102.101

ENGINEERING DIVISION
LIBRARY

FLOOD CONTROL DISTRICT
RECEIVED
MAY 31 1991

2	CH ENG		P & PM
1	DEP		HYDRO
	ADMIN		LMGT
	FINANCE		FILE
	C & O		
3	ENGR		

REMARKS

May 29, 1991

Property of
Flood Control District of MC Library
Please Return to
2801 W. Durango
Phoenix, AZ 85009

Hydraulics Section
U.S. Army Corps of Engineers
Los Angeles District
P.O. Box 2711
Los Angeles, California 90053-2325

Mr. Dan Sagramoso, P.E.
Chief Engineer and General Manager
Flood Control District of Maricopa County
3335 West Durango
Phoenix, Arizona 85009

Dear Mr. Sagramoso

Enclosed is a copy of EM 1110-2-4000 "Sediment Investigations of Rivers and Reservoirs" and a copy of EC 1110-8-1 (FR) "Stability of Flood Control Channels". This is the new Corps of Engineers sediment guidance that you requested at our meeting in the Corps Phoenix Area Office on May 23. If you want additional copies of the EM (or any Corps publication), you can obtain them by writing to:

Publications Depot
2803 52nd Avenue
Hyattsville, MD 20781

The EC is currently in draft form so you probably won't be able to get any additional copies until the final version is out.

If you have any further questions, please call me at (213) 894-5524.

Sincerely,

Brian Tracy

Brian Tracy, PE
Chief, Hydraulics Section

Enclosure

EC 1110-8-1 (FR)

ENGINEERING DIVISION

LIBRARY

STABILITY OF FLOOD CONTROL CHANNELS

Draft document prepared for the Waterways Experiment Station and the Committee on Channel Stabilization of the U.S. Army Corps of Engineers.

Prepared by Northwest Hydraulic Consultants Inc., Kent, Washington, in collaboration with an Editorial Board from the Committee on Channel Stabilization.

January 1990

Principal editor: Charles R. Neill (Northwest Hydraulic Consultants)

Associate editor: Thomas E. Munsey (OCE)

Collaborators:
Larry E. Banks (LMK)
Bobby J. Brown (WES)
Ronald .. Copeland (WES)
Victor J. Galay (NHC)
Alfred S. Harrison (MRD, retired))
John J. Ingram (WES)
Warren J. Mellema (MRD)
Samuel B. Powell (OCE, chairman CCS)
Richard P. Regan (NPS, retired)
Michael F. Spoor (ORH)

FOREWORD TO DRAFT OF JANUARY 1990

The impetus for preparation of this document arose out of an ongoing research program on the stability of flood control channels. The Waterways Experiment Station has responsibility for the technical work on the program while The Committee on Channel Stabilization (chairperson, Samuel B. Powell) provides direction, technical oversight and review. Work on this document was conducted from April 1988 to January 1990. Most of the editing and assembly was done through contracts with Northwest Hydraulic Consultants and reviewed periodically at meetings of an editorial board drawn from the Committee.

The rationale for the document was to assemble as much available guidance and information as possible on stability assessment and design for stable flood control channels, pending the results of ongoing, and necessarily extended, research programs. It is intended that the document should be applicable in the early stages of project analysis and that it should form a basis for decisions leading, if required, to more sophisticated design procedures.

The document is arranged in six main chapters. Chapter 1 briefly introduces the problem and approach. Chapter 2 reviews technical background, both geomorphic and hydraulic, in some detail. Chapter 3 describes a range of actual channel stability problems experienced in flood control projects, with case examples and illustrations. Chapter 4 discusses the assembly of basic field and office information useful for stability evaluation. Chapter 5 presents tentative methods, both qualitative and quantitative, for evaluating stability and gives an example of each type. Chapter 6 describes and illustrates some aspects of designing project features to maintain or enhance stability.

TABLE OF CONTENTS

		Page
Title Page		i
Foreword		ii
Table of Contents		iii
List of Figures		vi
List of Tables		xii
List of Photograph Locations		xiii
Glossary		xv
1.	**INTRODUCTION**	1-1
1.1	Purpose	1-1
1.2	General approach	1-1
1.3	Discussion	1-1
1.4	Systematic approach to channel stability	1-2
1.5	Related guidance	1-3
2.	**TECHNICAL BACKGROUND**	2-1
2.1	Characteristics of channels in erodible materials	2-1
2.1.1	Geomorphic context	2-1
2.1.2	Common channel types	2-2
2.1.3	Channel geometry and processes	2-10
2.2	Principles of channel equilibrium and response	2-21
2.2.1	Basic concepts	2-21
2.2.2	Applicability to flood control projects	2-22
2.2.3	Response of channels to altered conditions	2-24
2.2.4	Channel evolution and geomorphic thresholds	2-26
2.2.5	Hydraulic and geotechnical controls	2-29
2.3	Technical criteria for channel stability	2-35
2.3.1	General	2-35
2.3.2	Allowable velocity	2-35
2.3.3	Allowable shear stress	2-38
2.3.4	Stream power	2-41
2.3.5	Hydraulic geometry relationships	2-42
2.3.6	Sediment transport functions	2-42
2.3.7	Transport-modified hydraulic geometry relationships	2-45
2.3.8	Bank slope stability	2-45
2.3.9	Meanders and channel curvature	2-49
2.4	References and bibliography (Chapter 2)	2-51
3.	**STABILITY PROBLEMS WITH FLOOD CONTROL CHANNELS**	3-1
3.1	Types of channel modification for flood control	3-1
3.1.1	General	3-1
3.1.2	Clearing and snagging	3-1
3.1.3	Cleanout	3-2
3.1.4	Enlargement	3-2

ENGINEERING DIVISION
LIBRARY

TABLE OF CONTENTS (Cont'd.)

			Page
	3.1.5	Realignment	3-4
	3.1.6	Levees	3-5
	3.1.7	Floodways and bypasses	3-7
	3.1.8	Flow diversions	3-9
3.2	Case examples of stability problems		3-10
	3.2.1	Twenty Mile Creek	3-10
	* 3.2.2	Puerco River	3-12
	3.2.3	Grapevine Spillway Channel	3-14
	3.2.4	Snake River	3-16
	3.2.5	Little Tallahatchie River	3-16
	3.2.6	Red River	3-19
	3.2.7	Sacramento River	3-19
	3.2.8	Long Creek basin	3-21
	3.2.9	Tanana River	3-23
3.3	Causes of instability		3-25
	3.3.1	General	3-25
	3.3.2	Continuation of pre-existing processes	3-26
	3.3.3	Increased channel-forming discharge	3-26
	3.3.4	Realignment	3-27
	3.3.5	Removal of natural bank protection and roughness	3-27
	3.3.6	Flow regulation by reservoirs	3-27
	3.3.7	Alteration of base levels	3-30
	3.3.8	Inappropriate cross-section	3-30
	3.3.9	Inappropriate slope and velocities	3-30
3.4	Forms of instability		3-31
	3.4.1	Planform instability	3-31
	3.4.2	Profile instability	3-33
	3.4.3	Cross-sectional instability	3-35
	3.4.4	Combined cases	3-35
	3.4.5	Comments on sediment transport in relation to stability	3-36
3.5	References (Chapter 3)		3-37
4.	**ASSEMBLY OF INFORMATION FOR STABILITY EVALUATION**		**4-1**
4.1	Review of historical developments		4-1
4.2	Map and airphoto interpretation		4-1
4.3	Field inspection		4-6
	4.3.1	General	4-6
	4.3.2	Key points and features	4-7
4.4	Channel and floodplain surveys		4-12
	4.4.1	Topography	4-12
	4.4.2	Soils and materials	4-17
	4.4.3	Bank failure and erosion	4-17

TABLE OF CONTENTS (Cont'd.)

		Page
4.5	Streamflow and related data	4-17
	4.5.1 General	4-17
	4.5.2 Discharge records	4-19
	4.5.3 Flood frequency relationship	4-19
	4.5.4 Flow-duration relationship	4-19
	4.5.5 Stage-discharge relationship	4-19
4.6	Geologic and geotechnical information	4-21
4.7	Sediment transport	4-22
4.8	References (Chapter 4)	4-23
5.	**EVALUATION OF STABILITY**	5-1
5.1	General remarks	5-1
5.2	Levels of detail	5-1
5.3	Application of technical criteria	5-2
	5.3.1 General	5-2
	5.3.2 Velocities and shear stresses	5-3
	5.3.3 Hydraulic geometry relationships	5-9
	5.3.4 Sediment transport functions	5-15
	5.3.5 Slope stability analysis	5-16
	5.3.6 Meander geometry	5-16
	5.3.7 Channel evolution model	5-18
5.4	Steps in evaluation	5-19
	5.4.1 Description of existing channel system	5-19
	5.4.2 Classification and assessment of existing instabilities	5-20
	5.4.3 Identification of project features with stability implications	5-21
	5.4.4 Assessment of potential stability problems with project conditions	5-22
	5.4.5 Conclusions and recommendations	5-23
5.5	Example of qualitative evaluation	5-24
5.6	Example of more quantitative evaluation	5-27
5.7	References (Chapter 5)	5-32
6.	**DESIGN FOR STABILITY**	6-1
6.1	General remarks	6-1
6.2	Alignment and planform	6-2
	6.2.1 Single-channel streams	6-2
	6.2.2 Multi-channel streams	6-5
	6.2.3 Alluvial fans	6-5

TABLE OF CONTENTS (Cont'd.)

		Page
6.3	Longitudinal profiles and grade controls	6-9
	6.3.1 Causes of profile instability	6-9
	6.3.2 Grade control structures	6-9
6.4	Cross sections and hydraulic capacities	6-15
6.5	Control of meandering	6-15
6.6	Bank protection	6-18
6.7	Control of sedimentation	6-22
6.8	References (Chapter 6)	6-23

LIST OF FIGURES

		Page
Figure 1.4.1	Flow chart for systematic approach to channel stability	1-2
Figure 2.1.1	Drainage basin zones and some channel types	2-2
Figure 2.1.2	Typical longitudinal stream profiles and direction of change through time	2-2
Figure 2.1.3	Mountain torrent	2-5
Figure 2.1.4	Alluvial fan	2-5
Figure 2.1.5	Braided river	2-6
Figure 2.1.6	Arroyo	2-6
Figure 2.1.7	Meandering alluvial river	2-7
Figure 2.1.8	Incised channel	2-8
Figure 2.1.9	Regulated river	2-9
Figure 2.1.10	Delta	2-9
Figure 2.1.11	Some forms of stream planform (after Mollard and Janes 1984)	2-11
Figure 2.1.12	Association of planform type with other stream characteristics (after Schumm 1981)	2-12
Figure 2.1.13	Examples of meander shifting and bank erosion (after Brice 1983)	2-12
Figure 2.1.14	Mechanisms of cross-sectional adjustment to altered inputs of water and sediment	2-13
Figure 2.1.15	Associations between slope, planform and bed-material, Tanana River near Fairbanks, Alaska (after CRREL 1984)	
Figure 2.1.16	Processes of channel slope change	2-18
Figure 2.1.17	Bed forms in sand (Missouri River)	2-19
Figure 2.1.18	Response of bed forms in sand to increasing discharge [a through h] (after Simons, Richardson and Nordin 1965)	2-20
Figure 2.2.1	General trend of hydraulic geometry plots for channels in erodible materials	2-21
Figure 2.2.2	Generalized equilibrium concept for formation and response of erodible channels	2-22
Figure 2.2.3	Width-discharge plot for specific local set of channels	2-24

LIST OF FIGURES (Cont'd.)

		Page
Figure 2.2.4	Example of complex profile response to channelization	2-27
Figure 2.2.5	Channel Evolution Model for incised channels (Schumm et al 1984)	2-27
Figure 2.2.6	Slope-discharge chart distinguishing braided from non-braided channels	2-28
Figure 2.2.7	Classification of stream sediment loads	2-30
Figure 2.2.8	Bed-sediment grain-size distributions and correlation with slope [Tanana River near Fairbanks, Alaska]. (CRREL 1984)	2-31
Figure 2.2.9	Ice effects on banks of northern rivers: (a) boulder ridge and (b) vegetation trim line	2-33
Figure 2.2.10	Undercut bank erosion in frozen fine-grained alluvium	2-34
Figure 2.3.1	Allowable velocity criteria with provision for sediment transport (USDA 1977)	2-37
Figure 2.3.2	Insufficiency of allowable velocity or shear stress criterion for stability of alluvial channel	2-38
Figure 2.3.3	Boundary shear stress in uniform flow	2-39
Figure 2.3.4	Form of Shield's diagram for initial movement of noncohesive sediment on flat bed (Komura 1963)	2-40
Figure 2.3.5	Infilling of oversized flood control channel by deposition of sand in floods	2-43
Figure 2.3.6	Comparison of computed and measured bed load (CRREL 1984)	2-44
Figure 2.3.7	Effects of bed-sediment concentration on hydraulic geometry of alluvial channels, on basis of tables by White et al (1981)	2-47
Figure 2.3.9	Stability analysis for steep cohesive river banks (Thorne and Osman 1988)	2-48
Figure 2.3.10	Natural maintenance of channel width in shifting meanders	2-49
Figure 2.3.11	Meander geometry (after Nunnally & Shields 1985)	2-50
Figure 3.1.1	Clearing and snagging	3-3
Figure 3.1.2	Channel enlargement	3-3
Figure 3.1.3	Channel enlargement by side berm cut	3-4
Figure 3.1.4	Forms of channel realignment	3-4
Figure 3.1.5	Realigned channel without serious instability problems	3-6

LIST OF FIGURES (Cont'd.)

		Page
Figure 3.1.6	Lateral instability in realigned channel	3-6
Figure 3.1.7	Effects of levees on flood hydrographs	3-7
Figure 3.1.8	Bank protection necessitated by encroachment on levee setback	3-8
Figure 3.1.9	Floodway formed by high-level bend cutoffs	3-8
Figure 3.2.1	Cross-section and profile responses to channel enlargement Twenty Mile Creek	3-11
Figure 3.2.2	Induced instability upstream of channel enlargement, Twenty Mile Creek	3-13
Figure 3.2.3	Entrenched reach of Puerco River	3-13
Figure 3.2.4	Grapevine Spillway Channel after erosional episode	3-15
Figure 3.2.5	Snake River near Jackson Hole	3-15
Figure 3.2.6	Alternative levee locations along braided channel	3-17
Figure 3.2.7	Response of Little Tallahatchie River profile to upstream reservoir	3-18
Figure 3.2.8	Red River	3-20
Figure 3.2.9	Specific gage plot for Red River at Shreveport, LA over period 1892-1986	3-20
Figure 3.2.10	Outflanking of experimental bank protection on Sacramento River	3-22
Figure 3.2.11	Incised channel in Long Creek basin	3-22
Figure 3.2.12	Tanana River at Fairbanks showing in-river levee and groins	3-24
Figure 3.3.1	Stability of flood control works affected by pre-existing channel process	3-26
Figure 3.3.2	Response of channel to increased channel-forming discharge	3-26
Figure 3.3.3	Effects of storage reservoir on profile stability	3-28
Figure 3.3.4	Effect of storage reservoir on downstream flow-duration curve	3-28
Figure 3.3.5	Effect of storage reservoir on downstream bed-material transport	3-29
Figure 3.4.1	Side bar deposition and sub-meandering in straight channel	3-32
Figure 3.4.2	Sediment transport associated with shifting of meander bends	3-32
Figure 3.4.3	Examples of profile response in mobile-bed channels	3-34

LIST OF FIGURES (Cont'd.)

		Page
Figure 4.2.1	Airphoto of meandering river illustrating channel features	4-4
Figure 4.2.2	Comparison of modern and pre-settlement channel locations, Fannegusha Creek, Mississippi	4-5
Figure 4.3.1	Major sediment source: valley landslide	4-9
Figure 4.3.2	Tributary gullying	4-9
Figure 4.3.3	Stratification of bank soils	4-10
Figure 4.3.4	Bank failure	4-10
Figure 4.3.5	Piping and seepage in bank	4-11
Figure 4.3.6	Nick zone in degrading channel (clay layer)	4-11
Figure 4.3.7	Channel bar with various sediment classes and debris	4-13
Figure 4.3.8	Mouth of perched tributary	4-13
Figure 4.3.9	Exposed bridge piling	4-14
Figure 4.3.10	Flood stain marks on piers	4-14
Figure 4.4.1	Example survey cross-section	4-15
Figure 4.4.2	Example of stream profile	4-16
Figure 4.4.3	Grid photograph of coarse sediment and comparison of analysis methods	4-18
Figure 5.3.1	Velocities and depths in compound cross-section	5-3
Figure 5.3.2	Roughness changes in a large sand-bed river during floods (from Ackers 1988)	5-4
Figure 5.3.3	Approximate threshold velocities for bed movement of granular materials	5-7
Figure 5.3.4	Approximate threshold shear stresses and velocities for erosion of cohesive materials	5-7
Figure 5.3.5	Hydraulic geometry: bankfull width versus channel-forming discharge	5-10
Figure 5.3.6	Hydraulic geometry: mean depth versus channel-forming discharge	5-11
Figure 5.3.7	Hydraulic geometry: slope versus channel-forming discharge	5-12
Figure 5.3.8	Excess slope due to increased channel-forming discharge	5-14
Figure 5.3.9	Excess slope due to shortening plus increased channel-forming discharge	5-14

LIST OF FIGURES (Cont'd.)

		Page
Figure 5.3.10	Distortion of meander pattern upstream of protected length	5-17
Figure 5.6.1	Hydraulic geometry checks for example of Section 5.6	5-30
Figure 6.2.1	Regulated river with levees on meandering alignment	6-2
Figure 6.2.2	Construction of a meandering alignment	6-3
Figure 6.2.3	Limited alignment modifications to improve or eliminate troublesome bends	6-4
Figure 6.2.4	Suggested relationship between bankfull (channel-forming) discharge and meander wavelength for layout of new channel. (After Ackers and Charlton 1970)	6-5
Figure 6.2.5	Perched channel on aggrading alluvial fan	6-6
Figure 6.2.6	Debris basin and dam at head of alluvial fan	6-7
Figure 6.2.7	Concrete-lined channel on alluvial fan below debris dam	6-7
Figure 6.2.8	Principal active source of fan bed load may be downstream of apex	6-8
Figure 6.2.9	Cross-slope interceptor channels collecting flood flows from adjacent alluvial fans	6-8
Figure 6.3.1	Use of grade controls to limit profile degradation and downstream sedimentation	6-11
Figure 6.3.2	Classification of grade controls	6-11
Figure 6.3.3	Sheet-pile weir stabilizer (Biedenharn 1987)	6-12
Figure 6.3.4	Flume-type grade control/gauging structure	6-13
Figure 6.3.5	Drop structure with energy dissipator	6-13
Figure 6.3.6	Use of stepped sill on grade control structure to match upstream rating curve	6-14
Figure 6.4.2	Compound cross-section with low-flow channel, grassed berms and levees	6-14
Figure 6.4.1	Various types of modified cross-sections	6-16
Figure 6.5.1	Re-development of meanders in straightened channel following side bar development	6-17
Figure 6.6.1	Revetment necessitated by encroachment of bank caving on levee	6-19
Figure 6.6.2	Combined use of continuous toe protection and intermittent groins	6-19

LIST OF FIGURES (Cont'd.)

		Page
Figure 6.6.3	Use of "launching" apron to provide against toe scour below protected bank (Galay et al 1987)	6-21
Figure 6.6.4	Extension of outer bank protection downstream of inflection points	6-21

LIST OF TABLES

		Page
Table 2.1.1	Stream channel types and characteristic stability problems	2-4
Table 2.1.2	Miscellaneous reported rates of bank erosion (after Brice 1983)	2-16
Table 2.2.1	Expected response of channel characteristics to changes in driving variables or environmental conditions (see Figure 2.2.2)	2-25
Table 2.3.1	Example of allowable velocity criteria (from EM 1110-2-1601, 1970)	2-36
Table 2.3.2	Example of transport-modified regime relations (White et al 1981)	2-46
Table 3.3.1	Potential stability problems from flood control modifications	3-25
Table 4.1.1	Example of historical development calendar	4-2
Table 4.1.2	Suggested sources of historical information	4-3
Table 4.3.1	Checklist for field inspection	4-7
Table 4.5.1	Selected sources of information on hydraulic roughness of channels and floodplains	4-20
Table 5.3.1	Approximate mean channel velocities for "beginning of bed movement" of granular materials	5-5
Table 5.3.2	Approximate mean channel velocities for erosion of cohesive materials	5-6
Table 5.3.3	Sediment transport functions	5-15

LIST OF PHOTOGRAPH LOCATIONS

Figure No.	Location
Chapter 2	
2.1.3	near Clearwater, British Columbia, Canada
2.1.4	* West Magnesia Canyon, Rancho Mirage, California
2.1.5	White River below Mt. Rainier, Washington
2.1.6	* Puerco River near Gallup, New Mexico
2.1.7	Milk River near the mouth, Montana
2.1.8	Long Creek Basin near Oxford, Mississippi
2.1.9	Ouachita River below Blakely Mtn Dam, Arkansas
2.1.10	Athabasca Delta, Alberta, Canada
2.1.17	Missouri River
2.2.9 (a)	Kazan River, Northwest Territories, Canada
(b)	Churchill River, Manitoba, Canada
2.2.10	Kuskokwim River, Bethel, Alaska
2.3.5	* Puerco River at Gallup, New Mexico
Chapter 3	
3.1.1	Twenty Mile Creek, Mississippi
3.1.2	Big and Colewa Creek, Louisiana
3.1.5	Ditto
3.1.6	Walla Walla River at Milton-Freewater, Oregon
3.1.8	Snake River near Jackson Hole, Wyoming
3.1.9	Little Blue River, Missouri
3.2.2	Twenty Mile Creek, Mississippi
3.2.3	* Puerco River, New Mexico
3.2.4	Grapevine Spillway Channel near Dallas, Texas
3.2.5	Snake River near Jackson Hole, Wyoming
3.2.8	Red River, Louisiana
3.2.10	Sacramento River, California
3.2.11	Long Creek basin, Mississippi
3.2.12	Tanana River at Fairbanks, Alaska
3.4.1	Big Sand Creek near Greenwood, Mississippi
Chapter 4	
4.2.1	Pembina River, Alberta, Canada
4.2.2	Fannegusha creek, Mississippi
4.3.1	Oldman River, Alberta, Canada
4.3.2	Ditto
4.3.3	Long Creek basin, Mississippi
4.3.4	Ditto
4.3.5	* Gamerco Wash, Gallup, New Mexico
4.3.6	Long Creek basin, Mississippi
4.3.7	White River, Washington
4.3.8	Long Creek basin, Mississippi
4.3.9	Soldier Creek, Topeka, Kansas
4.3.10	Thompson River, British Columbia, Canada

LIST OF PHOTOGRAPH LOCATIONS (Cont'd.)

Figure No.	Location
Chapter 6	
6.2.1	Green River, Kent, Washington
6.2.2	Chena River near Fairbanks, Alaska
6.2.6	* San Antonio Creek, California
6.2.7	* Ditto
6.3.4	Goodwin Creek, Mississippi
6.3.5	Gering Drain, Nebraska
6.3.6	Little Sioux River, Iowa
6.4.2	Lost Creek, Columbus, Nevada
6.5.1	Yazoo basin, Mississippi
6.6.1	Ouachita River, Louisiana
6.6.2	Long Creek, Mississippi

GLOSSARY

afflux: rise in water level upstream of obstruction such as bridge pier

aggradation: upward progression of a channel's longitudinal bed profile by deposition of sediment

armoring: covering of bed with layer of stones generally coarser than underlying material

arroyo: ephemeral stream in arid land or desert

avulsion: sudden switch of main channel location as a result of flood flows, erosion and sedimentation

base level: controlling water-level at the mouth of a stream, for example lake or sea level

bed load: sediment transported in contact with the bed

bed forms: wavelike sediment deposits on channel bed, such as ripples, dunes etc.

bed-material (load): sediment (load) that rests on the channel bed at least during low flows

berm: flat area acting as step or terrace between upper and lower bank slopes

braided (river): consisting of a number of interlacing channels separated by bars and islands

caving: typical process of failure on fine-grained river banks involving periodic collapse of slabs by under-scour

channel-forming discharge: a discharge value or range that mainly controls channel geometry

channelization: conversion of a natural stream into a controlled or semi-controlled channel by re-alignment, enlargement, bank revetments etc.

clearing: removing permanent obstructions in a channel such as growing vegetation, boulders etc.

colluvial: derived from downslope movement of material with assistance from flowing water

cutoff: natural or artificial channel short-cutting across the neck of a meander bend

debris basin: basin for trapping and accumulation of bed load and trash

debris: (1) floating trash such as logs, branches etc.
(2) coarse sediment such as cobbles and boulders

degradation: downward erosion of a channel's longitudinal bed profile

detention (structure): holding flood flows temporarily to reduce peak

dominant discharge: see channel-forming discharge

grade control: device or structure designed to maintain bed level against degradation

drawdown: drop of river or reservoir levels in relation to nearby groundwater levels

GLOSSARY (Cont'd.)

entrenched (channel): cut down into surrounding ground so that overspill occurs rarely or never

evolution (channel): gradual process of change from one form or geometry to another

extremum principle: principle of maximizing or minimizing a parameter to arrive at a solution

fan (alluvial): fan-shaped deposit at a reduction of stream gradient, usually of coarse sediment

floodway (or flood bypass channel): artificial channel separate from original channel for supplementary flood capacity

geomorphology: study of landforms and relationships to processes such as stream erosion

groin: dike for bank protection, aligned more or less perpendicular to bank

gullying: formation of deep ravines by headcutting in easily erodible soils

headcutting: process of upstream-advancing degradation of channel bed

hydraulic geometry: relationships between channel cross-section, slope, sediments and controlling flows

incised (channel): generally same as entrenched

levee: flood protection dike parallelling river bank on floodplain

loess: characteristic fine-grained soil formed from windblown deposits

meandering: (1) type of planform exhibiting systematic alternation of characteristic right- and left-hand bends
(2) process of active shifting of such a planform by erosion and sedimentation on alternate banks

nick point (zone): upstream end of a headcut

oxbow: backwater channel or lake resulting from a cutoff

perched (channel): condition where bed of channel is higher than general ground contours in the vicinity

piping: formation of subsurface channel by erosion through streambank

regime: (1) suite of characteristics of channel with respect to flows, geometry, sediments etc.
(2) relationships of channel geometry to flows, sediment etc. (hydraulic geometry)

regulated (stream): with altered flow sequences due to upstream reservoirs or control structures

retention (structure): holding back flood flows for later release in dry periods

revetment: bank protection running along the length of the bank

riprap: loose rock or stone used as erosion protection

GLOSSARY (Cont'd.)

scour: (1) process of bed erosion due to local currents or disturbances
(2) bed depression so formed

sediment transport function: formula, equation or algorithm to predict sediment transport rate from hydraulic parameters

setback: distance between channel bank and levee on floodplain

sinuous: of winding planform but not necessarily meandering

snagging: removing temporary obstructions such as deadfall logs

suspended load: sediment transported in suspension - may include wash load and part of bed-material load

threshold: critical value of a parameter such as velocity above which significant erosion occurs

underfit (stream): occupying a channel or valley formed by a larger stream in prehistoric past (often in glacial period)

varved (soil): form of small-scale grainsize layering due to winter and summer deposition of sediments

wash load: sediment that travels suspended in the flow at practically all flow conditions

CHAPTER 1. INTRODUCTION

1.1 Purpose

This document provides guidance for determining potential channel instability in flood control projects. It is intended to facilitate consideration of (a) the type and severity of erosion and sedimentation problems, (b) the need for and scope of further hydraulic studies to address those problems, and (c) design features to promote channel stability.

1.2 General approach

The approach presented in this document is mainly qualitative but includes relatively simple numerical checks that are applicable in some cases. Confidence in the stability of the project design will be enhanced if several different techniques of stability evaluation are employed. Wherever possible, the procedures employed should have been developed under hydraulic and geomorphic conditions similar to those encountered in the project. If procedures appropriate to project conditions do not seem to be available, or if different methods of evaluation do not give similar results, a need for more sophisticated analyses may be indicated. Such analyses might involve quantitative sediment transport studies and numerical modelling of morphologic response, which are not covered in this document.

1.3 Discussion

Adverse effects of flood control modifications on channel stability may be more common than is generally known. In an article in the USACE magazine "Water Spectrum" (spring-summer issue of 1976), Mr. Walter C. Lindner, Chief Hydrologist of Kansas City District, wrote: "Once disturbed, a stream channel begins an automatic and relentless process that culminates in its reaching a new state of equilibrium with nature. .... In the past, too many problems ... have been handled by modifying the river channels involved without giving thought to the sediment being transported by the water. .... Techniques should be employed that consider sediment transport characteristics and stream equilibrium. .... The ultimate cost of the uncontrolled erosion and excessive downstream sediment deposition that follow traditional channel modification is often far greater than the initial cost of a design that recognizes the influence of sediment transport characteristics on a stream's state of equilibrium."

Channel instability in a flood control project is not always the result of project modifications to the hydrology or channel characteristics. It may also reflect the continuation of pre-existing conditions such as meandering. Potential consequences of channel instability, whether pre-existing or project-induced, include reduction of assumed flood conveyance, loss of land and structures, and excessive requirements for maintenance or rehabilitation.

1.4 Systematic approach to channel stability

Solution of channel stability problems in the planning and design of a flood control project requires the synthesis of field information, analytical procedures and previous experience in a complex fashion that cannot easily be summarized as a linear sequence of steps. The flow chart shown in Figure 1.4.1 is intended to convey how data, assessment and analysis can be integrated to attack stability problems. Numbers within the diagram blocks indicate subsequent Sections in this document.

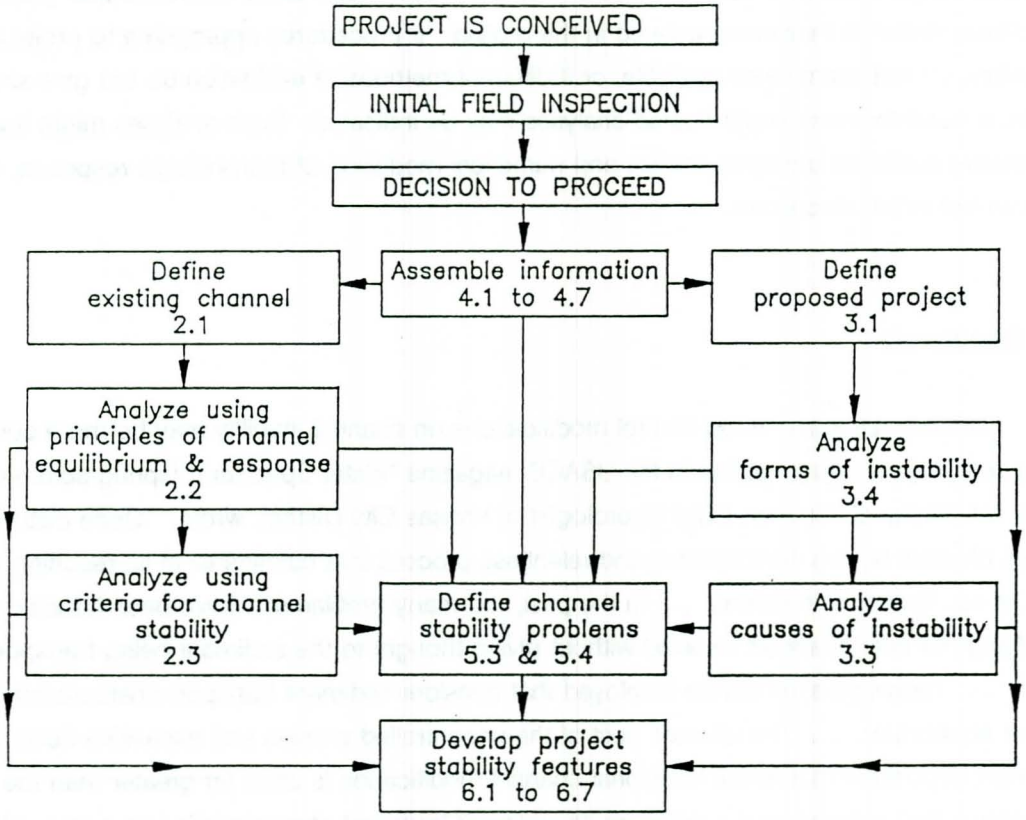


Figure 1.4.1 Flow chart for systematic approach to channel stability.

1.5 Related guidance

Other guidance documents relevant to flood control channels include the following:

Engineer Manual EM 1110-2-1601, Hydraulic Design of Flood Control Channels, 1970. This document deals mainly with the hydraulics of fixed-boundary channels. Problems of erosion and sedimentation are dealt with mainly in the context of riprap protection. In a revised edition of 1990, the riprap section of the manual is revised in the light of recent research.

Engineer Manual EM 1110-2-4000, Sedimentation Investigations of Rivers and Reservoirs, 1989. This document deals with field and office investigations of sediment problems for a variety of projects including reservoirs, navigation channels and flood protection channels. The scope of the studies indicated may often be impracticable for smaller flood control channel projects.

Engineer Manual EM 1110-2-1205, Environmental Engineering for Flood Control Channels, 1990. This document deals with environmental factors to be considered in channel projects and with environmental features that can be incorporated in channel design.

Engineer Regulation ER 1110-2-1405, Hydraulic Design for Local Flood Control Projects, 1982. This document covers design rationale and process.

Engineer Manual ....., River Hydraulics, 1990. This document covers the computation of uniform, non-uniform, steady and unsteady flow in rivers with fixed boundaries.

CHAPTER 2: TECHNICAL BACKGROUND

2.1 Characteristics of channels in erodible materials

2.1.1 Geomorphic context. In undertaking a stability assessment of a proposed flood control channel project, it is important to understand the relationship of the project length to the stream system and the basin geomorphology, and to see the project channel as part of an interlinked system. Geomorphology means here the relationship of stream channels and floodplains to the geology and physiography of the region. Factors that have produced the present channel features and will affect its response to engineering works include sources and supply of sediments, basin materials and vegetation, catastrophic events such as earth movements, landslides, eruptions and major floods, changes in land use and development, and past interferences including structures, dredging and diking. The existing condition of the channel may depend on factors far removed in space and time, and instability response to flood control works may affect locations beyond the project length far into the future.

In general terms, a drainage basin can be divided into three main zones: (i) an upper erosional zone of sediment production, (ii) a middle zone of sediment transport with simultaneous erosion and deposition, and (iii) a lower zone of sediment deposition (Figure 2.1.1). The actual situation is often more complex, because local geological controls or other factors can produce local depositional zones in the upper basin or local erosional zones in the lower basin. Flood control projects are more common in the middle and lower zones where the stream overflows frequently on to agricultural or urban land.

In the general case, the longitudinal profile of the stream system is tending to flatten through time by degradation in the upper reaches and aggradation in the lower reaches (Figure 2.1.2). In most natural systems this process is slow enough to be of little engineering concern, but where the stream system has been interfered with in the historical period, profile flattening may be proceeding at detectable rates. In some channelization projects, response of this type has been dramatic (see Chapter 3 for examples).

Methods of investigating basin and channel system geomorphology include examination of maps, surveys, hydrologic records, airphotos and satellite images, aerial and ground reconnaissance, study of geological and soils reports, analytical methods and consultation with specialists. The amount of study necessary or feasible depends on the scale of the project and the judged severity of potential instability problems. In the past, hydraulic design studies for flood-control channels often gave insufficient attention to stability aspects, or where stability was addressed, insufficient attention was given to longterm effects and responses beyond the project area.

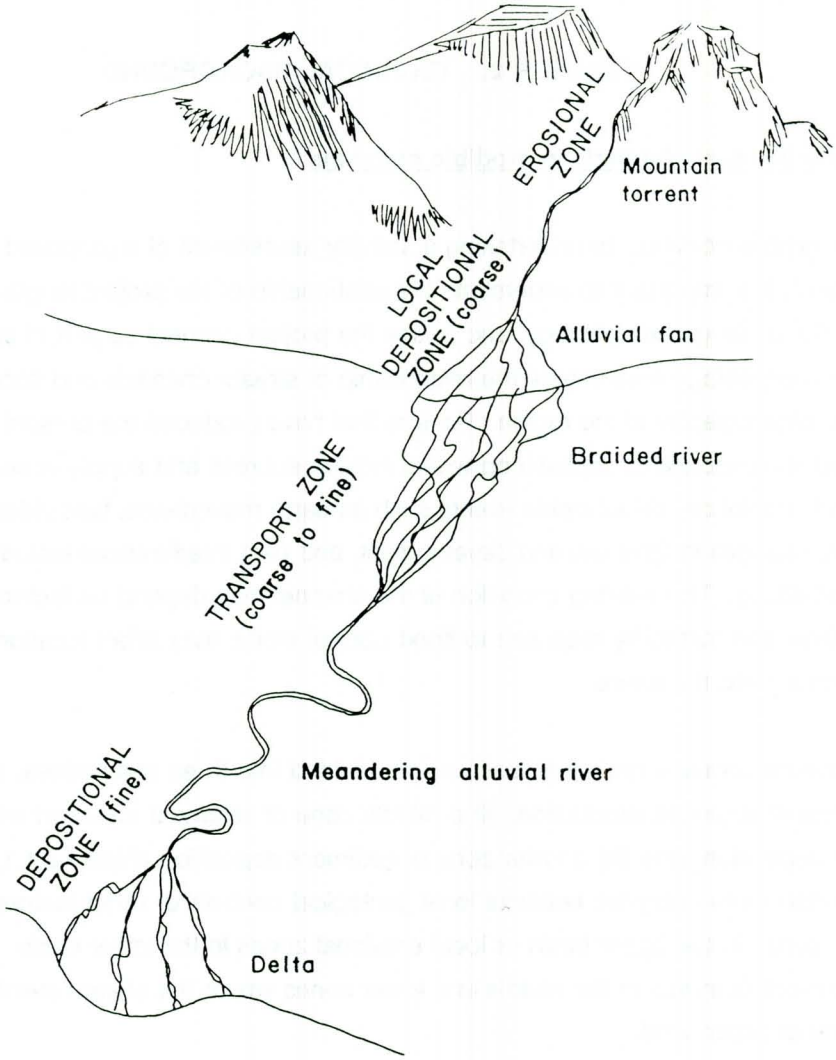


Figure 2.1.1. Drainage basin zones and some channel types.

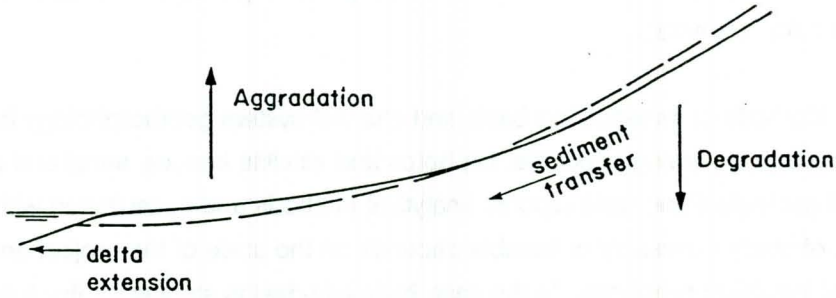


Figure 2.1.2. Typical longitudinal stream profile and direction of change through time.

Selected references on the geomorphology and hydraulics of stream systems are listed in the Bibliography at the end of this chapter.

2.1.2 Common channel types. A number of common channel types and their characteristic stability problems are described below and summarized in Table 2.1.1.

Mountain torrents. These are high-velocity streams on steep slopes, often exhibiting a sequence of drops and chutes controlled by large boulders, deadfalls etc. (Figure 2.1.3). Erosion and deposition is sometimes confined to severe flood events. Some mountain torrents on very steep slopes are subject to the phenomenon of "debris flows or "debris torrents" whereby under severe flood conditions the bed becomes fluidized and a virtual avalanche of boulders and gravel runs down the mountainside. In some regions, debris flows are caused by deforestation which increases flood runoff and destabilizes streambanks.

Alluvial fans. Fans generally occur where a stream emerges from a mountain valley on to relatively flat land (Figure 2.1.4). Fans are usually depositional features characterized by coarse alluvial materials, unstable multiple channels subject to frequent shifts or "avulsions". The main channel is often "perched" on the highest ground. Sometimes the fan is inactive depositionally and the stream is eroding into earlier deposits. Fans are usually easily recognizable on airphotos and sometimes on topographic maps. In wooded country they are not always easily recognized on the ground.

Potential stability problems on alluvial fans include avulsion of the stream at a point upstream of training works or channelization, thereby by-passing the works, and infilling of the designed conveyance channel by coarse sediment deposits. Flood control works should be carried sufficiently far upstream and consideration should be given to trapping or removal of coarse sediment upstream of the flood control zone. Location of the flood control channel requires consideration of local features and processes.

Braided rivers. Braided rivers consist of a network of interlacing channels with unstable bars and islands (Figure 2.1.5). They generally occur in the upper and upper-middle zones of a basin. Bed materials are usually gravels or cobbles, but braided sand rivers are found occasionally. Bed-material transport tends to be high, at least in flood periods. For flood-control purposes the wide braided flats are sometimes confined by training works to a single channel or floodway. Stability problems include how to maintain through transport of the bed-material load, and how to avoid serious disturbances of the longitudinal profile. Points that require consideration are the planned cross-section, the alignment in plan, and provision for future shifting and erosional attack.

Table 2.1.1 **Stream channel types and characteristic stability problems**

Channel type	Typical features	Stability problems
Mountain torrents	Steep slopes Boulders Drops and chutes	Bed scour and degradation Potential for debris flows
Alluvial fans	Multiple channels Coarse deposits	Sudden channel shifts Deposition Aggradation
Braided rivers	Interlacing channels Coarse sediments (usually) High bed load	Frequent shifts of main channel Scour and deposition
Arroyos	Frequently dry Wide flat channels Flash floods High sediment loads	Potential for rapid sedimentation
Meandering rivers	Alternating bends Flat slopes Wide floodplains Fine sediments	Bank erosion Meander migration Scour and deposition
Modified streams	Previously channelized Altered base levels	Meander development Degradation and aggradation Bank erosion
Regulated rivers	Upstream reservoirs Irrigation diversions	Reduced activity Degradation below dams Lowered base level for tributaries
Deltas	Multiple channels Fine deposits	Channel shifts Deposition and extension
Underfit streams	Sinuous planform Low slope Stable banks	Rare Shortening may not involve serious consequences
Cohesive channels	Irregular or unusual planform	Variable

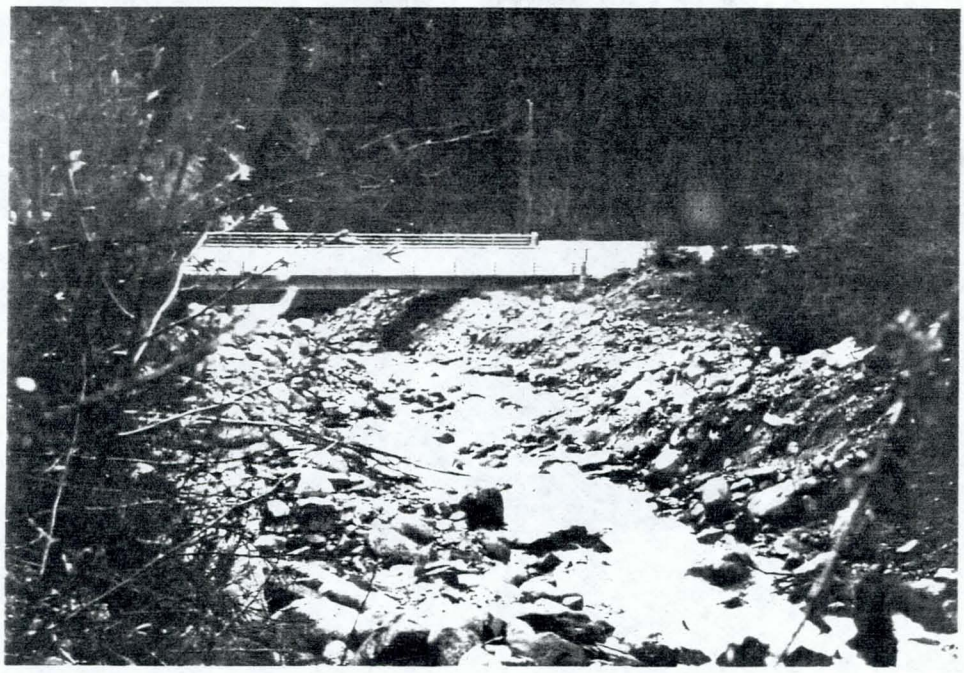


Figure 2.1.3. Mountain torrent.

Figure 2.1.4. Alluvial fan.

