2.0	34	22.58	73.68	67.18	66.01
	C	0.50	1.50	3.0	18	11.76	59.69	36.09	35.77
	A	0.25	1.00	4.0	33	24.00	72.34	54.00	52.49
% reduction NO_3-N	D	0.50	0.75	1.5	34	-10.00	96.15	67.50	62.05
	B	0.50	1.00	2.0	34	-533.33	94.12	28.10	2.23
	C	0.50	1.50	3.0	18	72.89	96.55	88.23	87.45
	A	0.25	1.00	4.0	30	-97.56	97.50	81.65	50.23
% reduction NH_4-N	D	0.50	0.75	1.5	34	-7.53	94.44	81.46	66.99
	B	0.50	1.00	2.0	34	44.44	75.00	65.15	63.14
	C	0.50	1.50	3.0	18	12.00	78.00	44.10	41.41
	A	0.25	1.00	4.0	33	37.50	85.29	76.19	72.11
% reduction Total N	D	0.50	0.75	1.5	34	46.15	76.96	58.80	58.94
	B	0.50	1.00	2.0	34	-68.42	71.64	44.26	41.81
	C	0.50	1.50	3.0	18	37.50	75.81	63.88	61.08
	A	0.25	1.00	4.0	32	-37.14	80.00	60.80	52.80
% reduction PO_4-P	D	0.50	0.75	1.5	33	-342.86	36.76	3.80	-42.34
	B	0.50	1.00	2.0	33	-142.86	37.50	7.32	-4.78
	C	0.50	1.50	3.0	18	-75.20	21.88	3.33	-7.32
	A	0.25	1.00	4.0	30	-77.78	98.09	0.00	-2.62
% reduction COD	D	0.50	0.75	1.5	23	-21.21	40.00	15.36	17.22
	B	0.50	1.00	2.0	34	-62.08	95.96	39.46	30.81
	C	0.50	1.50	3.0	18	-242.11	17.50	1.46	-42.60
	A	0.25	1.00	4.0	33	-193.62	45.45	-15.56	-29.01
% reduction BOD	D	0.50	0.75	1.5	23	0.00	50.00	0.00	17.60
	B	0.50	1.00	2.0	31	0.00	66.67	40.17	36.82
	C	0.50	1.50	3.0	18	0.00	0.00	0.00	0.00
	A	0.25	1.00	4.0	33	-66.67	75.00	33.33	23.61
% reduction TOC	D	0.50	0.75	1.5	34	3.53	33.70	15.15	16.82
	B	0.50	1.00	2.0	34	0.00	39.32	29.19	24.48
	C	0.50	1.50	3.0	18	-3.75	6.53	-0.31	-0.02
	A	0.25	1.00	4.0	33	-46.48	33.03	0.00	-0.83

Table E2. Descriptive statistics by HLR and depth for the Hayfield site H2 cell.

	TP	HLR	Depth	HRT_f	# cases	Min	Max	Median	Mean
% change Alkalinity	D	0.50	0.75	1.5	24	-6.94	4.62	-2.63	-1.63
	B	0.50	1.00	2.0	25	-17.31	12.71	-2.34	-1.76
	C	0.50	1.50	3.0	19	-19.48	-1.11	-8.93	-10.02
	A	0.25	1.00	4.0	40	-69.72	14.72	-7.11	-6.80
% reduction TSS	D	0.50	0.75	1.5	24	-1000.00	66.67	36.90	-76.13
	B	0.50	1.00	2.0	25	9.68	75.00	61.11	59.07
	C	0.50	1.50	3.0	19	0.00	66.67	33.33	26.48
	A	0.25	1.00	4.0	40	-250.00	90.91	35.96	13.73
% change TDS	D	0.50	0.75	1.5	24	-5.13	1.03	-1.22	-1.30
	B	0.50	1.00	2.0	25	-5.45	4.97	-1.32	-1.08
	C	0.50	1.50	3.0	19	-8.60	2.10	-5.13	-4.54
	A	0.25	1.00	4.0	40	-12.19	5.40	-3.53	-3.76
% change Cl	D	0.50	0.75	1.5	34	-3.70	7.69	-1.88	-1.44
	B	0.50	1.00	2.0	26	-33.33	70.32	-2.39	-1.20
	C	0.50	1.50	3.0	18	-3.00	78.35	-0.14	8.93
	A	0.25	1.00	4.0	37	-28.99	6.47	-7.59	-6.86
% reduction TKN	D	0.50	0.75	1.5	34	47.37	83.33	73.02	69.57
	B	0.50	1.00	2.0	26	45.16	67.65	64.03	62.15
	C	0.50	1.50	3.0	19	29.41	65.79	46.89	47.83
	A	0.25	1.00	4.0	40	13.04	70.18	56.07	53.44
% reduction NO_3-N	D	0.50	0.75	1.5	34	-10.00	92.31	57.41	53.77
	B	0.50	1.00	2.0	26	-633.33	84.14	29.45	-4.54
	C	0.50	1.50	3.0	19	48.27	82.76	71.70	70.31
	A	0.25	1.00	4.0	40	-106.67	97.67	92.03	59.02
% reduction NH_4-N	D	0.50	0.75	1.5	34	65.00	95.24	87.69	85.44
	B	0.50	1.00	2.0	26	44.44	80.77	66.67	64.66
	C	0.50	1.50	3.0	19	16.00	79.33	55.07	51.18
	A	0.25	1.00	4.0	40	12.50	84.85	74.34	69.49
% reduction Total N	D	0.50	0.75	1.5	34	48.04	80.35	57.64	60.35
	B	0.50	1.00	2.0	26	-60.53	64.20	42.91	38.30
	C	0.50	1.50	3.0	19	45.00	69.26	64.41	61.47
	A	0.25	1.00	4.0	40	-41.43	82.35	64.14	55.89
% reduction PO_4-P	D	0.50	0.75	1.5	33	-335.29	27.90	-5.33	-48.14
	B	0.50	1.00	2.0	25	-304.88	35.00	-12.79	-47.06
	C	0.50	1.50	3.0	19	-14.29	18.75	8.51	3.39
	A	0.25	1.00	4.0	40	-90.91	98.09	-3.30	-6.91
% reduction COD	D	0.50	0.75	1.5	24	-15.00	54.55	29.35	25.43
	B	0.50	1.00	2.0	25	-95.45	60.81	47.84	36.10
	C	0.50	1.50	3.0	19	-110.53	40.00	-10.89	-20.15
	A	0.25	1.00	4.0	40	-275.00	39.19	-3.83	-13.46
% reduction BOD	D	0.50	0.75	1.5	25	-322.79	50.00	0.00	3.05
	B	0.50	1.00	2.0	25	0.00	66.67	46.56	40.75
	C	0.50	1.50	3.0	19	0.00	33.33	0.00	8.21
	A	0.25	1.00	4.0	40	-100.00	75.00	33.33	31.84
% reduction TOC	D	0.50	0.75	1.5	34	8.86	38.04	23.97	24.31
	B	0.50	1.00	2.0	26	0.00	35.90	26.81	24.59
	C	0.50	1.50	3.0	19	-5.00	6.98	1.10	1.02
	A	0.25	1.00	4.0	40	-28.17	30.28	2.10	2.76

Appendix D

The following pages include cumulative frequency of water quality data collected at the Tres Rios Demonstration Constructed Wetlands Hayfield site and Cobble site. Data are included for the first three years of operational monitoring from August 1995 through December 1998.

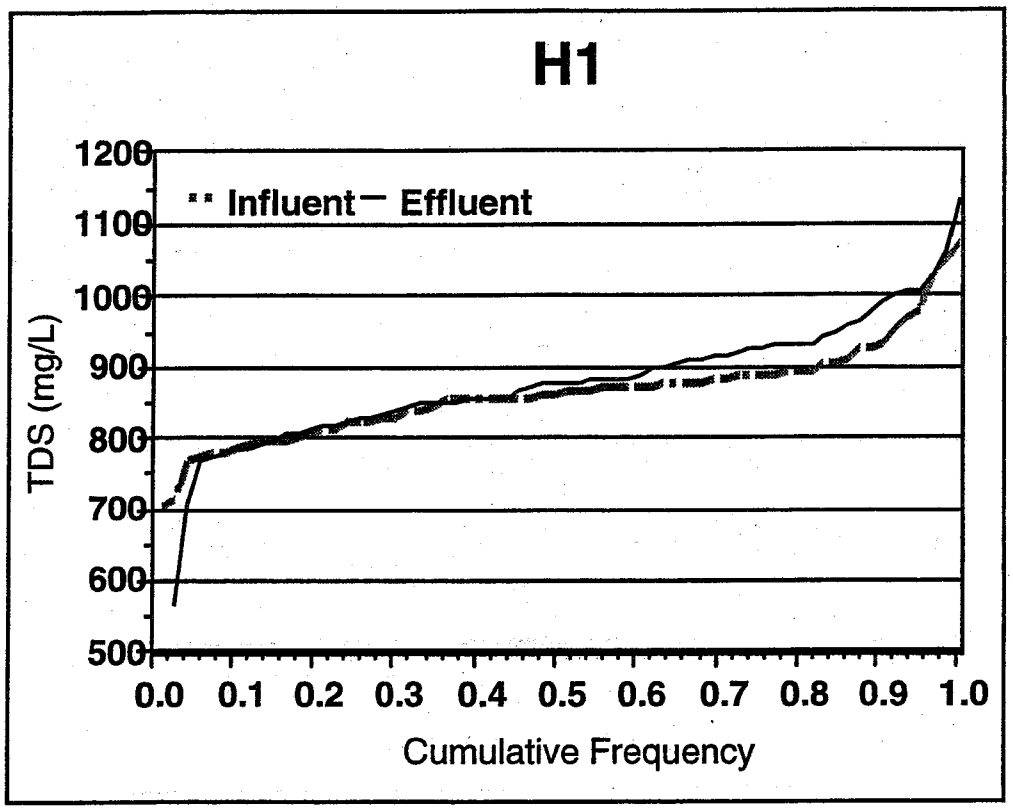
CONTENTS:

HAYFIELD SITE

- Total Dissolved Solids
- Total Suspended Solids
- Total Kjeldahl Nitrogen
- Nitrate Nitrogen
- Nitrate + Nitrite
- Ammonia Nitrogen
- Total Nitrogen
- Orthophosphate Phosphorus
- Total Dissolved Phosphorus
- Chemical Oxygen Demand
- Biochemical Oxygen Demand
- Total Organic Carbon

COBBLE SITE

- Total Dissolved Solids
- Total Suspended Solids
- Total Kjeldahl Nitrogen
- Nitrate Nitrogen
- Nitrate + Nitrite
- Ammonia Nitrogen
- Total Nitrogen
- Orthophosphate Phosphorus
- Total Dissolved Phosphorus
- Chemical Oxygen Demand
- Biochemical Oxygen Demand
- Total Organic Carbon



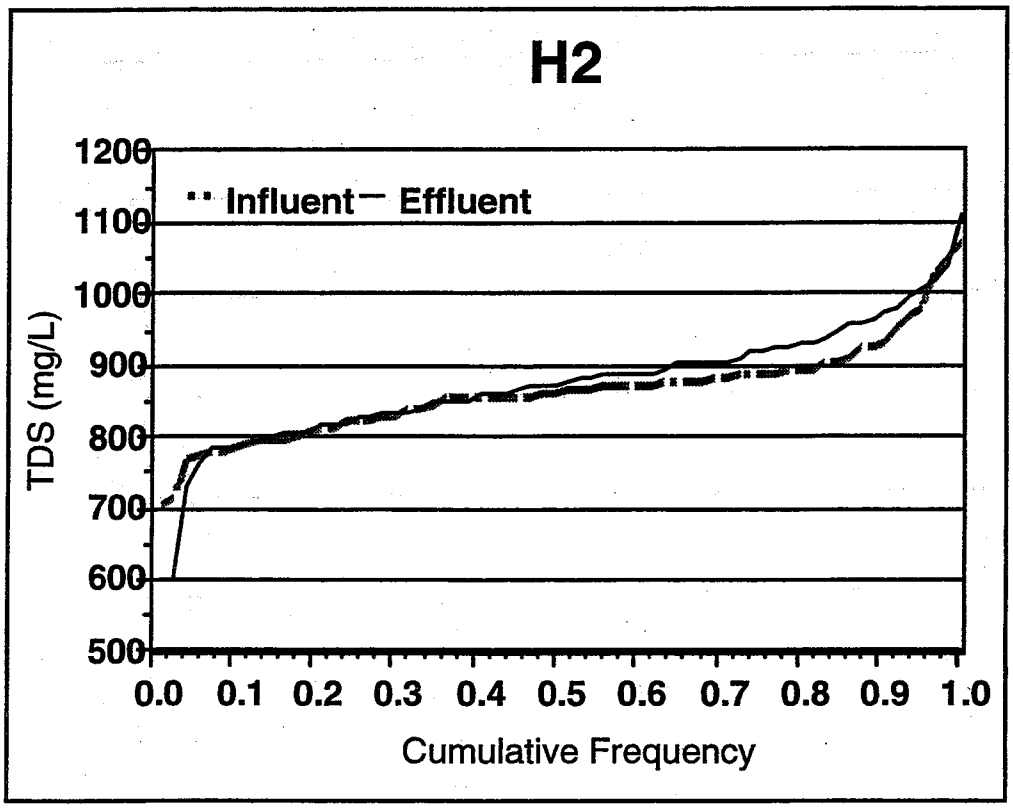
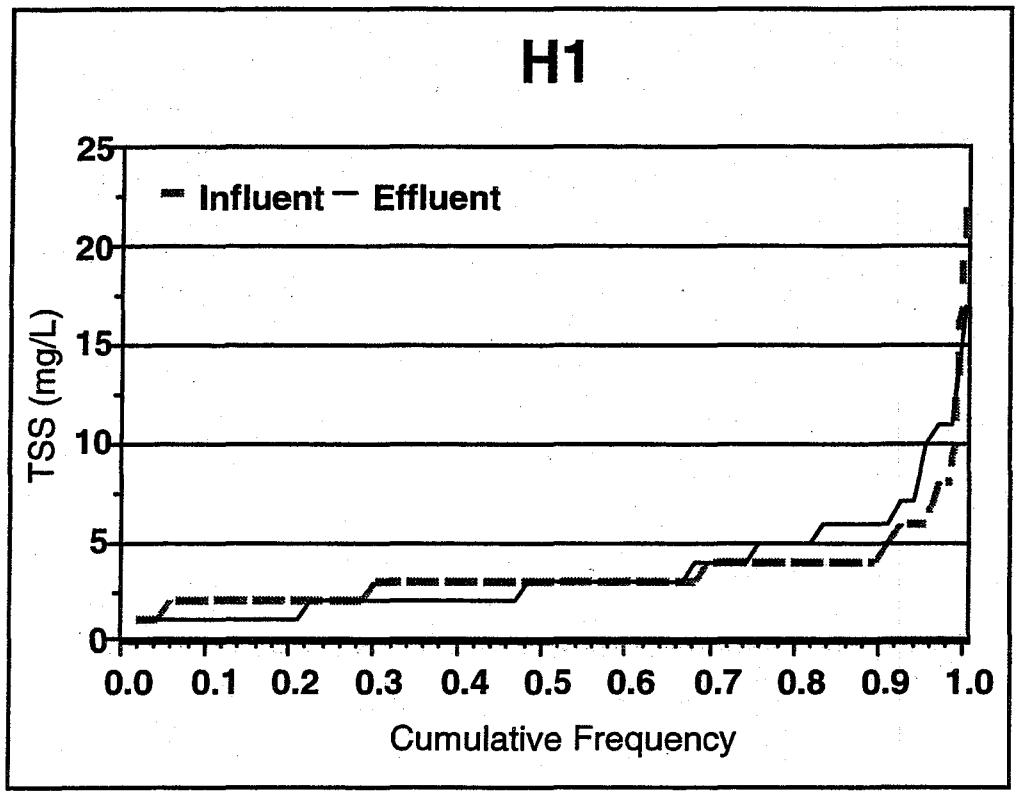