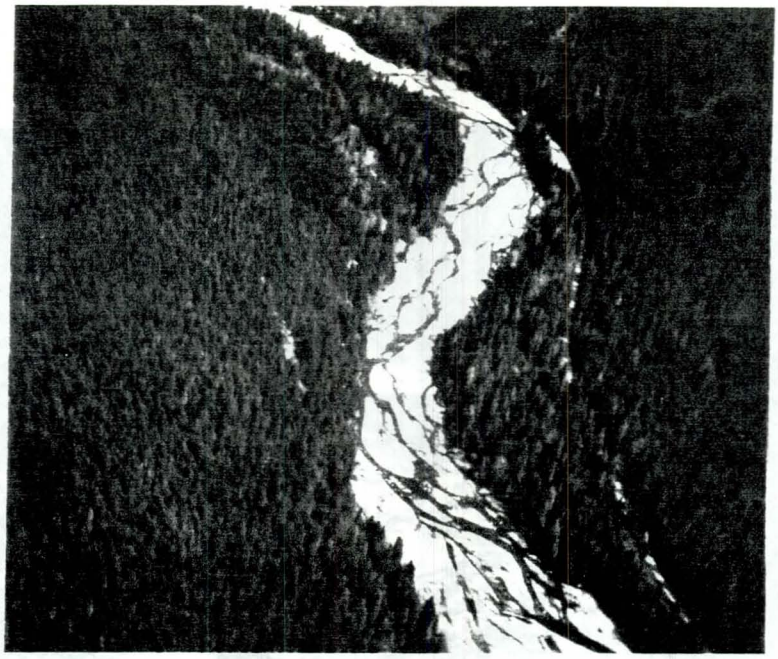


Figure 2.1.5. Braided river.

Arroyos. Arroyos are streams in deserts and arid areas that are dry much of the time but carry large discharges and heavy sediment loads under occasional flood conditions (Figure 2.1.6). The channel may be deeply incised into the terrain in some reaches and liable to frequent overspill in others. Because of the heavy sediment loads, infilling by sedimentation can occur very quickly if velocities are reduced by enlargement, weirs, or other works.

Figure 2.1.6. Arroyo.

Meandering alluvial rivers. These generally occur in the middle and lower zones of a basin. The single channel follows a characteristic sinuous planform and is normally eroding into the floodplain on one bank and creating new floodplain by deposition on the opposite bank. Bed material is usually sand, or sand and gravel. In undisturbed natural systems, future shifting of the channel is often predictable from comparison of sequential maps or airphotos. In many cases the traces of former channel locations are detectable on airphotos (Figure 2.1.7).

Figure 2.1.7. Meandering alluvial river.

Numerous stability problems arise from flood control works on meandering streams. Flood control may involve straightening, regulation or augmentation of flows, and alteration of sediment loads. Meandering systems are often sensitive to modest imposed changes and can respond with troublesome alterations of cross-sections, planforms, levels and gradients. Planning requires consideration of past channel behavior, of likely responses, and of the advisability of stabilization measures.

Modified streams. In some regions, many streams have been modified in the past by human activity and do not much resemble natural rivers. A common form of modification is straightening or enlargement for flood control, but if the changes occurred many decades ago the details may be difficult to discover. Another form of modification is by flood control works or reservoirs on a parent river, which produced changes in the stream of interest by altering base levels.

A particular regional type of modified stream is exemplified by the incised channels of northern Mississippi (Figure 2.1.8). These are hill streams in erodible soils that often have a long history of response to widespread basin erosion followed by channelization and altered base levels.

Planning of flood control works on a stream of this type should take into account its present state of evolution towards a new equilibrium.

Figure 2.1.8. Incised channel.

Regulated Rivers. These are generally streams where the flood discharges have been reduced and the low flows increased by upstream storage reservoirs (Figure 2.1.9). Such streams often exhibit a reduction in morphologic activity as compared to previous natural conditions, and their channels may have reduced in cross-section by deposition of sediment and encroachment of vegetation. But if the stream under natural conditions carried substantial loads of bed sediment, trapping of sediment in reservoirs may initiate slope changes downstream. The effects of regulation on stability are thus complex and depend on the previous characteristics of the stream as well as on the degree and mode of regulation.

Deltas. Deltas somewhat resemble alluvial fans but occur on flat slopes where a river discharges into static water and deposits its sediment load (Figure 2.1.10). Under natural conditions the river splits into a number of distributaries, whose bed levels rise over time as the delta extends into the water body. Flood control levees adjacent to deltas can require periodic raising, particularly if the river is confined artificially to a single channel. The potential for channel avulsions upstream of the works requires consideration.

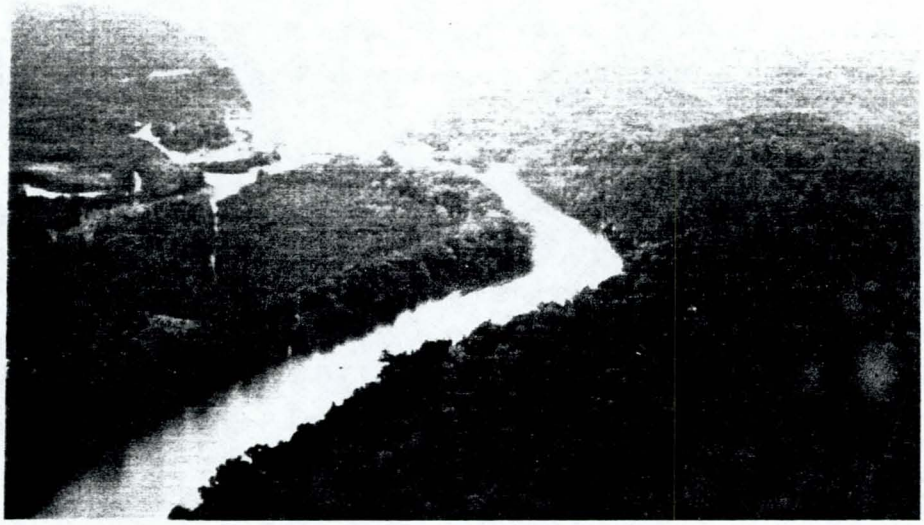


Figure 2.1.9. Regulated river.

Figure 2.1.10. Delta.

Underfit streams. Underfit stream are common in glaciated regions such as the northern Great Plains. They are generally small irregularly sinuous streams occupying a wide valley bottom that was formed and occupied by a much larger stream - usually the outflow from a glacial lake - near the end of the last glacial period. The slope along the valley bottom tends to be quite flat and the underfit stream is usually of low velocity, relatively stable, and with well vegetated banks. Sometimes the planform is highly contorted. Sometimes they may be realigned and shortened with relative impunity.

Cohesive channels. Channels in cohesive materials may be found in a variety of environments including glacial till plains, coastal marine deposits, filled lakes, etc. Channels in till tend to have irregular planforms: the occurrence of an occasional sequence of regular meanders may indicate intersection with an infilled alluvial channel. In uniform marine clays, channels sometimes exhibit a series of uniform wide flat meanders easily distinguished from meanders in alluvial materials. The stability of channels in cohesive materials may vary widely, but it is generally greater than in alluvial materials.

2.1.3 Channel geometry and processes. Channel geometry has four main components: planform, cross-section, slope (gradient), and bed topography. The term 'channel processes' generally refers to natural changes in planform, cross-sectional boundaries, longitudinal profiles, and bed topography.

Planforms. Stream planforms were once roughly classified as braided, meandering and straight but a wide variety of natural forms is now recognized. Figure 2.1.11 shows a more extended set of descriptions with associated environmental conditions.

Relationships between planform and other aspects of geometry and processes are difficult to systematize, although often appreciated intuitively from long experience of river observation. For example, braided rivers are usually wide and shallow and the limits of the braided area tend to remain relatively stable. Certain types of sinuous planform generally indicate a systematic process of down-valley meander migration, while others indicate a process of periodic bend cutoffs. Streams with highly contorted meandering planforms tend to have relatively flat slopes and low width-to-depth ratios. Figure 2.1.12 shows a diagrammatic association of planform type with other stream characteristics, and Figure 2.1.13 illustrates various forms of meander shifting.

The total length of most natural streams does not change appreciably over time despite dynamic changes in planform and channel location. For example, local shortening produced by occasional meander bend cutoffs is usually compensated by gradual lengthening of other bends. Where overall shortening is imposed - as for example by the Mississippi River cutoff program of the 1930s - the stream often responds by attacking banks and developing new meanders in an attempt to restore the original length.

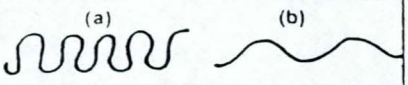
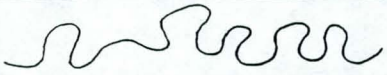
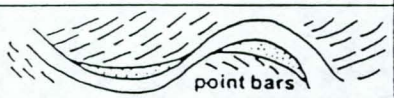
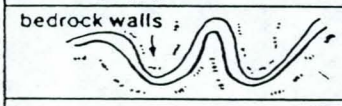
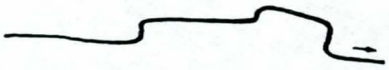
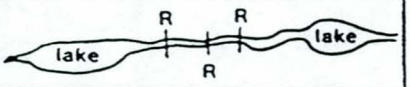
CHANNEL APPEARANCE	CHANNEL TYPE	TYPICAL ENVIRONMENT	TYPICAL BED AND BANK MATERIALS
	(a) Regular serpentine meanders (b) Regular sinuous meanders	Lacustrine plain	Uniform cohesive materials
	Tortuous or contorted meanders, no cutoffs	Misfit stream in glacial spillway channel	Uniform cohesive materials
	Downstream progression	Sand-filled meltwater channel	Slightly cohesive top stratum over sands
	Unconfined meanders with oxbows, scrolled	Sandy to silty deltas and alluvial floodplains	Slightly cohesive top stratum over sands
	Confined meandering	Cohesive top strata over sand substratum in steep-walled trench	Slightly cohesive top stratum over sands
	Entrenched meanders	Hard till or uniform rock	Till, boulders, soft rock
	Meanders within meanders	Underfit streams in large glacial stream spillways	Cohesive materials
	Irregularly sinuous meanders	Thin till over bedrock in plains	Hard and softer materials
	Wandering	Foothills and mountain valleys	Cobble-veneered sand
	Anastomosing	Foothills, plains. Sand bed or gravel paved rivers	Sand and gravel
	Classical braided	Glacial outwash. Foothills	Sand and gravel
	Dichotomic	Alluvial cones and fans	Gravel, sand, silt
	Irregular channel splitting	Large rivers in bedrock	Alternate sand, gravel and rock
	Rectangular channel pattern	Jointed rocks, mostly flat-lying sedimentary rocks	Rock
	Lakes and rapids (R)	Till-veneered Shield terrain	Till, cobbles, boulders, hard rock

Figure 2.1.11. Some forms of stream planform (after Mollard and Janes 1984).

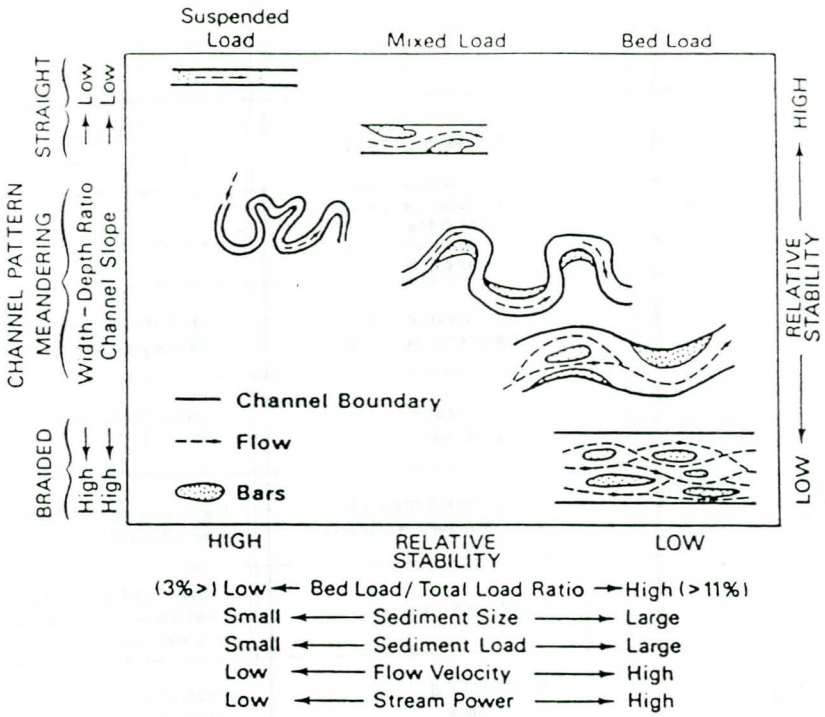


Figure 2.1.12. Association of planform type with other stream characteristics (after Schumm 1981).

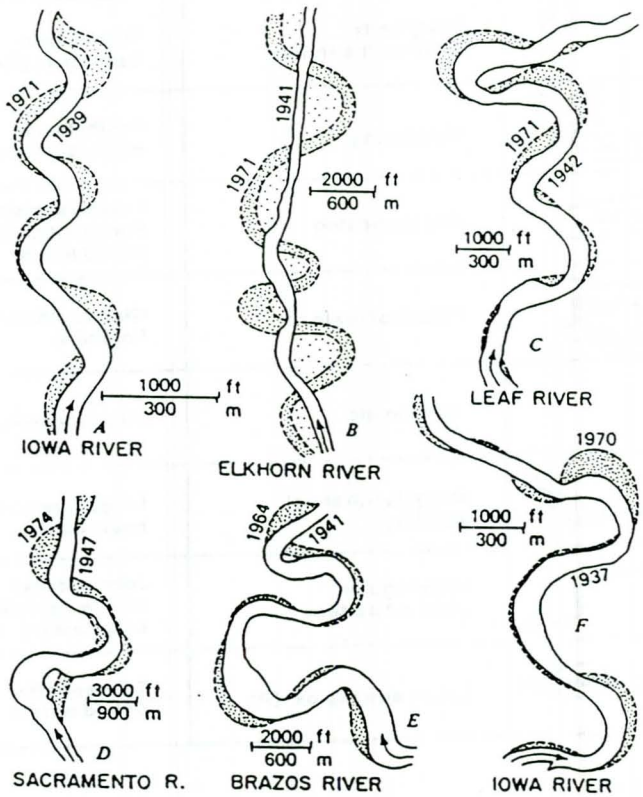


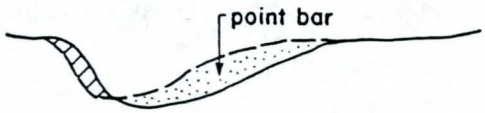
Figure 2.1.13. Examples of meander shifting and bank erosion (after Brice 1983).

Cross-sections. The cross-section of a natural channel depends on basin runoff, sediment input, and boundary soils and vegetation, as explained further in Section 2.2. Under natural conditions the average cross-section does not change much over a period of years, but it may alter temporarily in severe floods. Systematic trends of enlargement or shrinkage usually result from changes in discharge or sediment inputs as a result of basin changes or on-stream works. The variability of cross-sections from point to point along the channel depends on many factors: it may be quite small in stable nearly-straight channels, and very large in highly active channels of complex planform.

The process of cross-section enlargement by erosion is easy to visualize. The mechanism of shrinkage is less easy to visualize and varies considerably (Figure 2.1.14). In a more or less straight channel, it can occur as a result of deposition of suspended sediment on the banks and subsequent colonization by vegetation. In a shifting meandering channel, shrinkage will occur if deposition of sediment on the inner bank of bends outstrips erosion on the outer bank.

(a) Cross-section enlargement by bed scour and bank erosion.

(b) Cross-section shrinkage (straight channel) mainly by suspended sediment deposition.



(c) Cross-section shrinkage (meandering channel) by inner bank (point bar) deposition outstripping outer bank.

Figure 2.1.14. Mechanisms of cross-sectional adjustment to altered inputs of water and sediment.

A method for comparing cross-sections along a channel reach, or for establishing an average cross-section to estimate overall channel characteristics, is to establish a sloping reference plane parallel to the average water surface of a substantial but within-bank flow. The elevation of the reference plane is then transferred to each cross-section for visual comparison of sections relative to the plane. Widths and areas can be determined at various levels above and below the reference plane, and can be averaged to indicate average section properties at various levels relative to the plane. The same reference plane should be used as a basis for successive surveys to compare changes over time.

When making hydraulic computations of channel capacities and water surface profiles for active mobile-boundary streams, it is important to realize the transitory nature of cross-sections. Although the average channel cross-section over a long reach may be similar under low-water and flood conditions, individual cross-sections may change substantially according to the stage of flow. For example, bends and scour holes in meandering channels normally deepen in floods, and points of inflection ('crossings') tend to shoal. When water surface profiles are modelled using standard computational procedures that assume fixed boundaries, careful consideration should be given to possible cross-sectional changes from low to high flow conditions.

Further hydraulic difficulties with unstable cross-sections arise when in-channel flows are to be systematically increased as a result of flood control, for example by construction of floodplain levees close to the channel. If the channel is left in its natural state, it may enlarge systematically over a period of time as a result of erosion by the increased flows. Actual flood levels would then tend to be lower than those computed using existing cross-sections. On the other hand, if the channel is designed to be enlarged by excavation, the cross-sections provided may be partly infilled by sedimentation, in which case actual flood levels would be higher than computed.

A common error in designing modified channels for flood control is to provide too large a cross-section, intended to carry a rare flood without overbank flow. Such a cross-section is unlikely to maintain itself because it partly infills with sediment under more frequent flood conditions. Although a need for dredging or excavation to maintain the enlarged channel may be recognized and provided for in project agreements, experience has shown that it is often difficult to enforce maintenance obligations.

Slopes and profiles. The longitudinal profile of a stream is only partly determined by the landscape. The valley slope is not necessarily the land slope, and the slope along the channel is flatter than the valley slope unless the channel is straight. In many cases, the channel slope represents a longterm equilibrium condition. When a meandering stream is straightened, a steeper non-equilibrium slope is temporarily imposed. Responses in the form of erosion and sedimentation are then set in motion, in the direction of restoring equilibrium. Although the slope of a stream

usually flattens gradually from source to mouth, local anomalies due to geological controls and other factors are common: for example, the slope will be flatter upstream of a bedrock sill, and steeper below a tributary that delivers quantities of coarse sediment. Reduction of slope from head to mouth along a stream is related to changes in other characteristics; sometimes changes are relatively abrupt (Figure 2.1.15).

Processes of channel profile change through time at rates of engineering concern are usually referred to as aggradation and degradation (Figure 2.1.16). For example, aggradation tends to progress upstream from a dam or grade control structure, and degradation to progress downstream from a structure that traps sediment. A process referred to as "headcutting", common in channelized streams, involves degradation progressing upstream, often accompanied by aggradation progressing downstream. The upstream end of a headcut is called a "nick point", or "nick zone" if it is extended along the stream.

Bank erosion. Bank erosion and/or failure is probably the most widespread stability problem in flood control channels and streams generally. Often it has both hydraulic and geotechnical aspects. In many cases, erosion due to hydraulic forces at the foot of the bank or at least below the water surface is the most important driving mechanism, although in the immediate sense the bank may be failing due to oversteepening and geotechnical instability. Erosion due to hydraulic forces may be the expression of general channel processes such as meander migration or profile degradation, or it may reflect quite local conditions. In other cases (notably streams regulated by dams where natural erosive forces have been reduced) geotechnical instability persisting from past oversteepening, or associated with groundwater conditions and local runoff, may be the main factor in bank failure rather than hydraulic erosion. Other contributing factors may include waves and turbulence from vessels, freezing and thawing, piping, rapid drawdown of water levels, ice and drift, and loading of overbank areas by fills.

Rates of bank erosion vary greatly in different environments, even among streams of apparently similar type. Controlling factors include climate, bank soils and stratigraphy, river bed materials and stratigraphy, extent and rapidity of waterlevel fluctuations, and nature and density of bank and floodplain vegetation. Removal of vegetative cover and root systems is often an important cause of accelerated bank erosion. Table 2.1.2 lists bank erosion rates for a set of rivers of different sizes and types.

Bed topography and roughness. The bed topography and hydraulic roughness of natural channels may vary greatly along the channel and also with stage of flow. The total hydraulic resistance results from a combination of "grain roughness" and "form roughness". Form roughness can arise from bed and bank irregularities and from changes in planform. In active sand channels, "bed forms" may range from small ripples a few inches in height, to dunes a few feet in height, to

Table 2.1.2 **Miscellaneous reported rates of bank erosion (after Brice 1983)**

River and map reference (1)	Drainage area, in square miles (2)	Bank erosion rate, in feet per year (3)	Time period, in years (4)	River type (6)
1. Mississippi River (Fisk, 1944, pl. 22, sheets 11 and 12)	1,145,000	57.4	64 (1880-1944)	Sinuous point bar, locally braided.
2. Mississippi River (Fisk, 1944, pl. 22, sheet 13)	1,124,900	25.6	64 (1880-1944	Sinuous canaliform.
3. Yellowstone River (Crane 7½, Piche 7½, Savage 7½ Mont.)	69,100	15.4	29 (1938-67)	Sinuous braided and anabranched.
4. Apalachicola River (Orange 7½, Bristol 7½ Rock Bluff 7½, Fla.)	17,600	4.3	29 (1949-78)	Sinuous canaliform.
5. Sacramento River (Ord Ferry 7½, Llano Seco 7½, Calif.)	9,300	16.7	27 (1947-74)	Sinuous point bar, locally braided.
6. Elkhorn River (Valley 7½, Nebr.)	5,850	27.6	30 (1941-71)	Sinuous point bar, locally braided.
7. West Fork White River (Lyons 7½, Ind.)	4,700	5.6	29 (1937-66)	Sinuous point bar.
8. Iowa River (Hills 7½, Iowa)	3,300	2.8	33 (1937-70)	Sinuous point bar.
9. North Canadian River (Guymon NE 7½, Okla.)	1,200	14.8	30 (1936-66)	Sinuous braided.
10. Patoka River (East Mount Carmel 7½, Ind.--Ill.)	825	ND	29 (1937-66)	Sinuous canaliform.
11. Tallahala Creek (Ovett SE 7½, Miss.)	600	1.6	28 (1942-70)	Sinuous point bar.
12. Kanaranzi Creek (Adrian 7½, Minn.)	120	0.7	14 (1954-68)	Sinuous point bar.

Notes: ND = not detected.
Bank erosion rates are median values derived from a sampling and statistical procedure for specific lengths of channel.

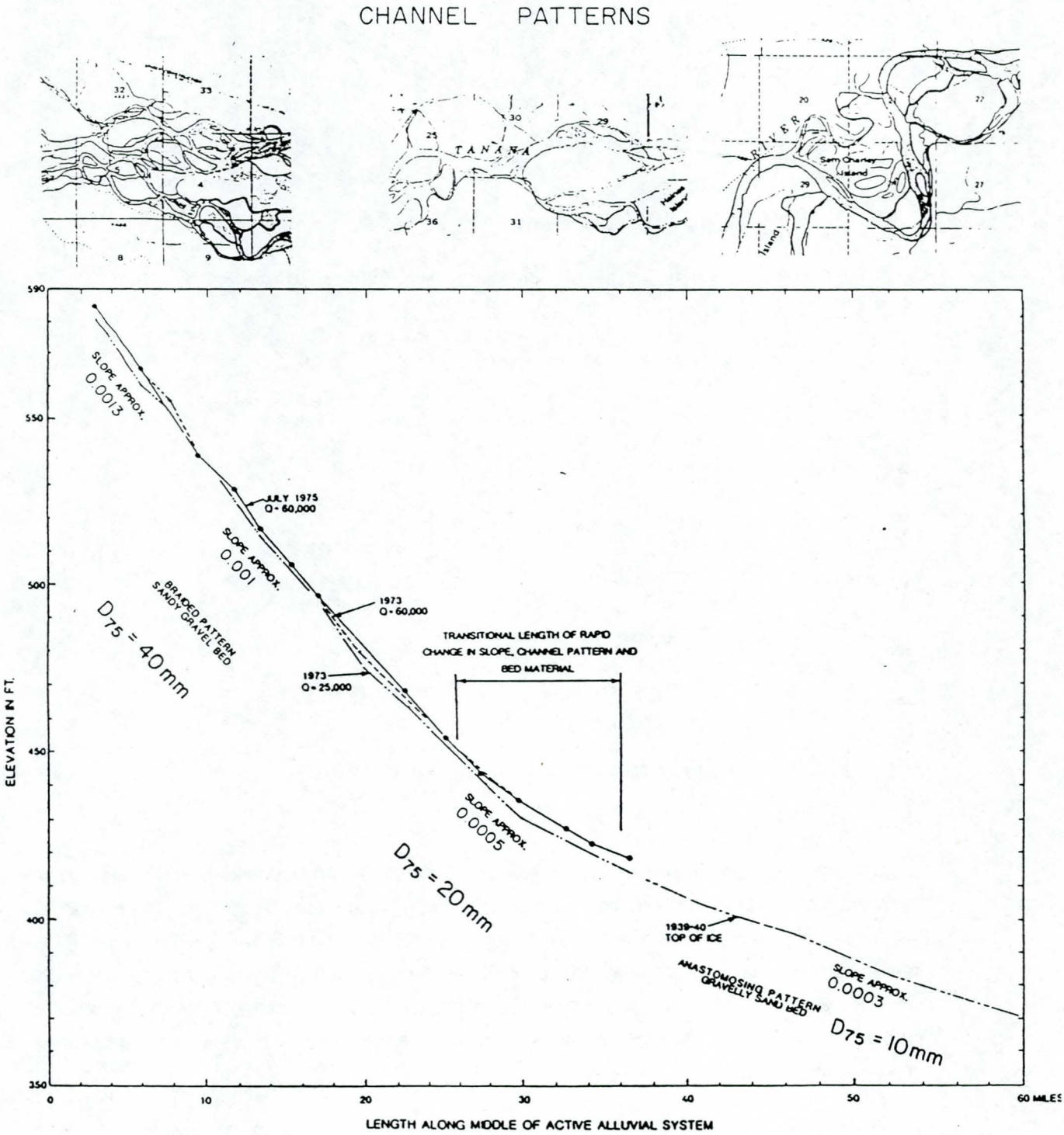


Figure 2.1.15. Associations between slope, planform and bed-material, Tanana River near Fairbanks, Alaska (after CRREL 1984).

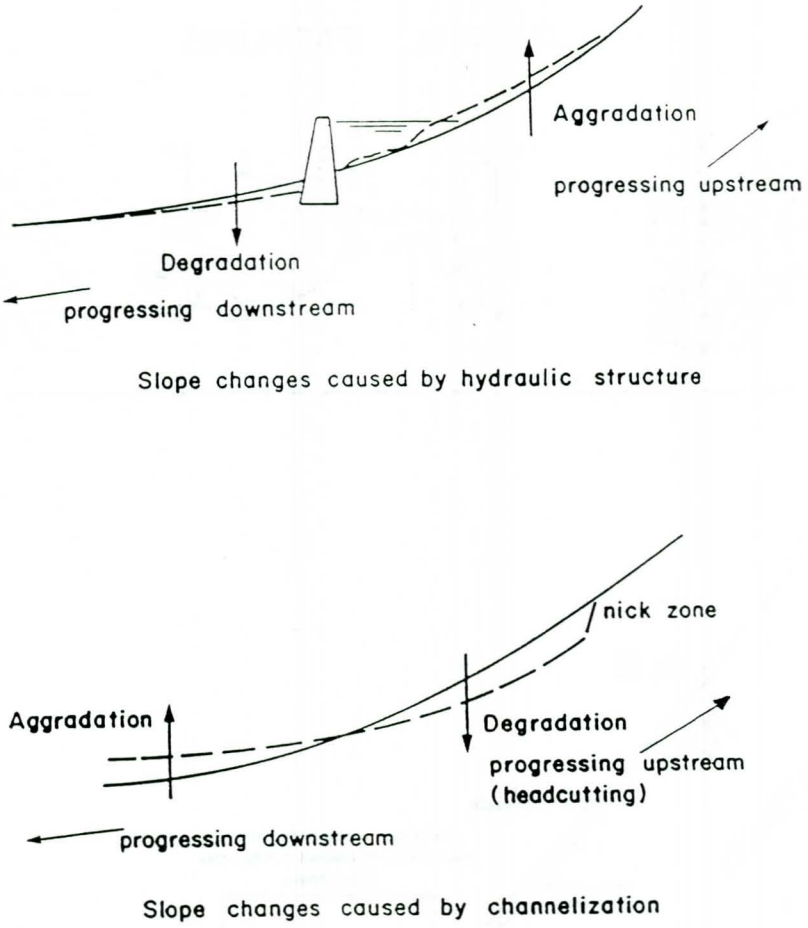
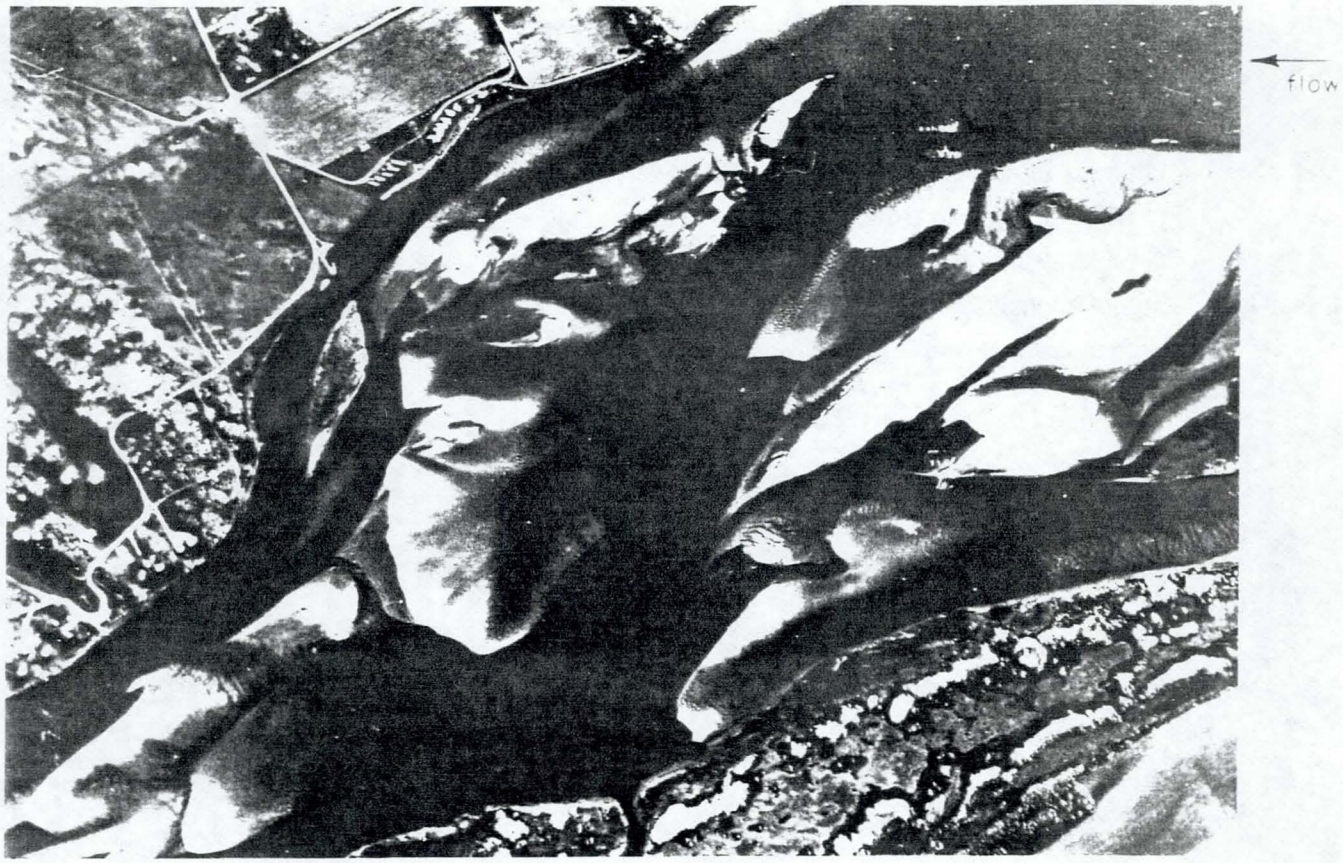


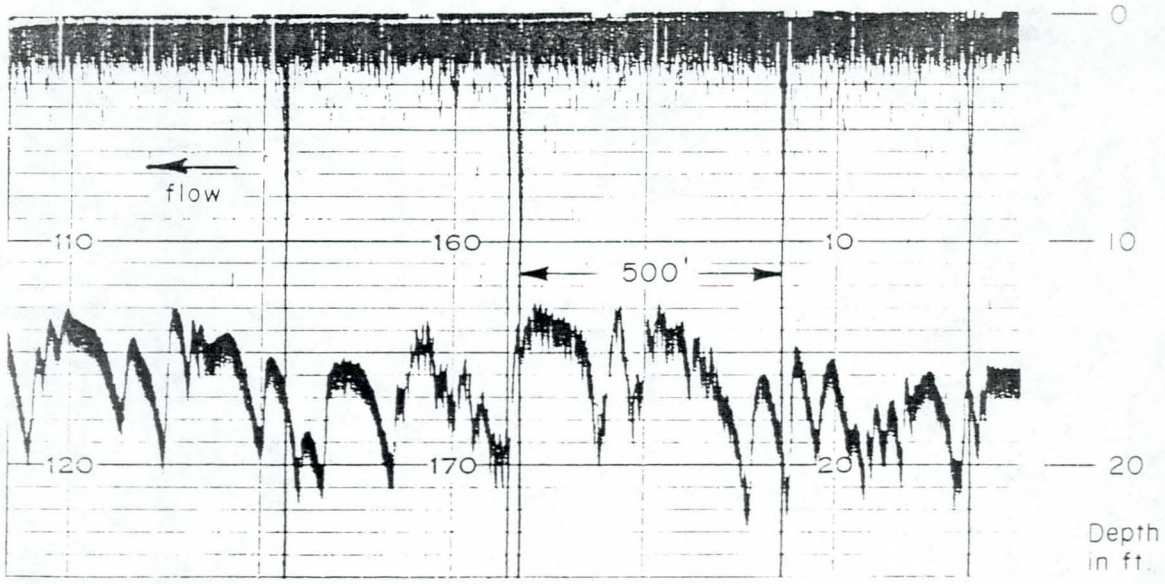
Figure 2.1.16. Processes of channel slope change.

larger waves and bars (Figure 2.1.17). These forms depend on flow conditions and mainly control the hydraulic roughness of the bed; also, the bed topography at any time depends on the preceding flow history as well as on present conditions. Roughness therefore varies with stage and is not always the same at similar stages - hence the looped or erratic stage-discharge curves found in many alluvial streams. Other important sources of form roughness are trees and bushes, river bank protection and structures, floodplain obstructions bedrock outcrops, bends and scour holes, and abrupt changes in cross-section.

In gravel streams, bed forms tend to consist mainly of large flat bars, and roughness is more strongly dependent on bed-material grain sizes. In the case of very coarse bed materials like cobbles and boulders, grainsize roughness is the main component of total roughness.



Plan



Longitudinal profile in main channel

Figure 2.1.17. Bed forms in sand (Missouri River).

When discharges are augmented by flood control works, the prevailing type of bed topography may alter significantly. For example, steep sand streams with high sand transport undergo an abrupt change at a certain flow threshold, whereby the bed forms "wash out" and a more or less flat bed with reduced roughness results (Figure 2.1.18). This phenomenon tends to reduce flood levels, but to increase velocities with adverse consequences for channel stability. It may cause abrupt anomalies in stage-discharge curves. In some sand-bed channels, bed topography and roughness may also respond to changes in water temperature at a constant flow.

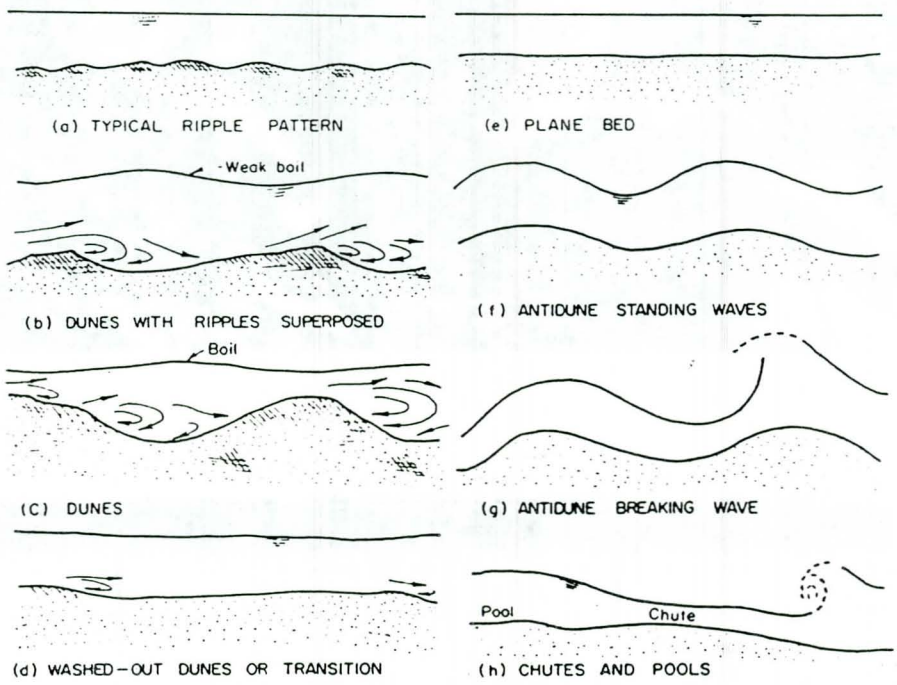


Figure 2.1.18. Response of bed forms in sand to increasing discharge [a through h] (after Simons, Richardson and Nordin 1965).

2.2 Principles of channel equilibrium and response

2.2.1 Basic concepts. The concept that the cross-section and slope of a channel in erodible materials tend to be in a state of equilibrium was developed more or less independently by engineers seeking to design unlined canals that would neither silt nor scour, and by geomorphologists studying the relationship of river channel geometry to hydrologic and environmental factors. The engineering concept was initially expressed by the term "regime channel" and the geomorphologic concept by the term "graded river". Some key quotations are as follows:

"When an artificial channel is used to convey silty water, both bed and banks scour and fill, changing depth, gradient and width, until a state of balance is attained at which the channel is said to be in regime" (Lindley 1919).

"The graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for transportation of the load from the drainage basin" (Mackin 1948).

"Similar equations (for hydraulic geometry) apply both to rivers and to stable ("regime") irrigation canals which neither scour nor aggrade their beds. The analogy demonstrates that the average river channel-system tends to develop in a way to produce an approximate equilibrium between the channel and the water and sediment it must transport" (Leopold and Maddock 1953).

The equilibrium or regime concept has been tested against sets of river and canal data from various parts of the world. (For reviews see Graf 1971, Mahmood and Shen 1971, Nunnally and Shields 1985). Channel widths, depths and slopes are usually plotted independently against a characteristic discharge. Plots are sometimes stratified according to bed-material size or other factors. Curves or equations are fitted and recommended for various analysis and design purposes. The general trend of plots by various investigators is illustrated in Figure 2.2.1. A number of specific plots of data sets are shown in Appendix A.

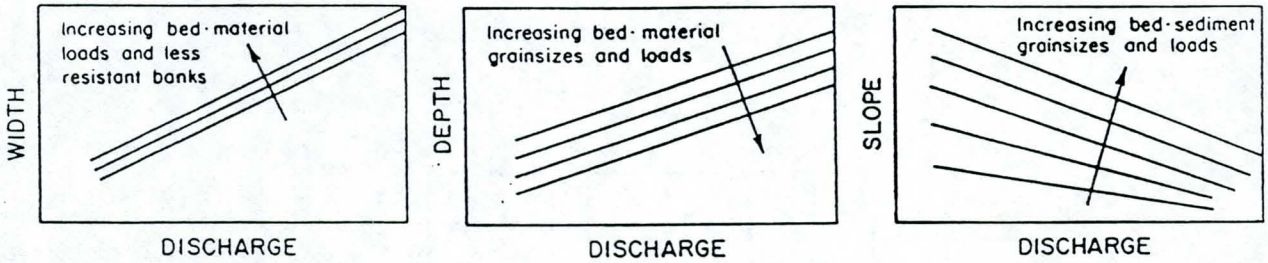


Figure 2.2.1 General trend of hydraulic geometry plots for channels in erodible materials.

The above-described approach to stability assessment and channel design is essentially empirical. It has been regarded cautiously by many hydraulic engineers because of lack of theoretical verification and sometimes because relationships derived from one region did not fit experience elsewhere. An article published in 1987 criticizes various aspects of the traditional approach, but concludes:

"Lindley's regime concept that an alluvial channel adjusts its width, depth and slope in accordance to the amount of water and the amount and kind of sediment supplied remains unchallenged here. Regime channels are those flowing in their own sediment" (Stevens and Nordin 1987).

Because the term "regime" has given rise to some confusion and controversy, it will be avoided herein where possible. The concept embodied in the above quotations will be called the "equilibrium concept" of channel formation and response. Relationships of channel dimensions and slope to discharge and other parameters will be called "hydraulic geometry". The user should be aware, however, that much literature from other countries refers to the regime concept or theory, and to regime relationships, with more or less the same general meanings.

2.2.2 Applicability to flood control projects. Reduced to essentials, the equilibrium concept implies that stable width, depth, slope (and perhaps planform) can be expressed as functions of controlling variables: discharge, boundary materials and sediment supply (Figure 2.2.2). Use of hydraulic geometry relationships may be useful in the planning stages of a flood control project for comparing alternatives and assessing certain stability problems.

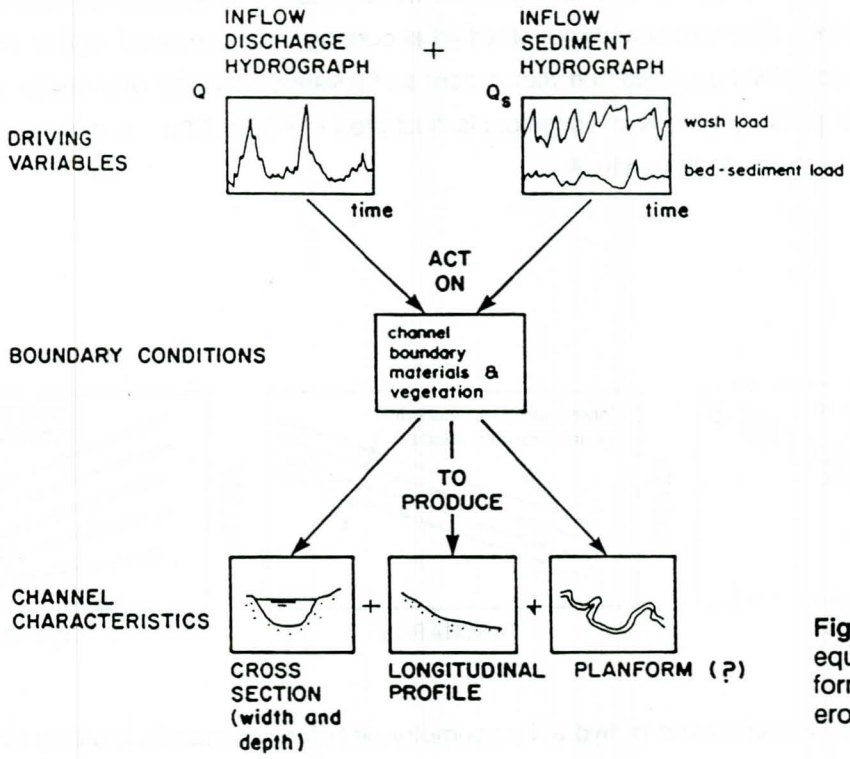


Figure 2.2.2. Generalized equilibrium concept for formation and response of erodible channels.

The concept of "degrees of freedom" is useful in visualizing forms of potential instability in erodible channels caused by changes in controlling variables. As a general case, a channel may have up to four degrees of freedom: that is, it can adjust its planform, width, depth and slope. (Other factors like roughness and sediment transport may also adjust, but not independently.)

Some difficulties that arise with the equilibrium concept are discussed below:

(1) Hydraulic geometry relationships generally refer to width, depth and slope, but not planform. Stability problems related to planform, for example whether meanders will develop in an initially straight channel, therefore seem to be outside the scope of traditional equilibrium concepts. Meander geometry is discussed in Section 2.3.9.

(2) Most hydraulic geometry relationships utilize a single characteristic discharge, intended to be representative of the actual varying discharges, as a primary independent variable. In natural streams this is often taken as the bankfull discharge, or a more or less equivalent flood-frequency parameter. The terms "channel-forming" and "dominant" discharge have been widely used in the literature, and are discussed further in Section 2.2.3.

(3) The primary role of discharge in determining channel cross-sections is clearly demonstrated, but there is a lack of consensus about which secondary factors like sediment loads, native bank materials and vegetation are significant, particularly with respect to width.

(4) The earlier hydraulic geometry relationships did not provide explicitly for sediment transport, and were therefore basically applicable to channels with relatively low bed-sediment inflows. Equilibrium slopes indicated by such relationships may be too flat to maintain transport of sediment in channels with substantial bed-material inflows. Some hydraulic geometry relationships incorporating sediment transport have been published (eg. White el al 1981), but the difficulty remains that at the planning stage of a project actual sediment inflows are seldom known. Information on assessing sediment inflows can be found in EM 1110-2-4000 (USACE 1989).

A method of applying equilibrium concepts, that avoids acceptance of relationships established in distant environments, is to develop local or regional hydraulic geometry relationships for the class of channels of interest. Derived relationships can then be applied to estimate flood control channel dimensions or responses in a particular stream. For example, in considering possible width adjustments resulting from augmentation of flood discharges, a locally-developed width-discharge plot would be used rather than a published plot derived from another region. Figure 2.2.3 shows an example.

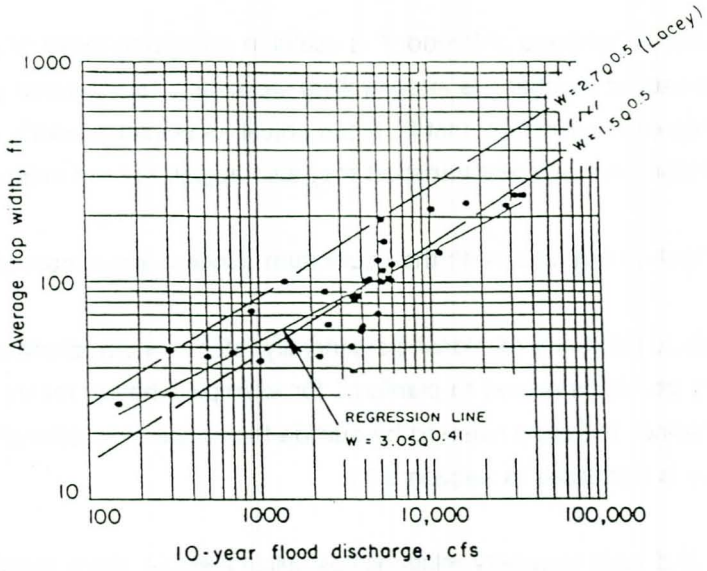


Figure 2.2.3. Width-discharge plot for specific local set of channels. (Note: 10 year discharge used because of special local circumstances).

2.2.3 Response of channels to altered conditions. If the controlling variables or boundary conditions (see Figure 2.2.2) are altered, the stream or channel will respond by altering cross-section, slope or planform. "Any project that changes sediment quantity or quality, alters discharges, or disrupts the geometry of a river, will always activate changes to some degree in all the other variables" (Winkley 1972).

It is often difficult to determine to what extent observed post-project instability represents a response, or whether it might have occurred in any case as a result of pre-project processes. This is especially difficult where the stream has a history of successive modifications from a long-ago natural state. In some cases, long-term responses to a historical sequence of interferences may be extremely difficult to distinguish.

Although initial response may occur mainly within the project length, long-term response may affect the stream system far upstream and downstream, including tributaries and distributaries. Where a pre-project stability assessment indicates potential problems, stabilization measures such as bank protection, grade control structures and sediment basins are often incorporated in the design. This will not necessarily eliminate upstream or downstream responses. For example, if a stream has migrating meander bends, stabilizing the bends within the project length may impact on bend migration processes upstream and downstream.

Table 2.2.1 indicates the general direction in which channel characteristics can be expected to respond to changes in driving variables or boundary conditions (see also Figure 2.2.1).

Table 2.2.1 Expected response of channel characteristics to changes in driving variables or environmental conditions (see Figure 2.2.2)

Variable subject to imposed change	Nature of change	Expected change in channel characteristics				
		Width	Depth	Slope	Planform type	Bank erosion
discharges	increased	increased	increased	reduced	no marked change	increased
	reduced	reduced or unchanged (1)	reduced	increased or unchanged (1)	no marked change	reduced
bed-sediment inflows	increased	unclear	reduced	marked increase	increased bars & channel splitting	may increase
	reduced	unclear	increased	reduced	less channel splitting	may reduce
bed-sediment grainsize	increased	insignificant	reduced	marked increase	unclear	unclear
	reduced	insignificant	increased	may reduce	unclear	unclear
bank conditions	add bank protection	may reduce	may increase locally	no marked change	as imposed	reduced locally, may increase downstream
	removal of woody vegetation	increased	may reduce	no change	increased bars	marked increase

(1) depending on availability of sediment for deposition

Some additional comments are as follows:

(1) Widths generally vary more or less as the square root of discharges, other things being equal. A widening response to increased flood discharges can generally be expected. In the case of reduced discharges, ultimate narrowing can be expected if the channel carries enough sediment to deposit on the banks or on side bars.

(2) In the case of meandering planforms, meander wavelength tends to maintain a more or less constant relationship to channel width. Increased flood discharges therefore tend to increase meander wavelength as well as width.

(3) The response of width to changes in bed sediment inflows is indicated as "unclear". Generally, channels with relatively high bed-material loads tend to be wider, but a channel with erosion-resistant banks will not necessarily widen in response to increased load.

(4) Depths increase with increasing discharges, but not so much as widths (Figure 2.2.1). Depths will generally reduce with increased bed-material inflow, as slopes increase (see below).

(5) Slopes vary inversely with discharges (Figure 2.2.1), and tend to reduce by degradation if flood discharges are increased. Slopes tend to increase by aggradation if bed-sediment inflows are increased, and depths reduce correspondingly. Increases in discharge and in bed-material input therefore have opposite effects on slope and may largely cancel out if they occur together, for example as a result of upstream deforestation.

A generalized slope relationship by Lane (1955) can be expressed in the form:

$$S \propto Q_s^a D^b / Q^c \qquad \text{(Eq. 2.2.1)}$$

where S is slope, Q_s is bed-sediment discharge, D is a representative diameter of bed material, and Q is discharge.

This form of relationship also applies in reverse to indicate that imposed increases in slope lead to an increase in bed-sediment transport. If a sinuous channel is straightened an increased slope is imposed. Increased bed-material transport occurs out of the straightened reach, causing degradation upstream and aggradation downstream. The channel thereby attempts to re-establish the original slope.

(6) Channel planform type responds to changes in bed-sediment input if discharges remain unchanged. Generally, increasing bed-sediment loads produce a more disorganized pattern with exposed bars. A densely braided pattern is the extreme example.

(7) Bank erosion and channel shift rates are sensitive to increased in-channel discharges and reduced bank resistance, particularly removal of woody vegetation. (Flood control levees may be an important reason for increased in-channel discharges).

2.2.4 Channel evolution and geomorphic thresholds. The sequence of responses to certain imposed changes, for example channelization, can be quite complex. An initial profile response may involve temporary aggradation while a later or final condition may involve degradation below original levels (Figure 2.2.4). Similarly, bed degradation may undercut high banks and deliver quantities of sediment that temporarily halt or reverse degradation at downstream points. The equilibrium concept generally refers to a supposed final condition following response to a change. In some cases, however, intermediate conditions during the evolution to an eventual equilibrium may be of equal interest.

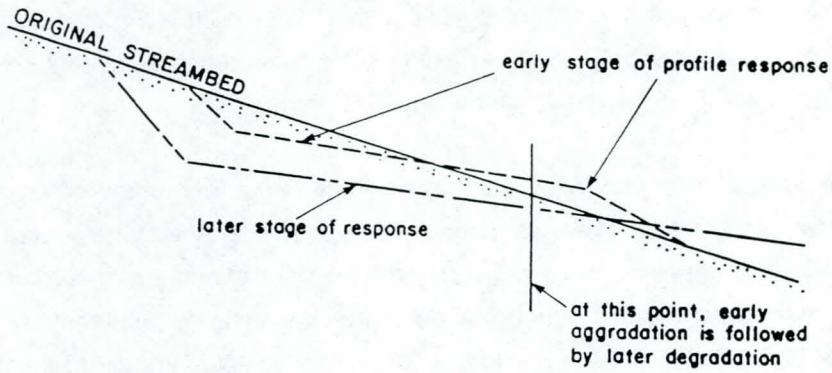
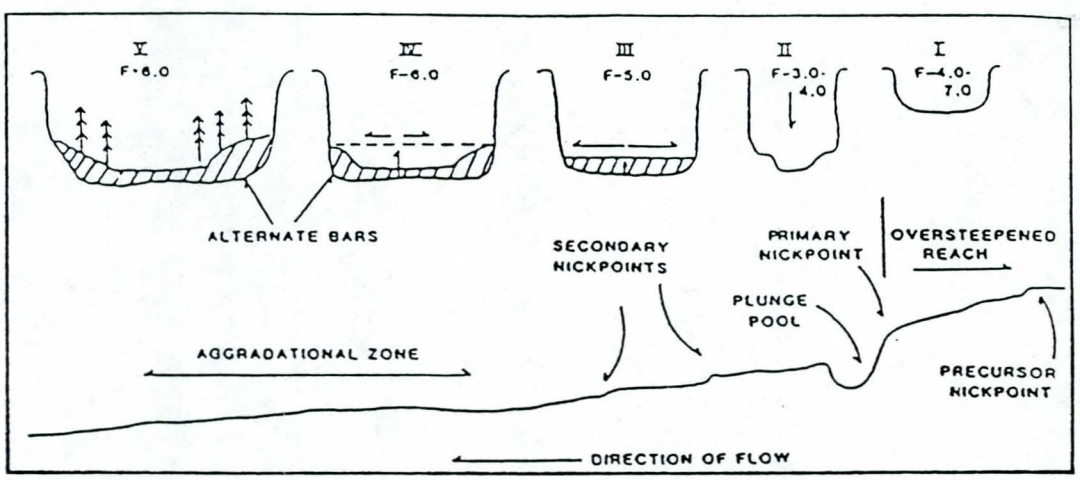


Figure 2.2.4. Example of complex profile response to channelization.

Conceptual models of evolutionary response to certain types of channel modification have been developed from field studies. Figure 2.2.5 shows a scheme developed for incised channels in northern Mississippi, where a complex sequence of responses has occurred as a result of historic basin erosion and sedimentation, past flood control channelization, and alteration of main-stem base levels (Schumm et al 1984). The model considers cross-sections and slopes, but not planforms. A space-time substitution is implied, whereby the illustrated sequence of cross-sectional types represents a down-channel progression at a point in time, but can also represent time-dependent progression at a point on the channel.



Notes: 1. F = width to depth ratio
2. See text for explanation of space and time progression

Figure 2.2.5. Channel Evolution Model for incised channels (Schumm et al 1984).

Quantitative analysis of response time sequences - for example, profile degradation following reduction of bed sediment supply - requires use of some form of computational process model. EM 1110-2-4000 (USACE 1989) should be consulted for information.

Some types of response may occur quite abruptly when one of the controlling variables passes a certain value. Cases of natural streams have been described where relatively small changes in climate or land-use appear to have triggered large changes in channel characteristics. These phenomena are expressed by the concept of geomorphic thresholds (Schumm and Beathard 1976, Ferguson 1984). Reliable data for numerical definition of thresholds appear to be scarce.

Various sets of data have been analyzed to discriminate between single and braided channels on the basis of discharge, slope and (in some cases) bed-sediment grainsize (see for example, Leopold Wolman and Miller 1964, Ferguson 1984, Struiksma and Klaassen 1988, Kellerhals and Church 1989). These show that for a given bed sediment and characteristic discharge, braiding is associated with higher slopes. This suggests that if a single channel is subjected to increasing bed-sediment inflows that cause slope to increase, a point will be reached at which braiding develops; however, this may not be possible if the channel is confined by resistant banks. Figure 2.2.6 shows a composite plot of braiding criteria.

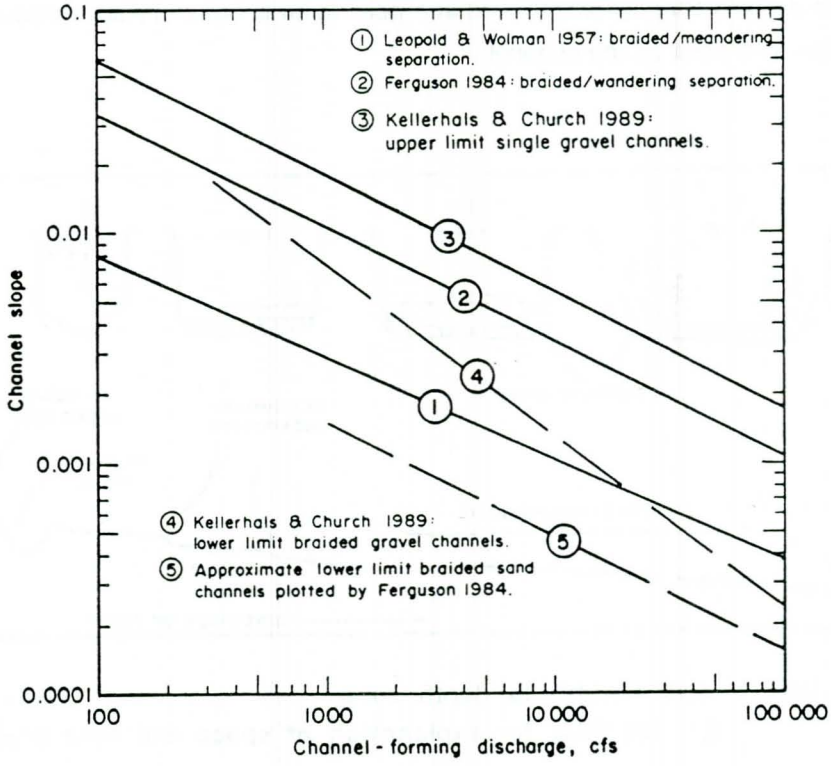


Figure 2.2.6 Slope-discharge chart distinguishing braided from non-braided channels.

2.2.5 Hydraulic and geotechnical controls. The main driving variables and boundary conditions that affect channel characteristics and response are discussed further below (see also Figure 2.2.2 and Table 2.2.1):

Discharge. A single discharge value is normally used in hydraulic geometry relationships to represent the spectrum of actual discharges. This discharge is sometimes called "channel-forming" and sometimes "dominant". Because "dominant" is sometimes used in a different sense in relation to sediment transport, the term "channel-forming" will be preferred herein.

In natural streams the channel-forming discharge can usually be taken as equivalent to the bankfull discharge. In terms of flood frequency, a return period of around 2 years appears to be common in the eastern half of the United States. In most cases a return period between 1 and 10 years is appropriate. The question of channel-forming discharge in modified channels is referred to in Chapter 5.

Sediment inflows. In regarding sediment inflows as an external control on channel equilibrium (Figure 2.2.2), it is implied that a sequence of sediment discharges enters the reach of interest, more or less independent of conditions within the reach. In fact, however, part of the sediment load interchanges with the channel boundaries and can accumulate within a reach or be augmented by erosion within the reach.

Sediment in streams can be divided into bed-material load and wash load (Figure 2.2.7). **Bed-material load** consists of grain sizes found in significant quantities on the bed. It travels either as bed load in contact with the bed, or as bed load plus suspended load when velocities are high enough. The rate of bed-material transport in both cases is a function of the hydraulic properties of the flow - velocity, depth and so on. **Wash load**, on the other hand, consists of finer grain sizes not found on the bed - usually very fine sand, silt and clay - and is all transported in suspension. Most channels can transport practically all the wash load received from basin erosion, so that the transport rate is determined by supply. Wash load travels through the channel to its destination in a static water body, and does not interchange significantly with the stream bed.

Bed-material load has an important influence on channel slope, planform and cross-section, as indicated by Table 2.2.1. Generally, increased bed-material load tends to reduce channel stability, because it forms local deposits which divert flow against banks and so on. Increased wash load, on the other hand, may increase stability, because it deposits silt and clay on banks during flood recessions, which tends to increase erosion resistance and promote vegetation growth.

In considering short term response to sudden slope changes - as from channel straightening - the slope may be regarded as a controlling variable and the bed-material load as

dependent. Eq. 2.2.1 is then inverted to the form:

$$Q_s \propto S^d Q^e / D^f \qquad \text{(Eq. 2.2.2)}$$

In the long term, however, the slope will readjust to the longterm bed-material input from the basin.

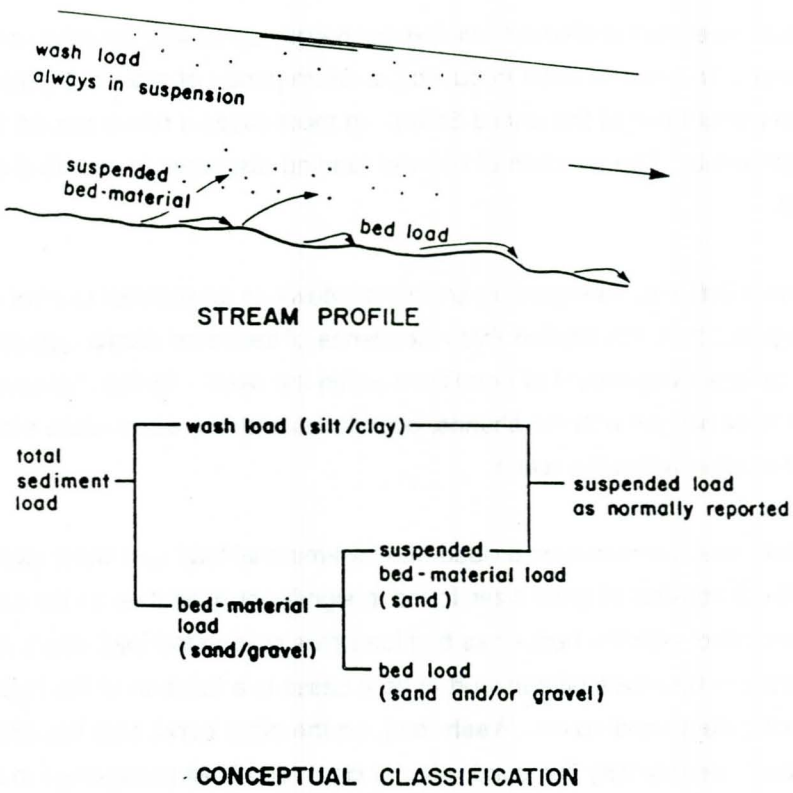
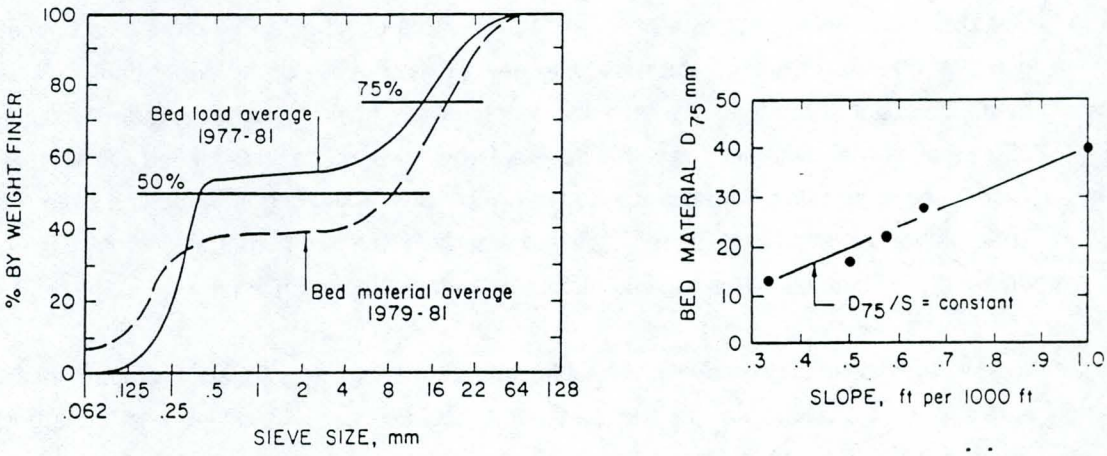


Figure 2.2.7. Classification of stream sediment loads.

Bed-material size. The grain size distribution of channel bed sediments is often characterized by D_{50}, the median size by weight. This simplification is acceptable for materials with a unimodal grainsize distribution of modest range. It may be misleading for very widely graded materials, particularly for sand-gravel mixtures with a bimodal distribution where the computed D_{50} size may be almost absent.

Figure 2.2.8 (a) shows grainsize distributions of bed material and measured bed load in a sand/gravel river. Because material in the coarse sand and fine gravel categories is virtually absent,

the two distributions show D_{50} values of 8 mm and 0.4 mm respectively, which greatly exaggerates the overall difference. When the D_{75} size, which falls clearly into the gravel range, was used to represent the bed-material distribution, a good correlation was obtained with slope variation along the river (Figure 2.2.8 b).



(a) grainsize distribution at one station

(b) correlation of D_{75} with slope along river

Figure 2.2.8. Bed-sediment grain-size distributions and correlation with slope [Tanana River near Fairbanks, Alaska]. (CRREL 1984).

The channel characteristic most affected by bed-material size is slope. For example, channels in coarse gravel and fine sand respectively, equal in terms of channel-forming discharges and sediment inflows, might have slopes differing by more than one order of magnitude. The coarser and steeper channel would also have smaller depths and higher velocities. The influence of bed-material size on widths is relatively small and difficult to separate from other factors.

Bank materials and vegetation. These factors may affect channel width, planform stability and rates of channel migration.

For fully alluvial streams flowing within an envelope of self-deposited sediments, it is debatable whether bank materials should be considered as independent factors affecting channel characteristics (see Figure 2.2.2). Vegetation, however, is more clearly an independent factor. Instability is often triggered by the clearing of vegetation from streambanks, and sometimes by eroded and deadfall vegetation within the channel. The role of bank vegetation varies greatly with the region and type of vegetation. Vegetation has recently been treated as a variable in hydraulic geometry relationships (Hey and Thorne 1986).

Many erodible stream channels are bounded wholly or partly by clay, compacted silt and loess, glacial till, or glaciofluvial deposits laid down in earlier geological periods. Although channel widths in such cases are often similar to those of alluvial streams, responses to imposed changes tend to be slower. Analogy with similar cases in the region of interest is the best guide to predicting response.

The effect of geotechnical bank stability on channel characteristics is important in some environments. River engineers have tended to regard bank instability more as a consequence than a cause of channel instability, the reasoning being that collapse of the upper bank is initiated by hydraulic scour at the toe. Geotechnical mechanisms, however, appear to be significant primary causes of alluvial bank failures within several large drainage basins. Hagerty et al (1986) discuss sequences of alluvial bank failure and erosion of failed soil along streams and rivers. According to Thorne and Osman (1988), bank stability characteristics affect hydraulic geometry in both straight and meandering channels. This topic is discussed further in Section 2.3.8.

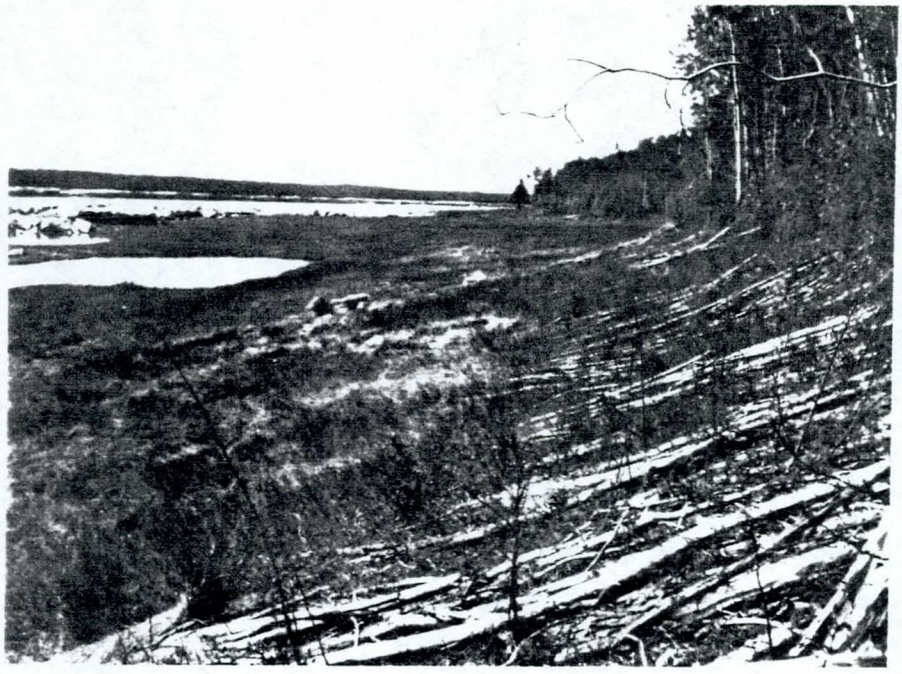
Ice and frozen ground. The influence of floating ice on channel characteristics and stability is relatively small except where the ice season is a large part of the year and the largest flows occur during ice breakup, as in Alaska and northern Canada. Channel characteristics in far northern regions include ice-formed features like boulder ridges and paving (Figure 2.2.9a), and peculiar forms of channel planform resulting from ice jamming. The direct erosive action of ice on river bank materials is generally small compared to that of flowing water, but ice easily removes vegetation up to the normal level of ice break-up (Figure 2.2.9b). Ice blockages can concentrate flows and cause bank erosion and bed scour at certain locations.

With regard to frozen ground, Gatto (1984) states:

"The effect of permafrost on erodibility is perhaps the factor about which there is most debate... Some investigators report that ice-rich permafrost increases bank recession... Other investigators conclude that frozen sediments are harder to erode..."

It therefore appears that frozen ground may accelerate or retard bank erosion, depending on the nature of the frozen sediments and the content of pure ice. Hydraulic geometry in cold regions does not appear to be greatly different from elsewhere, but frozen banks may exhibit unusual forms of erosion (Figure 2.2.10).

(a)



(b)

Figure 2.2.9. Ice effects on banks of northern rivers:
(a) boulder ridge
(b) vegetation trim line.

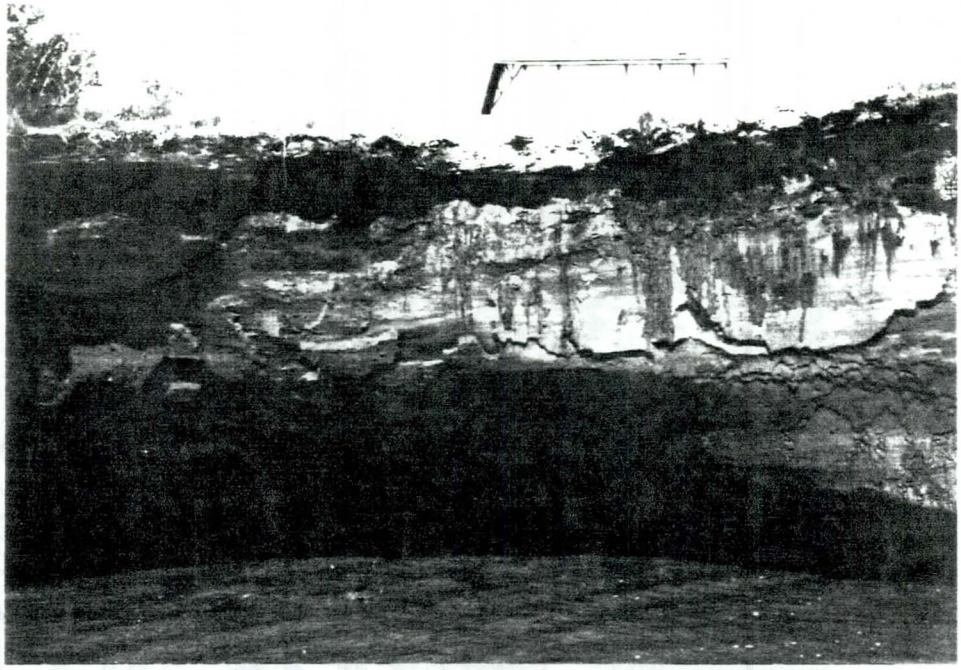


Figure 2.2.10. Undercut bank erosion in frozen fine-grained alluvium

2.3 Technical criteria for channel stability

2.3.1 General. Technical criteria applicable to channel stability problems include velocity, shear stress, stream power, hydraulic geometry relationships, sediment transport functions, and bank slope stability. The term "criteria" is used here to mean quantitative guidelines as given in technical references, with no implication of mandatory usage.

The criteria discussed here are partial in nature and do not provide a complete solution for evaluating channel stability. Technical criteria are best regarded as aids to judgment rather than as self-sufficient tools. For example, technical criteria alone cannot determine whether a given channel will be liable to meander development, because resistance to this type of instability is sensitive to factors like vegetation and cohesion that are difficult to quantify.

Adequate resistance to erosion does not necessarily produce stability if the channel has substantial inflows of bed sediment. The simpler criteria like allowable velocity or shear stress basically indicate what hydraulic conditions (velocity, depth, slope etc.) will initiate erosion in the absence of significant sediment inflows (see Figure 2.2.2). Modified or more complex criteria are required to take account of sediment inflows. In flood control channels, avoidance of sedimentation may be as important as avoidance of erosion. Focussing on an erosion criterion for channels with significant bed-sediment inflows may lead to sedimentation problems, because hydraulic forces as limited by the criterion may be too weak to maintain continuity of sediment transport.

Simple formulas for computing values of criteria - for example, the Manning velocity formula - generally yield a cross-sectional average value. This average value may be greatly exceeded at critical points where erosion occurs, for example on the outside bank of a bend. On the other hand, at points of sediment deposition the local value may be much less than the cross-sectional average. Adjustment factors for cross-sectional distribution may be needed in such cases.

The applicability and limitations of various specific criteria with respect to flood control channels are discussed below. When applying criteria to assessment and design, it is generally advisable to check two or more approaches. Application to stability evaluation is discussed further in Chapter 5.

2.3.2 Allowable velocity. The concept of allowable maximum velocities for various soils and materials has a long history. Table 2.3.1 shows mean velocity data provided as a rough guide in EM 1110-2-1601 (USACE 1970). Suggested values of allowable velocity for stability evaluation are presented in Chapter 5.

Table 2.3.1 Example of allowable velocity criteria (from EM 1110-2-1601, 1970)

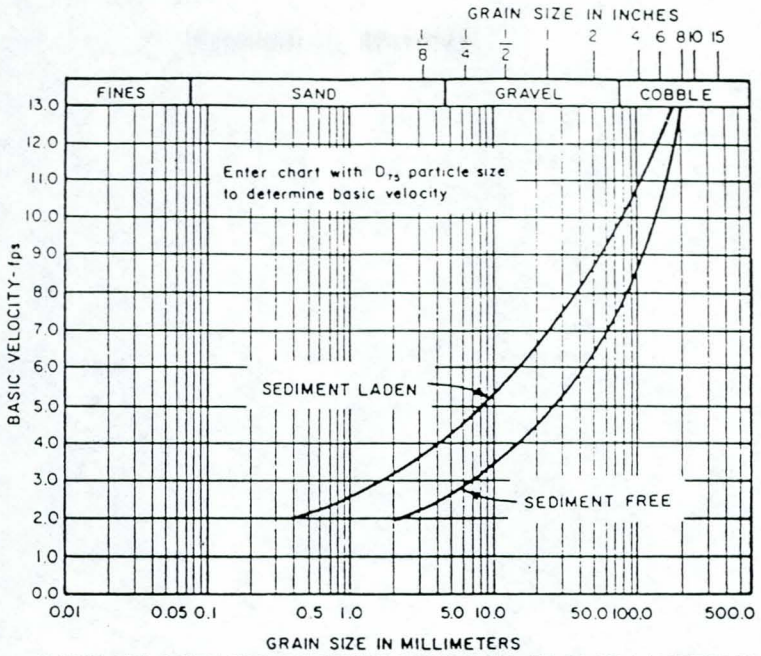
Channel Material	Mean Channel Velocity, fps
Fine sand	2.0
Coarse sand	4.0
Fine gravel††	6.0
Earth	
Sandy silt	2.0
Silt clay	3.5
Clay	6.0
Grass-lined earth (slopes less than 5%)‡	
Bermuda grass - sandy silt	6.0
- silt clay	8.0
Kentucky Blue Grass - sandy silt	5.0
- silt clay	7.0
Poor rock (usually sedimentary)	10.0
Soft sandstone	8.0
Soft shale	3.5
Good rock (usually igneous or hard metamorphic)	20.0

† Based on TM 5-886-4 and CE Hydraulic Design Conferences of 1958-1960.
†† For particles larger than fine gravel (about 20 mm = 3/4 in.), see plate 29.
‡ Keep velocities less than 5.0 fps unless good cover and proper maintenance can be obtained.

The following comments discuss applicability of the criterion.

(1) Theoretical objections can be raised to using velocity alone as a criterion. Velocities are however comparatively easy to measure, compute, or visualize. It is often useful to convert more sophisticated criteria so that velocity appears as a primary variable. For instance, the shear stress criterion can be converted to terms of velocities for specified depths of flow: see Section 2.3.3.

(2) Velocity criteria can be modified to allow for sediment transport and other factors. A Soil Conservation Service manual for open channel design (USDA 1977) provides basic allowable velocities for "sediment free" and "sediment laden" flow (Figure 2.3.1). Adjustment factors are suggested for depth of flow, channel curvature and bank slope angle. The difficulty arises, however, of interpreting terms like "sediment laden": in the USDA manual, it refers to a certain level of suspended sediment concentration.



BASIC VELOCITY FOR DISCRETE PARTICLES OF EARTH MATERIALS

(Notes: 1. Applies to 3 ft depth of flow.
2. Provided as example only of modified velocity criterion.)

Figure 2.3.1. Allowable velocity criteria with provision for sediment transport (USDA 1977).

(3) For channels with substantial bed-sediment inflows, an allowable minimum velocity to avoid sedimentation may be as important as an allowable maximum to avoid erosion.

(4) In applying velocity criteria it is important to consider the full range of discharges. One approach that has been used in designing modified channels is to match so far as possible the velocity-discharge curve of the natural channel. Experience with local constrictions and widenings of alluvial channels generally supports this approach: artificially constricted sections will often scour their beds to restore more or less the natural velocity, and widened sections will often infill similarly.

(5) An allowable velocity will not in itself provide a complete channel design, because a specified value can be satisfied by a wide range of width, depth and slope combinations. Any specified upper limit can be satisfied theoretically by providing a wide shallow cross-section (Figure 2.3.2). In fact, however, the stream may erode a narrower sub-channel within the wide cross-section and then degrade to a flatter slope, or it may silt in from the sides. A velocity criterion therefore has to be used in conjunction with other criteria or guidelines for slope, width, or cross-sectional shape.

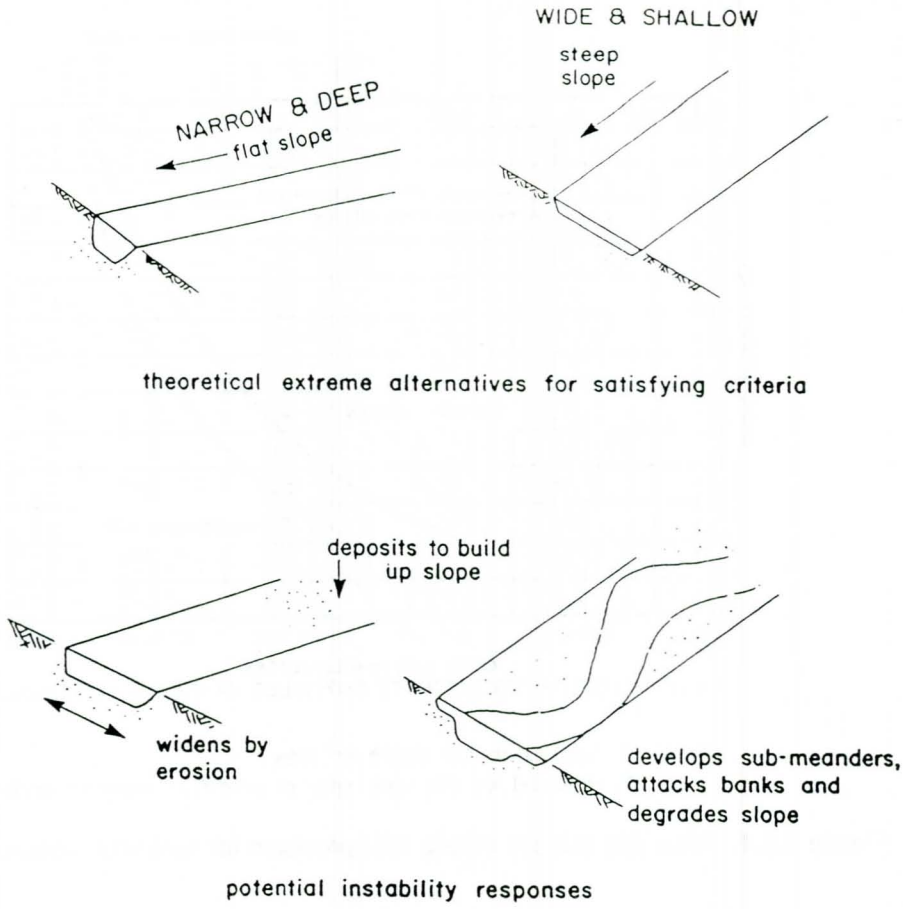


Figure 2.3.2. Insufficiency of allowable velocity or shear stress criterion for stability of alluvial channel.

2.3.3 Allowable shear stress. (The terms "tractive stress" and "tractive force" are used in some publications for the same parameter.) Use of boundary shear stress rather than velocity as a stability criterion became popular in the 1930s. The average boundary shear stress (τ) in straight uniform flow (Figure 2.3.3) is given by:

$$\tau = \gamma RS \qquad \text{(Eq. 2.3.1)}$$

where γ is the specific weight of water, R is the hydraulic radius and S is the slope. The alternative parameter V*, referred to as "shear velocity" because of its dimensions, is related to shear stress by:

$$V_* = \sqrt{gRS} = \sqrt{\tau/\rho} \qquad \text{(Eq. 2.3.2)}$$

where g is gravitational acceleration and ρ is the mass density of water. The actual velocity close to a rough boundary is in the order of 8 V*.

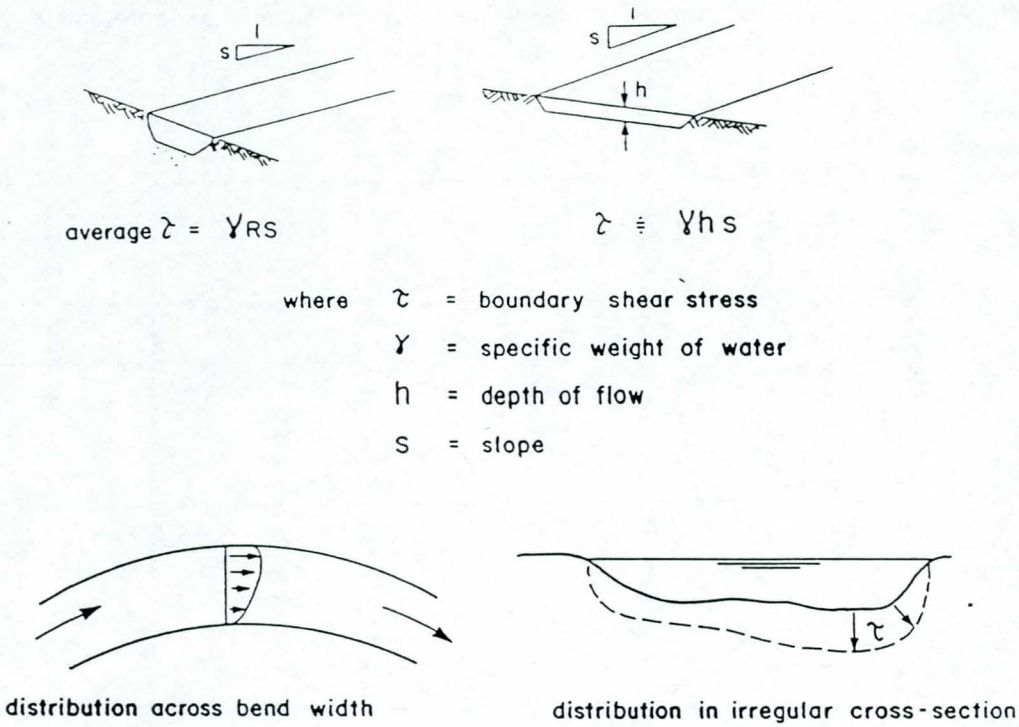


Figure 2.3.3. Boundary shear stress in uniform flow.

The following comments discuss applicability of the criterion.

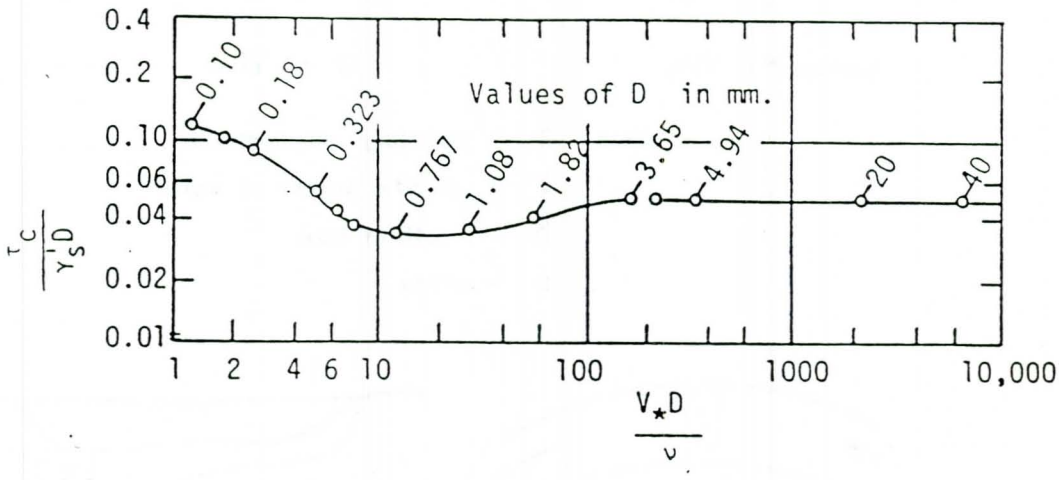
(1) Shear stress criteria for movement of noncohesive sediments on a flat bed are well established by the Shields diagram or its variants (Figure 2.3.4). This diagram is particularly applicable to straight channels in coarse granular materials. For the rough boundaries given by these materials, the generally accepted threshold-of-movement criterion is a Shields Number of approximately 0.045. The Shields Number is defined as $\tau / \gamma_s' D$ where γ_s' is submerged specific weight of sediment and D is sediment grainsize. In most natural channels, the bed shear stress in the main part of the channel can be approximated as:

$$\tau = \gamma h S \qquad \text{(Eq. 2.3.3)}$$

where h is the depth of flow. The Shields Number can then be written as:

Shields Number = $hS/(s-1)D$ (Eq. 2.3.4)

where h is depth of flow, S is hydraulic slope, s is dry specific gravity of sediment and D is grain size. For sediment mixtures, the median size by weight (D_{50}) is often used as representative.



Notation:
τ_c = critical (threshold) shear stress
γ_s' = submerged specific weight of sediment
V_* = 'shear velocity' (Eq. 2.3.2)
D = grain size (approx. D_{50} for mixtures)
ν = kinematic viscosity

Figure 2.3.4. Form of Shield's diagram for initial movement of noncohesive sediment on flat bed (Komura 1963).

(2) In sand-bed channels, the bed is normally covered with ripples or dunes and significant transport does not occur until shear stresses are considerably higher than indicated by the Shields diagram. The large roughness and varying characteristics of these "bed forms" raise difficulties with application of a shear stress criterion.

(3) Shear stress criteria have been applied to channels in cohesive and semi-cohesive soils. Efforts to relate allowable shear stresses to standard geotechnical parameters such as shear strength, plasticity index and so on have met with little success. A recent review states "The critical hydraulic shear stress of a particular cohesive soil cannot be determined a priori with sufficient confidence by any of the techniques suggested in the literature" (Andres 1985). Observation of existing channels and hydraulic testing of local materials is recommended.