Figure D–1: Cumulative frequency distribution of TDS at the Hayfield site



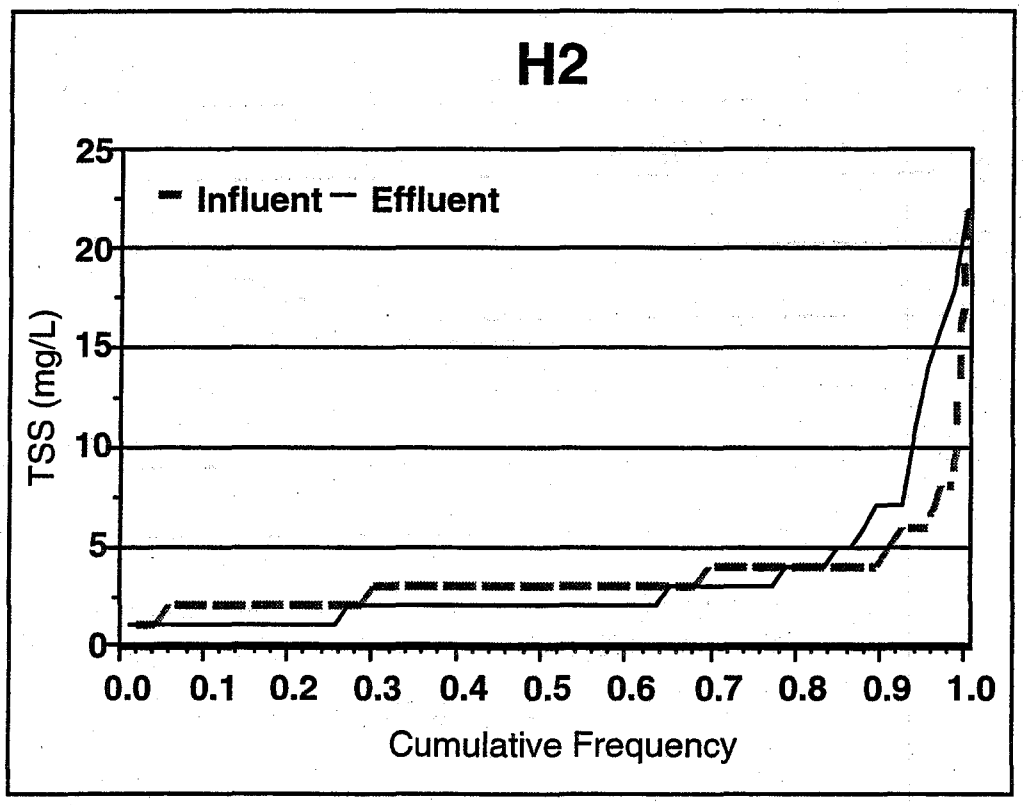
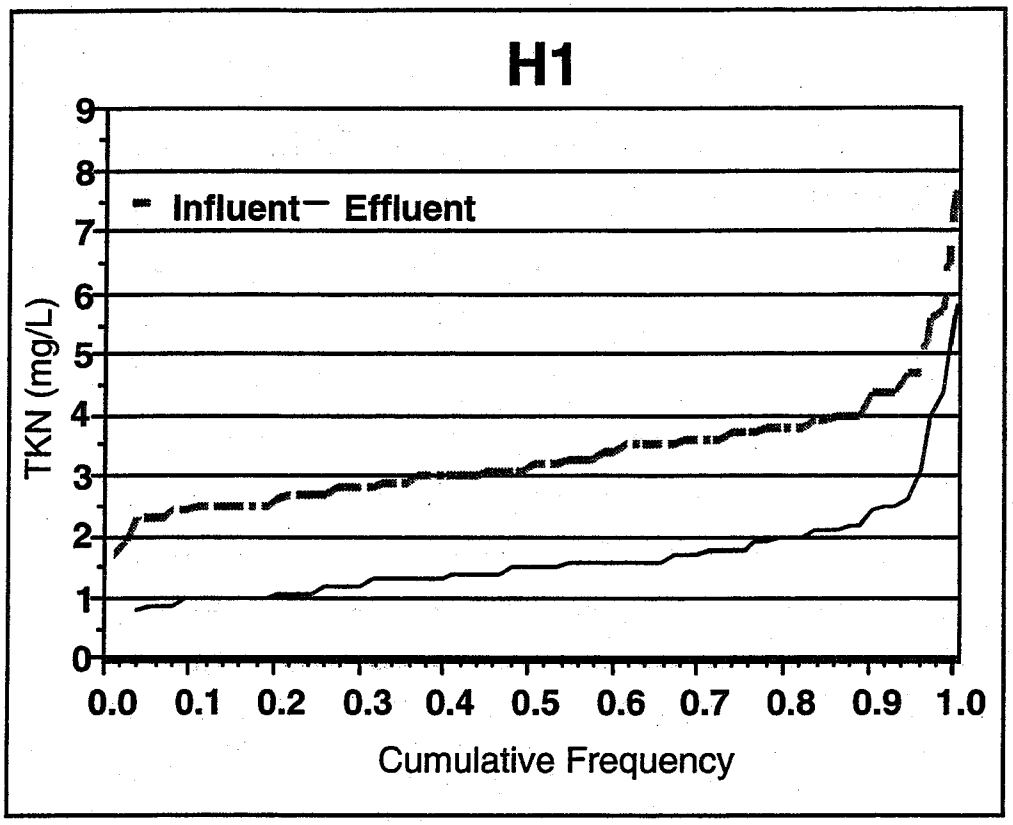


Figure D–2: Cumulative frequency distribution of TSS at the Hayfield site



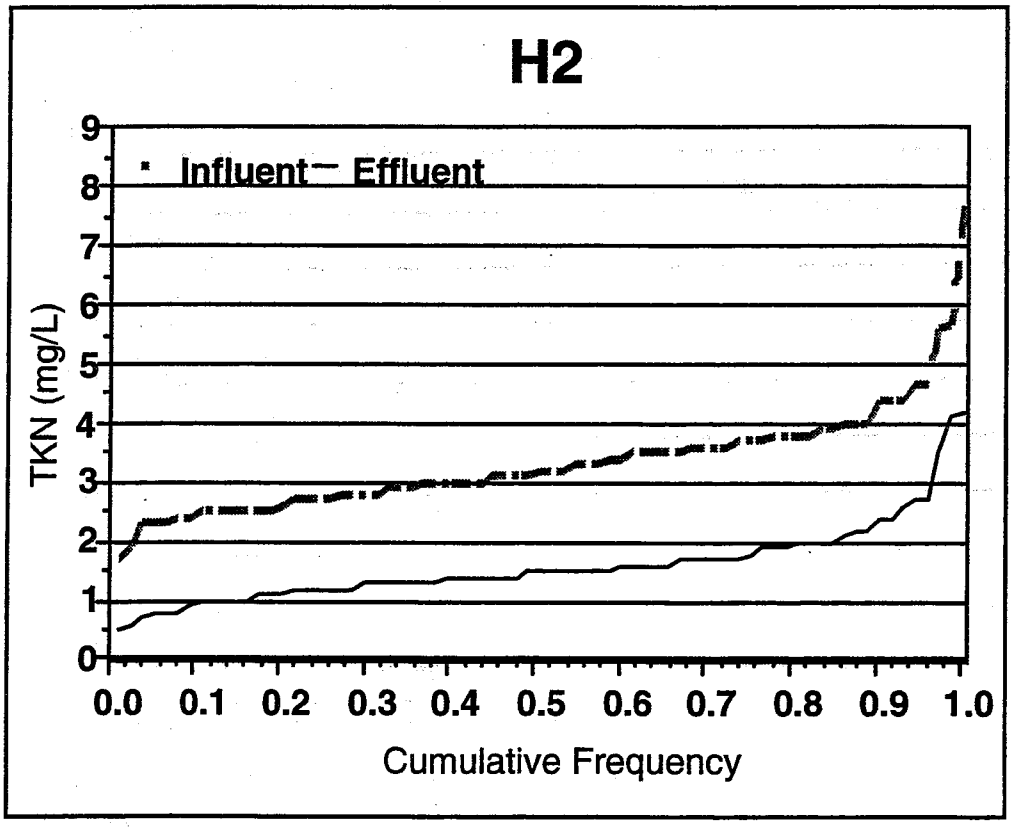


Figure D–3: Cumulative frequency distribution of TKN at the Hayfield site

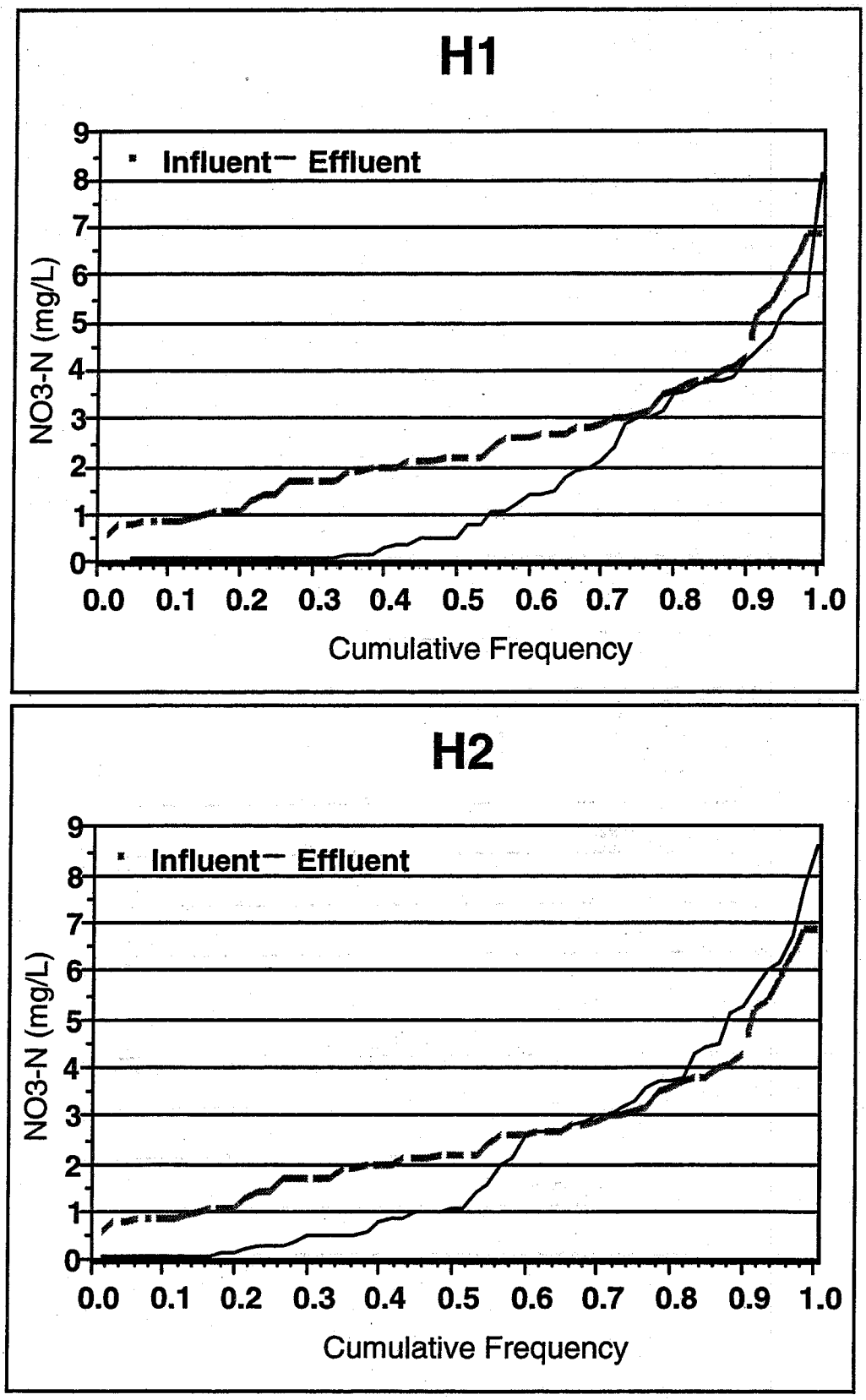
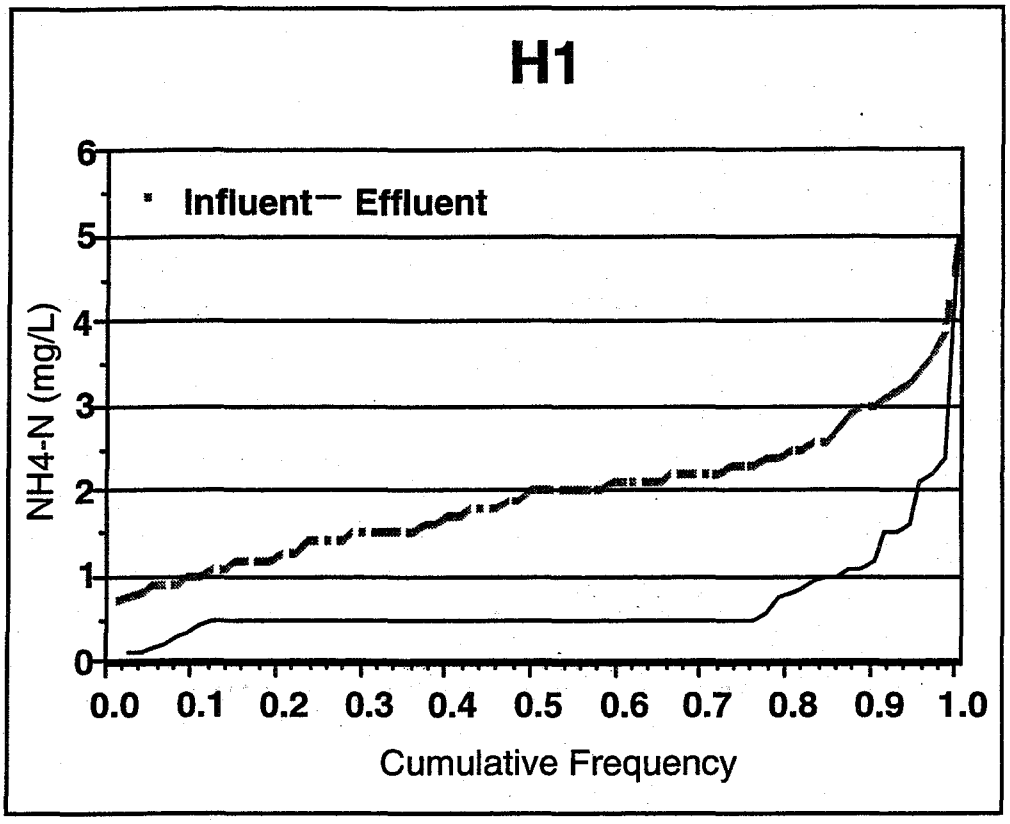