(4) Shear stress criteria can be converted theoretically to mean velocity criteria for various depths of flow. For example, the Shields threshold criterion for coarse material in a wide channel can be written:

$$\frac{hS}{(s-1)D_{50}} = 0.045 \qquad \text{(Eq. 2.3.5)}$$

A flow formula in terms of grain roughness k can be written (Ackers 1958):

$$\frac{V}{\sqrt{ghS}} = 8.41\left(\frac{h}{k}\right)^{1/6} \qquad \text{(Eq. 2.3.6)}$$

If these two equations are combined to eliminate S, and a relationship is assumed between k and D_{50}, an expression is obtained for mean velocity in terms of depth and grainsize. A reasonable assumption, for a moderate distribution of grain sizes is $k = 3\ D_{50}$. With this relationship, and taking $S = 2.6$, the allowable mean velocity becomes:

$$V = 10.66\ h^{1/6}\ D_{50}^{1/3} \qquad \text{(Eq. 2.3.7)}$$

Where V is in ft/s, and h and D_{50} are in ft.

A chart of mean velocity against grainsize, that uses this relationship for the coarser sizes, is provided in Chapter 5.

2.3.4 Stream power. Stream power is defined (ASCE 1975) as shear stress x mean velocity, that is:

$$\text{stream power} = \tau V = \gamma RSV = \gamma QS/P \qquad \text{(Eq. 2.3.8)}$$

where Q is discharge and P is wetted perimeter. The term "tractive power" is also used. The units of stream power signify power per unit area of stream bed.

Stream power was first used as a sediment transport parameter (Bagnold 1960). It has been recommended as a stability criterion for certain types of soil (USDA 1977). It has also been applied in theoretical development of hydraulic geometry relationships - see Section 2.3.7. For evaluating the stability of flood control channels, stream power has no evident advantage over velocity or shear stress used alone.

(A different parameter, defined as velocity x slope, has been termed "unit stream power" by some writers.)

2.3.5 Hydraulic geometry relationships. Equilibrium or "regime" concepts are described in general terms in Section 2.2. Associated hydraulic geometry relationships for straight stable channels were first formulated by Lacey (1929-30). Modified "regime" equations for an extended range of canal and river conditions were published by Blench (1957, 1969). Equations of similar general form (Simons and Albertson 1951) formed the basis for the "modified regime" method (USDA 1977). Updated research on similar lines is described in a conference proceedings (White 1988).

Hydraulic geometry relationships involve three independent relationships for (i) width or wetted perimeter, (ii) depth or hydraulic radius, and (iii) slope or velocity, all vs. discharge. They indicate the preferred cross-section and slope of a channel for a given channel-forming discharge and given boundary materials. The basic forms of the equations imply a straight single-channel planform and relatively low bed-sediment inflows, but modifications for meandering planforms and for bed-sediment transport are suggested in some of the references. The preferred channel is supposed to be stable with respect to cross-section and slope, but is not necessarily free from lateral shifting and meandering.

In considering channel modifications for flood control, the question of allowable slope is often primary. USDA (1977) states: "Determination of an acceptable safe slope for a channel is about the most difficult decision in channel design".

When three hydraulic geometry relations are used, roughness coefficients are not specified explicitly, but are implied as functions of the discharge and boundary materials. This appears appropriate for sandy beds where roughness is variable and determined mainly by bedforms, but less appropriate for coarse-grained boundaries. It is possible to use a hybrid procedure whereby channel cross-section is based on hydraulic geometry relationships but slope is then determined from the Manning or similar equation, using roughness values based on experience.

Graphical hydraulic geometry relationships for assistance in stability evaluation are presented in Chapter 5. Relationships incorporating sediment transport are discussed in Section 2.3.7.

2.3.6 Sediment transport functions. Many flood control channels have substantial inflows of sediment from upstream and from tributaries. Stability of channel cross-section and profile then requires not only that the channel should resist erosion, but also that the bed sediment should be transported through the channel without deposition and loss of designed hydraulic capacity. (Deposition of fine suspended sediment is seldom a serious concern except in delta and estuarial channels where velocities are very low.)

If the channel is dimensioned for flood capacity without consideration of sediment transport continuity, it may undergo deposition until transport continuity is attained, with a loss of designed flood capacity (Figure 2.3.5).

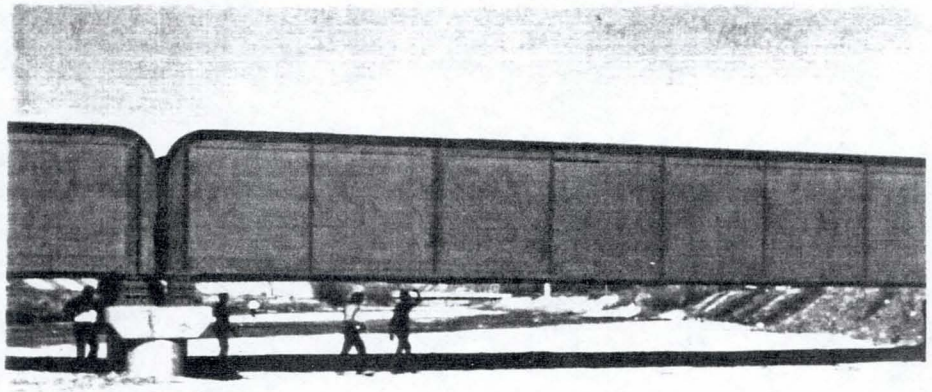


Figure 2.3.5. Infilling of oversized flood control channel by deposition of sand in floods.

Most sediment transport functions predict a rate of sediment transport for given hydraulic conditions - usually average cross-section, slope and depth of flow. It is important to know whether a given function is supposed to predict total bed-material load or bed load only (see Figure 2.2.7). For very coarse bed materials, the difference is of little significance. For sand, the suspended bed-material load may be an order of magnitude greater than the bed load.

It is generally agreed that "blind" computation of transport without calibration against independent data may give highly unreliable results. Different sediment transport functions were developed from different sets of field and laboratory data and are better suited to some applications than others. Different functions may give widely differing results for a specified channel. Unfortunately, acquisition of calibration data is usually very difficult. In the case of some actively shifting streams, it may be possible to make a rough check from considerations of bank erosion and bar deposition (Neill 1983, 1987).

An example where computed bed load transport was compared with field measurements is shown in Figure 2.3.6. Bed load consisted of gravel and coarse sand and was measured across a gauging section over a period of several years using a Helley-Smith sampler (Burrows et al 1981). The data, although widely scattered, are reasonably compatible with the Meyer-Peter and Muller bedload formula, which is considered applicable to gravel channels (see ASCE 1975).

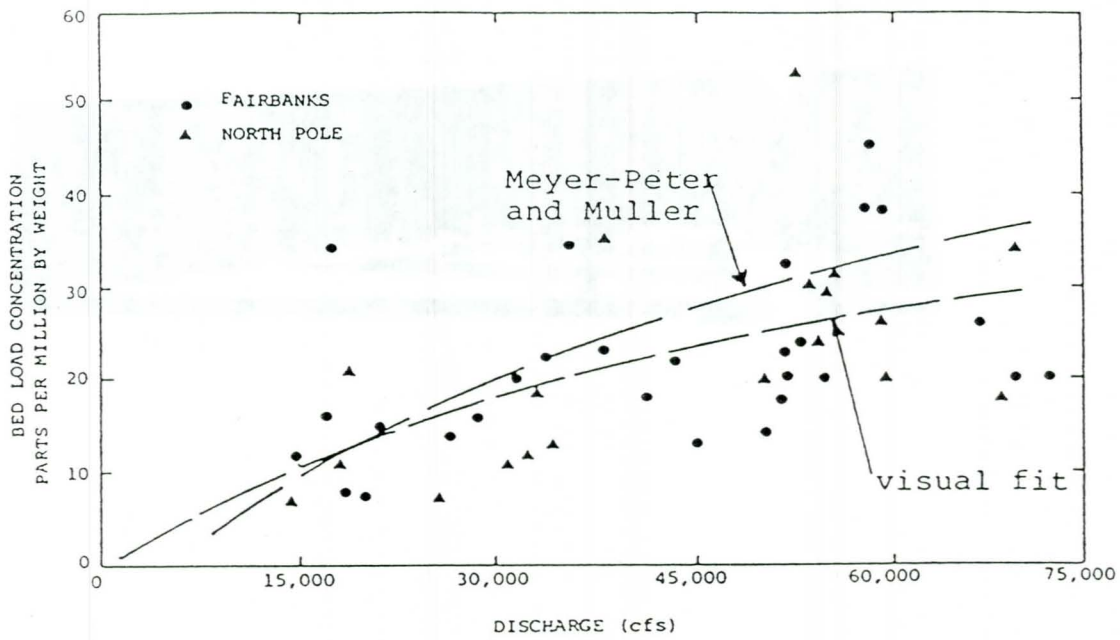


Figure 2.3.6. Comparison of computed and measured bed load (CRREL 1984).

A less demanding application of sediment transport functions is to compare the transport capacity of a proposed modified channel with that of the original channel under a range of equivalent flow conditions, and if possible to match the curves of sediment transport vs. fluid discharge. In this case absolute accuracy is not so important, however the transport function should be selected with some care to ensure that it is not grossly inapplicable.

In considering channel stability, continuity of transport over a year or more is generally more important than in one event lasting a few days or hours. To compute transport over a period of time, a transport rate vs. discharge table is normally combined with a flow-duration table. It is important, however, not to overlook the low-frequency events. In some rivers a low-frequency flood event may transport as much sediment as several years of ordinary flows.

2.3.7 Transport-modified hydraulic geometry relationships. Several attempts have been made to combine hydraulic geometry and sediment transport concepts in order to develop more complex relationships that take sediment transport into account. Recent examples are the theories of Chang (1980) and White et al (1981). Table 2.3.2 shows a sample table by White et al: the input data are channel-forming discharge, bed-sediment grainsize and bed-sediment concentration, and the output data are channel width, depth, slope, velocity and friction factor.

The Chang and White theories both use unproven extremum principles to provide a basis for the width relationship. Their results are best regarded as tentative and subject to testing. Figures 2.3.7 shows the effect of increasing sediment concentration, according to the White theory, on width-discharge, depth-discharge and slope-discharge relations for a sand-bed and a gravel-bed channel respectively.

A major difficulty in applying the White method is to determine the appropriate bed-sediment concentration. A possible procedure for comparing a modified with an existing channel would be: (i) enter the tables with existing dimensions and slope and read the sediment concentration, (ii) compute the existing sediment transport, and (iii) divide by the modified discharge to obtain the input concentration for the modified channel.

2.3.8 Bank slope stability. Bank erosion or failure often involves both hydraulic and geotechnical factors. In alluvial rivers, bank erosion is often seen as an inevitable accompaniment of an overall process such as meander migration (see Section 2.1.3). In many streams, however, geotechnical and biological factors are important in determining locations and rates of erosion and therefore in selecting the most appropriate type of bank protection. If failure is due mainly to geotechnical factors like drawdown or seepage, protection against hydraulic erosion may not be the best treatment. On the other hand, geotechnical failure may represent a delayed response to continuing scour at the bank toe, in which case toe protection against hydraulic erosion is essential. Other contributory causes of bank failure include boat-generated waves and turbulence, ice and debris jams, and traffic of animals and vehicles.

In streams where flood flows have been reduced by upstream regulation, hydraulic forces may be weakened to the point that channel migration ceases. Yet local bank failure may continue to be troublesome because of persisting geotechnical factors.

Mechanisms of bank slope failure in the Ohio River basin are described by Hagerty et al (1986). One identified process is "internal erosion" of sandy soil layers by groundwater outflow, followed by subsequent gravity collapse of overlying layers (Figure 2.3.8). Other processses referred

Table 2.3.2 Example of transport-modified regime relations (White et al 1981)

SAND SIZE 0.50 MILLIMETRES

VELOCITY (METRES/SEC)
SLOPE *1000
DEPTH (METRES)
WIDTH (METRES)
FRICTION FACTOR *10

SEDIMENT CONCENTRATION (PPM)	DISCHARGE (CUMECS) 0.5	1.0	2.0	5.0	10.0	20.0	50.0	100.0	200.0	500.0	1000.0
10	0.45	0.47	0.50	0.53	0.56	0.60	0.64	0.68	0.73	0.81	0.86
	0.237	0.191	0.156	0.121	0.101	0.086	0.070	0.060	0.053	0.045	0.040
	0.46	0.62	0.81	1.15	1.51	1.96	2.76	3.57	4.59	6.60	8.24
	2.4	3.4	5.0	8.2	11.8	17.1	28.2	41.0	59.8	93.8	141.9
	0.323	0.321	0.322	0.320	0.324	0.329	0.338	0.346	0.354	0.370	0.376
20	0.47	0.49	0.52	0.56	0.60	0.63	0.69	0.74	0.79	0.88	0.95
	0.309	0.256	0.214	0.171	0.146	0.126	0.106	0.094	0.083	0.073	0.066
	0.42	0.56	0.73	1.05	1.36	1.76	2.47	3.20	4.12	5.74	7.35
	2.5	3.6	5.3	8.5	12.4	17.9	29.3	42.2	61.1	99.2	143.3
	0.372	0.372	0.375	0.381	0.387	0.395	0.405	0.415	0.424	0.436	0.445
40	0.49	0.52	0.55	0.60	0.64	0.68	0.75	0.81	0.88	0.98	1.09
	0.425	0.360	0.307	0.253	0.222	0.196	0.168	0.151	0.137	0.122	0.113
	0.38	0.51	0.66	0.93	1.21	1.57	2.20	2.84	3.64	5.06	6.67
	2.7	3.8	5.5	9.0	13.0	18.6	30.2	43.3	62.3	100.4	137.7
	0.441	0.445	0.449	0.457	0.465	0.473	0.485	0.494	0.502	0.513	0.522
60	0.50	0.53	0.57	0.62	0.67	0.72	0.80	0.87	0.94	1.06	1.16
	0.524	0.449	0.389	0.326	0.289	0.258	0.225	0.204	0.187	0.168	0.156
	0.36	0.47	0.61	0.87	1.13	1.46	2.03	2.63	3.38	4.70	6.02
	2.8	4.0	5.7	9.2	13.2	19.1	30.8	43.8	62.6	100.3	143.0
	0.490	0.494	0.500	0.509	0.517	0.526	0.536	0.545	0.553	0.561	0.567
80	0.51	0.55	0.59	0.66	0.69	0.75	0.84	0.91	0.99	1.12	1.24
	0.615	0.532	0.464	0.395	0.351	0.316	0.278	0.254	0.234	0.211	0.197
	0.34	0.45	0.59	0.87	1.07	1.38	1.93	2.48	3.20	4.46	5.71
	2.9	4.0	5.8	8.8	13.5	19.3	31.0	44.3	62.8	99.9	141.8
	0.529	0.534	0.540	0.554	0.557	0.565	0.576	0.583	0.589	0.597	0.600
100	0.52	0.57	0.60	0.66	0.72	0.78	0.87	0.95	1.04	1.18	1.30
	0.699	0.611	0.536	0.458	0.412	0.371	0.328	0.302	0.279	0.253	0.237
	0.33	0.45	0.56	0.79	1.02	1.32	1.85	2.38	3.05	4.26	5.47
	2.9	3.9	5.9	9.5	13.8	19.5	31.1	44.3	63.1	99.7	140.9
	0.562	0.571	0.573	0.582	0.589	0.597	0.607	0.613	0.618	0.624	0.627
200	0.56	0.61	0.66	0.73	0.80	0.87	0.99	1.08	1.20	1.37	1.52
	1.078	0.958	0.858	0.751	0.684	0.628	0.566	0.526	0.491	0.452	0.426
	0.29	0.38	0.49	0.69	0.89	1.15	1.61	2.06	2.67	3.72	4.76
	3.0	4.3	6.2	9.9	14.0	19.9	31.6	44.8	62.5	98.1	137.9
	0.677	0.682	0.687	0.694	0.700	0.704	0.709	0.711	0.712	0.711	0.709
400	0.62	0.66	0.73	0.83	0.91	1.00	1.14	1.27	1.41	1.62	1.81
	1.734	1.572	1.427	1.274	1.176	1.092	0.998	0.938	0.882	0.819	0.778
	0.26	0.32	0.43	0.61	0.78	1.00	1.39	1.81	2.32	3.23	4.14
	3.2	4.8	6.3	10.0	14.2	20.0	31.6	43.4	61.5	95.3	133.2
	0.813	0.829	0.817	0.820	0.820	0.820	0.817	0.813	0.808	0.798	0.789
600	0.64	0.72	0.79	0.89	0.98	1.09	1.25	1.39	1.55	1.80	2.03
	2.336	2.127	1.951	1.757	1.633	1.527	1.403	1.323	1.252	1.169	1.113
	0.23	0.31	0.40	0.56	0.71	0.93	1.29	1.66	2.13	2.95	3.82
	3.4	4.5	6.4	10.1	14.2	19.7	31.1	43.3	60.4	94.1	129.1
	0.919	0.902	0.900	0.897	0.894	0.889	0.881	0.873	0.863	0.848	0.836
800	0.70	0.74	0.83	0.94	1.05	1.16	1.35	1.50	1.68	1.95	2.19
	2.897	2.660	2.449	2.220	2.074	1.943	1.797	1.697	1.609	1.507	1.438
	0.23	0.29	0.37	0.52	0.68	0.87	1.23	1.57	2.01	2.81	3.61
	3.1	4.7	6.5	10.2	14.0	19.8	30.0	42.6	59.2	91.2	126.4
	0.970	0.986	0.970	0.954	0.947	0.939	0.926	0.915	0.902	0.883	0.867
1000	0.71	0.79	0.85	1.00	1.10	1.20	1.42	1.58	1.79	2.08	2.34
	3.438	3.166	2.937	2.670	2.498	2.349	2.176	2.061	1.960	1.838	1.756
	0.21	0.28	0.35	0.50	0.64	0.79	1.16	1.49	1.94	2.69	3.45
	3.3	4.5	6.7	9.9	14.1	21.1	30.5	42.3	57.7	89.5	123.9
	1.021	1.016	1.030	0.998	0.989	0.987	0.962	0.948	0.932	0.910	0.891
2000	0.81	0.90	1.00	1.16	1.29	1.46	1.70	1.84	2.16	2.53	2.88
	5.973	5.557	5.197	4.788	4.516	4.275	3.993	3.807	3.631	3.425	3.286
	0.18	0.24	0.31	0.43	0.56	0.72	1.01	1.22	1.67	2.33	3.03
	3.4	4.7	6.5	10.1	13.9	19.1	29.3	44.4	55.4	84.6	114.4
	1.196	1.181	1.164	1.140	1.129	1.099	1.070	1.061	1.022	0.989	0.962
4000	0.94	1.05	1.18	1.37	1.55	1.74	2.06	2.32	2.71	3.13	3.54
	10.608	9.963	9.392	8.738	8.285	7.886	7.410	7.088	6.794	6.433	6.185
	0.16	0.21	0.26	0.37	0.48	0.62	0.87	1.12	1.52	2.04	2.64
	3.3	4.6	6.4	9.9	13.4	18.6	27.9	38.3	48.7	78.1	107.1
	1.382	1.352	1.323	1.282	1.250	1.218	1.174	1.141	1.102	1.063	1.045

(NOTES: 1. Sample table only.
2. Tables in reference are colour-coded.)

to include erosion and infiltration of cracks by overland flow and precipitation, and river erosion of soil berms deposited by previous failures (Figure 2.3.9). They conclude: "... alluvial stream and river bank failures and erosion are complex processes which include interactions of hydraulic and geotechnical causative mechanisms. These actions are not yet fully understood..."

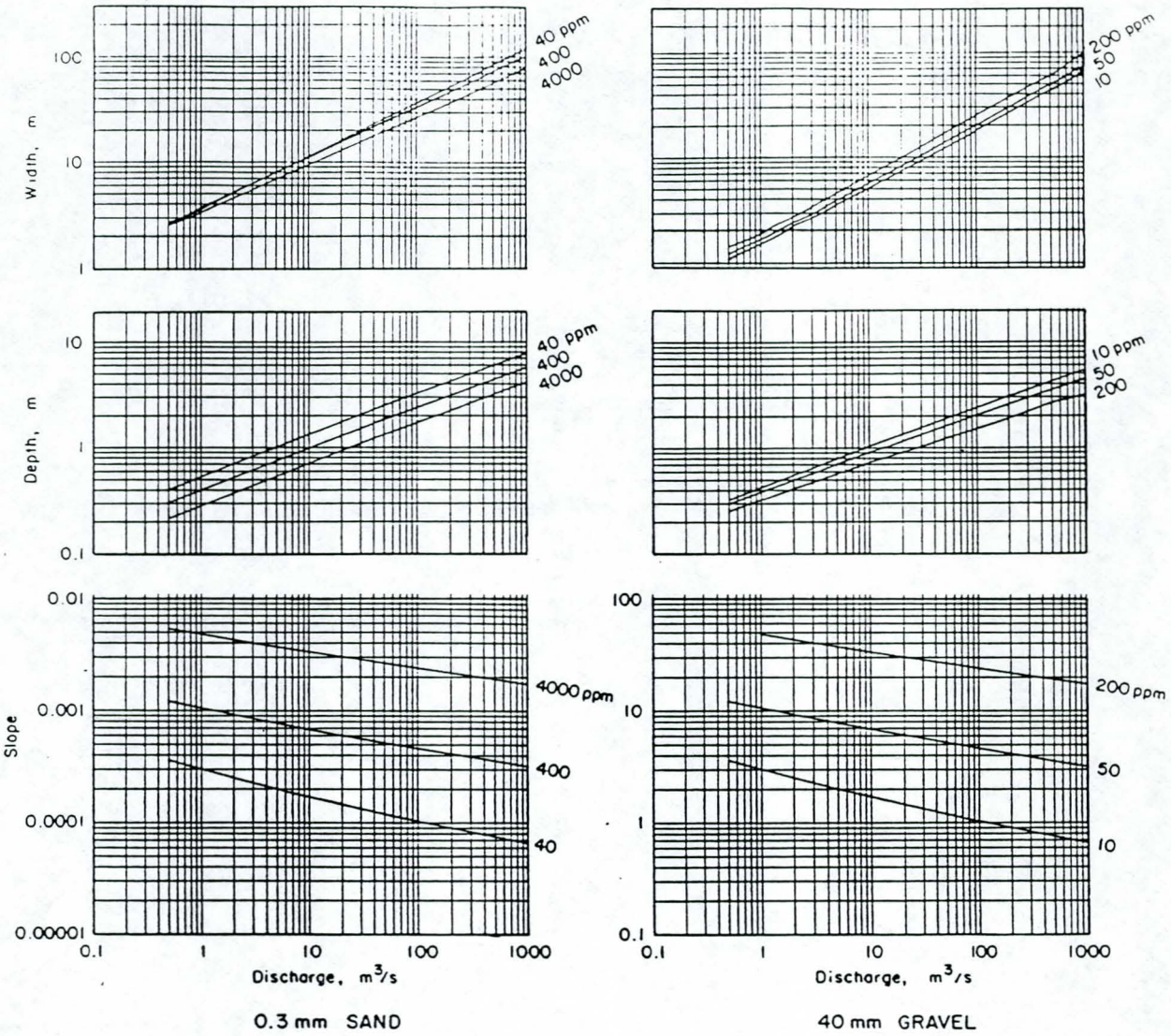


Figure 2.3.7. Effects of bed-sediment concentration on hydraulic geometry of alluvial channels, on basis of tables by White et al (1981).

A stability analysis method for steep cohesive river banks (Osman and Thorne 1988, Thorne and Osman 1988) was developed from studies in the bluffline streams of northern Mississippi. The conceived mechanism of bank failure is shown in Figure 2.3.9a. The analysis method is based on

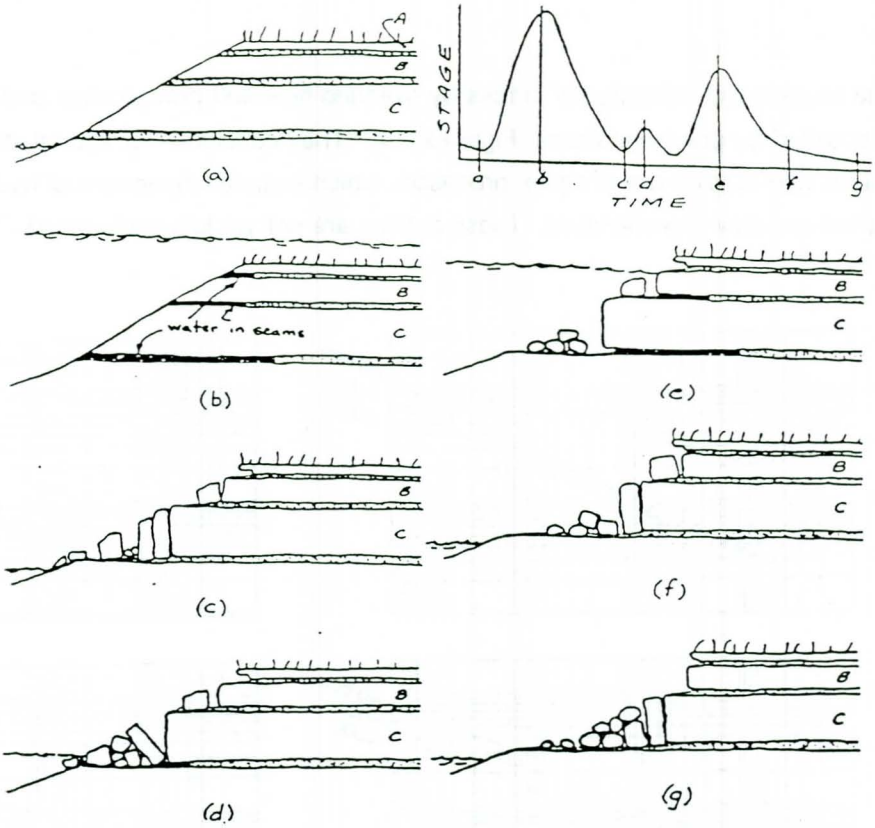
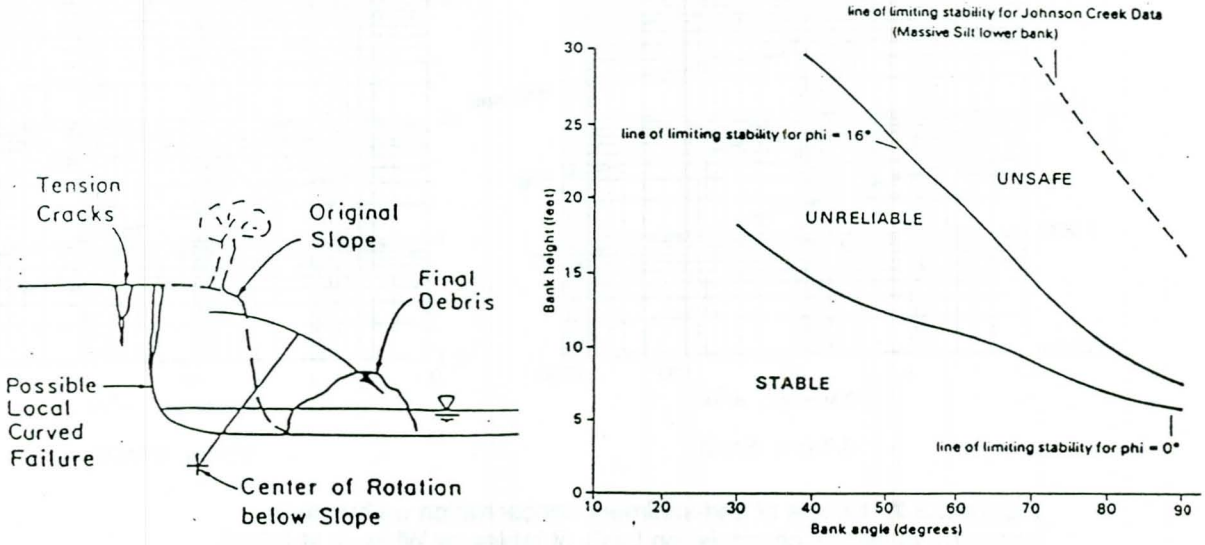


Figure 2.3.8. Mechanism of bank failure by "internal erosion" (Hagerty et al 1986).



(a) concept of bank failure mechanism

(b) sample chart for critical bank height - for specific local soil conditions

Figure 2.3.9. Stability analysis for steep cohesive river banks (Thorne and Osman 1988).

combining a computational model for hydraulic erosion of cohesive soil with a static analysis for gravity failure. For a particular locality with reasonably homogeneous soil conditions, a chart of critical bank height versus bank angle is developed using generalized values of local soil properties (Figure 2.3.9b). The chart implies that banks plotting in the "Unsafe" zone will fail frequently, provided that fluvial activity prevents the accumulation of toe berms. Banks plotting in the "Unreliable" zone are considered liable to failure if heavily saturated. Vegetation is not accounted for explicitly, which is admitted to be a shortcoming.

Bank slope stability is particularly relevant to the difficult problem of assessing and predicting meander development and rates of meander migration. The Thorne and Osman analyses appear to imply that bank failure leads to channel widening. This type of response however, happens mainly in degrading channels such as the Mississippi bluffline streams. In meandering alluvial streams with stable longitudinal profiles, high rates of bank failure cause rapid meander migration but not channel widening: an associated process of sediment exchange results in deposition opposite the eroding banks, so that channel width is maintained despite continual channel shifting (Figure 2.3.10).

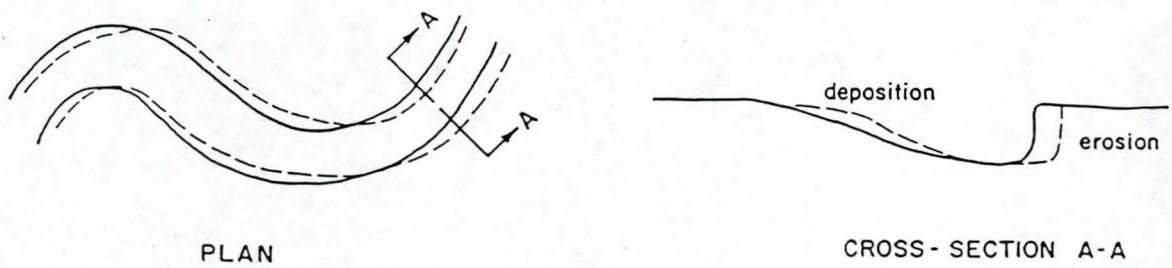


Figure 2.3.10. Natural maintenance of channel width in shifting meanders.

2.3.9 Meanders and channel curvature. The majority of natural streams in erodible materials have more or less meandering planforms. The following points are based on extensive studies of the geometry of meanders. (For more detailed discussions see Petersen 1986, ASCE 1983, Jansen et al 1979, Leopold Wolman and Miller 1964.)

(1) Plan dimensions of meanders scale with the width of the river. On maps and airphotos, large and small rivers appear generally similar, so that the appearance of a stream gives no clue as to the scale of a map.

(2) Meander wavelength and channel length between inflexion points (Figure 2.3.11) have both shown good correlations with channel width. Hey (1983) suggests as a preferred average relationship:

channel length between inflexion points = 6.3 x width

and cites theoretical support based on the size of circulation cells in bends.

(3) The ratio of minimum radius of curvature to channel width in well-developed meander bends is generally in the range 1.5 to 4.5, and commonly in the range 2 to 3.

(4) The amplitude of meander systems is quite variable, being controlled to some extent by the valley bottom width. However the ratio of amplitude to wavelength is commonly in the range 0.5 to 1.5.

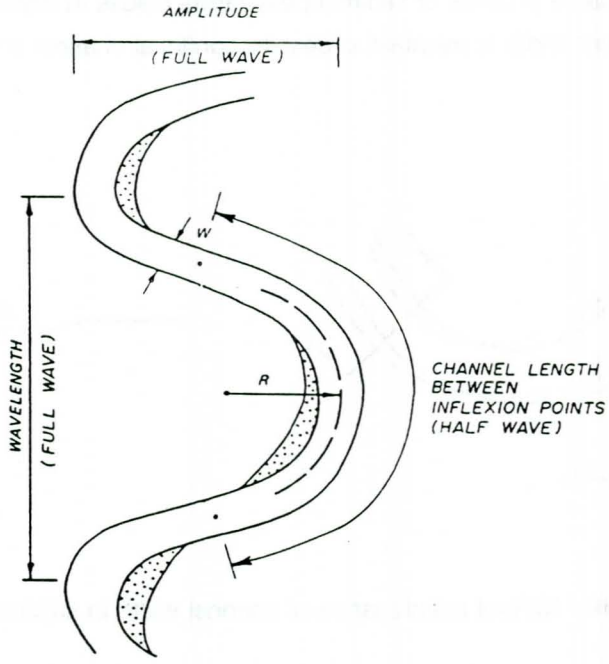


Figure 2.3.11. Meander geometry (after Nunnally & Shields 1985).

The relationships cited above refer to natural streams and are not criteria for stability of flood control channels: many meandering systems are obviously unstable with respect to planform. Nevertheless, the use of moderately sinuous rather than straight alignments is generally preferred, even where there are no existing constraints on alignment. Nunnally and Shields (1985) state: "Meandering alignments are not only aesthetically superior to straight channels, but they may also be more stable." It appears logical to dimension sinuous alignments in general accordance with the more stable natural systems. Geometric guidelines for channel design are suggested in Chapter 6.

2.4 References and bibliography (Chapter 2)

References (cited in text by author and date).

Andres, D.D. 1985. Hydraulic erodibility of cohesive materials. Report SWE 83/04, Alberta Research Council, Edmonton, Canada.

ASCE 1975. Sedimentation Engineering, ed. Vanoni. Manual 54, American Society of Civil Engineers.

ASCE 1983. River Meandering, ed. Elliott. American Society of Civil Engineers.

Bagnold, R.A. 1960. Sediment discharge and stream power. U.S. Geol. Survey Circular 421.

Blench, T. 1957. Regime Behaviour of Canals and Rivers. Butterworths Scientific Publications, London.

Blench, T. 1969. Mobile-bed Fluviology. Univ. of Alberta Press, Edmonton, Canada.

Brice, J.C. 1983. Planform properties of meandering rivers. In River Meandering, Am. Soc. Civ. Engrs. pp 1-15.

Burrows, R.L. Emmett, W.W. and Parks, B. 1981. Sediment transport in the Tanana River near Fairbanks, Alaska, 1977-79. U.S. Geol. Survey, Water Resources Investigations 81-20, Anchorage.

CRREL 1984. Overview of Tanana River monitoring and research studies near Fairbanks, Alaska. Cold Regions Res. & Engin. Lab., Corps of Engrs.

Chang, H.H. 1980. Stable alluvial canal design. J. Hydr. Div., Am. Soc. Civ. Engrs., May, pp 873-892.

Ferguson, R.I. 1984. The threshold between meandering and braiding. In Channels and Channel Control Structures, ed. Smith, Springer-Verlag, pp. 6-15 to 6-30.

Gatto, L.W. 1984. Relationships among bank recession, vegetation, soils, sediments and permafrost on the Tanana River near Fairbanks, Alaska. App. B in Overview of Tanana River Monitoring & Research Studies, Cold Regions Res. & Engin. Lab., Corps of Engrs.

Hagerty, D.J., Spoor, M.F. and Kennedy, J.F. 1986. Inter-active mechanisms of alluvial-stream bank erosion. In River Sedimentation Vol. III, ed. Wang, Shen and Ding, Univ. of Mississippi, pp 1160-1168.

Hey, R.D. 1983. Plan geometry of river meanders. In River Meandering, ed. Elliott, American Society of Civil Engineers.

Hey, R.D. and Thorne, C.R. 1986. Stable channels with mobile gravel beds. J. Hydr. Engin. (ASCE) August pp. 671-689.

Jansen, P., van Bendegom, L., van den Berg, J., de Vries, M. and Zanen, A. 1979. Principles of river engineering. Pitman.

Kellerhals, R. and Church, M. 1989. The morphology of large rivers: characterization and management. In Proceedings of the International Large River Symposium, ed. Dodge, Dept. of Fisheries and Oceans, Ottawa, Canada.

Komura, S. 1963. Discussion on "Sediment transportation mechanics - erosion of sediment". J. Hyd. Div., American Society of Civil Engineers, January.

Lacey, G. 1929-30. Stable channels in alluvium. Min. Proc. Inst. Civ. Engrs., U.K., Vol. 229.

Lane, E.W. 1955. Design of stable channels. Trans. Am. Soc. Civil Engineers, Vol. 120 pp. 1234-1279.

Leopold, L.B. and Maddock, T. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Survey Prof. Paper 252.

Leopold, L.B., Wolman, M.G. and Miller, J.P. 1964. Fluvial Processes in Geomorphology. Freeman and Co.

Lindley, E.S. 1919. Regime channels. Punjab Engin. Congress, India.

Mackin, J.H. 1948. Concept of the graded river. Geol. Soc. Am. Bull. Vol. 59, pp. 463-512.

Mahmood, K. and Shen, H.W. 1971. Regime concept of sediment-transporting canals and rivers. Chapter 30, River Mechanics, ed. and publ. Shen, Fort Collins.

Mollard, J.D. and Janes, J.R. 1984. Airphoto Interpretation and the Canadian Landscape. Dept. of Energy, Mines and Resources, Ottawa.

Neill, C.R. 1983. Bank erosion vs. bedload transport in a gravel river. In River Meandering ed. Elliott, Am. Soc. Civ. Engrs.

Neill, C.R. 1987. Sediment balance considerations linking long-term transport and channel processes. In Sediment Transport in Gravel-bed Rivers, ed. Thorne, et al, Wiley, pp. 225-242.

Nunnally, N.R. and Shields, F.D. 1985. Incorporation of environmental features in flood control channel projects. Tech. Report E-85-3, Waterways Experiment Station, Corps of Engineers.

Osman, A.M. and Thorne, C.R. 1988. Riverbank stability analysis I: theory. J. Hydr. Engineering (ASCE), February, pp. 134-150.

Petersen, M.S. 1986. River Engineering. Prentice-Hall.

Schumm, S.A. and Beathard, R.M. 1976. Geomorphic thresholds: an approach to river management. In Rivers '76, (Symposium on Inland Waterways), Am. Soc. Civ. Engrs.

Schumm, S.A., Harvey, M.D. and Watson, C.C. 1984. Incised Channels: Morphology, Dynamics and Control. Water Resources Publications.

Simons, D.B. and Albertson, M.L. 1951. Uniform water conveyance channels in alluvial material. Trans. Am. Soc. Civ. Engrs. Vol. 128 Pt. 1 pp. 65-107.

Simons, D.B., Richardson, E.V. and Nordin, C.F. 1965. Sedimentary structures generated by flow in alluvial channels. In Primary Sedimentary Structures and their Hydrodynamic Interpretation, ed. Middleton, Soc. Econ. Paleontologists and Mineralogists, Tulsa, pp 34-52.

Stevens, M.A. and Nordin, C.F. 1987. Critique of the regime theory for alluvial channels. J. Hydr. Eng. (ASCE) Nov. pp. 1359-1380.

Struiksma, N. and Klassen, G.J. 1988. On the threshold between meandering and braiding. In International Conference on River Regime, ed. White, Hydraulics Research Ltd. and John Wiley and Sons, pp. 107-120.

Thorne, C.R. and Osman, A.M. 1988. Riverbank Stability Analysis II: Applications. J. Hydr. Engin. (ASCE), February pp. 151-172.

U.S. Army Corps of Engineers 1970. Hydraulic design of flood control channels. Engineer Manual 1110-2-1601.

U.S. Army Corps of Engineers 1989. Sedimentation investigations of rivers and reservoirs. Engineer Manual 1110-2-4000.

USDA 1977. Design of Open Channels. Tech. Release no. 25, Soil Conservation Service.

White, W.R., Paris, E. and Beltess, R. 1981. (1) River regime based on sediment transport concepts. (2) Tables for the design of stable alluvial channels. Reports IT 201 and IT 208, Hydraulics Research Station, Wallingford, U.K.

White, W.R. (ed.) 1988. International Conference on River Regime. Hydraulic Research Ltd. and John Wiley and Sons.

Winkley, B.R. 1972. A river basin's response to man's activities. Preprint for ASCE Nat. Water Resources Engin. Conf., Atlanta.

Bibliography: selected references on geomorphology and hydraulics of stream systems (see Section 2.1.1).

Petersen 1986. River engineering. See References above.

Hey, Bathurst and Thorne (editors) 1982. Gravel-bed rivers. Wiley.

Knighton 1984. Fluvial forms and processes. Arnold.

Schumm 1977. The fluvial system. Wiley.

Simons and Senturk 1977. Sediment transport technology. Water Resources Publications.

Jansen et al 1976. Principles of river engineering. See References above.

Raudkivi 1976. Loose boundary hydraulics, 2nd edition. Pergamon.

Shen (editor) 1971. River mechanics, vols. I and II. Published by H.W. Shen.

Henderson 1966. Open channel flow. Macmillan. (Chapter 10, Sediment transport).

Leopold, Wolman and Miller 1964. Fluvial processes in geomorphology. Freeman.

Blench 1957. Regime behaviour of canals and rivers. Butterworths.

CHAPTER 3. STABILITY PROBLEMS WITH FLOOD CONTROL CHANNELS

3.1 Types of channel modification for flood control

3.1.1 General. There are many methods of channel modification that may be used to increase channel capacity and thereby provide flood control benefits. The local environment and the desired degree of capacity increase affect the choice of method. Generally, urban areas require more intense investigation than rural areas due to congested developments. Stability and environmental sensitivity must be considered when evaluating alternatives.

Modification of natural channels to provide increased flood capacity has come under increasing attack as an automatic response to flooding problems, because of stability and ecological problems that have arisen in many projects. Before committing to radical channel modification, consideration should be given to the potential benefits of offstream storage for avoiding or reducing ecological and stability problems. In many basins, natural storage on floodplains has been reduced by agricultural or urban developments and by flood control projects, leading to an increase in flood peaks and severity of flooding and to loss of ecological habitat. Creation of offstream storage basins can reverse this trend, and appears to be a favoured policy in parts of Europe (Mosonyi 1983, Schiller 1983, Schultz 1987).

General methods of channel modification available for consideration include clearing and snagging, cleanout, channel enlargement, channel realignment, levees, floodways, and flow diversions. These are discussed separately in subsequent paragraphs.

3.1.2 Clearing and snagging. This method is normally used when the channel is restricted by extensive vegetative growth, accumulation of drift and debris, or blockage by leaning or uprooted trees; and when only a modest increase in hydraulic capacity is required and can be obtained through reduction in channel roughness. The procedure involves removal of log jams, large trees spanning the channel, sediment blockages, underbrush and miscellaneous debris (Figure 3.1.1). It is generally advisable to avoid disturbing large stable trees on the banks (larger than 12 inches diameter at breast height), as well as all species of special environmental value. Clearing and snagging reduces hydraulic roughness, in some cases increases cross-sectional area, and reduces potential for further blockages and hang-ups of drift. Regular maintenance must be carried out to ensure continued satisfactory operation.

Potential stability responses to clearing and snagging are associated mainly with increased velocities and with removal of vegetation that may have acted locally as erosion protection. Effects

on stability may be adverse in some places and beneficial in others. Local experience is generally the best guide.

Retention of tree canopy is usually beneficial to fish and wildlife. Increased light due to reduction in canopy can encourage growth of silt-retaining reeds and willows, which can rapidly neutralize the hydraulic benefits of clearing and snagging.

Clearing and snagging is also discussed by Nunnally and Shields (1985) and in EM 1110 - 2 - 1205 (USACE 1990).

3.1.3 Cleanout. Channel cleanout normally involves removal of a specified thickness of material (usually 1 to 3 feet) around the wetted perimeter of a channel. This method is used when a relatively small increase in capacity is required but cannot be obtained by clearing and snagging.

Potential stability responses to cleanout are similar to those for channel enlargement, as discussed below.

3.1.4 Enlargement. Channel enlargement is normally utilized when hydraulic capacity must be significantly increased (Figure 3.1.2). Examples include a channel through a formerly rural area that has undergone suburban or urban development, or the upgrading of an urban channel to carry a 100-year flood, or a rural channel designed to minimize flood damages on crops and residences. Modes of enlargement include (1) increased bottom width, (2) flattening of side slopes by excavation, (3) channel deepening, (4) side berm cuts, or (5) a combination of two or more of those.

The extent of enlargement is determined by the desired increase in flood capacity or the desired reduction in flood levels consistent with permissible disturbance of rights of way, and considering the relationship with the environment and the requirements for maintenance.

Channel enlargement poses two major potential problems with respect to stability. Firstly, if depths are increased but the original slope is retained, velocities at the higher discharges will be increased and the bed and banks may erode, especially if bank stability previously depended on cohesive sediment deposits, armoring or vegetation that was removed in the enlargement process. It may be necessary to provide artificial drop structures to check the velocities. Secondly, if the channel carries substantial sediment loads and if the cross-section provided to meet flood control needs is too large (see Section 2.2), the section may partly infill with sediment deposits and the calculated flood capacity may not be achieved without maintenance.