Figure D–4: Cumulative frequency distribution of nitrate-nitrogen at the Hayfield site



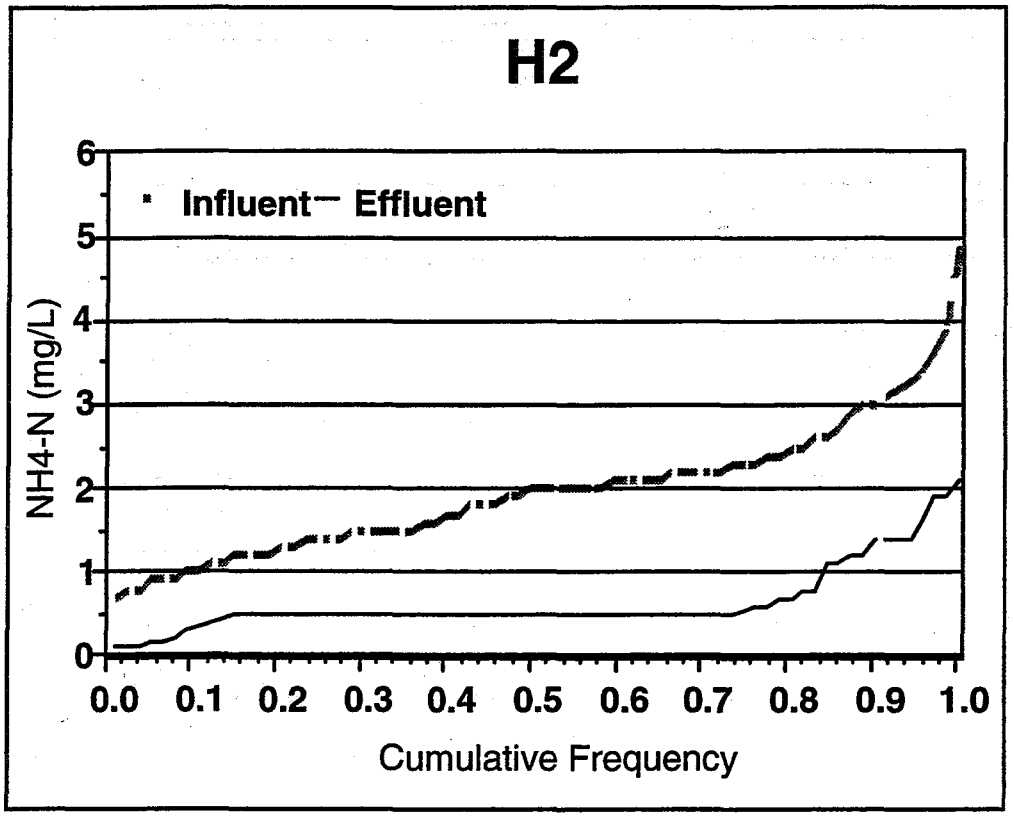


Figure D–5: Cumulative frequency distribution of ammonia-nitrogen at the Hayfield site

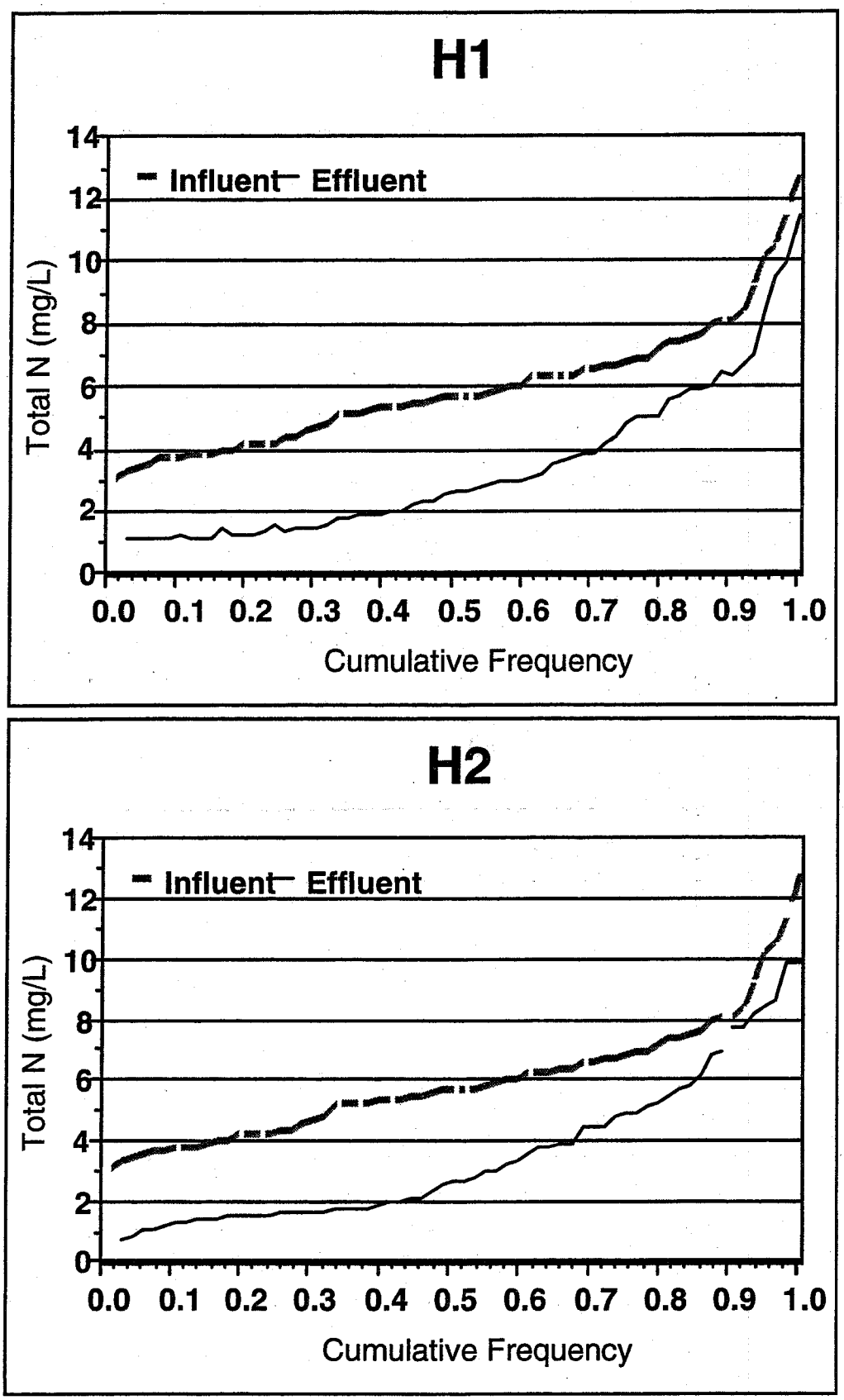
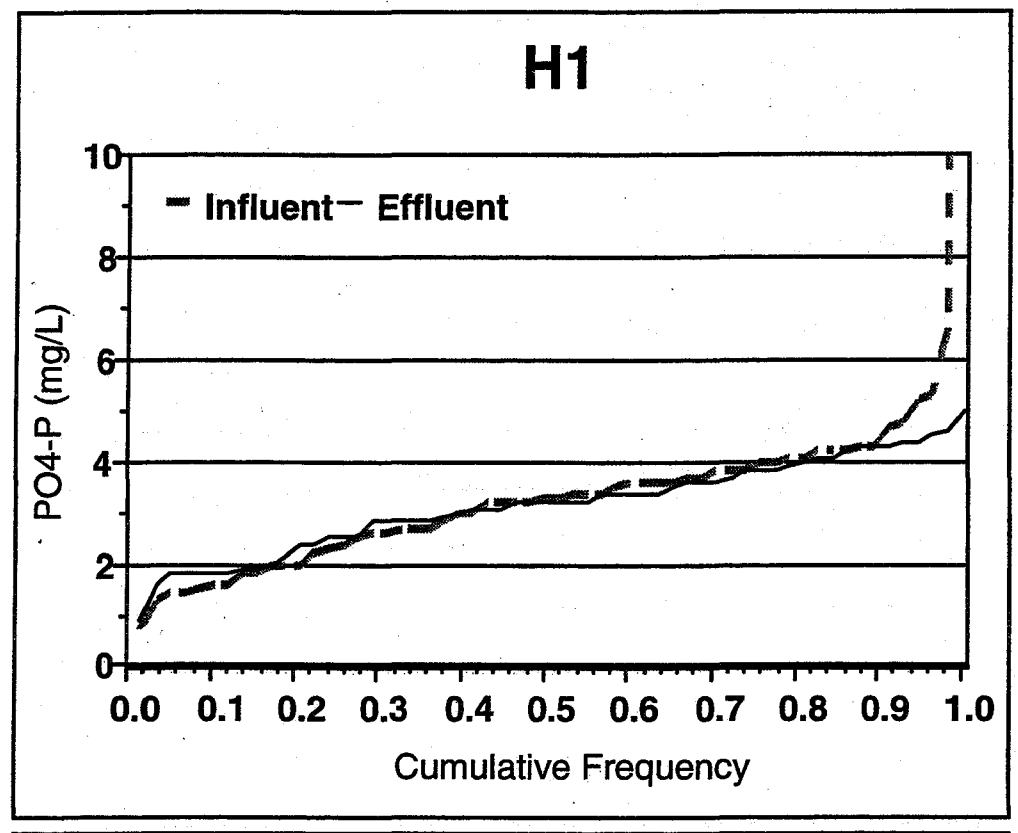