Figure 3.1.1. Clearing and snagging.

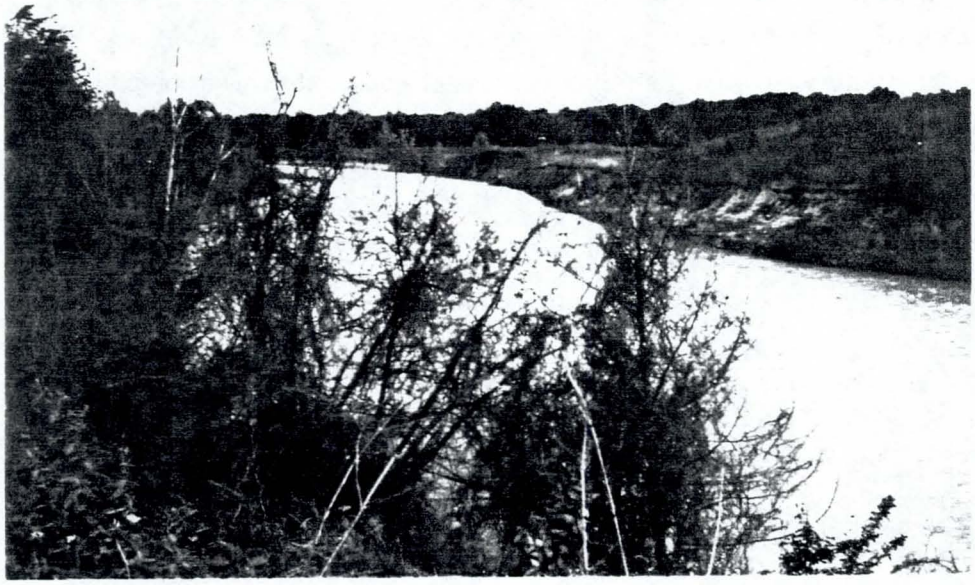


Figure 3.1.2. Channel enlargement.

A method of enlargement that can reduce instability problems is the use of side berm cuts to form a two-stage channel (Figure 3.1.3). This type of cross-section consumes more land than simple enlargement but is more effective for conveying bed sediment, because higher velocities are maintained at moderate discharges. The preferred arrangement is with the cut on the inside bank as illustrated. In incised channels, the level of the berms should if possible correspond to the channel-forming discharge under modified conditions (see Section 2.2.5). [Nunnally and Shields (1985) refer to this form of cross-section as a "highflow channel" and suggest that the berm should correspond to mean annual flood.]

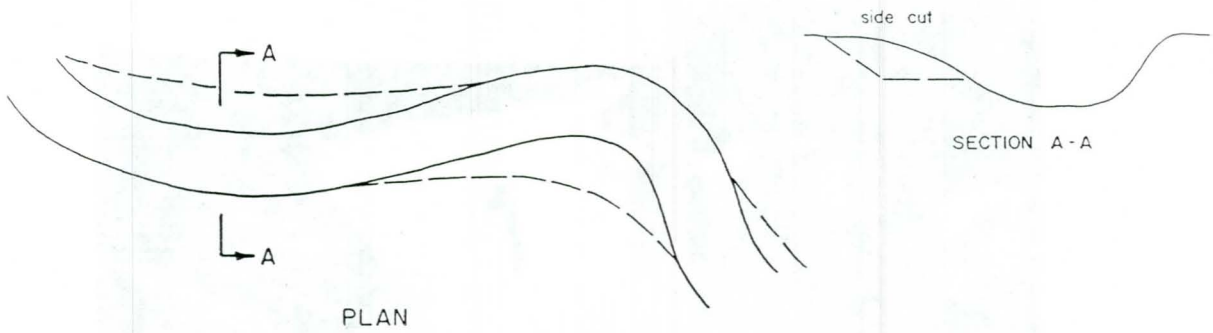


Figure 3.1.3. Channel enlargement by side berm cut.

3.1.5 Realignment. Realignment of meandering streams was widely used in the past as a flood control measure to increase hydraulic capacity and to reduce loss of land by meander migration. The realignment sometimes took the form of complete replacement of a meandering length by a straight channel, or alternatively, the elimination of selected meander bends by "cutoffs" (Figure 3.1.4). The increased capacity results partly from increased slope and partly from reduced eddy losses and roughness.

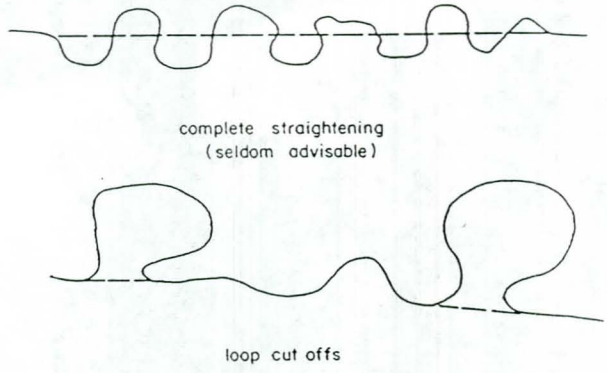


Figure 3.1.4. Forms of channel realignment.

The response of a stream to realignment can vary greatly depending on the stream characteristics and the environment. In some environments, streams with stable contorted meanders, flat slopes and erosion-resistant boundaries can be considerably realigned without serious consequences (Figure 3.1.5), especially if there are flood-regulating reservoirs. In other environments, straightening of meandering streams to enhance flood capacity has led to serious problems of channel degradation, bank erosion and tributary incision (Figure 3.1.6). In such cases realignment may be viable only if accompanied by grade control structures to check velocities, and bank protection to control development of new meanders.

3.1.6 Levees. Levees or embankments are often provided to protect floodplain property, without modifications of the channel itself. A case for levees in place of more radical methods is stated by Ackers (1972) as follows: "..the present width and gradient of the river, if it is indeed stable, are the regime values. Consequently, any attempt to make a significant alteration to the cross-section may be thwarted by a redistribution of sediment. It is preferable therefore to retain the regime width and slope, up to the level of the dominant discharge, and to provide the increased flood capacity by berms, and flood banks [levees] perhaps, that only come into effect at discharges with a frequency less than the dominant condition."

Levees are not, however, free from potential instability effects. Unless they are set far back from the channel banks, they may cause increased flood peaks in the channel proper because floodplain storage and conveyance are reduced (Figure 3.1.7a). This tends to increase the "dominant" or channel-forming flow in the channel and to initiate channel widening and lengthening of the meander bends.

The discharge-increasing effect of levees may be more pronounced in flat deltaic regions where under natural conditions, overbank flows may escape completely from the channel under consideration to reach the terminal water body by other routes (Figure 3.1.7b). In such cases the levees not only eliminate floodplain conveyance and storage, but prevent the escape flows. Long levee projects in such situations may lead to complete re-forming of meander patterns and to slope flattening by upstream degradation and downstream aggradation.

Levees may also cause channel sedimentation in streams with high sediment loads by restricting transport and deposition of sand on overbank areas. More sand is then retained in the channel to deposit further downstream in reaches of flatter slope. This may initiate a progressive upstream-advancing aggradation of the bed. Also, thick deposition of finer suspended sediment on the berm between the river bank and the levee (occurring mainly during flood recessions) may overload the bank to cause slump failures.

Figure 3.1.5. Realigned channel without serious instability problems.

Figure 3.1.6. Lateral instability in realigned channel.

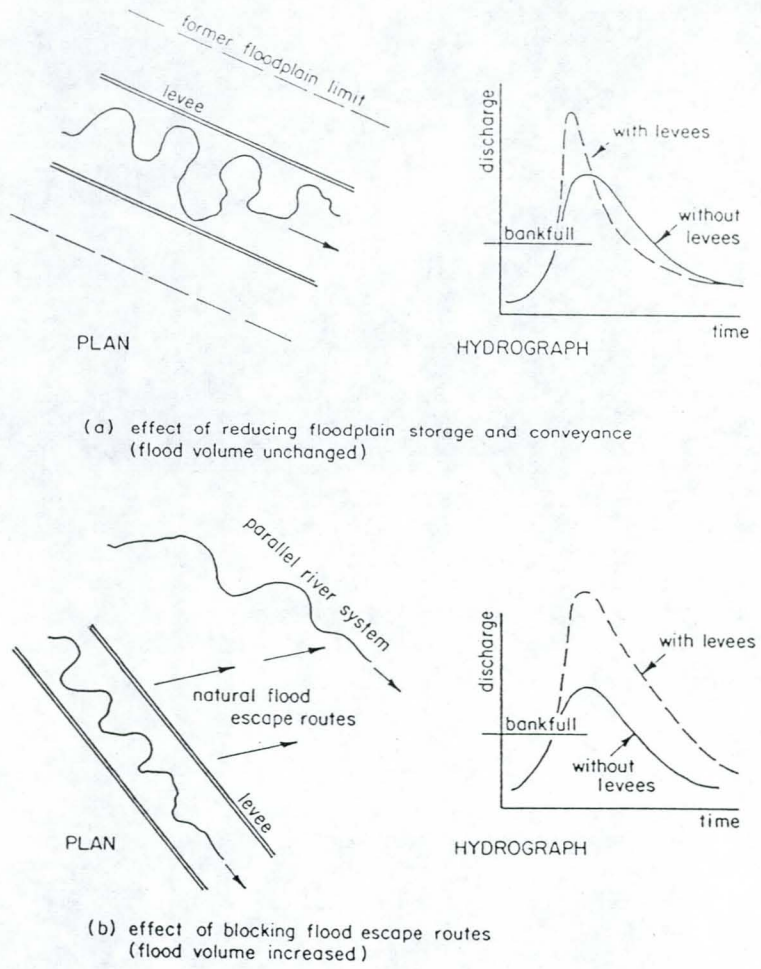


Figure 3.1.7. Effects of levees on flood hydrographs.

In actively meandering channels, the danger exists that continued meander migration, perhaps aggravated by increased in-channel discharges, will encroach on levee setback distances and attack the levee itself at various points. If populations depend on the levees for security, this may pose a critical situation in large floods. As time passes, levee projects in this type of situation tend to require ever-increasing vigilance and maintenance. Eventually large portions of the stream may be effectively canalized by bank protection of one form or another (Figure 3.1.8).

3.1.7 Floodways and bypasses. A floodway or flood bypass channel is usually completely separate from the existing channel whose capacity it is designed to supplement. In some cases the two channels may intersect at intervals as in the case of high-level bend cutoffs (Figure 3.1.9).

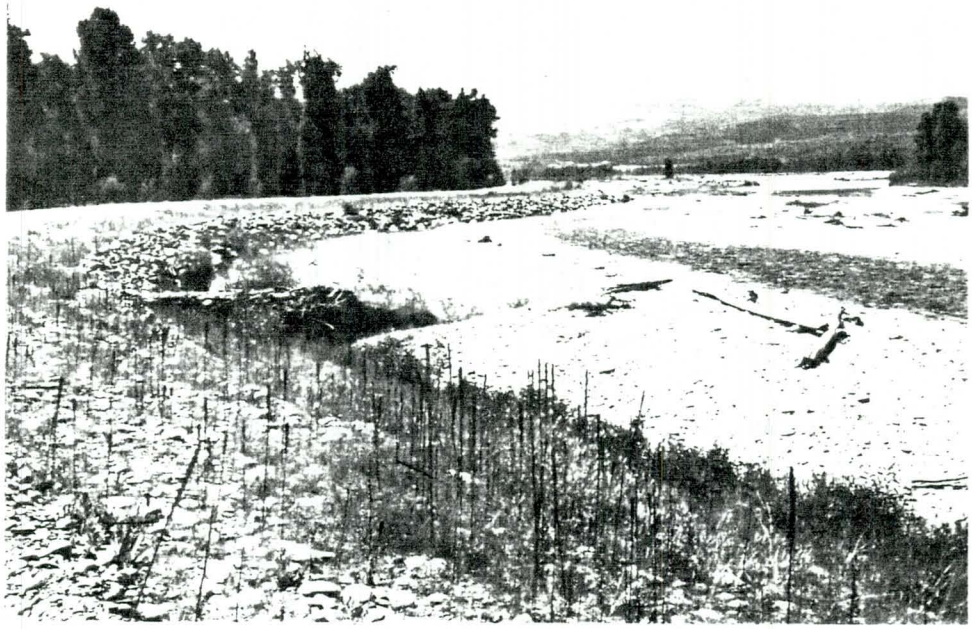


Figure 3.1.8. Bank protection necessitated by encroachment on levee setback.

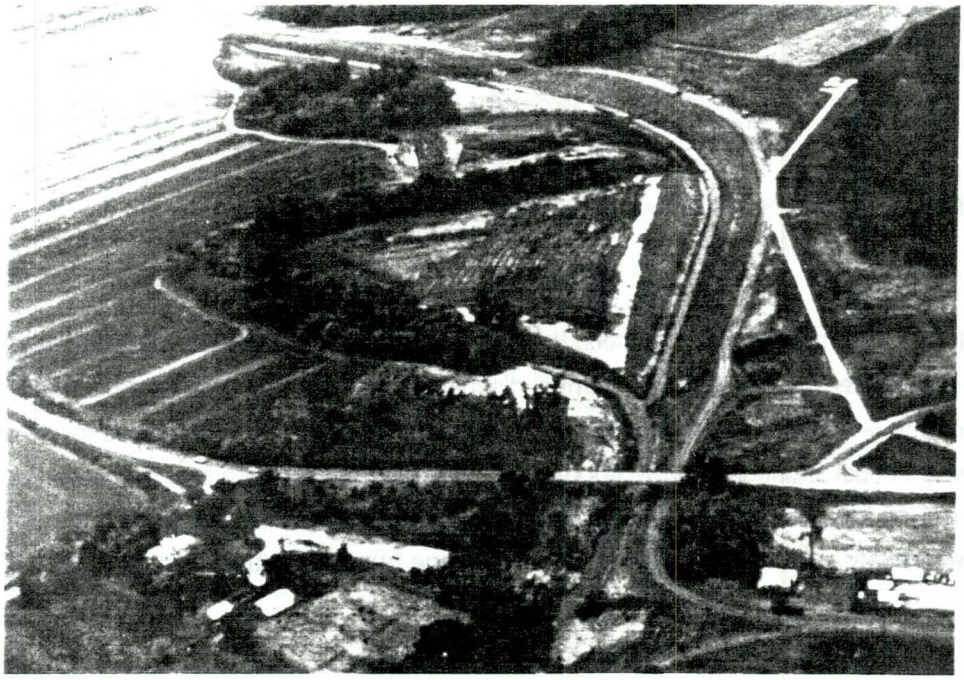


Figure 3.1.9. Floodway formed by high-level bend cutoffs.

The most appropriate application of floodways is usually for streams with relatively low bed-sediment loads. In other cases they may cause sediment problems if the division of sediment between the original channel and the floodway does not match the division of flow. Floodways should normally be provided with control structures at entrance and exit.

3.1.8 Flow diversions. A channel may be modified for flood control by diverting flow out of it to another system, or into it from another system.

When flows are diverted out, erosional problems are normally reduced downstream of the diversion. Sedimentation may occur in the main channel or the diversion or in both as the sediment-carrying capacity of both is likely to be less than that of the existing channel. The division of sediment between the two channels is not necessarily proportional to the division of flow. Further sedimentation problems may arise if there are substantial downstream inflows of sediment that the reduced flows are unable to transport.

When flood flows are diverted in but the channel is not deliberately modified to accommodate the increased discharges, serious erosional problems may ensue. The channel tends to respond by widening and deepening, and by flattening slope through upstream degradation and downstream aggradation. A spectacular example is illustrated in Section 3.2.3.

3.2 Case examples of stability problems

A number of cases of channel instability in flood control projects are summarized in order to illustrate the range of problems that can be encountered. All these cases have been investigated or analysed to some degree, but a full diagnosis and explanation of the problems is not always possible, especially where the stream or channel in question has a history of previous interventions. Cases are drawn from various regions of the United States and involve various types of channel.

3.2.1 Twenty Mile Creek. Twenty Mile Creek is a tributary of the Tombigbee River in mixed woodland and farmland in northeast Mississippi. The creek flows through easily erodible sandy-silty alluvial deposits underlain by clay at variable depths, typical of streams in northern Mississippi. Most of the creek was apparently cleared and straightened to some extent by local agencies at various periods between 1910 and 1940, but it was probably not substantially enlarged at that period. A length of 12 miles upstream from the mouth was channelized by the Corps between 1965 and 1967: the lower 9 miles was widened and deepened and the upper 3 miles was cleared and snagged. The combined effect was to increase the average cross-sectional area by about 200%, the slope by 50%, and velocities by 50% or more. The magnitude of flood peaks at given return periods increased greatly, partly because the enlarged channel captured flood runoff that had previously flowed overland, and partly because of increasing intensity of agricultural land use in the basin.

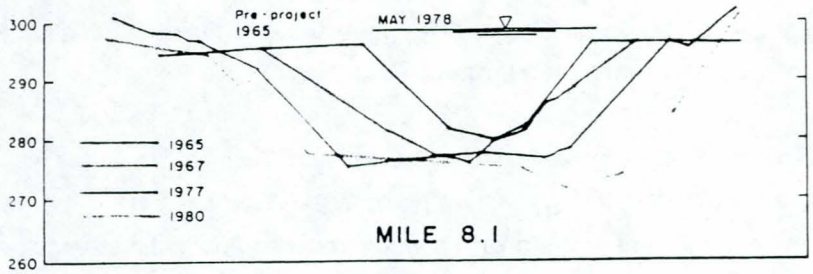
Instability response to the project was rapid and extensive. The main changes documented up to 1982 were as follows:

(1) The channel widened substantially over a large part of the project length, especially by increase of bed widths (Figure 3.2.1). As-constructed side slopes of 3 horizontal to 1 vertical steepened substantially by toe erosion.

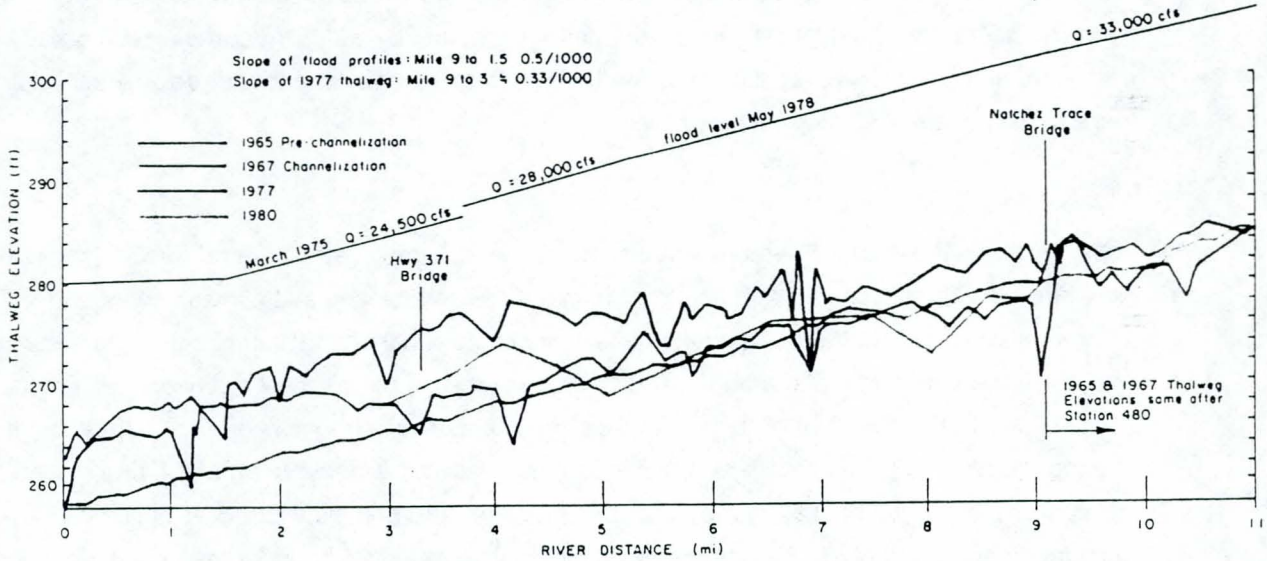
(2) The longitudinal slope flattened substantially over the project length, by bed aggradation at the lower end and degradation at the upper end (Figure 3.2.1). Bed sediment deposited at the lower end was derived from widening and meandering farther upstream. Dredging was required near the mouth to maintain channel capacity.

(3) The bed degraded by headcutting, the channel widened, and meanders developed over a length of stream extending at least 7 miles upstream of the head of the project (Figure 3.2.2).

(4) Headcutting was initiated in several tributaries as water levels in Twenty Mile Creek were reduced by the enlarged cross-sections and bed degradation.



CROSS - SECTION



LONGITUDINAL PROFILE

Figure 3.2.1. Cross-section and profile responses to channel enlargement Twenty Mile Creek.

Remedial measures were applied to check the instability. Grade control structures were installed at several points on Twenty Mile Creek and on several tributaries. Some riprapping and planting of vegetation was done for bank protection.

The main factor in the instability response of Twenty Mile Creek was probably a large increase in channel-forming ("dominant") discharge. This was caused partly by basin changes but also by the enlargement of the channel, which reduced floodplain storage and conveyance. A possible secondary factor was the use of rather flat bank side-slopes for geotechnical reasons. The longitudinal slope imposed by the project features was excessive: the larger in-channel discharges would have required a flatter slope to maintain stability, whereas the project modifications resulted in a steeper slope than before. A second point is that the as-constructed cross-sections, with their flat bank side-slopes, had bed widths that were too narrow for the augmented discharges. As the channel bed degraded at and upstream of the upper end of the project, more and more overbank flow was diverted into the channel itself, further aggravating the deviation of the channel from hydraulic geometry suited to the new discharges. As erosion by widening and deepening advanced upstream, more and more sediment was available to form channel bars farther downstream and thereby initiate lateral shifting and meandering.

3.2.2 Puerco River. The Puerco River is an arroyo or ephemeral stream in arid uplands in northwest New Mexico. The history of response to historical land-use changes and climatic change is somewhat obscure, but there is evidence of substantial regional changes in channel characteristics after the introduction of cattle around 1880. Some reaches of the channel are deeply entrenched (Figure 3.2.3), others are not. The plan and profile are constrained locally by rock ridges, but the channel mostly has a flat smooth bed of fine to medium sand, suggestive of a high rate of bedload transport. The natural banks are mostly of stratified fine sand and silt with occasional layers of cemented sand and gravel. Floods are extremely flashy, lasting 24 hours or less, but carry very high concentrations of sand and silt. The bed is active only during a few flood events each year.

Various works have been constructed to control the channel through the town and reduce flooding of urban land. Two lengths each about 2 miles long were channelized in the 1970s in connection with an interstate highway project. The main features and responses were as follows:

Upper channelization. The channel was straightened and shortened rather severely. Channelized cross-sections appear on average considerably wider than natural sections. Limited bank protection using jacks was installed, and the excess slope was partly compensated by installing grade control structures. The main response seems to be a trend to resumption of a meandering pattern.

Figure 3.2.2. Induced instability upstream of channel enlargement, Twenty Mile Creek.

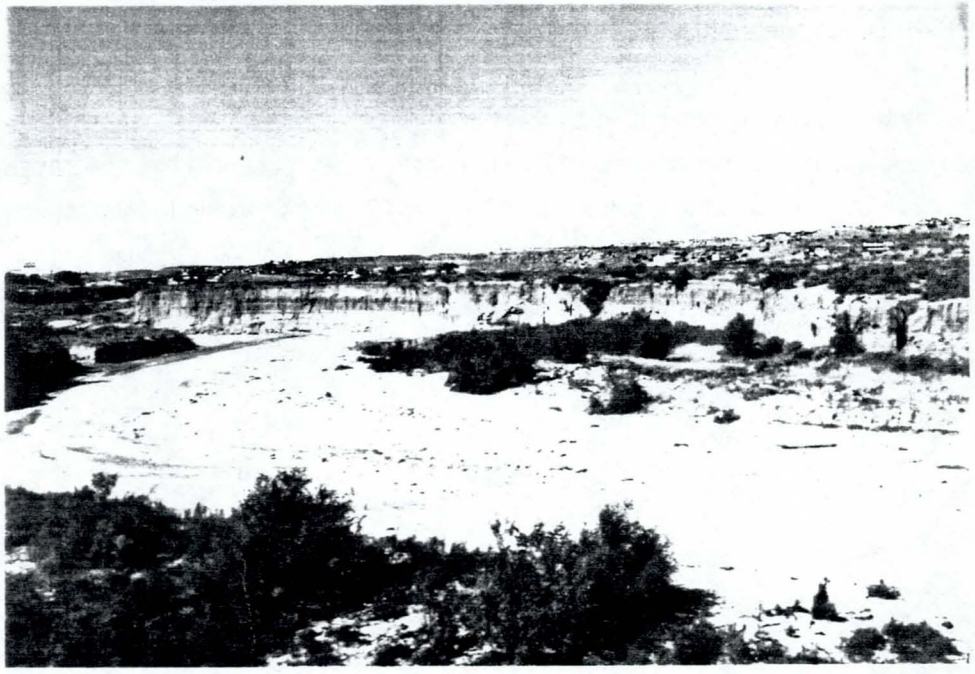


Figure 3.2.3. Entrenched reach of Puerco River.

Lower channelization. The river was fixed in a sinuous planform using concrete side slopes. The width provided was about 50% greater than the natural width. The main response seems to have been deposition of sand and a consequent rise of 3 to 5 ft in bed levels. Clearance under bridges was seriously reduced (see Figure 2.3.5 in Chapter 2).

Analysis of the instability problems of the Puerco River is hampered by incomplete information and by the special characteristics of ephemeral arid-land channels with high sediment inflows. In the lower channelization the enlarged channel appears unable to transport all the inflowing sand, presumably because of lowered velocities. The observed aggradation might, however, be caused in part by a deficiency of larger floods. This cannot be checked because of lack of reliable streamflow data.

3.2.3 Grapevine Spillway Channel. Grapevine Lake is a flood control, water supply and conservation reservoir on Denton Creek northwest of Dallas, Texas, completed in 1952. The spillway, designed for a PMF flow of nearly 200,000 cfs, discharges into what was originally a small creek. A spillway discharge episode in 1981, the first since construction, lasted about 3 weeks with a peak flow of about 10,000 cfs. This episode produced dramatic enlargement and downcutting of the creek channel over a length of several miles (Figure 3.2.4). The erosion is partly into silty-sandy overburden but extends well down into a horizontally-bedded shale or siltstone that is apparently highly susceptible to disintegration by weathering and to hydraulic erosion. The erosion in the upstream part of the channel is of the "badlands" type.

The main point demonstrated by this case is the potential for extremely rapid enlargement and downcutting, even in partly consolidated materials, when a channel is subjected to flows grossly in excess of the channel-forming discharge. The damaging flows exceeded the channel-forming discharge of the creek by one to two orders of magnitude.

Figure 3.2.4. Grapevine Spillway Channel after erosional episode.

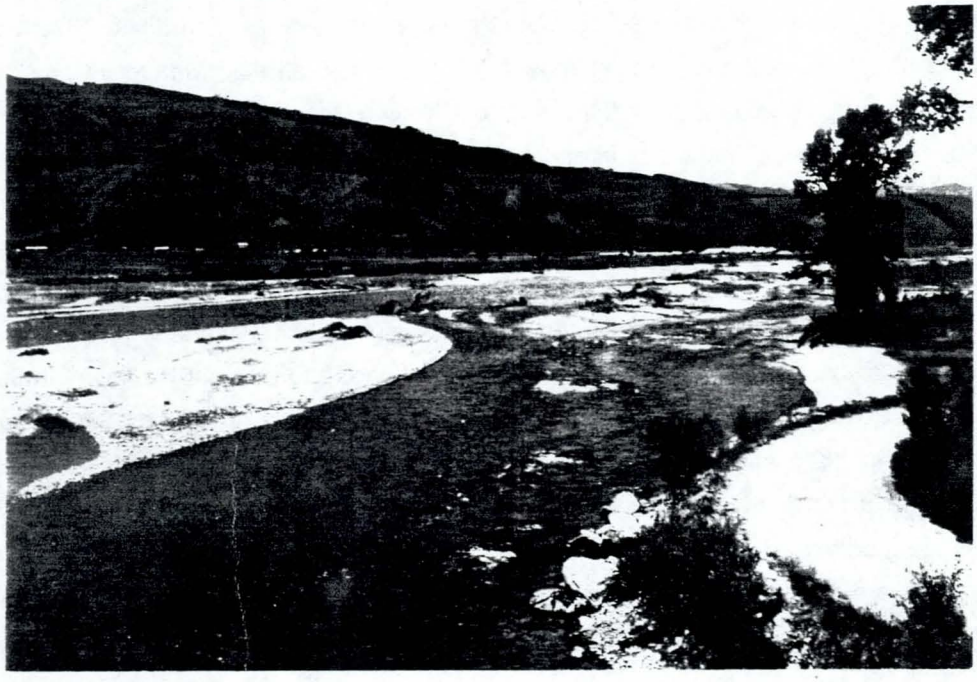


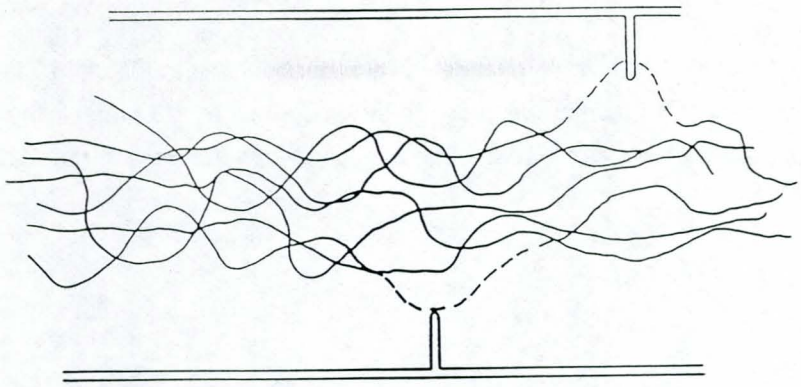
Figure 3.2.5. Snake River near Jackson Hole.

3.2.4 Snake River. The Snake River near Jackson Hole in western Wyoming is a braided gravel river in a wide floodplain (Figure 3.2.5). Bed-material transport is moderately high. Upstream of the town of Jackson, the active braided system is bounded by flood control levees built in the 1960s. Downstream of Jackson, there is an intermittent system of short levees and other flood protection works. The total length of river wholly or partly protected is about 25 miles. The main instability problem (as of 1987) was the heavy cost of emergency maintenance of the existing system during and after flood events: the river continuously shifted the location and orientation of its main channel and attacked the levees at new points. Damage to existing riprap protection is usually caused by the main flow impinging more or less at right angles against the banks and undermining the toe as it turns abruptly and produces a deep scour hole. Heavy driftwood and tree trunks add to the force of the attack. Original riprap protection seemed to be deficient in size and thickness and especially in toe protection.

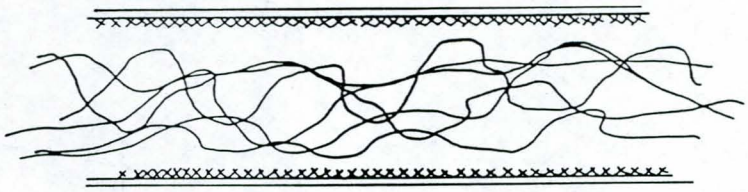
The main form of instability exhibited by the Snake River is an irregular and more or less unpredictable shifting of the main channel during floods. This type of shifting is characteristic of active braided rivers.

In this type of river, three alternatives for levee location might be considered (Figure 3.2.6): (1) provide wide setback distances, with protective groins added as and where required; (2) provide moderate setback with bank and toe protection sufficient to resist right-angled attack at any point; or (3) confine the river to a sinuous course that enforces flow parallel to the banks and prevents braiding. The second alternative, which more or less corresponds to the Snake River situation, is likely to be the most expensive, because deep toe scour has to be allowed for at any point. The third alternative reclaims more land from the river but is likely to raise environmental objections. In some cases, study of historical maps and airphotos may reveal that the pattern of channel shifting is more predictable than at first appears.

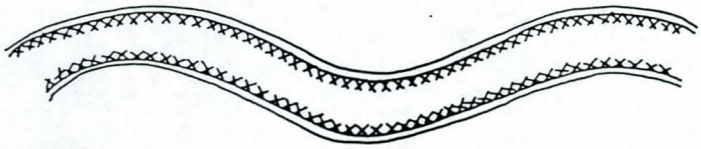
3.2.5 Little Tallahatchie River. The Little Tallahatchie River is a meandering sand-bed tributary to the Yazoo River basin in northcentral Mississippi, discharging to a leveed floodway in the Mississippi/Yazoo floodplain. About 85% of its drainage area is controlled by Sardis Dam, constructed in 1939 for flood control purposes and located about 22 miles above the present mouth. A certain amount of channel improvement was done downstream of the dam, in the form of clearing and snagging and cutoff of a few meander bends. As a result of the dam, downstream flood discharges were greatly reduced: whereas pre-dam floods had frequently exceeded 20,000 cfs, post-dam floods were generally limited to 6500 cfs, more or less the bankfull capacity of the channel (see Figure 2.1.9 in Chapter 2).



(1) wide setback with groins as required



(2) moderate setback with continuous bank and toe protection



(3) realigned and confined sinuous channel

Figure 3.2.6. Alternative levee locations along braided channel.

The initial instability response of the river below the dam was slope flattening by downstream-progressing degradation, resulting from trapping of the bed-sediment load in the reservoir. This is a typical response downstream of reservoirs that trap bed material (see Table 2.2.1 in Chapter 2). As a result of the combined effects of smaller flood discharges and bed degradation, the water levels at the mouths of tributary streams were substantially lowered, so that the tributaries were "rejuvenated" by augmentation of their hydraulic gradients. Bed degradation started progressing up the tributaries, followed by bank failures and meandering, and quantities of coarse sand and gravel bed material

were delivered to the Little Tallahatchie channel. The reduced flows in the Little Tallahatchie were unable to transport all of this material: as a secondary response to the project, the channel therefore started to aggrade, except for a 3-mile reach immediately below the dam (Figure 3.2.7).

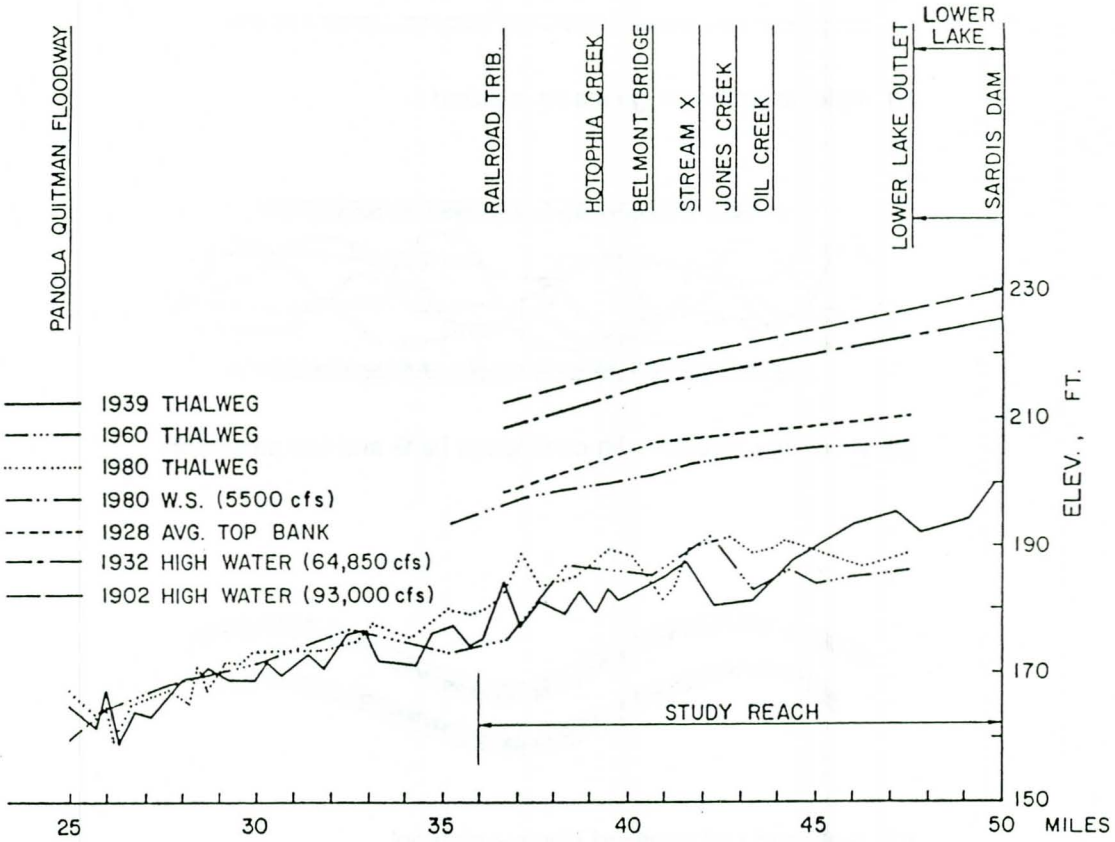


Figure 3.2.7. Response of Little Tallahatchie River profile to upstream reservoir.

As a result of this complex response, dredging has been required on the Little Tallahatchie channel to maintain flood capacity and flood control benefits, and erosion protection and grade controls have been required on several tributaries to reduce loss of land and delivery of coarse sediment. The case demonstrates how initial and final instability responses may operate in opposite directions, and how tributaries may degrade when mainstem flood levels are lowered by flood control.

3.2.6 Red River. The Red River, one of the major streams in the southern United States, has its source in New Mexico and flows generally east along the Texas-Oklahoma border and through Arkansas to join the Atchafalaya River in east-central Louisiana. The Red River is a dynamic river, continually shifting its planform through bank caving and meandering (Figure 3.2.8). The sediment load is relatively high.

A historical phenomenon that affected the river system was the formation and subsequent removal in the mid 19th century of a huge series of log jams called the Great Red River Raft, which at its greatest extent covered a length of about 160 miles in Louisiana. The raft was removed in 1873, and further accumulations were cleared periodically. The river has been affected in more recent times by various works for flood control and navigation. Nearly 60% of its drainage area is controlled by Dennison Dam, located about 500 miles above the mouth and constructed in 1943. Base levels at the mouth have been lowered by channel improvements on the Atchafalaya and lower Mississippi Rivers, and the river itself has been trained and shortened in various places for flood control and navigation.

The combined response to all these developments includes a marked incision of the lower river, such that a 50-year flood is now contained within banks in many places, and widening of the channel by a factor of up to 2 or 3. The incision is illustrated by Figure 3.2.9 which shows "specific gages" at Shreveport in western Louisiana over the period 1890-1986.

The Red River case illustrates the difficulty of sorting out responses to a series of historical events and developments. For example, it is not immediately clear to what extent the incision illustrated in Figure 3.2.9 represents a response to removal of the log raft or to subsequent base level lowering. There is no evident response to construction of Dennison Dam in 1943.

3.2.7 Sacramento River. The Sacramento River flows south through over 200 miles in the Central Valley of California. It is a meandering sand-bed river in its lower part but has a significant content of gravel bed-material in its middle and upper reaches. It is regulated by Shasta Dam in its upper reaches and affected by irrigation diversions and bypass floodways in the lower valley. Considerable lengths are bordered by flood protection levees that follow the margins of the meander belt.

Historically, the river was greatly disturbed by hydraulic mining operations in the mid-19th century. This supplied large quantities of coarse sediment to the river and caused aggradation of up to 30 ft in certain reaches. This temporary slug of sediment has by now largely worked through the system.

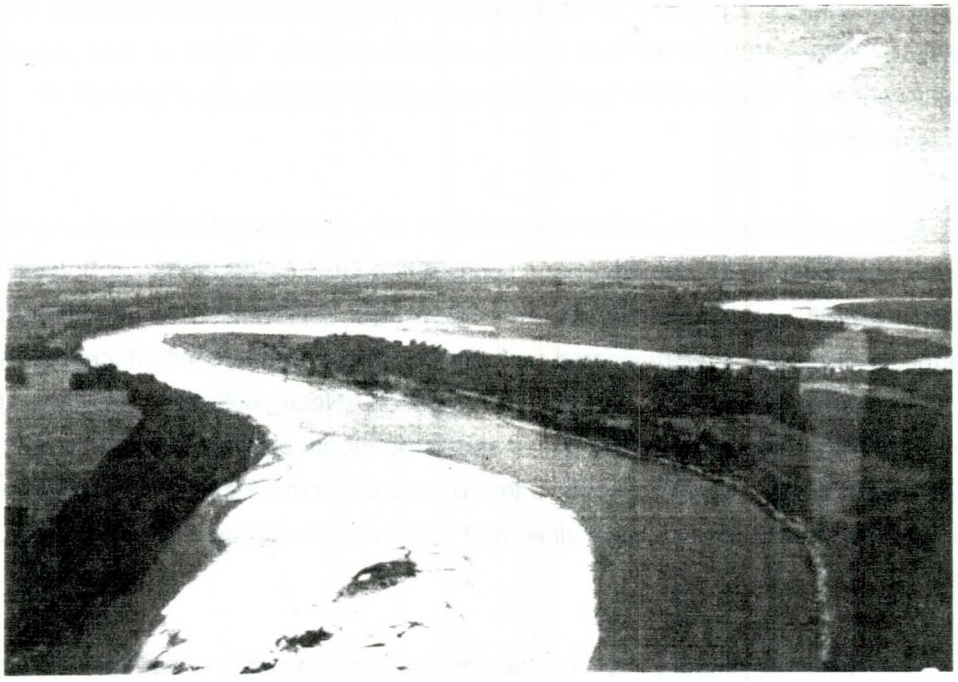


Figure 3.2.8. Red River.

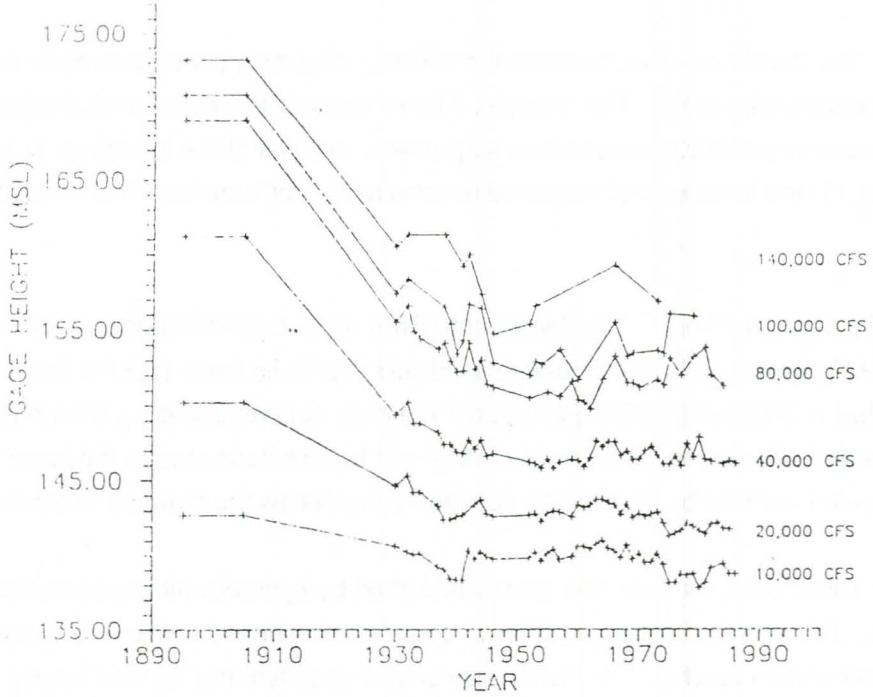


Figure 3.2.9. Specific gage plot for Red River at Shreveport, LA. over period 1892-1986.

Recent studies show no systematic trend of changes in the longitudinal profile. Rates of bank erosion apparently reduced by about 25% after construction of Shasta Dam in 1943, but remain a troublesome problem for security of the levees and because of loss of valuable agricultural land. Various methods have been tried for bank protection in response to environmental concerns over use of riprap, but success with alternative systems has been limited (Figure 3.2.10).

The main instability problem affecting flood control works on the Sacramento River is bank erosion associated with systematic shifting of meanders. This is essentially a continuation of pre-development trends and there is no evidence of aggravation by recent developments. Reduction of bank attack could be achieved by further storage regulation to reduce flood peaks and bed-sediment loads. In the absence of such measures, there is little alternative but to focus on bank protection.