Figure D–6: Cumulative frequency distribution of total N at the Hayfield site



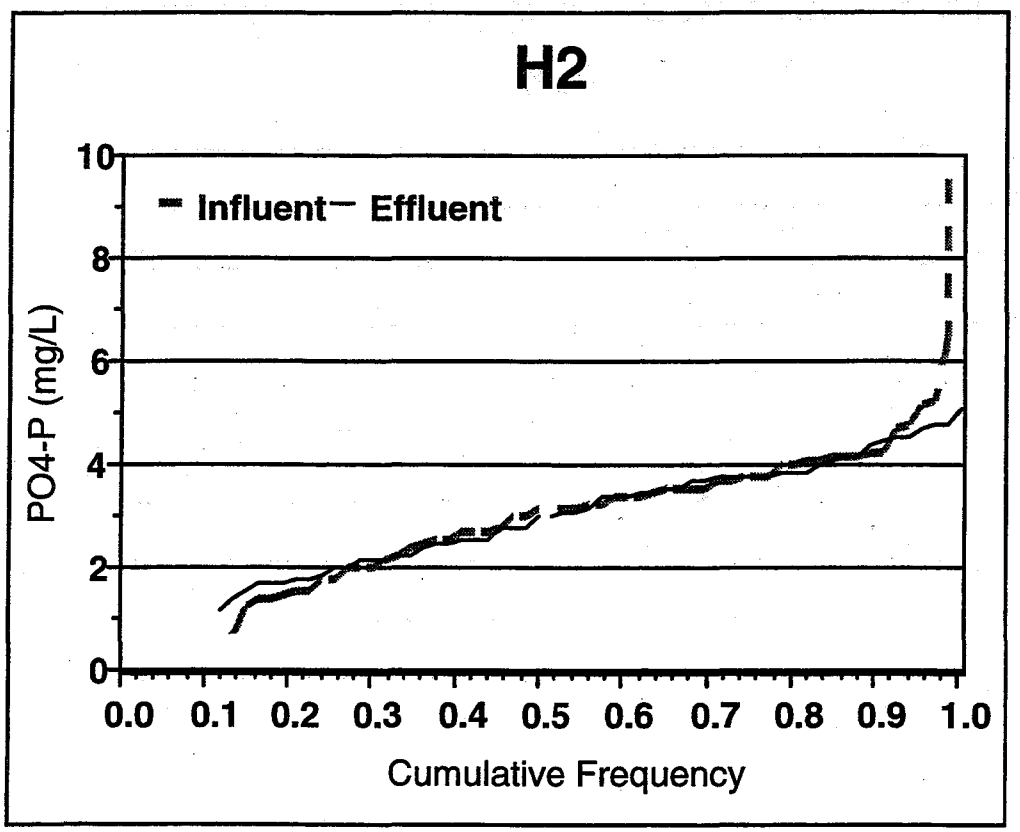


Figure D–7: Cumulative frequency distribution of orthophosphate-P at the Hayfield site

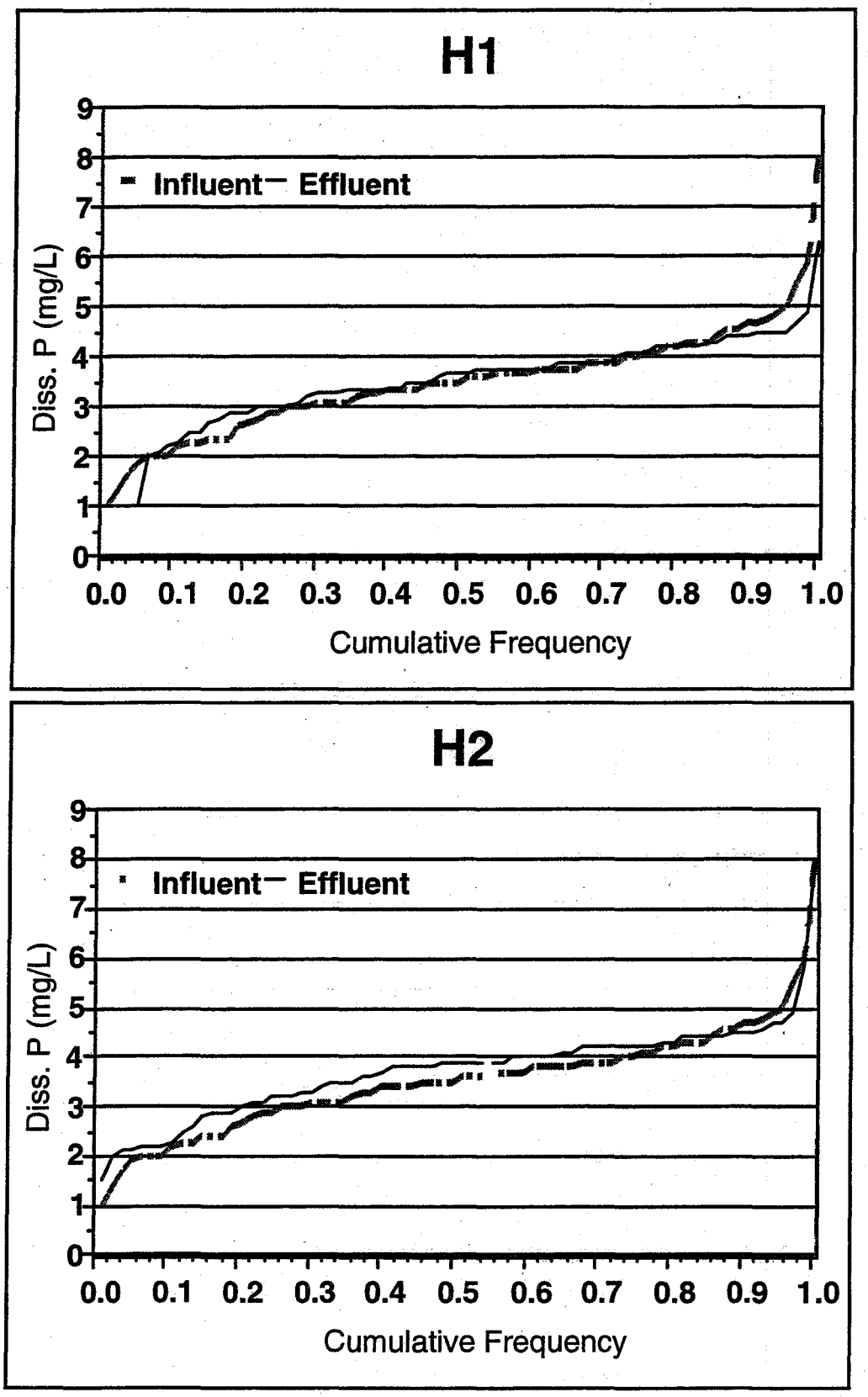
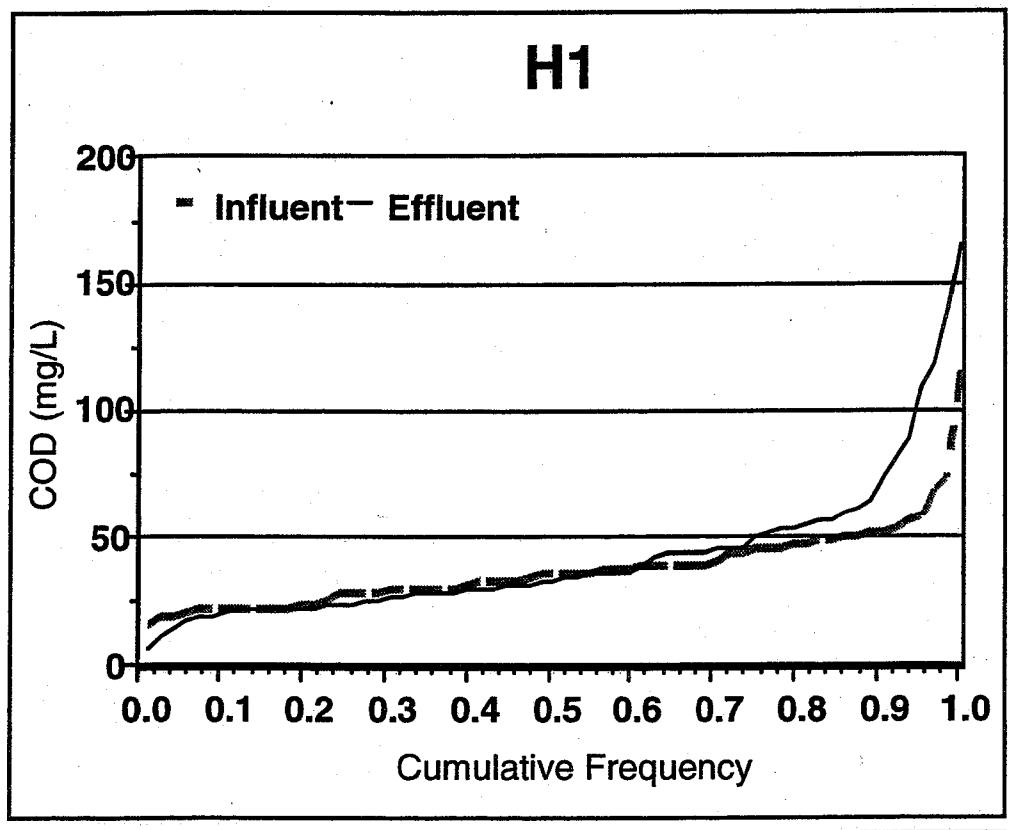


Figure D–8: Cumulative frequency distribution of total dissolved P at the Hayfield site



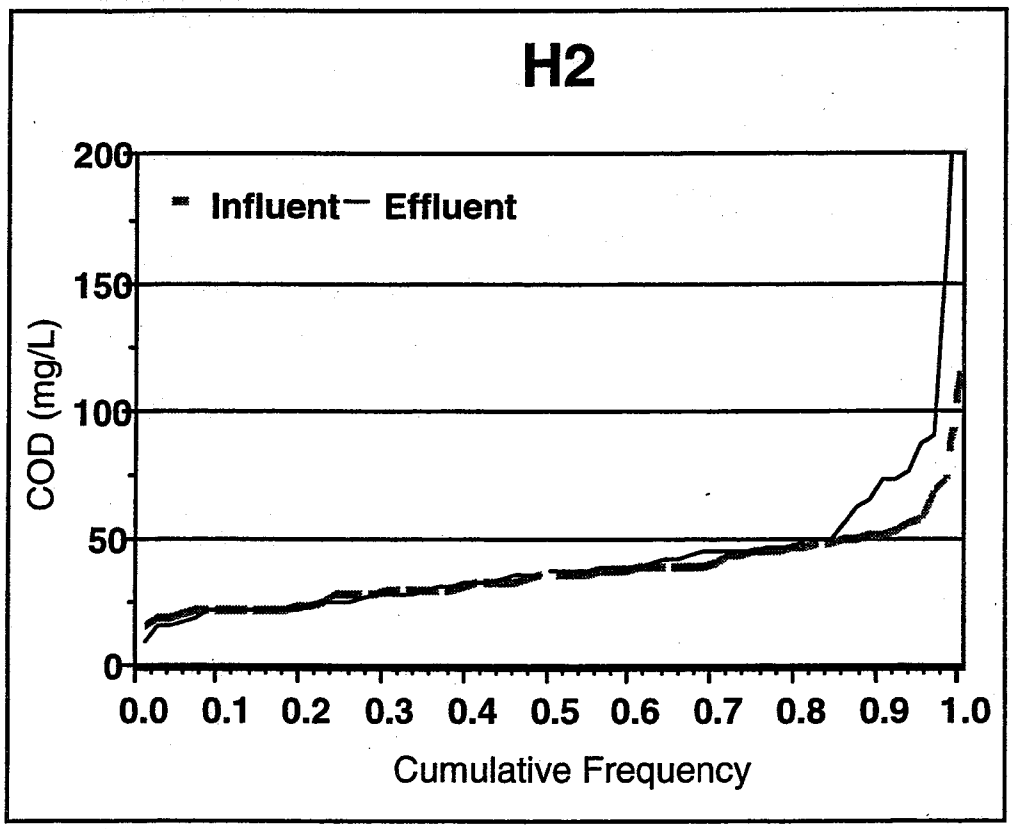


Figure D–9: Cumulative frequency distribution of chemical oxygen demand at the Hayfield site