3.2.8 Long Creek basin. Long Creek near Oxford in northern Mississippi is a tributary of the Yocona River, which since 1953 has been regulated by Enid Dam located about 7 miles upstream of the mouth of Long Creek. Like many other basins in the Yazoo Basin uplands east of the Mississippi Valley, Long Creek basin was devastated by exploitative cotton agriculture in the mid-19th century. Many of the stream channels have cut through "Post-Settlement Alluvium": this valley-wide deposit is derived from severe hillslope and sheet erosion during the early cotton period. The Post-Settlement Alluvium and the underlying older alluvial and lacustrine deposits are generally very susceptible to hydraulic erosion.

The recent history of basin changes, in-stream works and instability responses is complex. Starting in the 1930s, considerable lengths of stream channel were straightened and re-channelized for flood control. Base levels were lowered by regulation of the Yocona River and also by flood control in the Mississippi valley. Some reforestation and soil conservation has been done in the upper watershed, and some land has reverted from cultivation to woodland. Grade control structures and lengths of bank protection have been installed in parts of the watershed to arrest bed degradation (incision) and bank erosion.

The main instability responses to 20th century developments appear to be (1) a general incision that has advanced to the middle and upper parts of the basin by upstream migration of "nick zones" (Figure 3.2.11), and (2) re-formation of meanders in reaches that had been straightened for flood control. The incision process has been checked by installation of grade control structures, or in some cases by road culverts. The meander development has been checked by provision of various forms of bank protection.

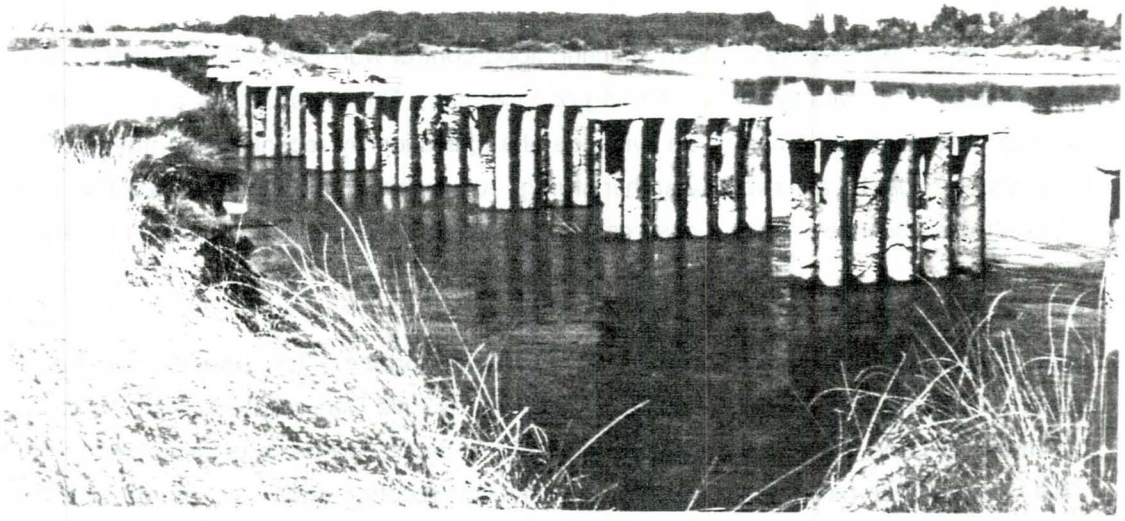


Figure 3.2.10. Outflanking of experimental bank protection on Sacramento River.

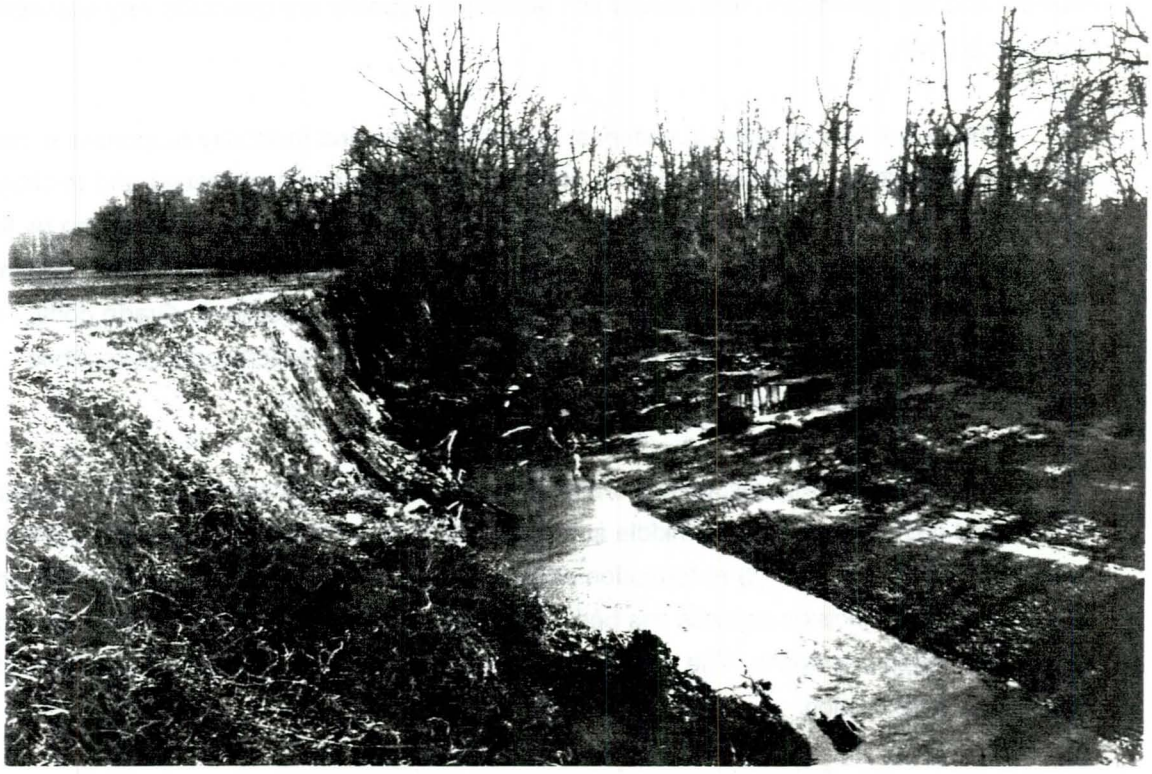


Figure 3.2.11. Incised channel in Long Creek basin.

Experience with Long Creek and similar basins in Mississippi shows the potential for widespread channel incision when base levels are lowered in areas of highly erodible soils. Incision is followed by bank failures, channel widening, and transport of sediments to downstream locations of deposition. The problem of maintaining straight alignments in face of a natural tendency to meander development is also demonstrated.

3.2.9 Tanana River. The Tanana River is a tributary of the Yukon River that rises in the Alaska Range in central Alaska and forms the south boundary to the City of Fairbanks. Upstream of Fairbanks, it is an active braided river with a gravel bed. Some distance downstream, it changes to a more or less meandering river with a sand bed. In the vicinity of Fairbanks it displays a transitional planform consisting of several channels with large semi-stable islands.

Flood control works were constructed in the 1970s to protect Fairbanks. The Chena River tributary that passes through the city was controlled with a dam and floodway so that flood flows are diverted to the Tanana upstream of the city. A set-back levee was built along the right floodplain for a distance of approximately 20 miles, with occasional groins to resist specific threatened encroachments by the river. At its downstream end, it was found necessary to build the levee out into the river because no land was available between recently eroded river banks and valuable existing developments. This in-river length of the levee was provided with several long groins that project out into the river to deflect the main flow away from the levee (Figure 3.2.12). The in-river construction was a matter of local controversy and generated public concerns, but was eventually approved and implemented.

The main observed response of the river to the flood control project was from the in-river construction. During construction a pilot channel had been excavated to encourage the river into a new channel outward of the groins (Figure 3.2.12). Alluvial material from the pilot channel excavation, instead of being removed, was stockpiled alongside. In the following high-water season the river removed most of this material, plus additional material eroded from the pilot channel area, and deposited much of it downstream in the form of new channel bars. Dredging was required initially to safeguard navigational access into the mouth of the Chena River, but the problem more or less resolved itself over subsequent seasons.

Prior to and contemporaneous with the flood control project, other developments interfered with natural evolution of the river to some extent. These were mostly connected with gravel extraction from mid-river islands and associated access roads. One access road that closed off a minor channel probably triggered rapid shifting of a sharp main-channel bend. It was this shifting that more or less forced in-river construction of the downstream end of the levee.

Figure 3.2.12. Tanana River at Fairbanks showing in-river levee and groins.

3.3 Causes of instability

3.3.1 General. This section describes various specific causes of instability in flood control channels. The classification may assist in diagnosing existing problems and evaluating potential problems. The information provided supplements more general information on channel response contained in Chapter 2.

A number of case examples that involve various types of channel instability are described in Section 3.2. Numerous examples of past problems are described in a Congressional document on stream channelization (U.S.Government 1971). A nationwide inventory of flood control channels (Reese 1987) indicated that the most common problems were bank instability and channel siltation and that the most frequent and severe problems were with streams of the meandering type.

Table 3.3.1 summarizes the most common potential problems associated with various types of channel modification described in Section 3.1.

Table 3.3.1 Potential stability problems from flood control modifications

Form of channel modification	Potential stability problems		
	Within reach directly affected	Upstream	Downstream
Clearing and snagging	bank erosion and bed scour	headcutting	sedimentation
Cleanout or enlargement	bank erosion; sedimentation	headcutting	-
Realignment	bank erosion and bed scour; meandering	headcutting	sedimentation
Levees	meander encroachment on setback	-	increased flood peaks
Floodways and bypasses	sedimentation of original channel	-	-
Diversions out	-	-	sedimentation
Diversions in	-	-	bank erosion and bed scour
Base level lowering (parent stream)	-	bed scour, widening, tributary degradation	-
Storage reservoir or sediment basin	-	delta formation; aggradation	bed degradation

3.3.2 Continuation of pre-existing processes. In many cases an existing channel that is to be incorporated a flood control project will have existing stability problems. Even if these are of minor consequence under natural conditions, they may have major implications under post-project conditions. One example is meander migration, which might result in erosive attack on project levees (Figure 3.3.1). It is therefore important to survey and assess existing stability problems, even where the project is not expected to cause new problems.

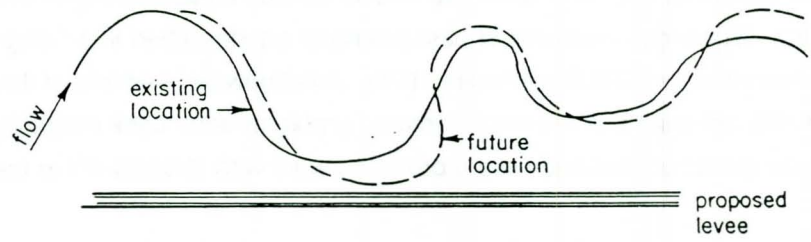


Figure 3.3.1. Stability of flood control works affected by pre-existing channel process.

3.3.3 Increased channel-forming discharge. This is a likely consequence when existing channels are modified. As discussed previously, various forms of modification cause in-channel discharges of a given frequency to be larger than before. Generally, increased discharges tend to result in widening and deepening of cross-sections, flattening of slope, lengthening of meander wavelengths, and accelerated meander migration. These responses increase sediment supply and tend to cause sedimentation towards the downstream end of the modified reach and beyond (Figure 3.3.2). Upstream of the modified reach, degradation (incision) tends to advance upstream as a headcut.

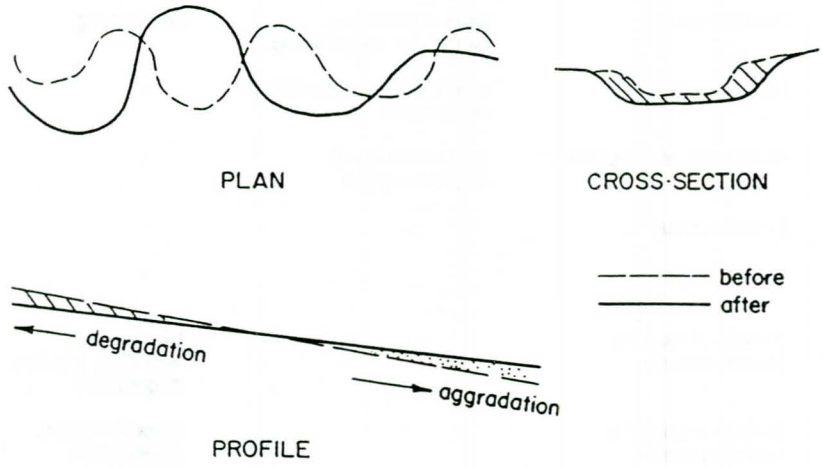


Figure 3.3.2. Response of channel to increased channel-forming discharge.

Once channel incision is initiated by an increase in in-channel discharges, the channel may capture more and more flood runoff that would otherwise have flowed overland or been stored on the floodplain. The actual flood frequency curve then deviates farther and farther from the project design curve. The apparent hydrologic change may be ascribed to climatic or basin changes, when in fact it results mainly from the channelization project.

3.3.4 Realignment. Straightening has usually been done to increase the hydraulic gradient and capacity of the channel, or to reduce loss of land caused by bend erosion. Unless grade control structures are incorporated in the design - which tends to negate the hydraulic gradient effect - the induced higher velocities are liable to initiate bed and bank erosion, upstream degradation and downstream sedimentation. Although bank erosion and meander migration problems may be relieved for a time, many straightened channels tend to revert to a meandering state unless bank protection is provided.

3.3.5 Removal of natural bank protection and roughness. Modifications such as clearing and snagging and cleanout (usually employed in relatively small channels) often involve at least partial removal of vegetation and some reduction of channel roughness. Velocities near the channel boundaries are thereby increased while the resistance of the banks to erosion may be reduced. Unless they are carefully planned, conducted and monitored, these modifications are liable to cause increase bank erosion and supply of sediment.

3.3.6 Flow regulation by reservoirs. A reservoir affects the stability characteristics of a channel both upstream and downstream. The upstream channel for some distance is subject to higher base levels due to backwater effects. Bed material that was formerly transported through the reach is now deposited in a delta at the head of the reservoir (Figure 3.3.3). As the delta grows, the backwater reach and the sediment deposition tend to extend farther upstream, so that lands not initially affected may later be subject to aggravated flooding. More pronounced meandering may also develop in the backwater reach.

The downstream flow and sediment regimes are affected by alteration of discharges and retention of sediment. Potential responses to these effects include changes in longitudinal bed profiles (Figure 3.3.3), cross-sections, planforms, bed-material constitution and vegetation.

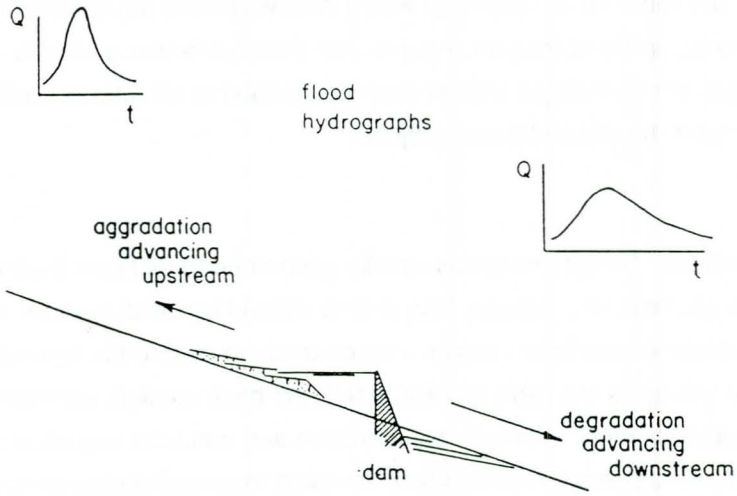


Figure 3.3.3. Effects of storage reservoir on profile stability.

The specific purpose of the reservoir, and the proportion of runoff at the channel reach of interest controlled by the reservoir, determines the magnitude of the effect on flow regime. Generally, reservoirs reduce downstream flow peaks and increase low flows (Figure 3.3.4). These flow changes, which signify generally a reduction in channel-forming discharge, tend to reduce rates of erosion and therefore to enhance stability in the main stream, but tributaries may be de-stabilized because of lower flood levels at their mouths, as in the case described in Section 3.2.5.

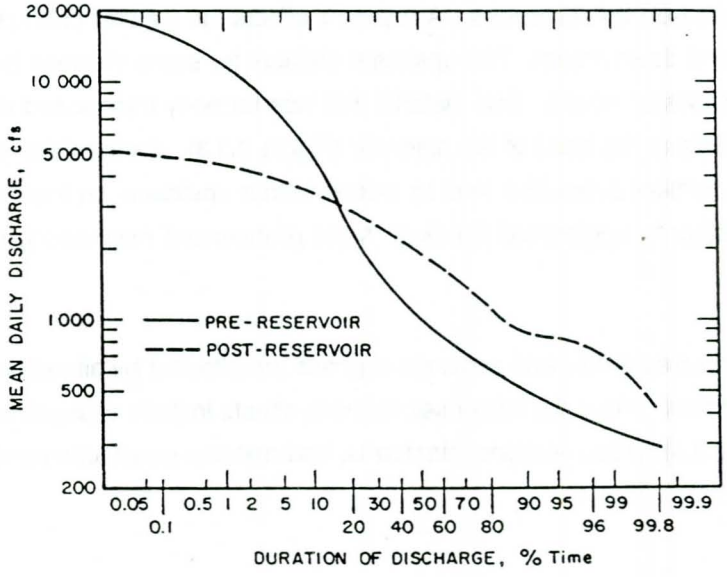


Figure 3.3.4. Effect of storage reservoir on downstream flow-duration curve.

Storage reservoirs generally capture practically all the bed load of the incoming stream, as well as a high proportion of the suspended load (Figure 3.3.5). The distance required for a channel to regain its original sediment load may vary from a short distance to hundreds of miles. In the case of the North Canadian River downstream of Canton Dam, more than 100 miles and possibly up to 300 miles is reported (Williams and Wolman 1984). The channel downstream of the dam, being deprived of its normal bed material load, tends to flatten its slope by a process of degradation that starts immediately below the dam and propagates downstream (Figure 3.3.3). As the wedge of degradation extends downstream, more and more of the channel contributes to restoring the original load and the rate of vertical degradation slows until it may be virtually undetectable.

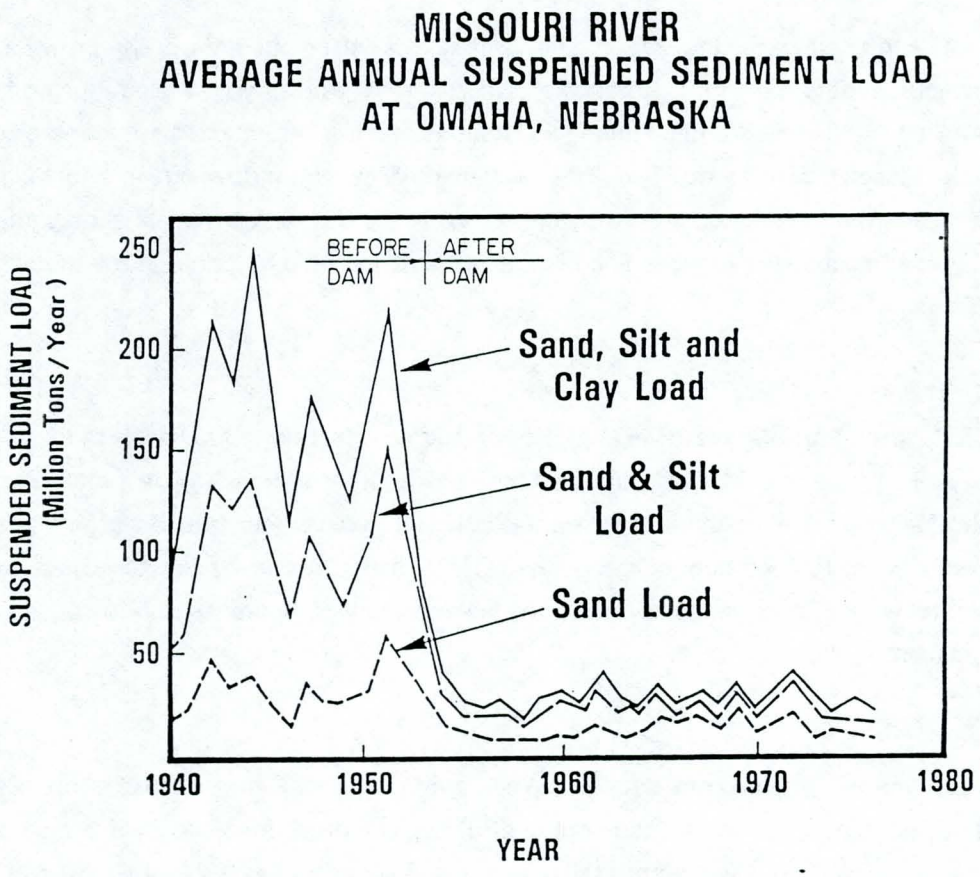


Figure 3.3.5. Effect of storage reservoir on downstream bed-material transport.

Bed degradation downstream of dams is of most concern in streams with fine alluvial beds. In beds of widely graded coarse alluvium, the bed surface becomes armoured with the larger stones as a result of selective transport, and the depth of degradation is limited accordingly.

The effects on the longitudinal profile of reduced flood peaks and reduced bed-material load are partly compensating. Whereas reduced bed-sediment loads tend to flatten the slope by degradation, reduced flood peaks tend to steepen it if sediment continues to be supplied by tributaries. If flood peak reduction is severe enough, degradation due to reduced sediment supply may not occur.

The effect of reservoirs on downstream channel widths is quite variable. Reduced channel-forming discharges tend to reduce widths, but on the other hand bank erosion may be aggravated by rapid stage fluctuations or because bed degradation undermines the banks. Studies of 17 cases found widening in about 50% of cross-sections, narrowing in about 25% and no change in about 25% (Williams and Wolman 1984).

In some cases the stability effects of storage reservoirs are opposite to what might be expected on the basis of the foregoing discussion. If the reservoir, while reducing high flood peaks, releases bankfull discharges for longer durations that the natural stream, bank erosion may actually be increased downstream. Also, if bed sediment inflows from downstream tributaries are high relative to those from the area controlled by the reservoir, the downstream channel may aggrade rather than degrade because the reduced flood releases may be unable to transport the tributary sediment inflows.

3.3.7 Alteration of base levels. The de-stabilizing effect on tributaries of reduced mainstem water levels is one case of instability induced by "base level" alterations. Widespread channel incision in the bluffline streams of northern Mississippi is believed to have been caused in part by base level lowering due to flood control in the Mississippi Valley. Base levels can also be raised by flood control works, which tends to reduce the flow capacity of tributaries and to cause deposition of sediment.

3.3.8 Inappropriate cross-section. When a new channel is constructed or an existing channel is modified to accommodate flood control discharges, there is theoretically a certain cross-section that is optimum for the new pattern of discharges and sediment inflows (see Chapter 2). If the cross-section provided is too narrow and deep, it will tend to widen and shoal; if it is too wide and shallow, it will tend to be occupied by a narrower and deeper channel with sub-meanders and side bars.

3.3.9 Inappropriate slope and velocities. Similar considerations apply to slope and velocities. If the slope provided is too steep, it will tend to flatten by upstream degradation and downstream

aggradation. If it is too flat, it will tend to steepen by upstream aggradation. In either case, parts of the channel length will be infilled by deposition and will be unable to carry their designed flood capacities. The selection of an appropriate slope is therefore important to ensure a continuance of flood control capacity without excessive maintenance.

When channels are modified for flood control, the existing slope is usually too steep for augmented discharges and should be reduced by the use of grade control structures that impose energy dissipation through local drops. This is particularly the case if the channel is shortened by realignment.

3.4 Forms of instability

A number of additional points about various forms of instability in flood control channels are discussed in this section, and references are given for more detailed information.

3.4.1 Planform instability. Planforms of natural streams are discussed in Section 2.1.3. In flood control channels, the most common form of planform instability is meander shifting, either pre-existing meanders or new meanders. Meanders can take a wide variety of forms and can shift and evolve in a wide variety of ways. The following points are based in part on an extensive conference proceedings on meandering (ASCE 1983):

(1) The widespread impression that erosion occurs on the outer concave bank and deposition on the inner convex bank is not always correct. In some forms of meander shifting, the situation is reversed at certain points on the channel.

(2) The question of whether bed-sediment transport is necessary for initiation of meandering has been widely debated. A straight channel with significant bed-sediment transport tends to lay down alternating side bars (Figure 3.4.1) which may then initiate erosion on the opposite bank to start the meandering process. In some cases, however, the inherent instability of straight flow appears sufficient to start meandering without prior deposition. Either way, active meander development and shifting involves sediment exchange between eroding and depositing locations (Figure 3.4.2). In well-developed meander systems, most of the bedload may move only short distances between erosion and deposition.

(3) Initial meander development tends to be self-reinforcing because it generates bed-sediment transport that feeds the process. In an incipient stage it may be relatively easy to check, whereas later it may require expensive rehabilitation.

Figure 3.4.1. Side bar deposition and sub-meandering in straight channel.

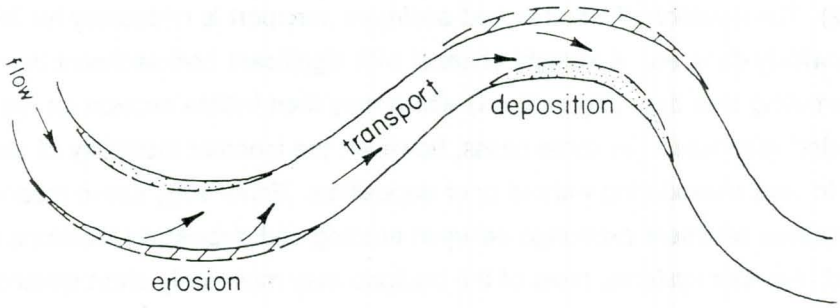


Figure 3.4.2. Sediment transport associated with shifting of meander bends.

(4) It is presently impossible to predict analytically whether a given channel is liable to start meandering. Simons and Julien (1983) state: "Meandering systems are difficult to investigate due to the large number of factors, forces and processes involved.....Existing theories....are generally limited to simplified meandering systems. These theories must be applied with care to most river systems in order to prevent improper designs." Reliance should preferably be placed on local experience with similar channels. Post-project monitoring is advisable, to detect meandering tendencies before they advance too far for economical treatment.

(5) Design of sinuous rather than straight planforms is frequently advocated on environmental grounds (Keller and Brookes 1983, Rechard and Schaefer 1983, Nunnally and Shields1985), and it is sometimes claimed that meandering channels are morphologically more stable. For given flow and sediment conditions, there may be an optimum meander geometry that can maintain itself better than a straight planform, but reliable quantitative guidance is generally lacking. Analysts have focussed mainly on relationships between meander wavelength and width or channel-forming discharge, and on the geometry of meander bends, as discussed in Section 2.3.9.

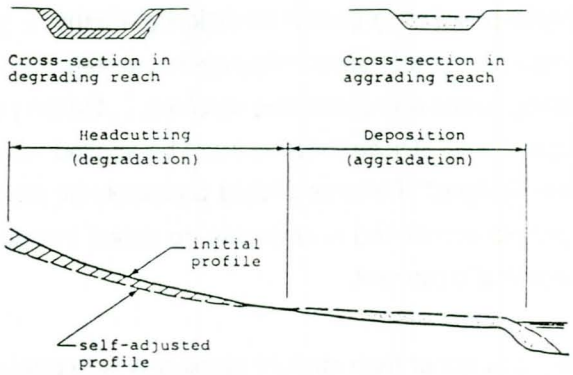
Braiding instability occurs mostly in channels with high slopes and high bed-sediment loads. Threshold slopes for braiding are referred to in Section 2.2. Gregory (1983) reports a case where a narrow meandering channel widened and partly braided when the slope was increased by base-level lowering and straightening for flood control. If a braided channel is constricted between inerodible banks, the braiding can be suppressed.

3.4.2 Profile instability. A wide variety of causes and forms of bed degradation are described by Galay (1983). The longitudinal response of channelized streams is discussed extensively by Schumm et al (1984). Other examples are described by Neill and Yaremko (1988). The general direction of slope responses to input changes is indicated in Section 2.2.3. Various forms of profile response are illustrated in Figure 3.4.3. The following points are important:

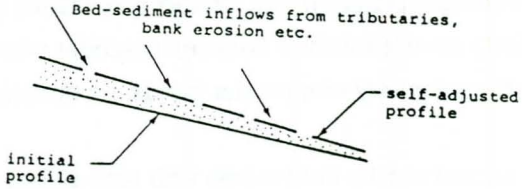
(1) An increase in channel-forming discharge generally tends to flatten slopes. However, if bank erosion and meandering are accelerated, the resulting increase in bed-sediment inputs may oppose and even reverse the slope-flattening tendency, at least for a time.

(2) If increased channel-forming discharge is combined with erosion control, both changes might tend to cause slope flattening.

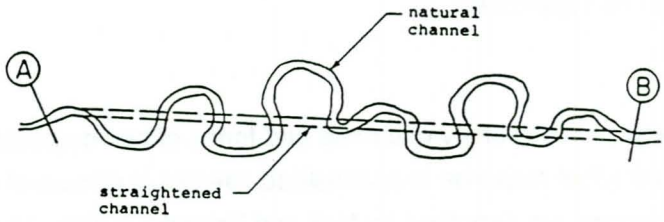
(3) The degree and rate of slope change depend partly on the grainsize distribution of the bed. In coarse alluvial materials with a wide range of grainsizes, armoring often limits degradation. Armoring means the development of a surface layer of stones that can only be moved in large floods.



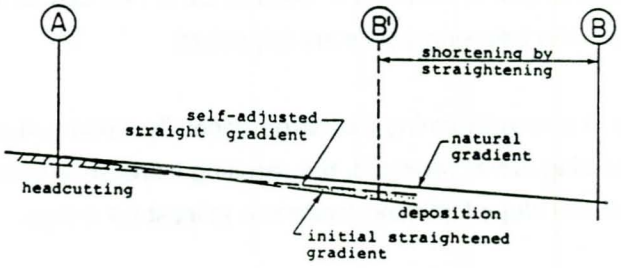
SLOPE FLATTENING: RESPONSE TO INCREASED CHANNEL-FORMING DISCHARGE



SLOPE STEEPENING: RESPONSE TO INCREASED BED-SEDIMENT INPUTS



PLAN



PROFILE

SLOPE RESTORATION: RESPONSE TO SEVERE REALIGNMENT
(NOT RECOMMENDED)

Figure 3.4.3. Examples of profile response in mobile-bed channels.

(4) Longitudinal profile response of alluvial channels is reasonably amenable to time-step analysis using one-dimensional computer programs like HEC-6 (USACE 1977). Considerable investigation and experience may be required to construct a reliable computer model for an actual channel.

3.4.3 Cross-sectional instability. Cross-sections of natural streams are discussed in Section 2.1.3. The general direction of width and depth response to input changes is indicated in Section 2.2.3. The following additional points are important:

(1) Severe cross-sectional changes tend to follow longitudinal profile degradation. Banks are undercut and the cross-section may go through a complex cycle of changes (Schumm et al 1984, Thorne 1988).

(2) A very wide cross-section does not necessarily ensure bank stability. The stream may form a meandering inner channel between the designed banks and then attack these at severe angles.

(3) A relatively narrow, deep channel is sustainable only with flat slopes and low velocities. Natural channels of this type are found mainly in very fine-grained or organic materials with low bed-sediment loads.

(4) For similar materials and similar bed-sediment concentrations, width-to-depth ratios increase with the scale of the system: large sand-bed rivers have greater width-to-depth ratios than small ones. Width generally increases faster than depth as channel-forming discharge is increased (see Figure 2.2.1 in Chapter 2).

3.4.4 Combined cases. In assessing instability in existing channels and considering possible response to a project, it is important not to focus on one form of instability without due consideration of others. For example, while profile degradation may be the most common response downstream of storage reservoirs, it may not be the most important in a particular case. One form of instability is usually accompanied by or gives rise to others: for example, profile degradation generally initiates bank instability, and cross-sectional enlargement produces a supply of sediment that affects the longitudinal profile and may initiate meandering.

3.4.5 Comments on sediment transport in relation to stability. It is sometimes implied that instability problems in flood control channels arise basically from sediment transport. However, instability may occur in a channel that initially carries negligible quantities of sediment, because velocities are too high for the boundary materials. Sediment transport is then a result and not a cause of instability. On the other hand, pre-existing bed-sediment transport may initiate or contribute to planform instability by forming side bars that encourage erosional attack on the opposite bank.

Bed-sediment transport and wash load have different effects on channel stability. Generally, increasing bed-sediment transport tends to promote instability. On the contrary, relatively heavy wash loads may promote bank stability by depositing a cohesive layer during flood recessions, thereby increasing erosional resistance and promoting growth of vegetation.

The designed slope and cross-section for a project channel should be capable of maintaining transport of incoming bed-sediment. For heavy bed-sediment loads, the slopes required may be many times greater than for a channel with a just-mobile bed.

The relationship of sediment transport to meander shifting is complex. If erosion on one bank is balanced by deposition on the other, as occurs in some alluvial floodplains, there is basically a sediment exchange with no increase in sediment supply. If, however, there is erosion of high banks and deposition of berms at a lower elevation, meander shifting results in an increased sediment supply to downstream reaches.

3.5 References (Chapter 3)

Ackers, P. 1972. River regime: research and application. Journal Inst. of Water Engineers (UK) pp. 257-281.

ASCE 1983. River Meandering, ed. Elliott. American Society of Civil Engineers.

Biedenharn, D. 1983. Response on Little Tallahatchie River downstream of Sardis Dam. In ASCE 1983 (see above).

Galay, V.J. 1983. Causes of river bed degradation. Water Resources Research vol. 19, no 5. pp. 1057-1090.

Gregory, D.I. 1983. Response of a meandering river to artificial modification. In ASCE 1983 (see above).

Keller, E.A. and Brookes, A. 1983. Consideration of meandering in channelization projects: selected observations and judgements. In ASCE 1983 (see above).

Mosonyi, E.F. 1983. Studies for intake structures of flood detention basins to be established along the Upper Rhine. In Hydraulic Aspects of Floods and Flood Control, BHRA Fluid Engineering, Cranfield, England.

Neill, C.R. and Yaremko, E.K. 1988. Regime aspects of flood control channelization. In International Conference on River Regime, ed. White, Hydraulics Research Ltd. and John Wiley & Sons.

Nunnally, N.R. and Shields, F.D. 1985. Incorporation of environmental features in flood control channel projects. TR E-85-3, Corps of Engineers.

Rechard, R.P. and Schaefer, R.G. 1983. Stripmine streambed restoration using meander parameters. In ASCE 1983 (see above).

Reese, A.J. 1987. Flood control channel nationwide inventory. Report to USACE Waterways Experiment Station.

Schiller, H. 1983. River canalization with preservation of natural retention areas within the flood plains. In Hydraulic Aspects of Floods and Flood Control, BHRA Fluid Engineering, Cranfield, England.

Schultz, W.M. 1987. Flood mitigation strategy for medium-sized streams. Canadian Water Resources Journal vol. 12, no. 3, pp. 17-26.

Schumm, S.A., Harvey, M.D. and Watson, C.C. 1984. Incised Channels: Morphology, Dynamics and Control. Water Resources Publications.

Simons, D.B. and Julien, P.Y. 1983. Engineering analysis of river meandering. In ASCE 1983 (see above).

Thorne, C.R. 1988. Analysis of bank stability in the DEC watersheds, Mississippi. Report to U.S. Army European Research Office.

USACE 1977. HEC-6 Scour and deposition in rivers and reservoirs. Users Manual, Hydrologic Engineering Center.

U.S. Army Corps of Engineers 1990. Environmental engineering for flood control channels. Engineer Manual 1110-2-1205.

U.S. Government 1971. Stream channelization, Parts 1, 2 and 3. Hearings before a House Subcommittee, 92nd Congress. U.S. Govt. Printing Office.

Williams, .. and Wolman, .. 1984. TO BE PROVIDED.

CHAPTER 4. ASSEMBLY OF INFORMATION FOR STABILITY EVALUATION

Evaluation of channel stability (see Chapter 5) requires assembly of relevant information on the channel and drainage basin. Guidance is provided here on collection and assembly of information. Many of the information items may also be required for other project purposes, such as hydraulic and geotechnical design and environmental assessment.

Guidance is provided below under a number of headings, corresponding more or less to separate steps appropriate to a project of substantial scope. In the case of small projects, information assembly may be consolidated in accordance with the time and resources available.

4.1 Review of historical developments

In assessing an existing stream system, it is important to identify historical developments that may have affected its morphology and stability. In some areas the present characteristics of many streams are partly a result of past developments and interferences. Documentary information on alterations prior to federal involvement may be difficult to find. However, comparative examination of historical maps and of ground and aerial photographs can provide clues as to when significant changes occurred. It may then be possible to obtain information on what actually happened to cause the changes.

Historical information is needed for the project stream itself and also for the upstream basin. Large-scale changes in land use often affect channel stability by altering runoff, drainage conditions and sediment supply. Information on major historical floods pre-dating gauge records is often useful. Past diversions into or out of the stream for flood control, irrigation etc. may be key factors. Repairs and modifications to bridge crossings, river structures etc. may be significant.

Information can be summarized in the form of a brief calendar of the most significant administrative, social and technical changes known to have occurred. An example is shown in Table 4.1.1. Suggested sources of historical information are listed in Table 4.1.2.

4.2 Map and airphoto interpretation

Topographic maps of various scales can indicate the nature of the drainage basin and stream system, the planform of the channel and its relation to the floodplain, and physiographic controls like valley walls, intersecting ridges etc. Maps of different dates can sometimes be used to examine

TABLE 4.1.1 **Example of historical development calendar**

Date	Development	Agency
1880 - 1900	Agricultural settlement: conversion from forest to farmland	-
1907	Extreme flood - not measured - extensive damage to farms and communities	-
1910 - 1925	Channelization and straightening of parts of stream system	Local drainage district
1934 - 1938	Construction of few soil conservation dams in upper basin	SCS
1955	Hydraulic study followed by limited dredging and bank protection work over lower 10 miles of main stream	COE
1950 - 1970	General intensification of agricultural development	-
1967	Highest gaged flood	USGS
1972	Flood control study with recommendations for channel improvements	COE
1977	Environmental study: recommended halt to channel improvement plans	EPA

planform changes, and approximate longitudinal profiles and slopes can be developed from contour maps. For smaller streams, however, standard topographic maps may be of limited use.

Stereoscopic black-and-white airphotos are usually the most practical remote-sensing tool for study of stream channels and their changes (Figure 4.2.1). They are good for most cases except perhaps smaller streams in heavily wooded terrain. Frequently a number of series dating back to the 1950's or even the 1920's are available. Airphotos permit examination of sediment deposits and bars, rapids, erosion sites, ice-formed features and the general characteristics, location and planform of the channel at various times. Extensive examples of airphoto interpretation of channel patterns and features can be found in several publications (Mollard 1979, Mollard and Janes 1984, Cornell University 1952).

TABLE 4.1.2 Suggested sources of historical information

Previous studies and reports: COE, SCS, USBR, consultants, etc.
USGS Quadrangle Sheets - old and new series
Aerial photographs: for some areas AAA photos from the 1920s are available
Topographic maps by AMS and others
County maps and city plots
Offices of county, state, highway and railroad engineers
Local newspapers
Older inhabitants, especially farmers
USGS: gage histories and descriptions, gaging notes, rating curves through period of record; water supply papers; provisional discharge records
NWS: storm and flood records
Municipal water and power plants: gage records
Irrigation and drainage districts: gage records

Quality of photography and suitability of scales may vary greatly between different dates. Low-level large-scale photographs are not always the best for showing channel features, especially in wooded terrain, because morphologic features tend to be obscured by vegetation, and tone contrasts between different sediments and ground covers tend to be suppressed. For medium-sized streams, scales in the range of 1:10,000 to 1:30,000 are often best. Experienced interpreters generally use a pocket stereoscope for viewing.

In comparing airphotos of different dates, account should be taken of water-level differences, which may be obtainable from hydrometric gage records. Care is also required in horizontal registration of overlays of different dates, with attention to fixed control points and the edge distortion inherent in uncorrected vertical photographs.

In a case study in Mississippi, airphotos of 1986 were compared with pre-settlement maps of 1830 to examine major changes in channel location that had been initiated by agricultural development and subsequent basin-wide erosion and sedimentation. In some reaches the mapped

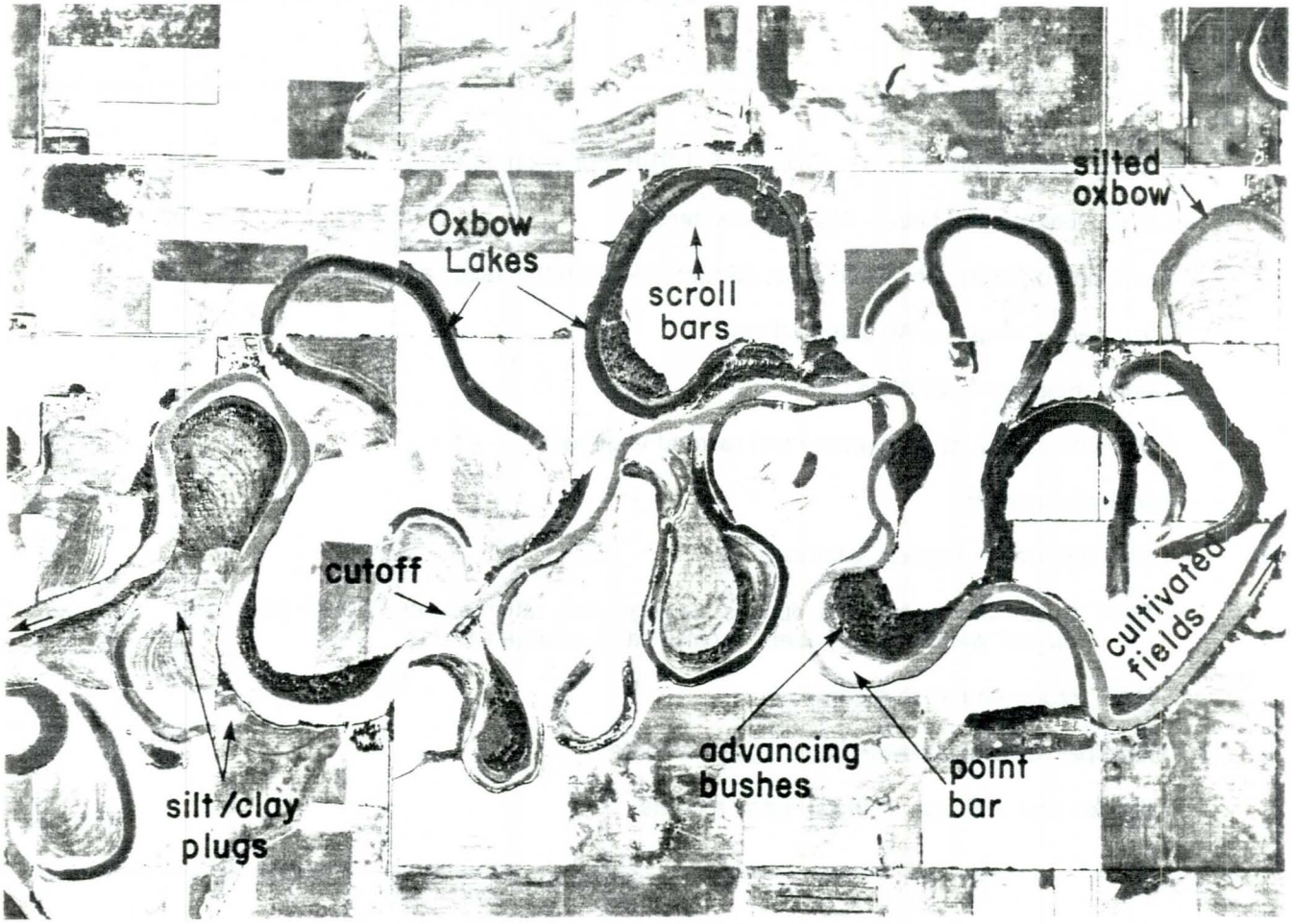


Figure 4.2.1 Airphoto of meandering river illustrating channel features.