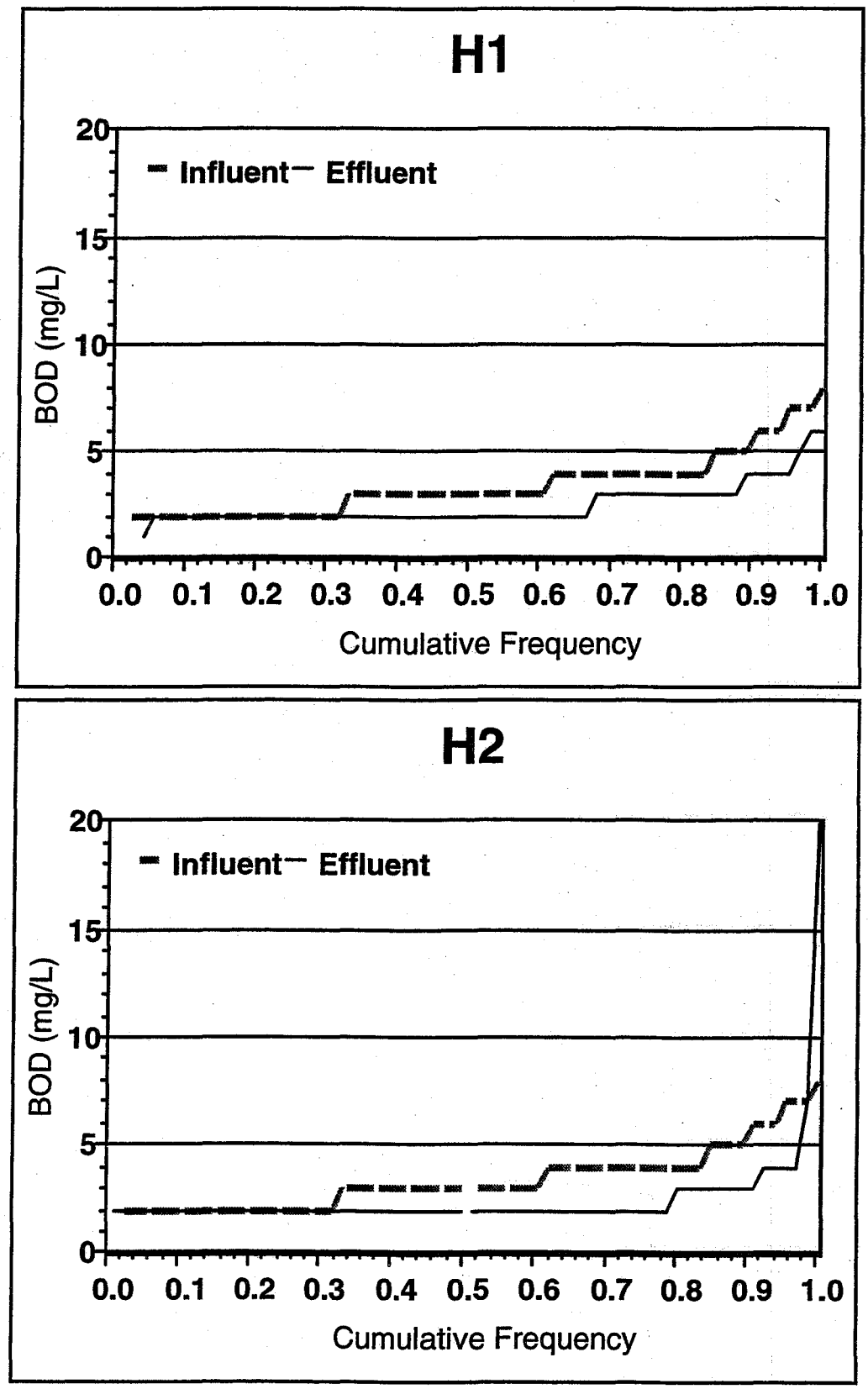
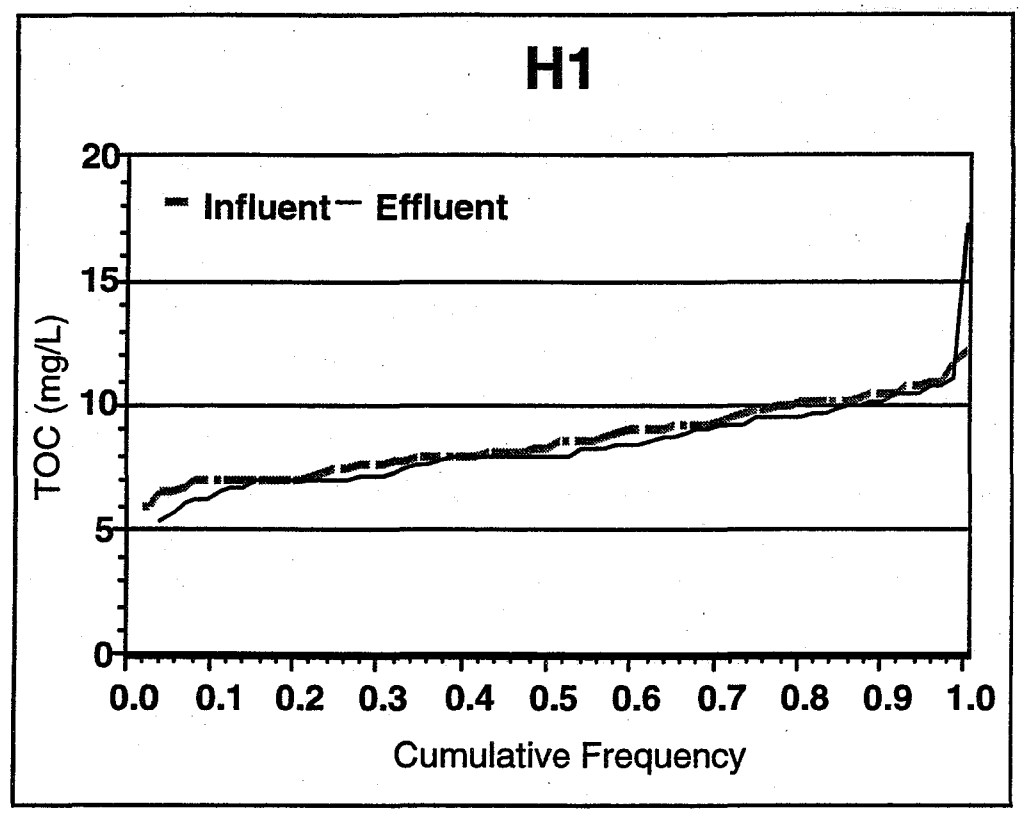


Figure D–10: Cumulative frequency distribution of biochemical oxygen demand at the Hayfield site



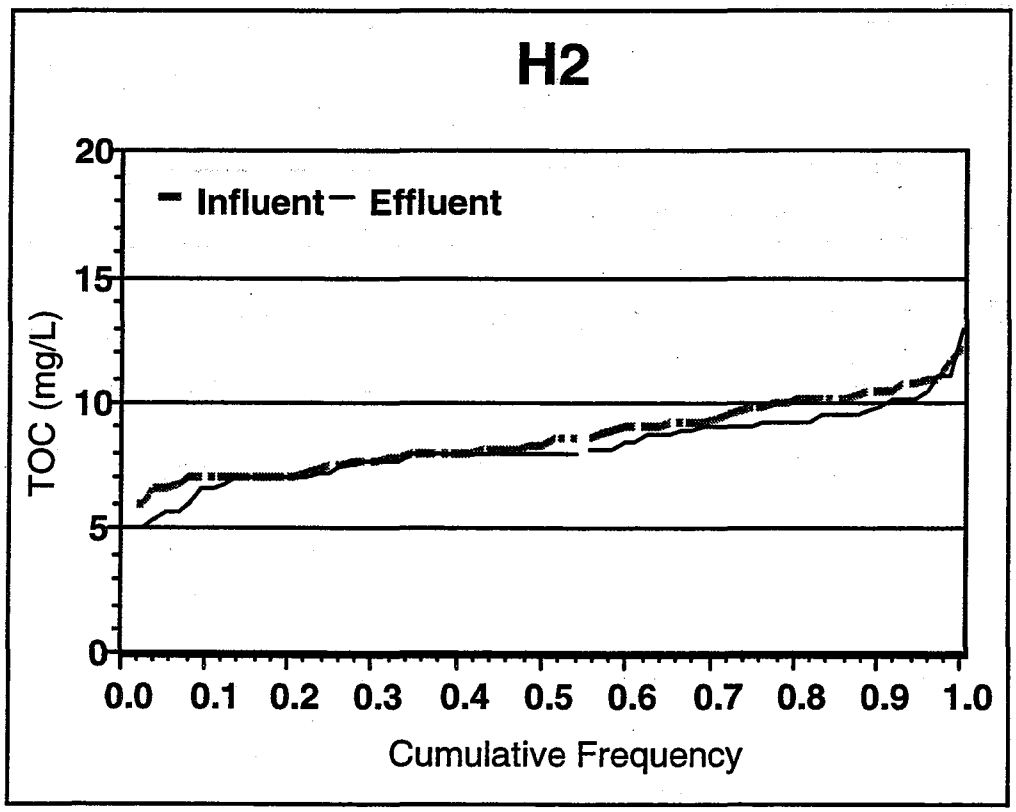
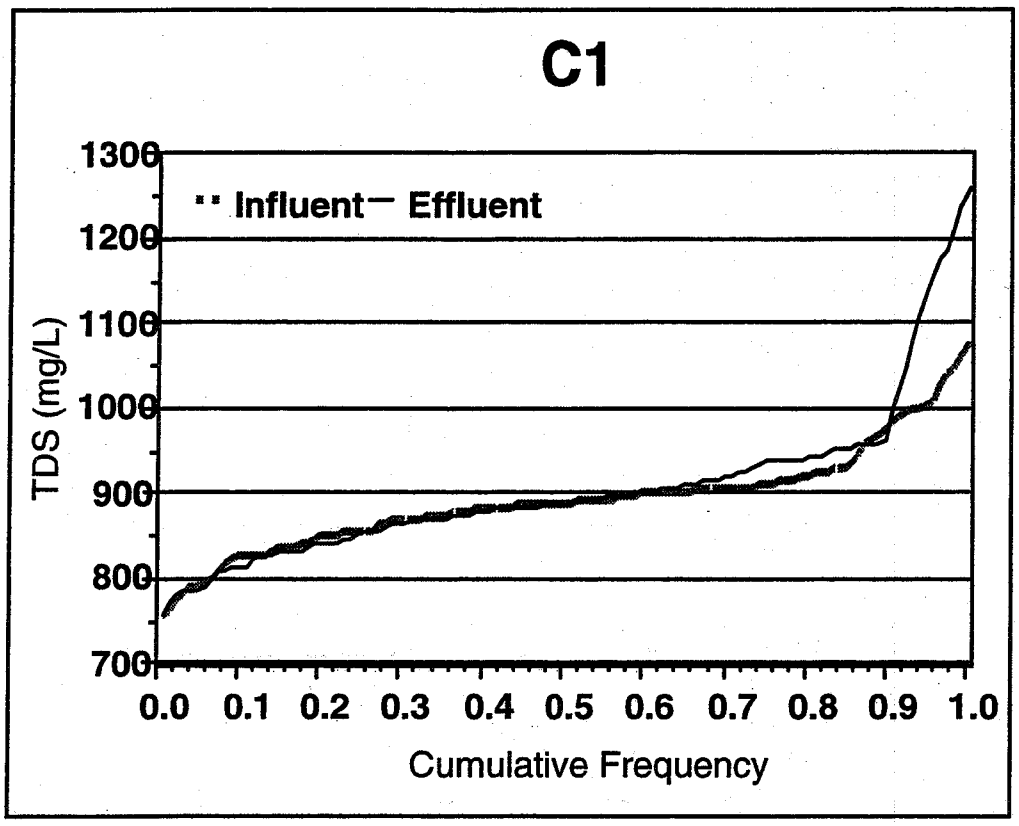


Figure D–11: Cumulative frequency distribution of total organic carbon at the Hayfield site