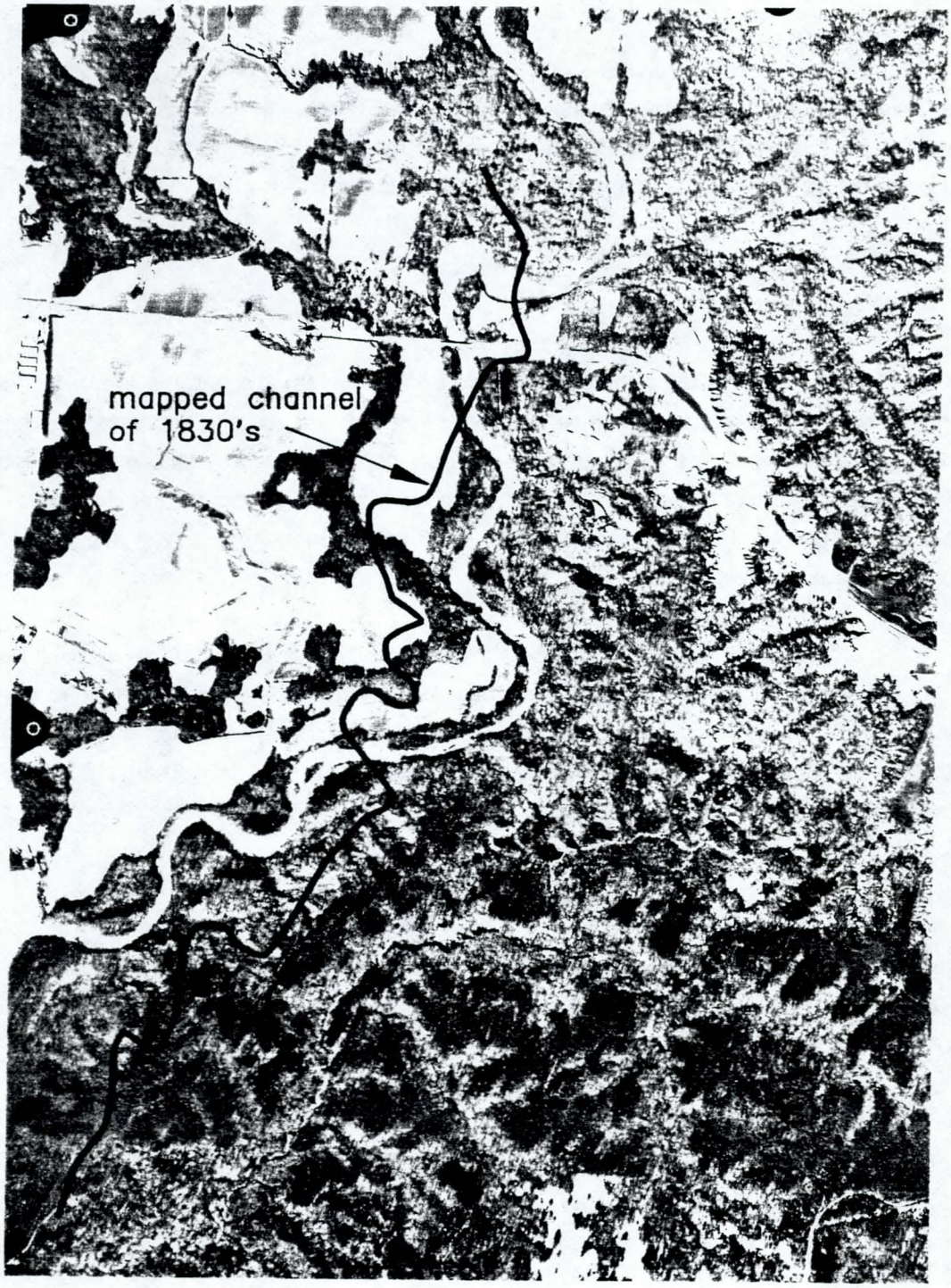


Figure 4.2.2 Comparison of modern and pre-settlement channel locations, Fannegusha Creek, Mississippi.

location of the 1830 channel was detectable from stereo viewing of the 1986 photos, being marked by contrasts in vegetation, edges of tree belts, and terrace scarps (Figure 4.2.2).

Satellite imagery, available from 1972, may be useful for examining basin characteristics and land-use changes. The coarse resolution of most early imagery limits its usefulness for channel studies, but this limitation is expected to improve in future. Infrared imagery and photography can be used to define major drainage features and soil boundaries.

4.3 Field inspection

4.3.1 General. In evaluating the stability of an existing stream and basin, field observation is very important. Field inspection should be done after a review of maps and airphotos. Further visits may be required at later stages. Both ground and aerial inspection are advisable where possible. Photographs (panoramic where appropriate) and notes or audio records should be taken of all significant features. Photographs should be mounted and annotated to show key features, and numbered for ease of retrieval. Video records may be useful in some cases.

Inspection should be done by persons experienced in river hydraulics and stability problems. The main inspection should normally be done under low to moderate flow conditions when the bed and banks of the streams are more easily seen, and preferably when foliage is absent. Additional observations under storm or flood conditions may be appropriate. In cold regions, the main inspection must be done when channels are free of ice and snow, but additional observations under ice conditions may be appropriate.

Electronic means of notetaking such as tape-recordings are favored by some observers, but they can require a troublesome amount of subsequent processing and interpretation. Excessive photography poses similar problems. Recording of information should be guided by considerations of necessity and sufficiency.

Excessive reliance should not be placed on observations from bridge crossings. In many cases, bridges tend to be built at special sites that are not typical of the stream as a whole. Also, bridges may create hydraulic anomalies in the course of time. On the other hand, evidence of extensions, underpinning and remedial work at bridges may reveal instability problems.

The guidance provided here applies particularly to hydrotechnical aspects of stability. Joint inspections with geotechnical and environmental evaluation personnel may offer technical and economic advantages.

4.3.2 Key points and features. Points and features to be particularly looked for in field inspections are listed below under several heads. For background on the significance of points listed, reference should be made to Chapter 2, particularly Sections 2.1.3 and 2.2.5. The list does not necessarily include all features that may be significant in a particular case. Table 4.3.1 provides a summary checklist.

TABLE 4.3.1 Checklist for field inspection

Upstream basin conditions

Topography, soils, vegetation, landuse, ongoing changes
Erosion/deposition zones, sediment sources
Drainage/irrigation systems, diversions
Geomorphic controls and boundaries

Channel planform and banks

Geological and structural controls
Channel shifting and migration
Bank soils, stratigraphy, failures, ice, seepage
Vegetation, bank protection, floodplain conditions

Channel profile and bed

Profile control points, irregularities
Sediment deposits and stratigraphy
Sizes and movement of bed material
Degradation and aggradation

Water surface profile and hydraulics

Highwater marks, debris/ice jams, flood conditions
Velocities and roughness

Downstream reaches

Prior interference
Features susceptible to upstream changes

General

Photographs
Overflight
Witnesses to past floods
Past interferences and responses

Upstream basin conditions

Topography, soils, vegetation, land use and ongoing changes that may impact on channel stability. (Some items may be more easily obtainable from reports, maps and airphotos.)

Active zones of erosion and deposition, and evident sediment sources: sheet, rill and gully erosion, etc. (Figure 4.3.1).

Drainage and irrigation systems, diverted inflows and outflows.

Tributary instability: gullying, headcutting etc. (Figure 4.3.2).

Dominant geomorphic controls: ridges, scarps, landform and channel type boundaries, etc. - see Sections 2.1.1 and 2.1.2. (May require specialist input.)

Channel planform and banks

Geological and structural controls on stream migration: valley walls, outcrops of rock and clay, clay plugs, bridges and dams, etc.

Channel shifting and migration processes: meandering, cutoffs, braiding, etc.

Bank soils and stratigraphy (Figure 4.3.3): composition, grainsize ranges, layering, lensing, etc.

Bank failures and erosion (Figure 4.3.4): locations, causes and mechanisms (see Sections 2.2.5 and 2.3.8).

Drainage and seepage conditions especially after high flows (Figure 4.3.5), adjacent impoundments, irrigation and cultivation practices.

Types and densities of vegetation and root systems on banks and floodplain, and their significance with respect to erosion, slope stability, hydraulic roughness, trapping of sediment and debris, channel shifting, etc. Age and succession of vegetation on channel banks and bars can sometimes indicate rates of shifting and heights of flooding.

In cold regions: ice action on banks and vegetation, freeze-thaw action, frozen ground and ice lenses. (See Figures 2.2.9 and 2.2.10; geotechnical input may be required.)

Existing and past bank protection work, damage and failures and their causes.

Floodplain conditions: natural and artificial levees, obstructions to flow, presence and clearing of vegetation, hydraulic roughness, etc.

Channel profile and bed

Profile controls: outcrops, falls and rapids, nick points and zones (Figure 4.3.6), culverts, weirs, beaverdams, etc.

Irregularity of stream bed, occurrence of scour holes and shoals, alluvial bedforms, etc.

Locations, forms and grainsize distributions of sediment deposits and bars (Figure 4.3.7).

Thicknesses of active bed sediment, where probing or excavation to substratum is practicable.

Figure 4.3.1 Major sediment source: valley landslide.

Figure 4.3.2 Tributary gullying.

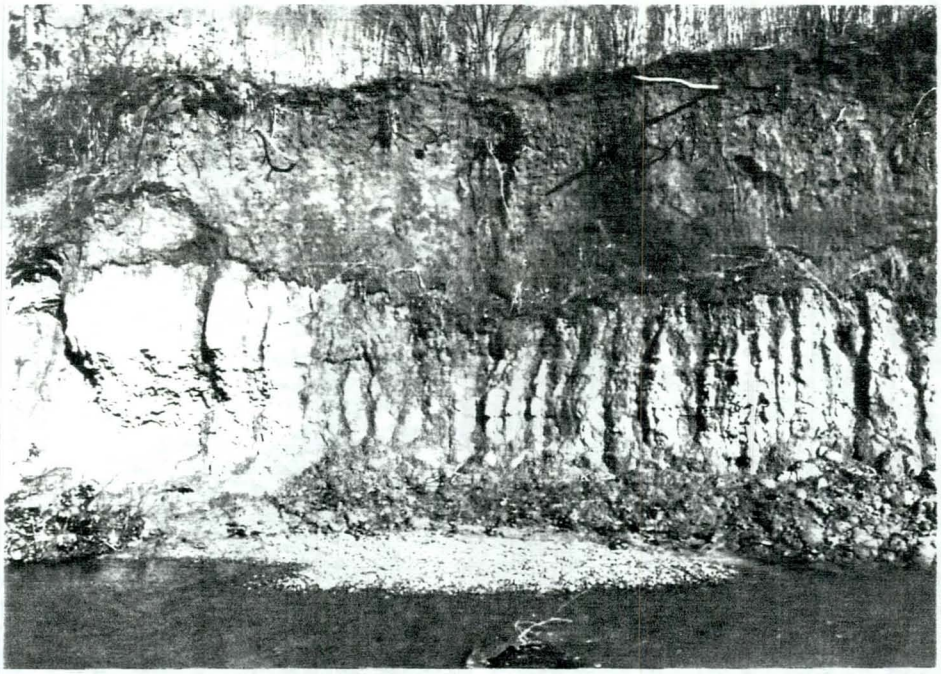


Figure 4.3.3 Stratification of bank soils.

Figure 4.3.4 Bank failure.

Figure 4.3.5 Piping and seepage in bank.

Figure 4.3.6 Nick zone in degrading channel (clay layer).

Indications of frequency of bed-sediment movement; largest bed-sediment sizes moved in past floods; relative intensity of bed-sediment transport in the context of streams generally or of the region in question.

Evidence of degradation: perched tributaries (Figure 4.3.8), exposed bridge piling (Figure 4.3.9), banks undercut both sides, etc.

Evidence of aggradation; reduced bridge clearances (see Figure 2.3.5), overtopped levees, buried intakes, etc.

Water surface profile and hydraulics

Recent high water marks and probable dates.

Water marks of afflux and drawdown around bridge piers (Figure 4.3.10). (Can sometimes be used to infer flood velocities.)

Debris jams and accumulations.

Evidence of ice jams and accumulations: tree scars, stripped vegetation, etc.

Local photographs or witnesses' descriptions of flood conditions: depths of overbank flooding, standing waves, directions of attack on banks, overflow and escape routes, etc.

Approximate velocities as observed.

Estimates of hydraulic roughness based on general experience of channels (for confirmatory purposes when other means of estimating are available).

Downstream reaches

Channel conditions should be inspected for some distance downstream of the project reach, with particular attention to features susceptible to project-induced changes such as sedimentation: see Chapter 3, particularly Section 3.3. Downstream conditions may require further attention at a later stage in project formulation.

General

If the channel has been subject to past works and interferences, efforts should be made during the field inspection to detect response in the form of changes to cross-sections, slopes, planform, channel shifting, sedimentation, etc.

4.4 Channel and floodplain surveys

4.4.1 Topography. Topographic or photogrammetric surveys to provide ground contours, channel and floodplain cross-sections and longitudinal profiles are normally required for the basic flood control aspects of the project. Attention to a number of points can improve the usefulness of survey information for stability evaluation.

Figure 4.3.7 Channel bar with various sediment classes and debris.

Figure 4.3.8 Mouth of perched tributary.

Figure 4.3.9 Exposed bridge piling.

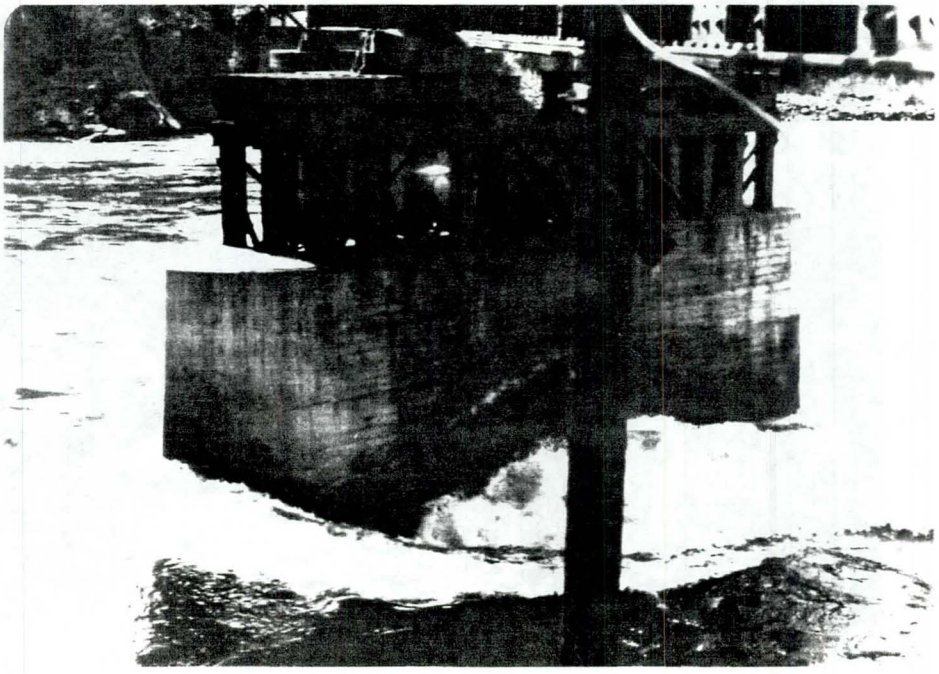


Figure 4.3.10 Flood stain marks on piers.

Cross-sections should show margins and significant changes of vegetation cover, elevations of visible changes in bank soils, bank protection, water levels at time of survey, and detectable high water marks. Section locations should be selected to cover a representative range of planform types - bends, straights, points of inflection, etc. - and a range of channel widths. If recent aerial photographs or a photomosaic plan are available, they can be used to select cross-section locations in advance and then to identify the locations on the ground. An example cross-section is shown in Figure 4.4.1.

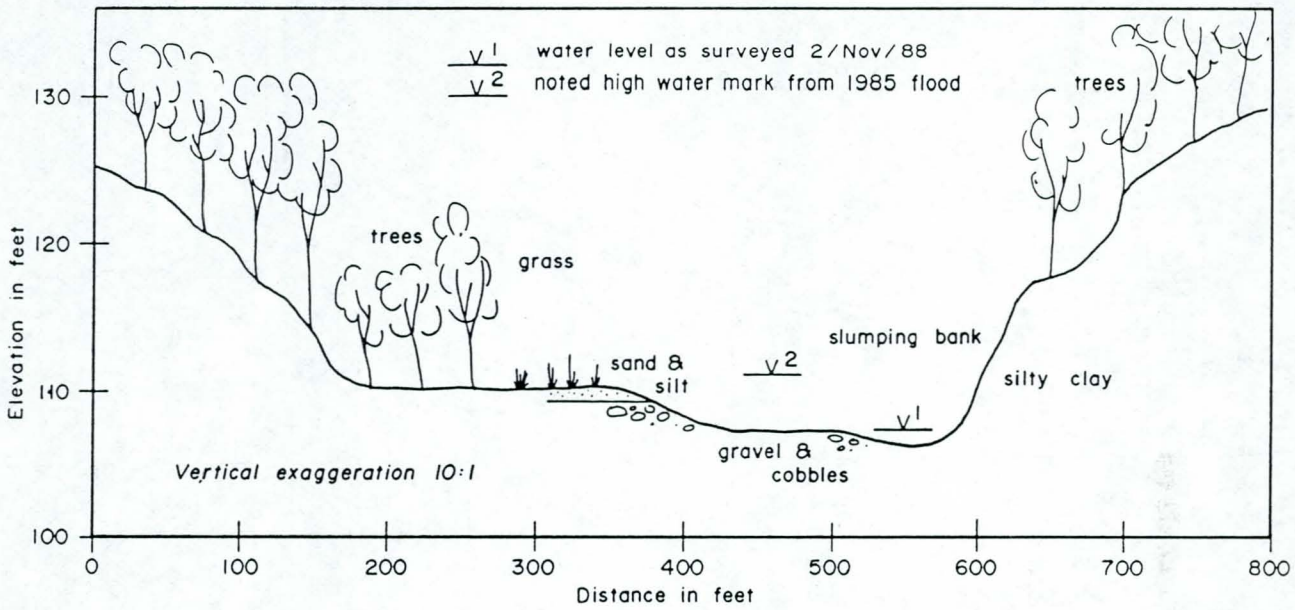


Figure 4.4.1 Example survey cross-section.

The longitudinal profile should show bed levels, low or ordinary water levels, top of banks, and high water levels. Various bases for these delineations can be used. The bed levels may be along centerline, or along the thalweg (locus of deepest points). The low or ordinary water level may be a surveyed line on a specific date, or a computed line corresponding to mean annual flow or other hydrologic parameter. The high water level may be a surveyed high water mark, or a computed line corresponding to a flood of specified return period. For streams with definite floodplains, top of bank lines should correspond more or less to floodplain levels unless there are bank levees. Notable discontinuities in the bed such as nick points, rapids and falls, and structures should be shown. An example profile is shown in Figure 4.4.2.

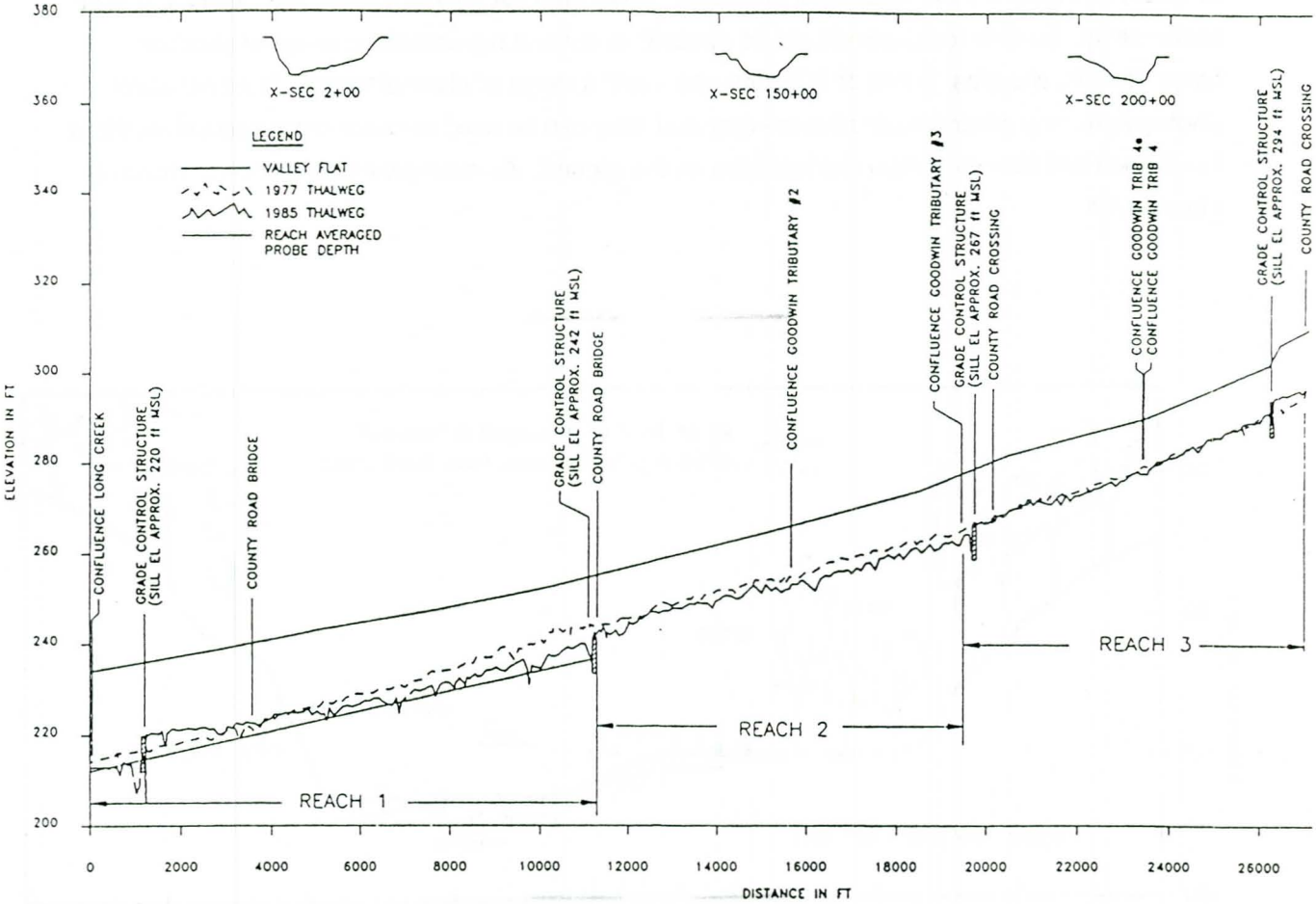


Figure 4.4.2 Example of stream profile.

Distances shown in profiles of single-channel streams should normally be measured along the channel centerline. Where the stream splits into two or more channels, the main or largest channel should be used. In fully braided systems it is more practical to measure along the center of the braided belt. The basis for distance measurement should be clearly stated. Fixed points such as road crossings, tributary confluences, etc. should be shown. Quoted slopes should be based on fall divided by distance as shown. When a stream has been shortened by previous channelization work and superimposed profiles are to be shown, it is best to superimpose fixed points such as bridges and show different distance scales; otherwise, false impressions of degradation and aggradation may be conveyed.

4.4.2 Soils and materials. Samples of bed and bank materials should be taken for analysis of grainsize distributions and for determination of other properties as required. The locations and frequency of sampling should be selected on the basis of previous field inspection and airphoto interpretation. Due account should be taken of variation of soils and sediments along and across the stream, below the streambed, and up the banks.

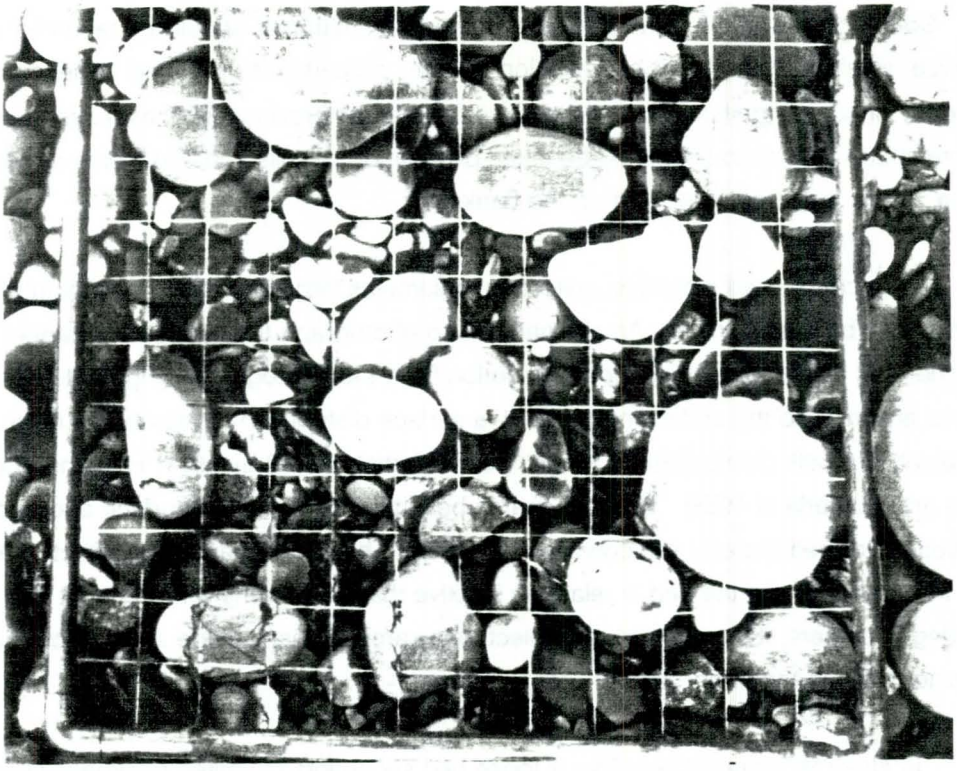
With coarse bed materials, collection of samples large enough for meaningful grainsize analysis may be inconvenient. An alternative is to photograph the surface of channel bars though a wire grid, and to analyze the surface distribution from the photographs (Figure 4.4.3). If the surface material is similar to the underlying material, a surface distribution by number is more or less equivalent to a bulk distribution by weight (see Kellerhals and Bray 1971, Hey and Thorne 1983, Diplas and Sutherland 1988). In some coarse-bed streams, however, surface and underlying distributions of bed material are considerably different because of armoring effects. Armoring is more likely in streams where the bed is relatively inactive than in streams with frequent bed transport. If armoring is present, it is preferable to collect bulk samples that include subsurface material as well as the larger sizes in the armor layer.

In streams with relatively fine or loose bed sediments of limited thickness overlying more consolidated materials, the bed can be probed at intervals with a metal rod to determine thicknesses of active sediment. Such determinations are particularly valuable in considering potential for bed degradation. Geophysical methods of determining sediment thickness are feasible in some cases. With very loose estuarial and coastal sediments, some form of echo sounding may be feasible. Where probing or indirect methods of investigating stratigraphy are not feasible, soil borings or excavations may be advisable.

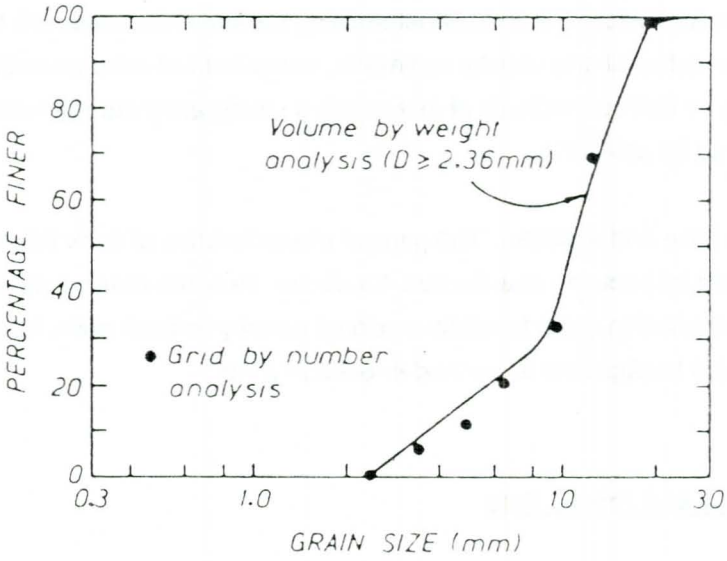
4.4.3 Bank failure and erosion. The general characteristics of bank failure and erosion will be noted in the field inspection - see Section 4.3 above. In some cases a detailed survey of erosional sites may be required in order to relate erosional severity to bank soils, heights and slopes etc. Related technical background is outlined in Section 2.3.8.

4.5 Streamflow and related data

4.5.1 General. Streamflow data are basic to engineering analysis of channel stability - see Section 2.3. Normally these data are analyzed for flood control aspects of the project. Data presentations required include (1) discharge records, (2) flood-frequency relationship, (3) flow-duration relationship, and (4) stage-discharge relationship. Where there is a hydrometric gage in the basin, the first three can usually be generated for the project length without great difficulty. A gage stage-discharge relationship, however, be difficult to transfer to the project reach. In ungaged basins,



Typical grid photograph.



Comparison of Grid by Number Analysis with Volume by Weight Analysis—Laboratory Tests

(Diplas & Sutherland 1988)

Figure 4.4.3 Grid photograph of coarse sediment and comparison of analysis methods.

synthetic discharge estimates may be generated from hydrologic analogy or from watershed modelling. In small flood control projects, lack of streamflow data often limits the practicability of stability analysis. If reliable streamflow information is not available, experienced judgement may be more useful than analysis.

4.5.2 Discharge records. The historical sequence of annual maxima is useful for interpreting field inspection and surveys. Especially in small basins, attention should be paid to peak instantaneous discharges rather than maximum daily discharges. If there has not been a large flood for many years, the channel may convey a false impression of long-term stability. On the other hand, a recent extreme flood might have severely destabilized the channel, presenting an exaggerated impression of long-term instability.

If the flood sequence exhibits peculiar features or anomalies, it may be advisable to examine the gage history and ask the gaging agency about the reliability of the records.

4.5.3 Flood frequency relationship. A graphical relationship using any standard method of plotting is usually sufficient. Extrapolation to return periods far beyond the length of the record should be regarded skeptically. Efforts should be made to determine the frequency of the bankfull discharge. If the stream has a definable bankfull condition and its return period appears to fall outside the range of 1 to 5 years, there may be a case for reviewing the hydrologic data, especially if they are synthesized.

4.5.4 Flow-duration relationship. A flow-duration relationship may be useful for a rough assessment of how frequently the stream bed material is in motion, if used in conjunction with a beginning-of-motion analysis (see Section 2.3). It is also needed for estimating annual volumes of sediment transport.

4.5.5 Stage-discharge relationship. A reliable stage-discharge relationship is needed for quantitative stability analysis. An incorrect stage-discharge relation may be quite misleading, especially if velocities are used as a stability criterion.

Where there is no suitable gage record, stage-discharge relationships are normally synthesized either by non-uniform flow analysis using HEC-2 or similar programs, or by uniform flow analysis of cross-section and slope data. The limitations of non-uniform flow analysis as applied to mobile-boundary channels are not always sufficiently appreciated. Sections based on low-water surveys may be incorrect for high-water stages, because of channel scour and fill. If the channel is

relatively regular in cross-section and slope, uniform flow analysis in which the Manning or similar equation is applied to an average cross-section and slope may be sufficient and in some cases as reliable as non-uniform analysis.

The greatest difficulty in synthesizing a stage-discharge relationship is correct estimation of hydraulic roughness, especially during the large floods that are critical for stability. Every effort should be made to check computed stages against observed or indicated water levels in past floods of known or estimated discharge.

There is an extensive literature on the roughness of natural streams. Selected sources of information are listed in Table 4.5.1.

TABLE 4.5.1 Selected sources of information on hydraulic roughness of channels and floodplains

---

(See Section 4.8 for full references)

Traditional approaches - selection or compositing of Manning n from descriptions and photographs:

Arcement and Schneider 1984.
Barnes 1967.
Chow 1959. Especially Chapter 5, Sections 5-7 through 5-10.

Semi-theoretical approaches based on roughness height or grain roughness, applicable mainly to channels in coarse granular materials:

Bathurst 1985.
Bray 1979.
Griffiths 1981.
Limerinos 1970.
USACE 1970. Especially Plate 3, friction coefficients in terms of relative roughness. Also revised edition 1989, Section 14d, Riprap Design: includes Strickler equation relating n and grain roughness.

Analytical approaches for alluvial (mainly sand-bed) streams, dependent on bed forms and flow regime:

ASCE 1975. Especially Chapter II, Section F, Hydraulic relations for fluvial streams.
Brownlie 1983.
White, Bettess and Wang 1987.

Empirical approaches predicting velocity or stage without explicit use of a roughness coefficient:

Lacey and Pemberton 1972.
Riggs 1976.

Special cases:

Hejl 1977: urban areas.
Hewlett, Boorman and Bramley 1987: reinforced grass waterways. Especially Sections 4.2.1 through 4.2.3, Hydraulic roughness.
Kouwen, Li and Simons 1981: vegetated waterways.

General source:

Yen 1989: conference proceedings.

4.6 Geologic and geotechnical information

Geologic and geotechnical information is often useful in evaluating channel stability. Generally, it is helpful to understand the geologic origins and geotechnical properties of soils and sediments that interact with the channel processes. Information may be obtained from previous reports or by involvement of a specialist.

In an dynamic channel system, rock outcrops, cemented gravels, tills and clay plugs may form hard points that resist erosion and constitute more or less fixed nodes in the planform. Some cohesive or cemented deposits and soft rocks, however, break down fairly rapidly into cohesionless sediments under the influence of weathering, particularly freeze-thaw and wet-dry cycles.

Geotechnical conditions that often result in bank failure in alluvial and glacial outwash soils include (i) internal erosion of dispersive clay, silt and fine sand through piping; (ii) tension crack formation and displacements; (iii) saturation and drawdown with flood rise and recession; and (iv) surface slaking and soil flows due to temperature and moisture changes.

Lacustrine and glaciolacustrine soils and low flow deposits may be layered or "varved". Many banks in such soils exhibit slope instability.

Wind-deposited soils such as loess, comprised of silt and clay-size particles, can stand on very steep slopes when dry, but are susceptible to loss of cementation when wetted and to erosion by overland flows.

Colluvial soils, derived from weathering of underlying rocks and subsequent gravity movement, are often found on steep river valley slopes. In wet periods they are subject to reduction in strengths and increases in unit weight which tend to initiate bank failures. They may contain silty clay and weathered rock fragments. Erosion of the silty clay may leave a temporary layer of rock fragments, too thin to act as a stabilizing berm, that becomes covered by subsequent landslides.

Glacial till is generally a compact mixture of clay, silt, sand, gravel and boulder sizes. Most deposits are fairly resistant to erosion, and most streams in a till environment exhibit relatively low rates of erosion and channel shifting. Longterm incision of streams in till soils often leaves a surficial armor layer of cobbles or boulders that is resistant to movement by the stream.

4.7 Sediment transport

Data needs for analysis of sediment transport are covered in EM 1110-2-4000 (USACE 1989), to which reference should be made if a full sedimentation analysis is judged advisable. In many small to medium flood control projects the necessary time and resources are not available, yet some qualitative assessment is desirable. The following points may assist such an assessment:

(1) The relative degree of bed-material transport - for example, low, medium or high - can be judged to some extent by experienced observers from the aerial and ground features of the channel under relatively low flow conditions. Channels with high transport have large areas of exposed bars exhibiting clean rounded bed-material without growths and vegetation. Channels with low transport tend to have few exposed bars, stable banks, and individual grains or stones covered with algae.

(2) The degree of wash load can be similarly judged from recent silt and clay deposits in slack-water areas and on the upper banks and floodplain. Channels with high wash load will exhibit substantial thicknesses of silt/clay not yet colonized by vegetation. Channels with low wash load will have clean granular sediments on the upper banks and floodplain.

(3) Notwithstanding the above comments, appearances are sometimes deceptive in the absence of local or regional experience. For example, the appearance of a medium-transport channel may vary considerably from arid to humid regions and from cold to hot regions. Description of bed material transport as low, medium or high refers essentially to high flow conditions, for example discharges like the mean annual flood. Such a scheme may not be useful for ephemeral streams in arid regions, where floods capable of transport may occur at rare intervals and the channel is dry much of the time.

(4) In meandering streams exhibiting systematic migration through an alluvial floodplain, the degree of bed-sediment transport is linked to the rate of meander shifting. The severity of bank recession can be visualized in terms of channel widths: for example, a rate of one channel width per year would be very high, whereas a rate of 1% of channel width per year would be quite low.

(5) A braided planform usually indicates high bed-material transport. A contorted meander planform without visible point bars usually indicates low bed-material transport, although wash load may be high. More generalized relationships of this type are discussed in Section 2.1.3.

4.8 References (Chapter 4)

Arcement, G.J. and Schneider, V.R. 1984. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. Rpt. FHWA-TS-84-204, US Dept. of Transportation, Federal Highway Admin.

ASCE 1975. Sedimentation Engineering. Manual no. 54 (V.A.Vanoni, editor).

Barnes, H.H. 1967. Roughness characteristics of natural streams. USGS Water Supply Paper 1849.

Bathurst, J.C. 1985. Flow resistance estimation in mountain rivers. J. Hydr. Engin. (ASCE), April pp. 625-643.

Bray, D.I. 1979. Estimating average velocity in gravel-bed rivers. J. Hydr. Div. (ASCE), Sept. pp. 1103-1122.

Brownlie, W.R. 1983. Flow depth in sand-bed channels. J. Hydr. Engin. (ASCE), July pp. 959-990.

Chow, V.T. 1959. Open channel hydraulics. McGraw-Hill.

Cornell University 1952. Airphoto analysis, vol. 4, Waterlaid materials. Prepared for Office of Naval Research.

Diplas, P. and Sutherland, A.J. 1988. Sampling techniques for gravel sized sediments. J. Hydr. Engin. (ASCE), May pp. 484-501.

Griffiths, G.A. 1981. Flow resistance in coarse gravel bed rivers. J. Hydr. Div. (ASCE), July pp. 899-918.

Hejl, H.R. 1977. A method for adjusting values of Manning's roughness coefficient for flooded urban areas. Jour. Research U.S. Geol. Survey, Sept.-Oct. pp. 541-545.

Hewlett, H.W.M., Boorman, L.A. and Bramley, M.E. 1987. Design of reinforced grass waterways. Construction Industry Research and Information Association (UK).

Hey, R.D. and Thorne, C.R. 1983. Accuracy of surface samples from gravel bed material. J. Hydr. Engin. (ASCE), June pp. 842-851.

Kellerhals, R. and Bray, D.I. 1971. Sampling procedures for coarse fluvial sediments. J. Hydr. Div. ASCE, August pp. 1165-1180.

Kouwen, N., Li, R.M. and Simons, D.B. 1981. Flow resistance in vegetated waterways. Trans. Am. Soc. Agric. Engrs. v. 24 no. 3, May-June pp. 684-698.

Lacey, G. and Pemberton, W. 1972. A general formula for uniform flow in self-formed alluvial channels. Proc. Inst. Civ. Engrs. (UK) pt. 2, Sept. pp. 373-381.

Limerinos, J.T. 1970. Determination of the Manning coefficient from measured bed roughness in natural channels. USGS Water Supply Paper 1898-B.

Mollard, J.D. 1979. Airphoto interpretation manual. Published by J.D. Mollard and Assocs. Regina, Canada.

Mollard, J.D. and Janes, J.R. 1984. Airphoto interpretation and the Canadian landscape. Dept. of Supply and Services, Ottawa.

Riggs, H.C. 1976. A simplified slope-area method for estimating flood discharges in natural channels. Jour. Research U.S. Geol. Survey, May-June pp. 285-291.

U.S. Army Corps of Engineers 1970. Hydraulic design of flood control channels. Engineer Manual 1110-2-1601.

U.S Army Corps of Engineers 1989. Sedimentation investigations of rivers and reservoirs. Engineer Manual 1110-2-4000.

White, W.R., Bettess, R. and Wang S. 1987. Frictional characteristics of alluvial streams in the lower and upper regimes. Proc. Inst. Civ. Engrs. (UK), Dec. pp. 685-700.

Yen, B.C. 1989 (editor). Proc. Intern. Conf. Channel Flow and Catchment Runoff. Dept. Civil Engin., Univ. of Virginia, Charlottesville.

CHAPTER 5. EVALUATION OF STABILITY

5.1 General remarks

As stated in Chapter 1, the purpose of this manual is to provide guidance for evaluating the stability of existing or proposed channels that form part of a flood control project, and for incorporating design features to maintain or enhance stability. This Chapter outlines a systematic approach to evaluation and provides examples. Chapter 6 deals with practical measures to preserve or enhance stability. Background information is contained in Chapters 2, 3 and 4. Stability in this context signifies freedom from undesired erosional or depositional effects.

A stability evaluation of some type should be conducted at an early stage in project planning in order to screen out alternatives that would present serious stability problems and to identify needs for further studies. As planning progresses, successive evaluations with increasing detail may be required. In some environments, potential future consequences of erosional instability can have an overwhelming impact on the longterm viability of a project. Once key planning decisions have been taken it may be difficult to modify the project sufficiently to avoid serious stability problems.

There has been a tendency in the past to defer treatment of stability problems to post-construction maintenance, and such a policy has sometimes been supported by cost-benefit studies. It is often difficult, however, to implement adequate maintenance even where it is clearly provided for in project agreements. The expected time scale of channel response has an important bearing on the advisability of relying on maintenance. It may be reasonable to rely on maintenance to accommodate gradual development of instability but not rapid development.

Stability evaluation will normally be directed towards preparation of a statement describing the stability characteristics of the existing channel system and the stability implications of the proposed project. Recommendations will be formulated on whether special measures are required to counter existing problems or adverse impacts.

5.2 Levels of detail

Evaluation can be done at various levels, ranging from a purely qualitative process based on inspection to a partly quantitative process using numerical data and analyses. As stated in Chapter 1, this manual is intended primarily for smaller projects where funds for investigation are limited, or for larger projects in their preliminary stages. When stability evaluation indicates a need for detailed studies of sediment yield, transport or deposition, reference should be made EM 1110-2-4000 (USACE 1989).

The appropriate level of detail for a particular evaluation depends on the status of the planning study, the perceived seriousness of potential problems, the scale of the project and the resources available. In some cases, persons highly experienced in stream morphology and hydraulics may be able to make a valid assessment using judgment or simple criteria where less experienced persons might require more detailed investigations.

5.3 Application of technical criteria

5.3.1 General. A number of technical criteria available for analyzing certain aspects of channel stability are reviewed in Section 2.3. These criteria do not provide a complete analytical solution to channel stability in three dimensions and are best regarded as aids to judgment. Further guidance is provided here for their application to stability analysis. Analysis is not always required: a purely qualitative evaluation may be adequate for the nature of the project or the stage of the study.

Caution should be observed against relying on a single criterion. Wherever possible, several approaches should be compared and efforts made to reconcile differences. Numerical values drawn from the technical literature should be checked against local experience, as they may not account for all the factors operating.

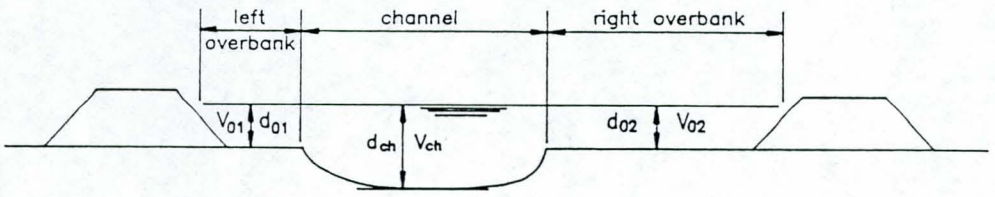
The erosional and depositional stability of mobile-boundary channels is a complex multi-dimensional problem. Analytical knowledge is very incomplete compared with that for non-erodible channels. Previous experience with the behavior and response of similar channels in a similar environment is an invaluable guide to evaluation. If analysis conflicts with experience, the analysis should be reviewed critically.

Numerical parameters computed for the existing channel are principally of value as a basis for comparison with post-project values, rather than as indicators of existing stability. In most cases, the stability of the existing channel will be assessed from field observations and visual data such as aerial photographs.

It is important to fit available analytical tools to the problem at hand. For example, if the perceived main problem is bank erosion associated with active meandering, hydraulic geometry relationships may not be of much help. In applying analytical tools, the user should consider what physical process or feature a given parameter or criterion represents and how that is related to observed or anticipated forms of instability.

5.3.2 Velocities and shear stresses (see also Sections 2.3.2 and 2.3.3). Cross-sectional average velocities and boundary shear stresses should be determined over a range of discharges. Velocities are normally computed as discharge divided by wetted area. Shear stresses are computed as indicated in Section 2.3.3.