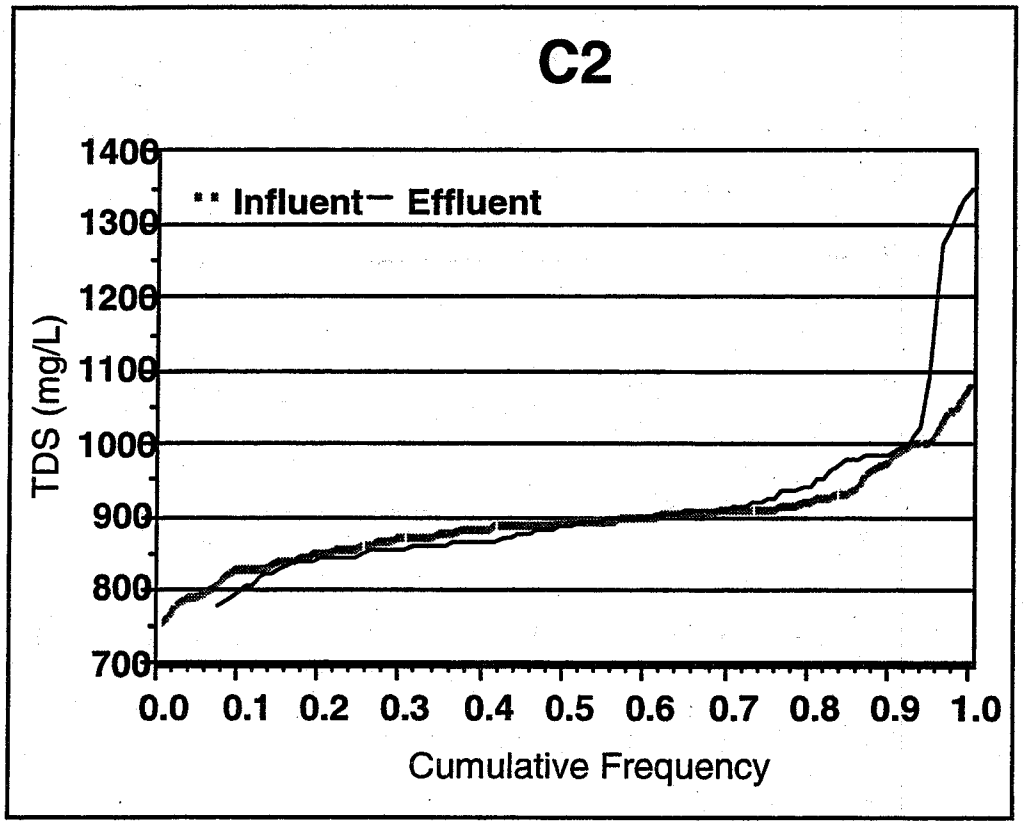


Figure D–12: Cumulative frequency distribution of TDS at the Cobble site

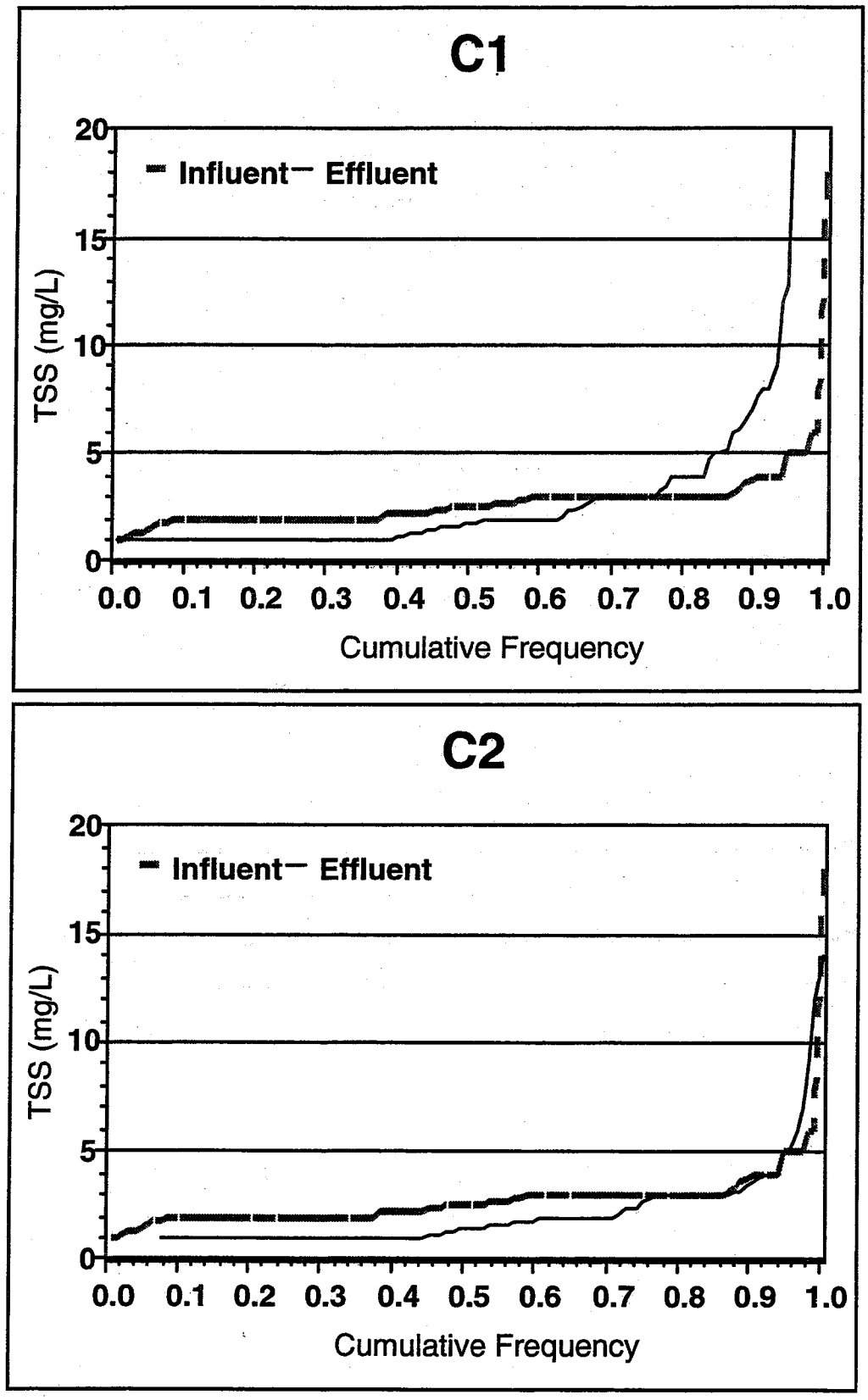


Figure D–13: Cumulative frequency distribution of TSS at the Cobble site

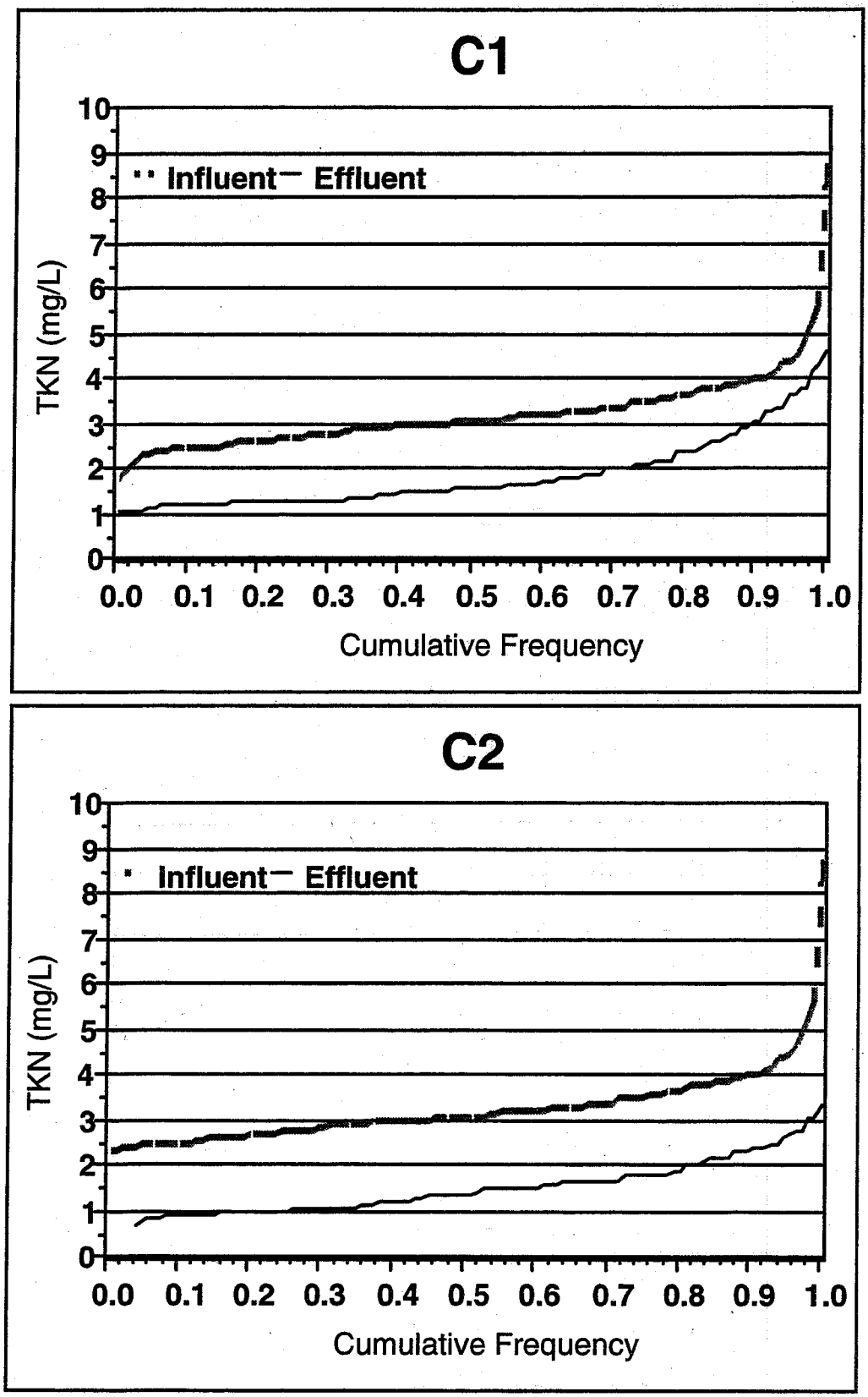
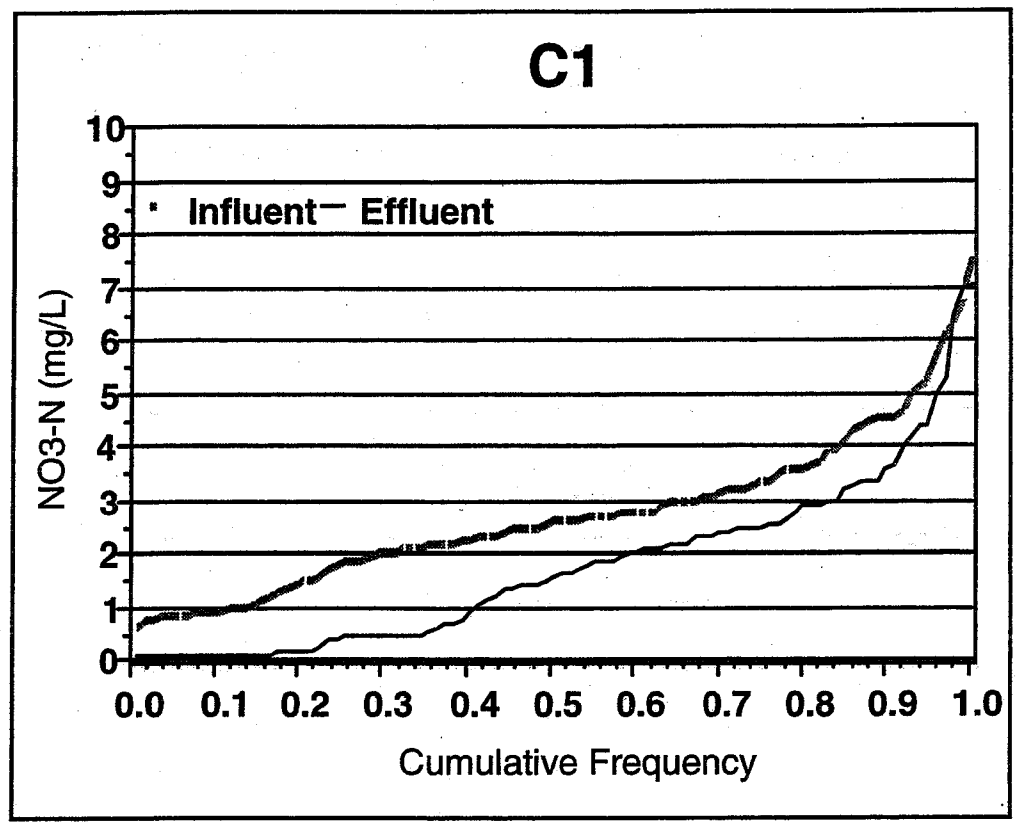


Figure D–14: Cumulative frequency distribution of TKN at the Cobble site



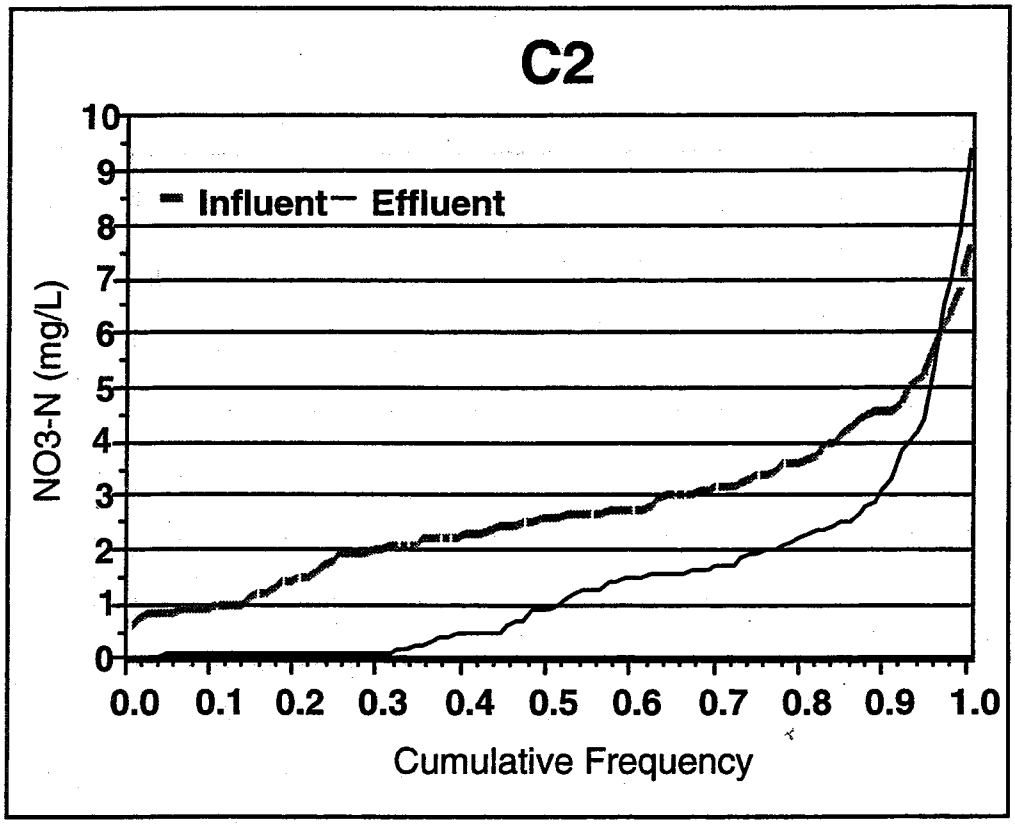


Figure D–15: Cumulative frequency distribution of nitrate-nitrogen at the Cobble site

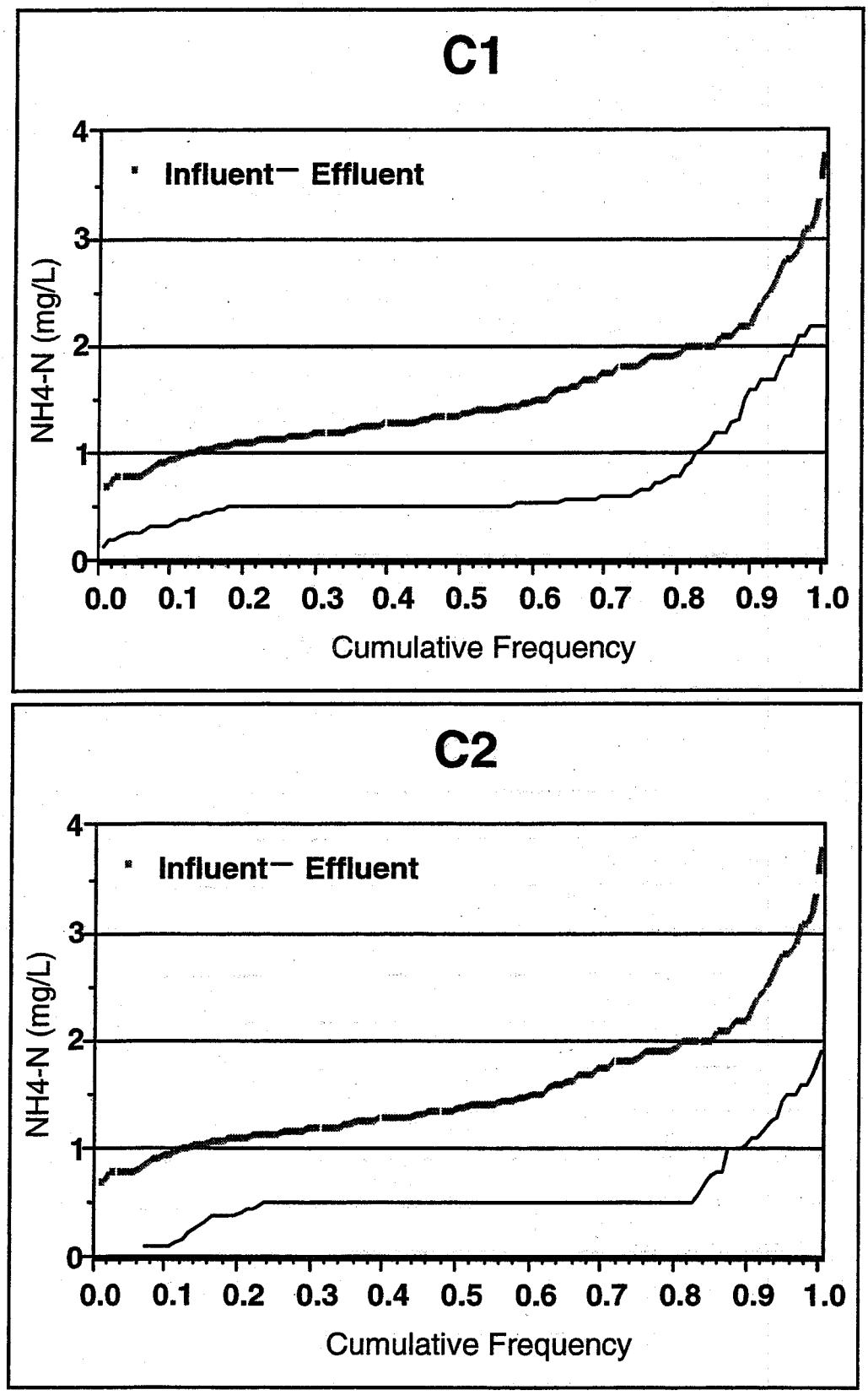


Figure D–16: Cumulative frequency distribution of ammonia-nitrogen at the Cobble site

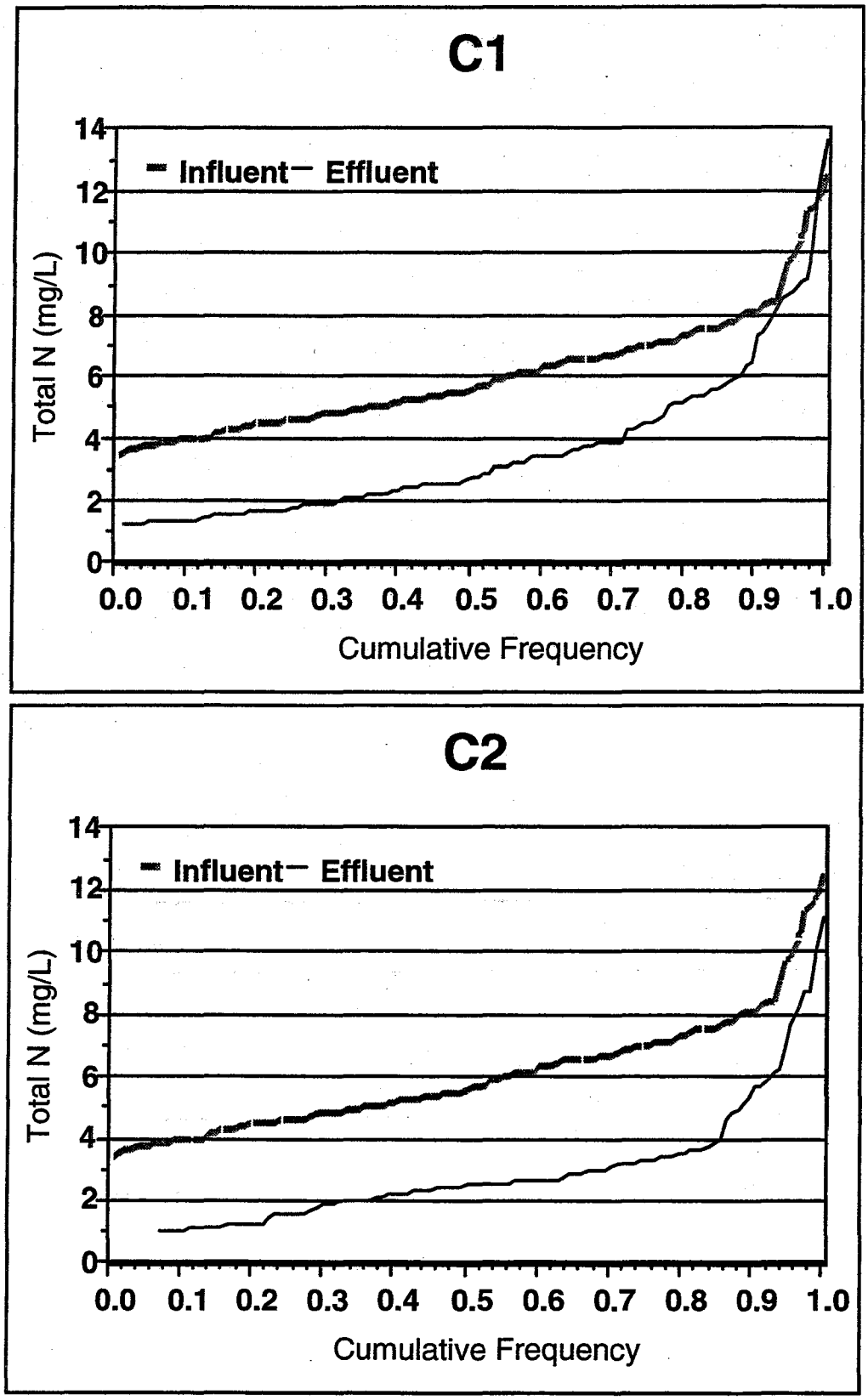


Figure D–17: Cumulative frequency distribution of total nitrogen at the Cobble site

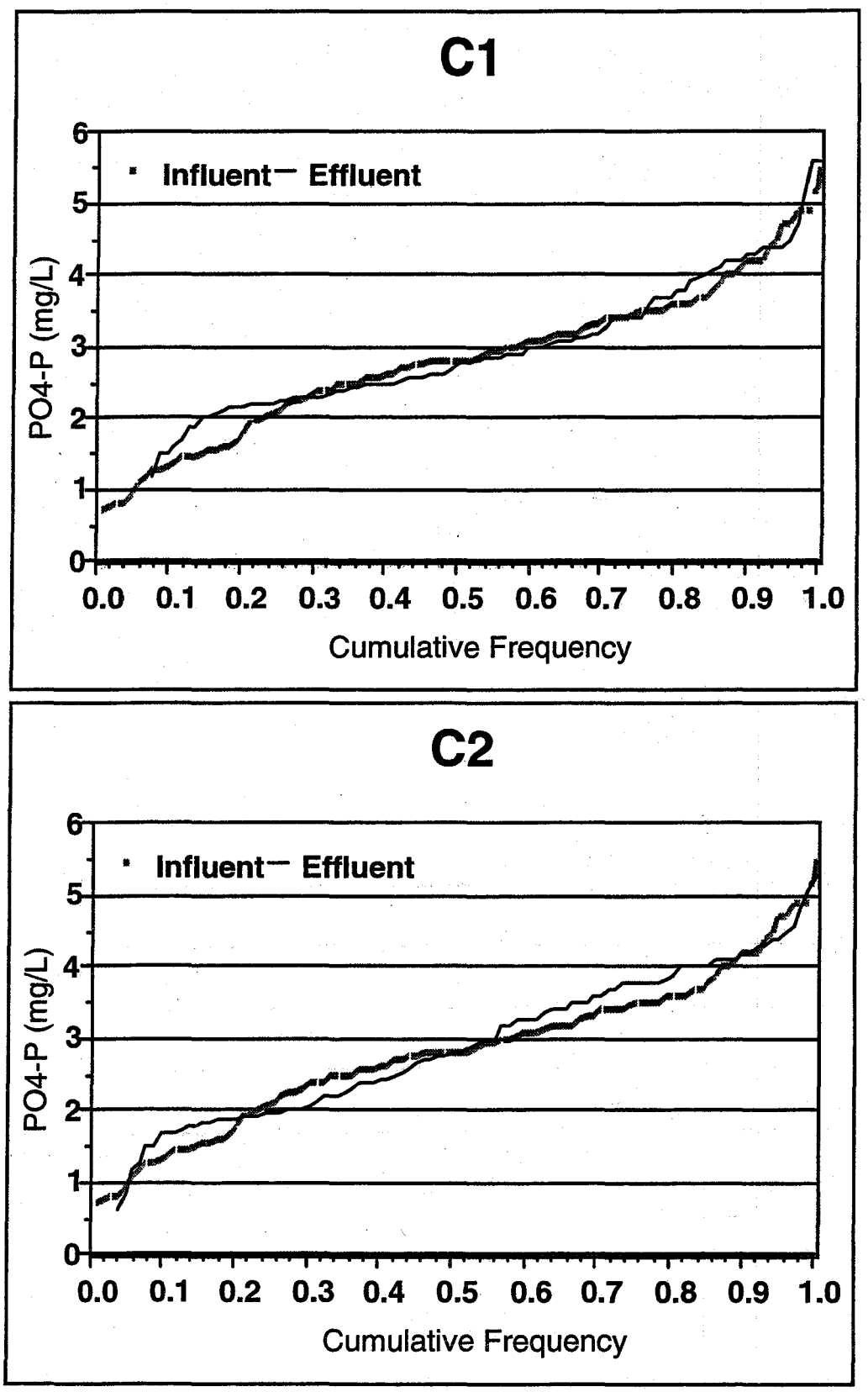
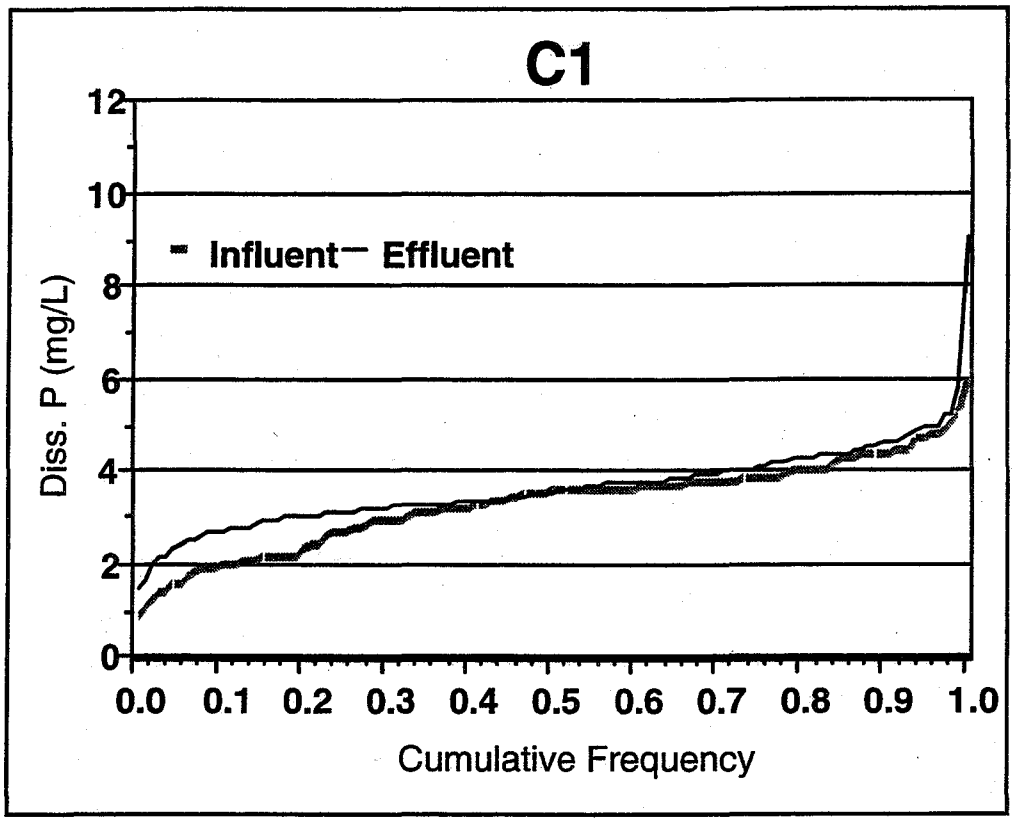


Figure D–18: Cumulative frequency distribution of orthophosphate-P at the Cobble site



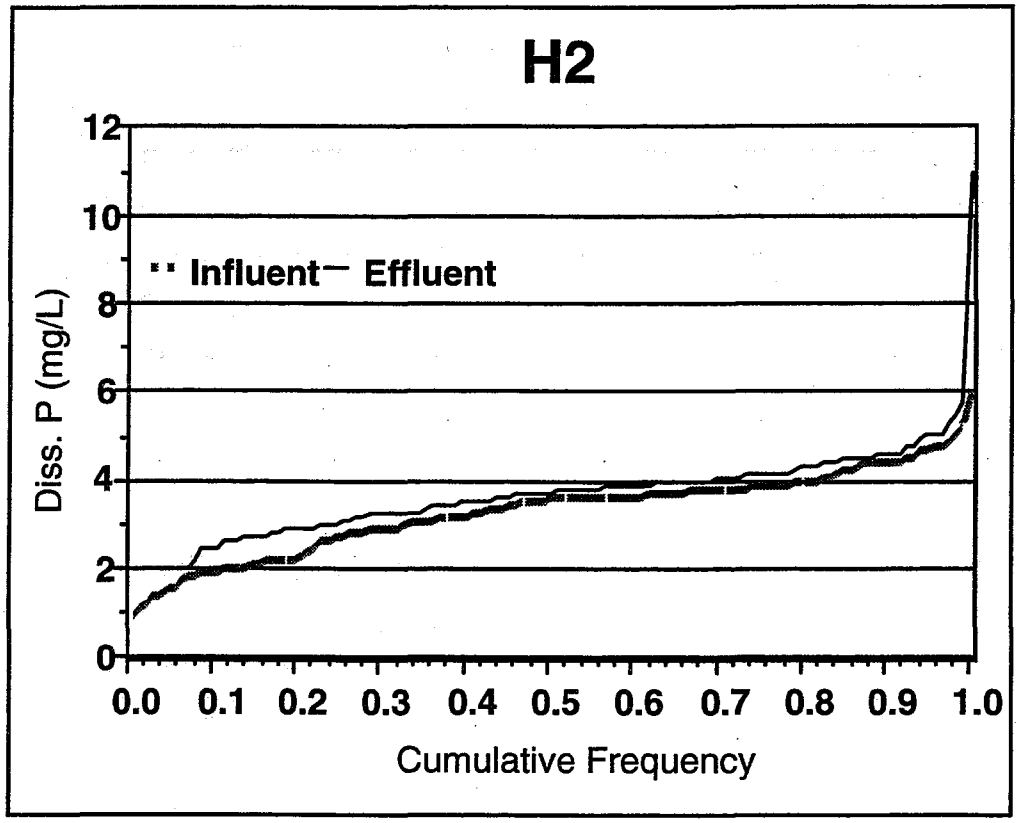
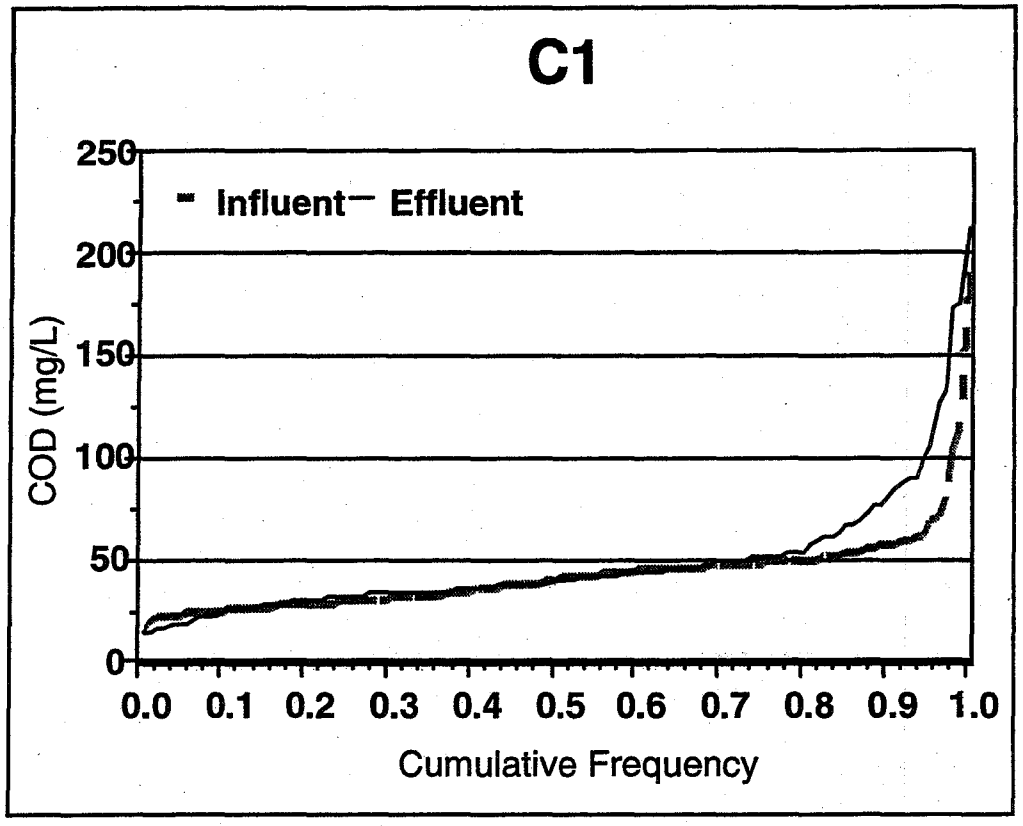


Figure D–19: Cumulative frequency distribution of total dissolved P at the Cobble site



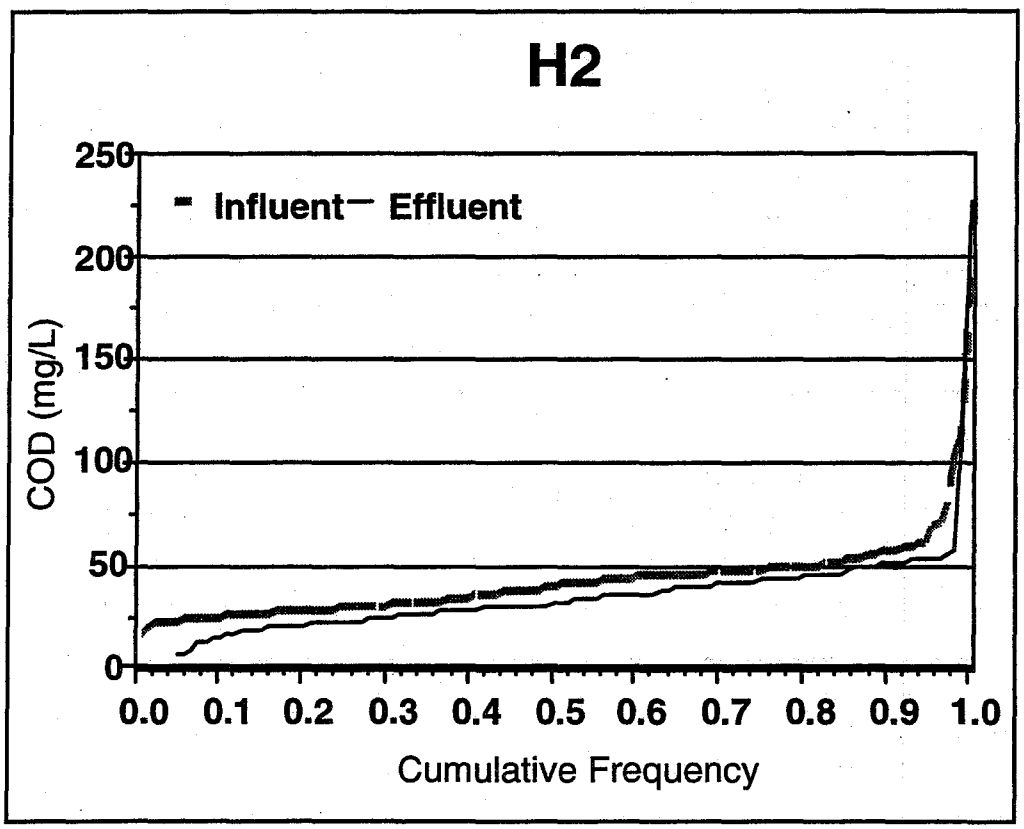


Figure D–20: Cumulative frequency distribution of chemical oxygen demand at the Cobble site

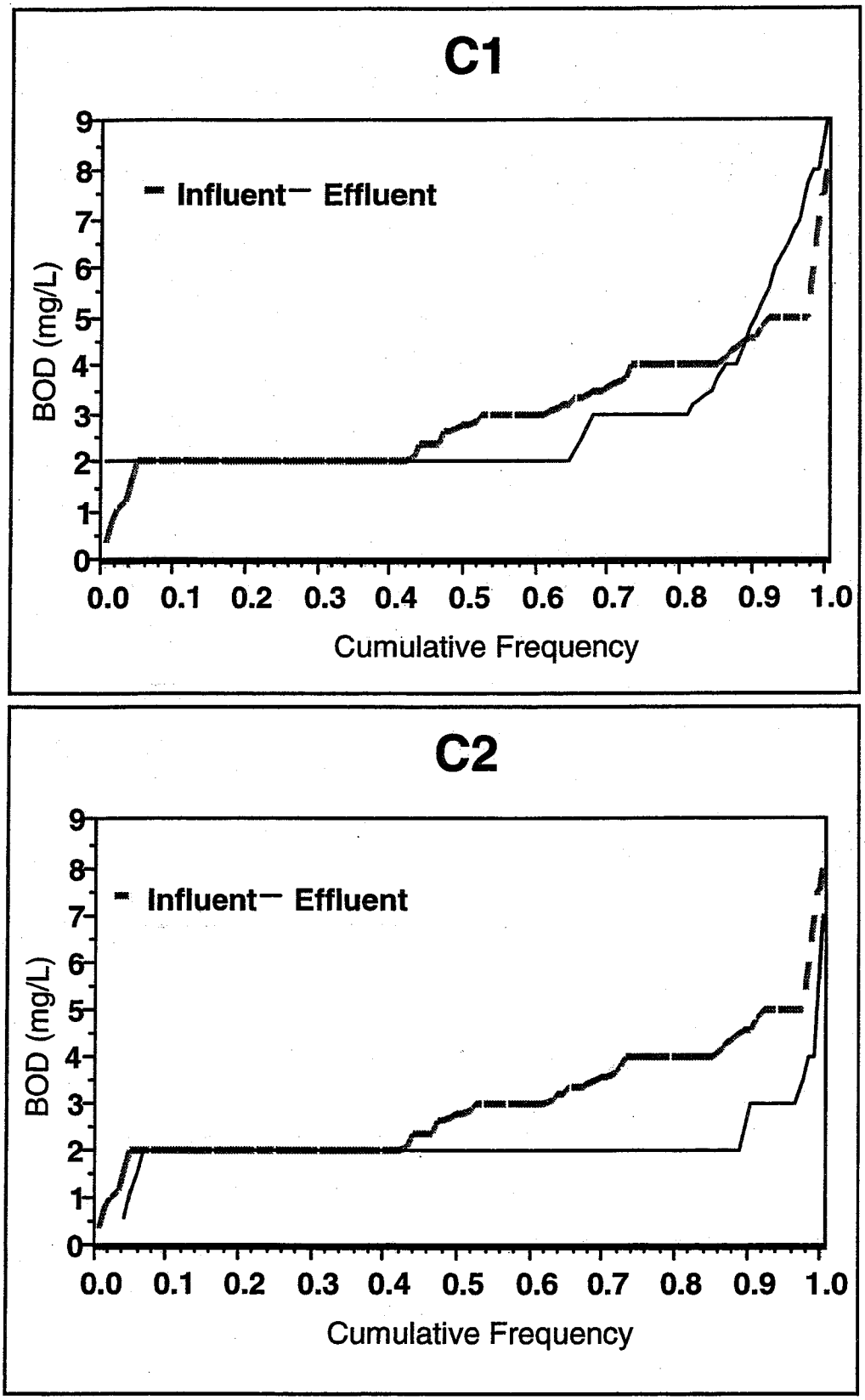


Figure D–21: Cumulative frequency distribution of biochemical oxygen demand at the Cobble site

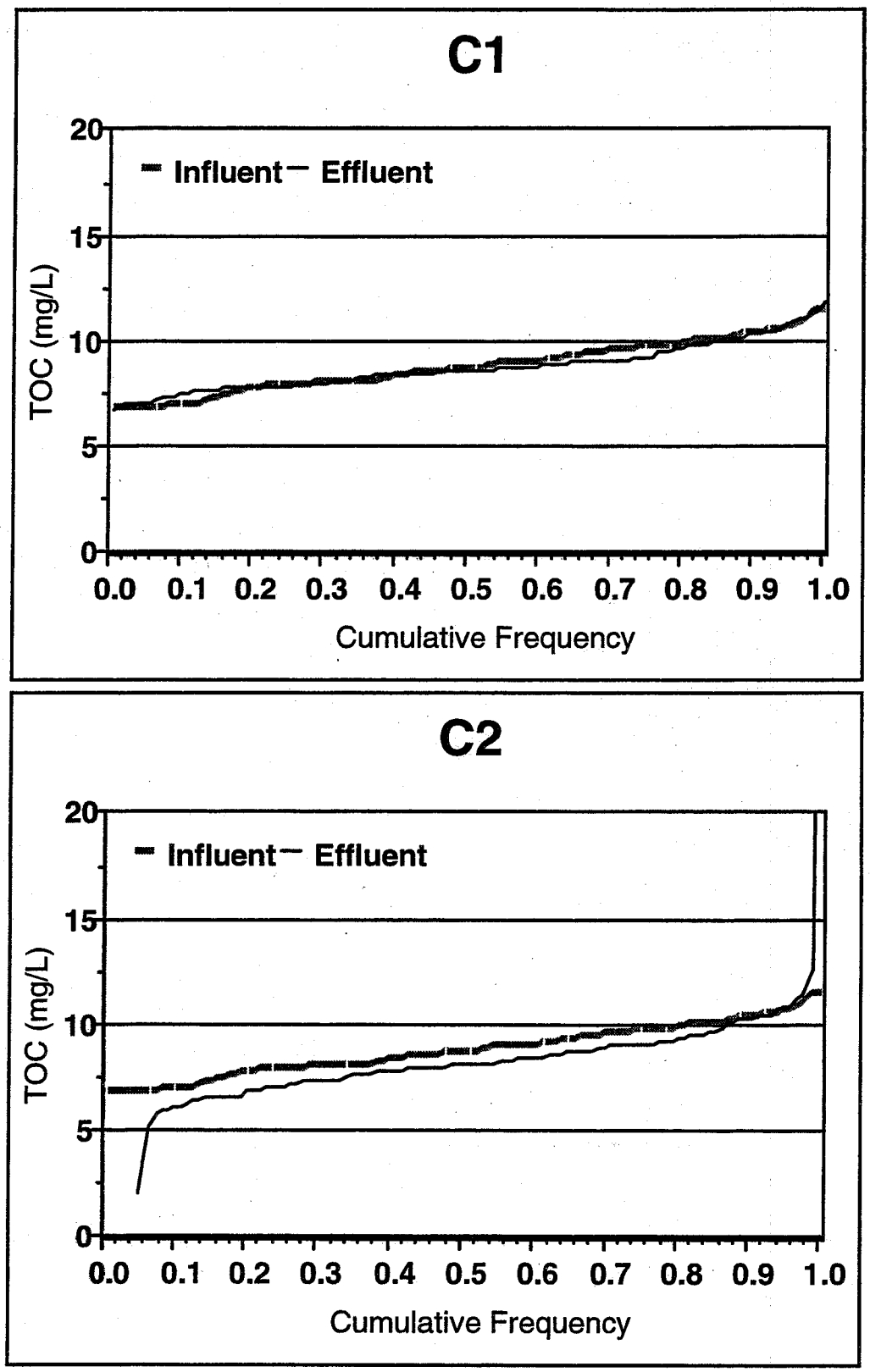


Figure D–22: Cumulative frequency distribution of total organic carbon at the Cobble site