Under overbank flow conditions, the velocities used for stability evaluation should be in-channel values, not averages over a compound cross-section (Figure 5.3.1). Bed shear stress should be computed from the average flow depth in the channel proper. Stage-discharge relationships in compound channels are reviewed by Williams and Julien (1989.)



Use V_{ch} and d_{ch} for channel stability evaluation

Figure 5.3.1. Velocities and depths in compound cross-section.

For existing channels, it is preferable to use stage-discharge relationships established from gaging station records or from known water marks. Where observations are not available, uniform-flow computations with estimated roughnesses may be used to synthesize a relationship (see also Section 4.5.5). In active alluvial streams, roughness may reduce appreciably at high stages because of changes in bed topography (Figure 5.3.2). In the selection of roughness values, the interests of flood protection design and channel stability evaluation are different: for design of levee heights it is safer to estimate high, whereas for stability evaluation it is safer to estimate low.

If cross-sections and slope are reasonably uniform, computed velocities and shear stresses can be based on an averaged cross-section. Otherwise the project length can be divided into reaches. If cross-sections are highly variable even within reaches, it may be appropriate to consider values for small, medium and large sections.

For an existing channel, computed velocities can be compared with "beginning of bed movement" (threshold) velocities appropriate to the boundary materials, as given in Tables 5.3.1 and 5.3.2 or Figures 5.3.3 and 5.3.4. Plotting a stage-velocity or discharge-velocity curve will enable estimation of flow conditions for beginning of bed movement. The frequency of this condition can

indicate the potential for certain kinds of instability. For example, if bed movement occurs only under 2-year flood or higher conditions, the potential for profile changes due to slightly increased project velocities is likely to be limited. On the other hand, if movement occurs under flows that occur many times per year, the channel is relatively active and may respond quickly to imposed changes.

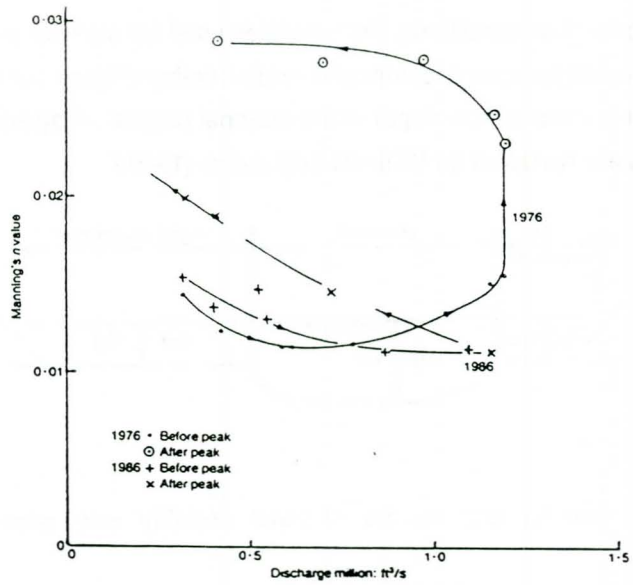


Figure 5.3.2. Roughness changes in a large sand-bed river during floods (from Ackers 1988).

The above comments about velocities apply similarly to shear stresses. The Shields Number based on shear stress is a generally accepted threshold criterion for coarse granular materials (see Section 2.3.3). The excess shear stress over threshold is used as a key parameter in several bed-material transport relationships. The allowable velocity chart shown in Figure 5.3.3 is based on the Shields criterion for the coarser sizes.

In meandering streams, bank erosion and meander migration may occur even when average velocity and shear stress are below threshold values. This is because of uneven velocity and shear distributions across bend sections and because of secondary currents in bends and scour holes. For information on distributions of velocity and shear stress in bends see EM 1110-2-1601 (USACE 1970). On the other hand, deposition may occur in slackwater zones even when average velocity and shear stress are well above threshold values.

Table 5.3.1 Approximate mean channel velocities for "beginning of bed movement" of granular materials

Grain size mm	Grain size ft	Depth of flow ft	Approximate velocity ft/sec
0.1	-	5	2
		10	3
		20	4
0.2		5	2
		10	3
		20	4.5
0.5		5	2.5
		10	3.5
		20	5
1	0.003	5	2.5
		10	4
		20	5
2	0.0066	5	3
		10	4
		20	5.5
5	0.016	5	3.5
		10	4.5
		20	6
10	0.033	5	4.5
		10	5.5
		20	6.5
20	0.066	5	5.5
		10	6.5
		20	7.5
50	0.164	5	7.5
		10	8.5
		20	9.5
100	0.328	5	9.5
		10	10.5
		20	12
200	0.656	5	11.5
		10	13.5
		20	15
500	1.64	5	16
		10	18
		20	21

Note: Values are given for approximate guidance only. Threshold velocities will vary with grainsize distribution, bed forms, flow curvature and other factors.

Table 5.3.2 **Approximate mean channel velocities for erosion of cohesive materials**

Description of material	Depth of flow ft	Approximate velocity ft/sec
Very soft	5	2
	10	2.5
	20	3
Soft	5	2.5
	10	3
	20	3.5
Average	5	3.5
	10	4
	20	4.5
Stiff	5	4.5
	10	5
	20	5.5
Very stiff	5	5.5
	10	6
	20	7

Note: Erosion of cohesive and semi-cohesive materials is affected by a wide variety of physical and chemical factors. Where possible, values should be determined by previous experience or laboratory testing.

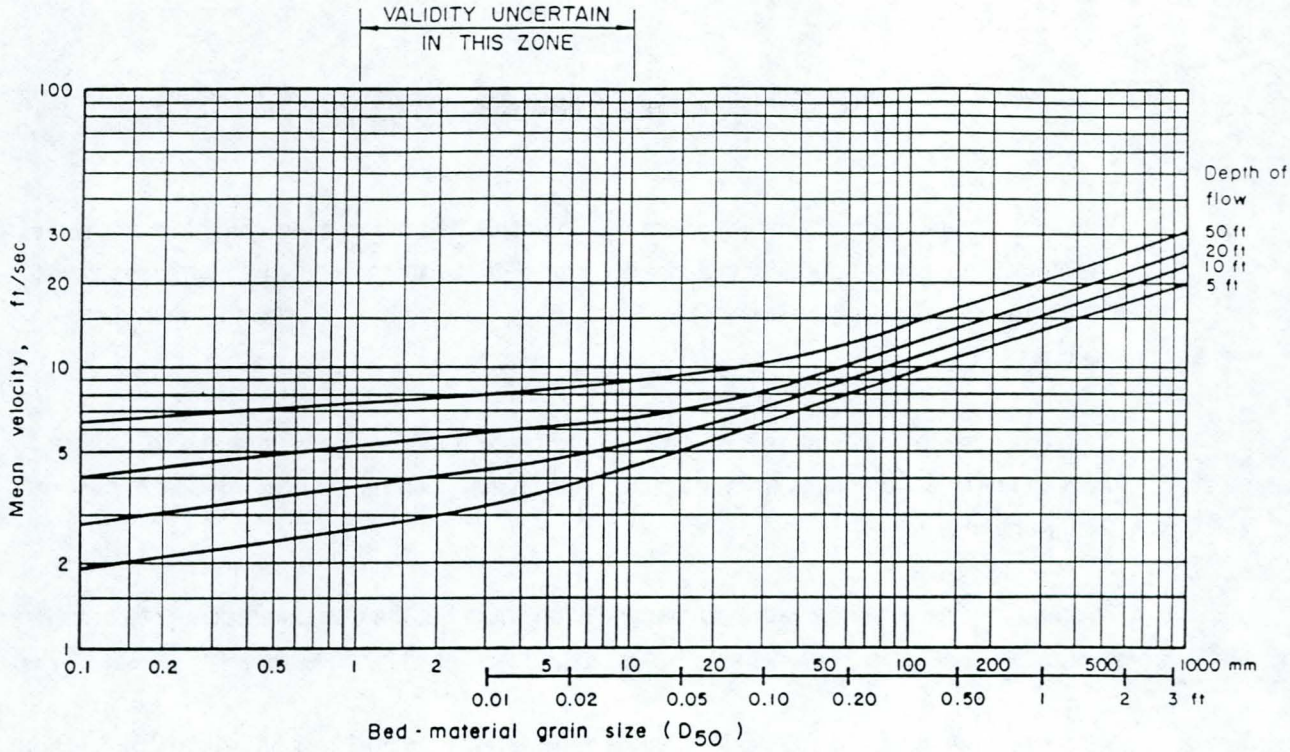
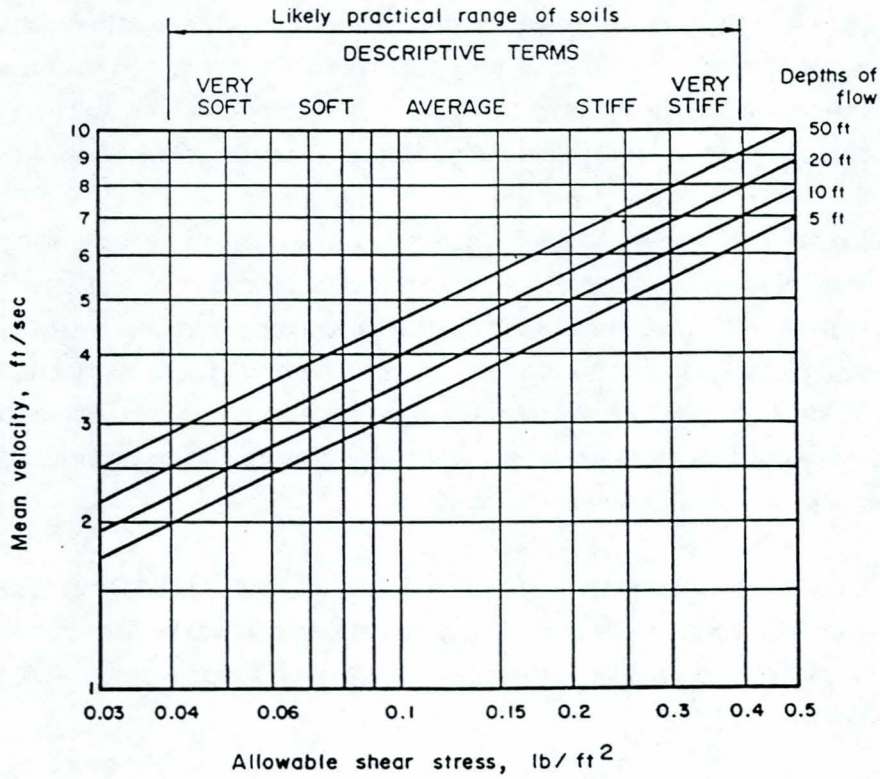


Figure 5.3.3 Approximate threshold velocities for bed movement of granular materials.



NOTE: Where possible, allowable shear stresses should be determined from previous experience or laboratory testing.

Figure 5.3.4 Approximate threshold shear stresses and velocities for erosion of cohesive materials.

Applications of velocity and shear stress criteria are illustrated by the four cases outlined below:

Case 1. Evaluation of pre-project stability indicates that the existing channel is not subject to erosion. For example, the boundary material is a firm clay and the computed shear stress is well below the threshold value indicated by Table 5.3.2. Field observation confirms that there is little significant erosion.

In this case the main interest is in comparing post-project values with threshold values. Threshold values may be derived from the tables and charts given herein or from local experience with similar channels.

Case 2. The existing channel is marginally unstable but the computed post-project values are substantially increased. For example, velocities are increased by 30%, or shear stresses by 60%.

In this case the project is likely to cause considerable channel response unless protection measures are included.

Case 3. Values for the existing channel are substantially above threshold values and the channel is clearly active. For example, the case may involve a sand-bed stream with active bank erosion, meander migration and sand transport. Post-project parameter values are only moderately increased: for example, velocities increase by 15%, or shear stresses increase by 30%.

The relatively modest increase in parameter values caused by the project, in a channel that is already unstable in some respects, may not offer a clear prognosis of detectable increases in instability. If the existing instability is not detrimental to project features, it may be acceptable to defer special measures to counter instability and plan on post-project monitoring to detect any undesirable developments. On the other hand, the project may contain features that are vulnerable to existing instability - such as levees that would be threatened by meander encroachment. Bank protection may then be required in any case.

Case 4. The existing channel exhibits a relatively high bed-sediment load. Average velocity under 2-year flood conditions is more than twice the threshold value. The cross-section is to be widened by 30% to reduce flood levels. Velocities at given flood frequencies will be reduced correspondingly.

The substantial reduction in velocity can be expected to cause deposition of bed sediment in the widened channel. The apparent flood-level reduction benefits of the enlargement may evaporate

unless the channel is re-excavated periodically. To evaluate the rate of sedimentation, a sediment study involving computation of transport rates and quantities would be required - see EM 1110-2-4000 (USACE 1989).

5.3.3 Hydraulic geometry relationships (see also Sections 2.2, 2.3.5 and 2.3.7). The main value of plotting hydraulic geometry data is to infer likely future changes due to the project. The comments below should not be interpreted as definitive guidance to assessing the stability of an existing channel.

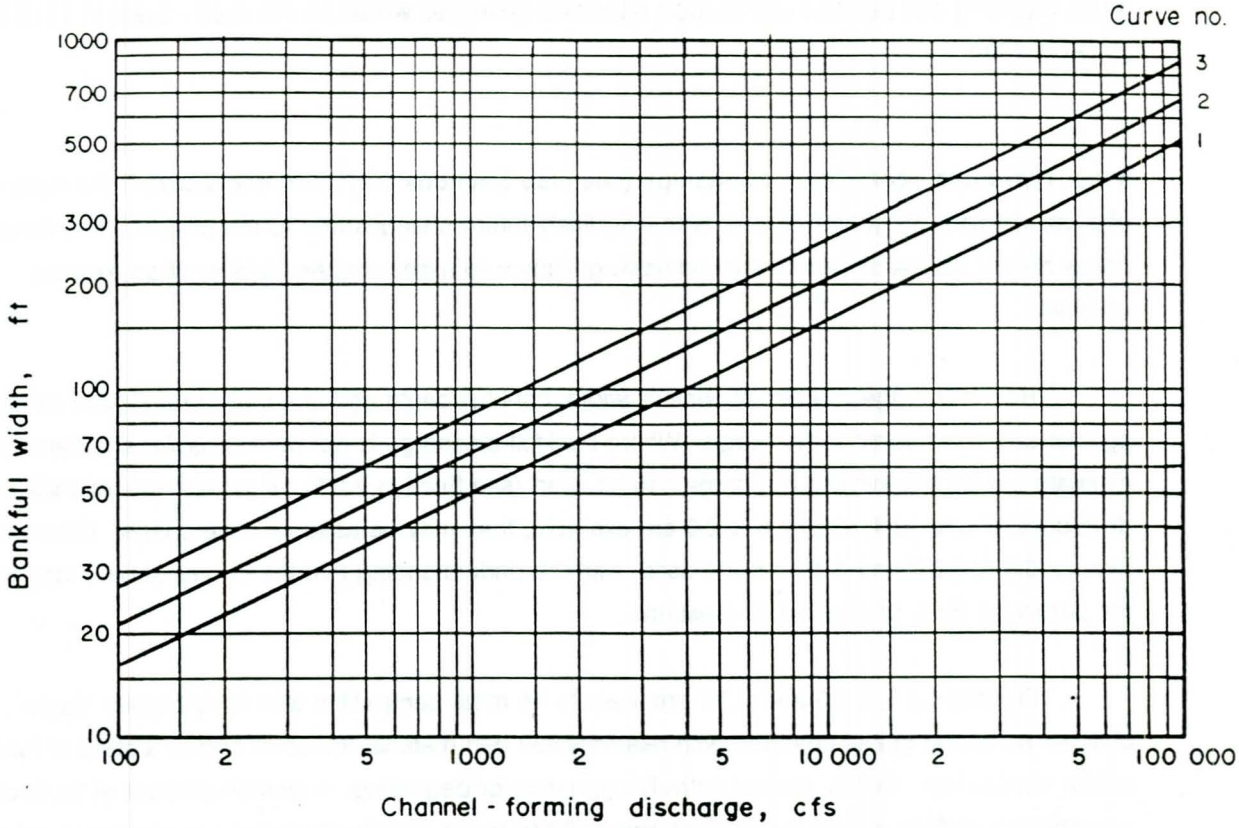
Reach-averaged values of bankfull width, bankfull depth and channel slope should be plotted against estimated bankfull discharge. Where bankfull discharge is not determinable, an alternative estimate of channel-forming discharge can be used (see Section 2.2.5). If locally or regionally developed charts such as Figure 2.2.3 are available, they may be used as base charts. Otherwise, Figures 5.3.5, 5.3.6 and 5.3.7 can be used, with the understanding that the curves shown may not suit the particular class of channel in question.

Figures 5.3.5, 5.3.6 and 5.3.7 are likely to be most compatible with fairly regular single-channel sand and gravel channels with relatively low bed-material transport and in a state of longterm profile equilibrium - that is, neither actively aggrading or degrading. A certain amount of bank erosion and channel shifting is unlikely to affect compatibility much, but the three factors discussed below may cause substantial deviations between plotted data and the curves.

(1) **Bed-sediment transport.** If bed-sediment transport is high in the channel under study, the plotted slope may be many times higher than indicated by Figure 5.3.7, especially with sand beds. In the case of gravel rivers, the plotted slope is unlikely to be more than 3 or so times the curve slope unless the river is multi-channelled. See notes on planform below.

If the plotted slope is high relative to the curves, the plotted depth is likely to be correspondingly low. The plotted width is unlikely to be much above the curves unless the stream is multi-channelled.

(2) **Planform.** A multi-channelled or braided planform is normally associated with higher bed-sediment transport. Depth will tend to be low and slope high relative to the curves of Figures 5.3.6 and 5.3.7. The width of an individual branch of a multi-channel system will probably be fairly compatible with Figure 5.3.5, if the bankfull discharge of the branch is assumed to be channel-forming. The total width between outer banks is likely to be substantially greater than indicated by the curves.

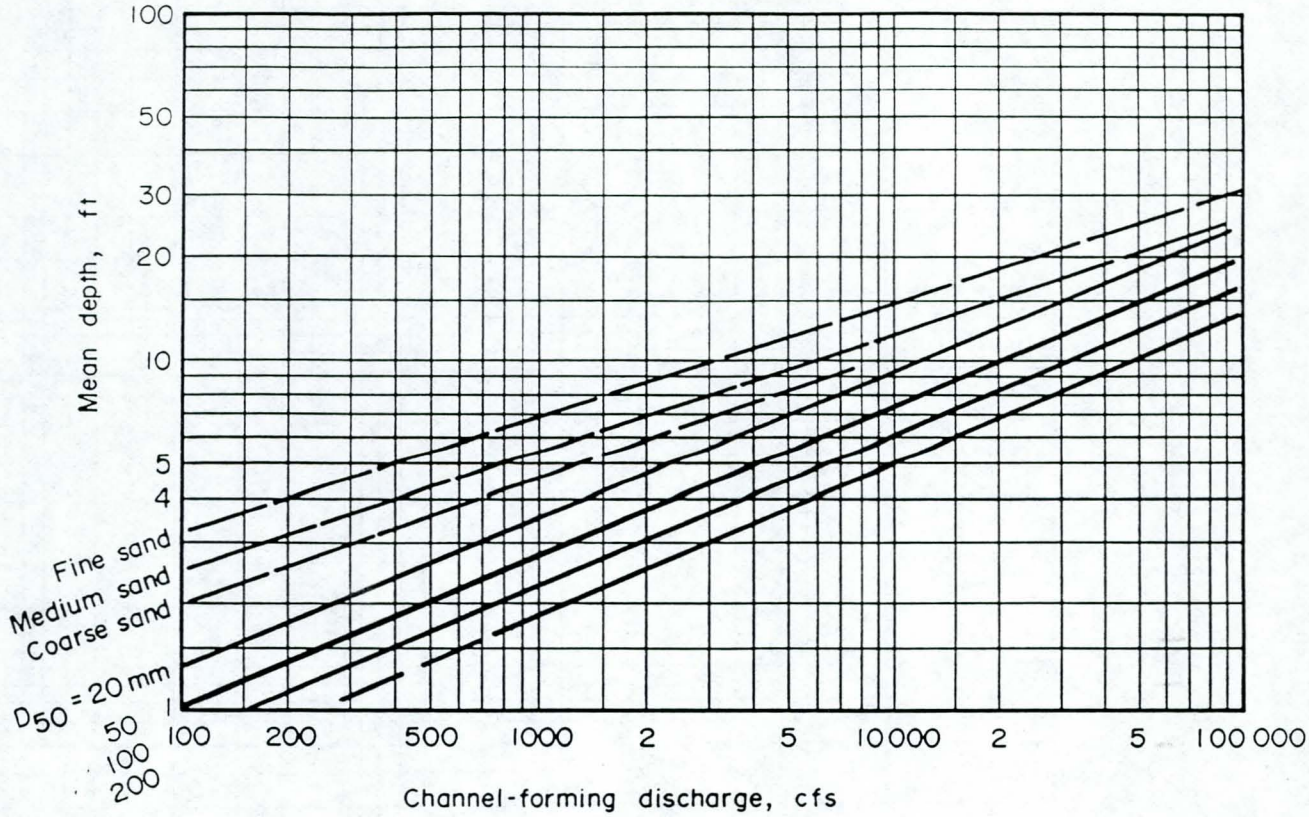


Tentative guidance: Curve 1 : stiff cohesive or very coarse granular banks.
Curve 2: average cohesive or coarse granular banks.
Curve 3: sandy alluvial banks.

See section 5.3.3 of text for limitations.

Formula: $W = CQ^{0.5}$ with $C = 1.6, 2.1, 2.7$

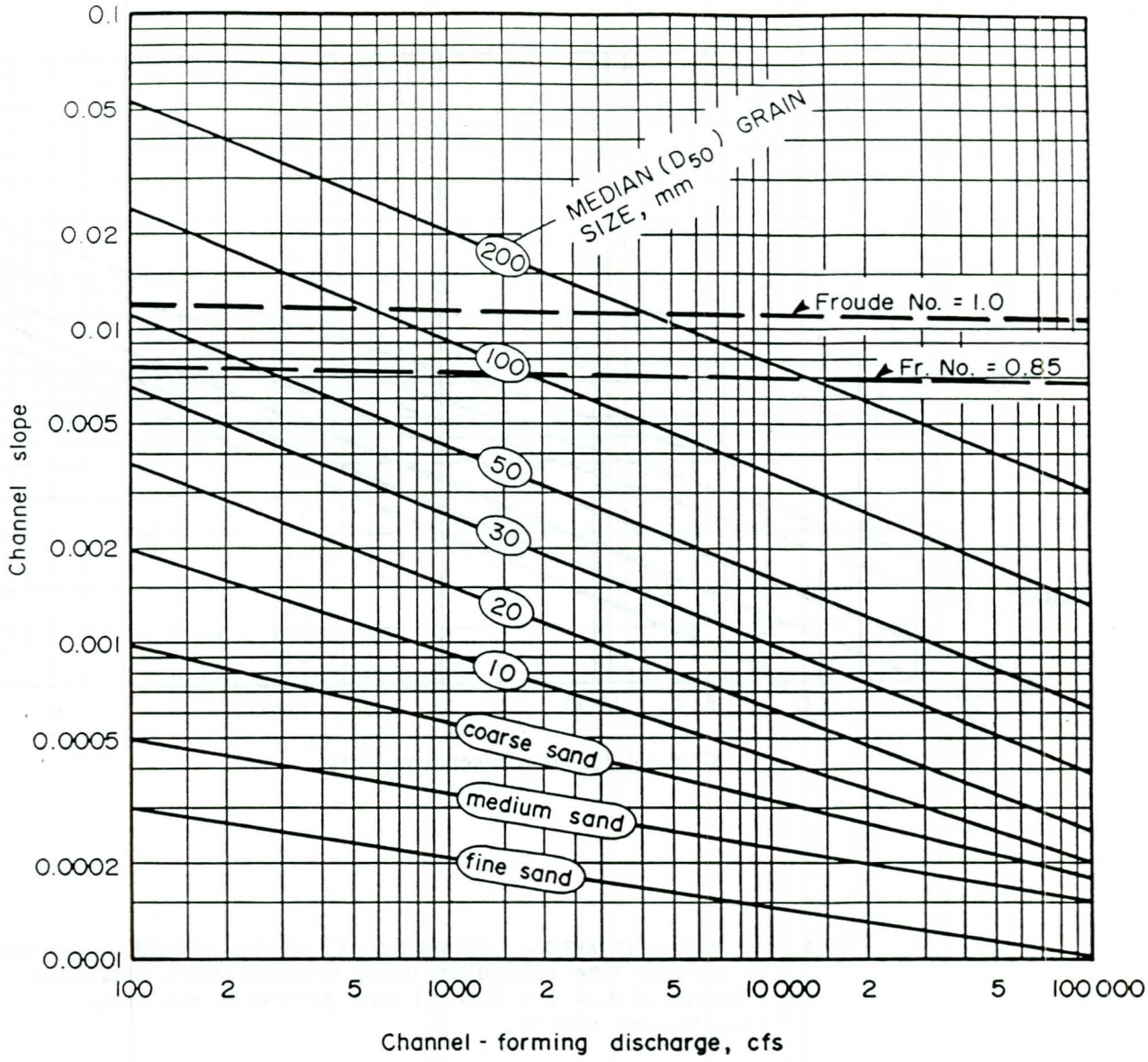
Figure 5.3.5 Hydraulic geometry: bankfull width versus channel-forming discharge.



Note: for very approximate guidance only; depths should be checked by uniform-flow calculation using selected width and slope (Figures 5.3.4 and 5.3.5) and estimated roughness (see Section 4.5.5).

Applies basically to channels with low bed-sediment transport.

Figure 5.3.6 Hydraulic geometry: mean depth versus channel-forming discharge.



Note: for limitations see Section 5.3.3 of text. Curves are basically for single channels with fully alluvial bed but low bed - sediment transport. Slopes may be much higher with high sediment transport, especially with sand beds.

Figure 5.3.7 Hydraulic geometry: slope versus channel-forming discharge.

(3) **Profile instability.** Aggrading channels are likely to plot high with respect to width and low with respect to depth. Depending on the nature of the aggradation process, the slope could be either way. It might be low as a result of bed-sediment deposition in a reach affected by backwater, or high as a result of increased bed-sediment supply from upstream. Conversely, degrading channels are likely to plot low as to width, and high as to depth below top-of-bank. If degradation is advancing upstream by nickpoint migration, slope is likely to be high unless degradation has advanced to a point where there is little supply of bed sediment. If degradation is advancing downstream below a sediment-trapping reservoir, the slope is likely to plot fairly close to the curves.

If the plotted data appear inconsistent with the above guidance, consideration can be given to revising the estimate of channel-forming discharge. Some hydraulic geometry parameters, however, may not be reconcilable with the guidance. The dimension most likely to fit the guidance is the width. Width is relatively insensitive to bed-sediment transport, the factor usually most responsible for deviations in slope and depth.

Plots of hydraulic geometry for the existing channel can be used to indicate the direction and magnitude of likely project changes. Guidance is given below for three types of project change.

(1) **Altered channel-forming discharge (see also Sections 2.2.3 and 2.2.5).** The channel-forming discharge for the existing channel will normally be taken as the bankfull discharge. For post-project conditions, the channel-forming discharge may be taken as that having the same frequency as the existing bankfull. For example, if the existing bankfull discharge has a 2-year return period, a project-adjusted frequency curve should be used to obtain the new 2-year value, even if this will not all be contained initially within the channel proper.

If the post-project discharges are greater than existing (the most common case), width and depth can generally be expected to increase and slope to decrease, as indicated by the trends of Figures 5.3.5, 5.3.6 and 5.3.7. If the expected slope reduction (Figure 5.3.8) involves unacceptable degradation, grade control structures should be considered.

(2) **Altered slope (as by realignment).** Increased slope due to a proposed realignment may be accompanied by increased channel-forming discharge due to elimination of overbank flow or storage. Referring to Figure 5.3.9, point A represents the existing channel slope, point B represents a slope for equivalent stability at the augmented channel-forming discharge, and point C represents the anticipated initial slope after realignment. The difference, C minus B, then represents the excess slope. Grade control or drop structures, may be required to stabilize the profile - see Chapter 6.

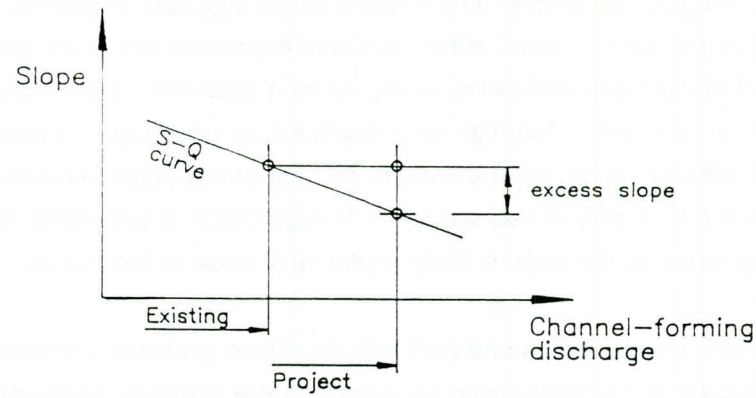


Figure 5.3.8. Excess slope due to increased channel-forming discharge.

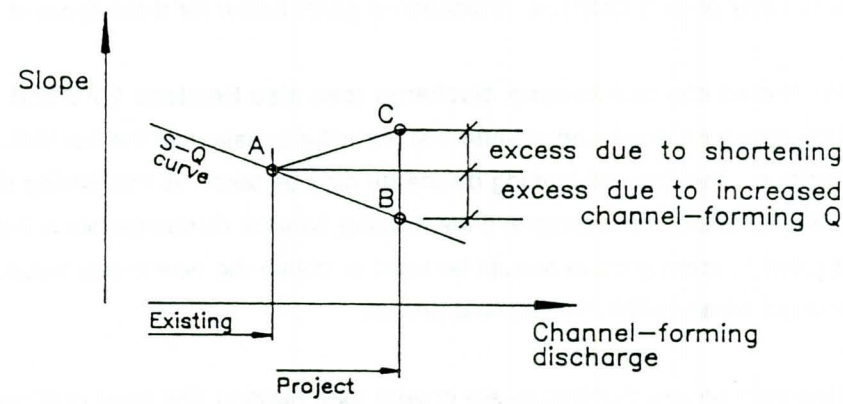


Figure 5.3.9. Excess slope due to shortening plus increased channel-forming discharge.

(3) **Altered cross-section.** If a channel is enlarged, the full augmented channel capacity will not necessarily act as a channel-forming discharge. If full flow occurs only rarely and if there is active sediment transport at lesser flows, the stream may be unable to maintain the enlarged channel without periodic clean-out. Enlargement by side berm cuts, retaining the existing channel, avoids some of the difficulty (see Chapter 3). If full cross-section enlargement appears desirable - perhaps with provision for maintenance clean-out - hydraulic geometry plots of width and depth against discharge may be used to indicate suitable proportions for the enlarged cross-section.

5.3.4 Sediment transport functions (see also Section 2.3.6). Where checks of velocity, shear stress and hydraulic geometry concur with field observations to indicate substantial bed-material transport in the existing channel, one or more sediment transport functions may be applied to estimate transport rates over a range of flow conditions. Guidance on the most appropriate functions for various channel types is provided in Table 5.3.3. It may be appropriate to conduct a formal Sediment Impact Assessment as described in EM 1110-2-4000 (USACE 1989).

Table 5.3.3 Sediment transport functions

Tentative guidance is provided below for functions most appropriate to various classes of channels. This guidance is based on experience in the Waterways Experiment Station and various Districts, primarily with simulations involving the HEC-6 computer program. In the HEC-6 program, the functions as originally published have been modified in most cases to compute transport by size classes and to allow for high washload concentrations where necessary.

Class of channel	Suggested functions	[a]References
Large sand-bed rivers	Laursen-Madden Toffaleti	USAEHEC 1977 Toffaleti 1976
Intermediate-size sand-bed rivers	Laursen-Madden Yang unit stream power	USAEHEC 1977 Yang 1973, 1984
Small sand-bed rivers	Yang unit stream power Colby for streams with high sediment concentration	Yang 1973, 1984 Colby 1964a, 1964b
Sand and gravel-bed rivers	Yang unit stream power Toffaleti combined with Meter-Peter and Muller	Yang 1973, 1984 see above and below
Gravel-bed rivers	Meyer-Peter and Muller	Meyer-Peter and Muller 1948

a See Section 5.7 for full citations.

Bed-material transport computations may be used to compare theoretical transport potential in a project channel with that in an existing channel and therefore to estimate potential rates of erosion or sedimentation. Such a procedure is applicable mainly to the following types of response: (1) profile aggradation or degradation resulting from slope change due to realignment or incompatibility of existing slope with altered discharges, (2) erosional response in an undersized project cross-section, and (3) sedimentation response in an oversized project cross-section. Transport rates are less useful in evaluating meander development and associated bank erosion. The reliability of computed transport rates may be low unless they can be checked against known quantities of erosion, deposition or dredging.

5.3.5. Slope stability analysis (see also Section 2.3.8). Where observed bank failures are due primarily to geotechnical processes associated with the local geology and soils, it may be advisable to analyze bank slope stability using approaches of the types referred to in Section 2.3.8. Where bank failure and erosion are inevitable accompaniments of a generalized channel process such as meander migration (see Chapter 2), focusing on the geotechnical mechanisms of bank collapse may be of limited use for overall stability evaluation.

Understanding of the interaction of hydraulic and geotechnical factors in stream bank failure and erosion is not well developed. A number of papers under the theme "Mechanics of River Bank Erosion" are contained in a conference proceedings (ASCE 1989).

5.3.6 Meander geometry. As indicated in Section 2.3.9, meander dimensions in natural systems tend to scale with channel width. Project changes that tend to alter channel width, mainly increased channel-forming discharges, tend also to alter meander dimensions in the course of time. Meander wavelength, like channel width, will vary roughly as the square root of channel-forming discharge.

If active meander shifting exists in the pre-project channel, this is likely to continue after the project is constructed unless specific measures are taken to arrest meandering. If velocities and shear stresses are increased by the project, the rate of shifting is likely to increase.

It is generally observed that meander loops tend to crowd together and increase in amplitude upstream of a hard point, protected bank, or hydraulic control such as a river confluence (Figure 5.3.10). Where intermittent bank protection only is proposed, progressive distortion of the meander pattern may occur upstream of each protected length.

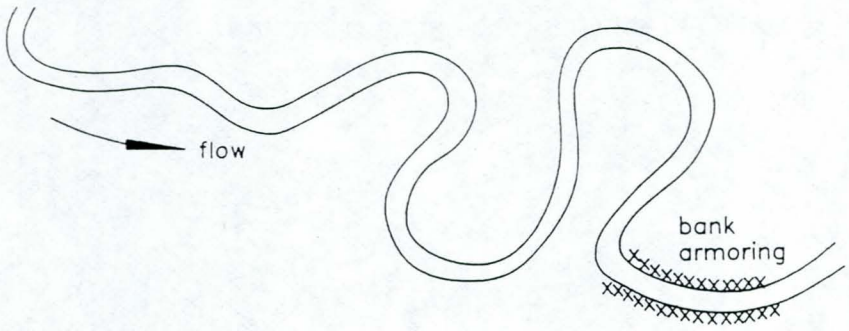


Figure 5.3.10. Distortion of meander pattern upstream of protected length.

5.3.7 Channel evolution model (see also Section 2.2.4).

TO BE PREPARED BY VICKSBURG DISTRICT

5.4 Steps in evaluation

Stability evaluation can be conducted as a sequence of steps as follows:

(1) Description of existing channel system.

(2) Identification and assessment of existing instabilities.

(3) Identification of project features with stability implications.

(4) Assessment of potential stability problems under project conditions.

(5) Conclusions and recommendations.

Guidance for each step is provided in Paragraphs 5.4.1 to 5.4.5 following. Examples of evaluations are given in Sections 5.5 and 5.6.

At each step investigator should consider the questions: what are the vulnerable aspects of this channel system and this project with respect to channel stability? What might happen with respect to erosion and sedimentation if the project is constructed as planned? What project modifications or measures should be considered to mitigate potential instability? The principles of channel equilibrium and response outlined in Section 2.2 of Chapter 2 should be helpful in this connection, but previous experience with similar projects in similar channels may be of equal value.

5.4.1 Description of existing channel system. Detailed guidance is provided in Chapter 4 on assembly of information. The questions below provide a checklist for describing the existing channel system using assembled information. All questions are not necessarily important in all cases. Illustrations may be used in place of description where appropriate.

Instability attributable to the project may propagate upstream and downstream of the actual project area and also affect tributaries. Where judged appropriate, the description should therefore cover upstream and downstream reaches and tributaries.

Drainage basin:
Approximate area and shape?
General nature of physiography?
Surface and subsurface soils?
Land uses and ongoing changes?
Evident erosional areas and sediment sources?

Channel system: Geomorphic context, channel types and planforms, principal channel processes? (See Section 2.1 of Chapter 2.)
Length of main stem and length directly affected by project?
Channel slopes and sinuosities?
Significance of tributaries with respect to flood flows and sediment inputs?
Historical changes, natural or artificial?
Storage reservoirs or grade control structures?
Existing flow diversions, out or in?

Hydrology: Flood frequencies and major historical floods?
Bankfull discharge and frequency?
Recent large floods?

Project length: Cross-sectional dimensions and shapes?
Flood plain widths and land use?
Interferences, e.g. bridges and encroachments?
Special features of longitudinal profile - falls, nick zones, etc?
Existing flood protection dikes, levees etc?

If the project length of channel is substantial it may be advisable to segment it into reaches with distinct hydrologic or morphologic characteristics and describe each separately. The reasons for notable changes in characteristics should be considered.

Boundary materials: Bed materials - classification, grainsizes, thicknesses etc?
Bank materials - classification, stratification etc?
Vegetation on banks and floodplain?
Existing bank protection work?

Evident instability: Prevalence of bank caving, erosion or failure?
Apparent nature of failures?
Channel and floodplain sedimentation?
Bed degradation or aggradation?
Undermining of structures?
Presence of spoil banks indicating clean-out?

Other features: Nature and intensity of sediment transport?
Ice or debris jams?
Boat traffic?
Local experience of stability problems arising from flood control work?

5.4.2 Classification and assessment of existing instabilities. In this step, various forms of instability are identified and their severity is assessed. The following questions can be addressed:

Drainage basin: Significance of erosional areas and sediment sources?
Impact of recent, ongoing or expected changes in land use?
Impact of existing or planned engineering works other than the flood control project?

Channel system: Principal zones of erosion, sedimentation and channel processes?
Key historical changes in channel location, alignment or planform?
Areas sensitive to alteration of flows or sediment inputs?

Project length (may be divided into several reaches):

Significance of lateral instability and bank erosion?
Status of longitudinal profile: ongoing degradation, aggradation or nickpoint migration?
Channel widening or narrowing? Possible reasons?
Channel deepening or shoaling? Possible reasons?
Relationship of profile and cross-section to Channel Evolution Model? (Incised channels; see Section 2.2.4.)

The following additional questions can be addressed if significant instabilities have been identified and if the required level of evaluation warrants analysis of stability parameters. Section 5.3 provides guidance on application of technical criteria.

Flow conditions for beginning of bed material movement or erosion?
Excess over threshold velocity or shear stress at (i) bankfull and (ii) design flood conditions?
Locations of (i) width, (ii) depth and (iii) slope on hydraulic geometry charts, and inferences with respect to stability?
Results of bank slope analysis?
Relationship of meander dimensions to channel widths and key discharges?

5.4.3 Identification of project features with stability implications. Features to be considered should include those that may ultimately affect channel stability upstream, downstream and in tributaries, also those that might be susceptible to existing instabilities. The following questions can be addressed:

Hydrology (see Sections 2.2, 3.3 and 4.5):

Effects of proposed upstream measures - such as reservoirs or diversions - on flood frequencies? (Regulation effect.)
Is it certain that existing upstream regulation measures will remain effective over the project life?
Effects of reduced floodplain storage - by levees or other flood protection measures - on flood frequencies? (De-regulation effect.)
Will flood flows that presently escape to another drainage system be blocked off and retained within the system?

Channel modifications:

Is the channel to be re-aligned and/or enlarged?
Are measures - eg, clearing and snagging - proposed that will affect hydraulic roughness and conveyance?
How will effective floodway cross-sections be altered by levees or dikes?
Are bank protection or grade control measures proposed?
Will land uses and/or vegetation adjacent to the channel be altered?

Other factors:

Are upstream measures proposed - eg, basins or soil conservation - for reduction of sediment inputs?

Will they remain effective over the project life?
Other aspects of the project with potential impacts on channel stability - e.g., boats, access to streambanks, recreation etc?

5.4.4 Assessment of potential stability problems under project conditions. The project features identified above are considered in relation to the channel system and its existing instabilities in order to predict potential instability problems with the project. The following general questions can be addressed:

Discharges (see Sections 2.2.2, 2.2.5 and 5.4.1)

Will changes in flood frequencies and flow distribution between channel and overbanks alter the channel-forming discharge, and by how much?

What other significant differences are expected between the flood flow regimes of the existing and project channels, with respect to both total flows and in-channel flows?

Sediment inputs (see Section 2.2.5)

Are project features or expected upstream changes in land use expected to alter sediment inputs to the project length of channel? What size classes of sediment might be affected?

Lateral instability

Are existing rates of bank erosion and channel shifting tolerable by the project?
Are project-induced changes likely to increase existing shift rates?
Is the existing channel close to a threshold condition at which project changes might cause a basic change in planform, eg. from meandering to braided? (See Section 2.2.4.)
Is an expected reduction in bed-sediment inputs likely to reduce lateral instability or cancel out the effect of destabilizing factors?
Is bank protection proposed as an integral project feature?

Profile instability

If flood discharges are increased by the project, is the channel slope liable to flatten? Or will slope response be limited by geological controls, bed armoring, etc?
If slope flattening takes place by bed erosion, where are erosion products likely to be deposited? How far upstream might degradation proceed? Would tributaries be affected?
Is an reduction of sediment inputs liable to aggravate slope flattening?
If flood discharges are reduced, might sediment that presently passes through be deposited in the channel?

Cross-sectional instability

If flood discharges are increased, is the channel liable to widen or deepen? Are there existing factors or proposed measures that may restrict widening?
If bank vegetation is cleared, is the channel liable to widen from this cause?
How fast is widening expected to develop? Where would erosion products be deposited?

If flood discharges are reduced, is the channel liable to narrow by deposition of bars and berms?

The following additional questions can be addressed if significant stability problems with the project have been identified and if the required level of evaluation warrants analysis of stability parameters. Section 5.3 provides guidance on application of technical criteria.

What is the relationship of post-project channel velocities and shear stresses to existing values at the same flood frequencies?
What are the implications of changes with respect to bank erosion and bed stability?
How do computed velocity-discharge curves compare for the existing and project channels?
What are the potential changes in (i) width, (ii) depth and (iii) slope indicated by plotting existing values on regime charts and shifting parallel to trend lines on basis of altered channel-forming discharge (see Figure ...)?
How do computed curves of bed-sediment transport vs. discharge compare for the existing and project channels? (See Section 2.3.6.)

5.4.5 Conclusions and recommendations. The objective of this step is to summarize the indications of the stability assessments and to recommend further levels of evaluation, or modifications to the project designed to maintain or improve channel stability. The following questions can be addressed.

Conclusions

Does the existing channel have significant instabilities?
Will these instabilities, if continued, be of detriment to the project?
Will the project tend to initiate or aggravate instability in plan, profile or cross-section?
What specific maintenance problems would arise as a result of this instability?
Are sufficient features to control instability proposed as part of the project?

Recommendations

Is a further level of evaluation based on additional investigations warranted?
If not, are project modifications required to reduce instability and maintenance problems?
What specific measures are suggested against instability in (i) plan, (ii) profile and (iii) cross-section?

5.5 Example of qualitative evaluation

The following fictional example illustrates a qualitative stability evaluation based on a reconnaissance level of information gathering. The evaluation involves basically a review of office information and a field inspection. Although this evaluation might be insufficient for project design, it demonstrates that key stability considerations have been addressed. Some of the information below is presented in telegraphic form for the sake of brevity, following more or less the arrangement presented in Section 5.4. Accompanying maps, airphotos and field photos would help clarify the presentation. Reference would also be made to sources of information such as previous reports by government agencies.

FLATFISH RIVER NEAR STONY FORKS - project length 10 miles

Step 1 - Description of existing channel system

Drainage basin. 500 sq.miles, length 40 mi. max width 18 mi.
Low hills and alluvial valley.
Residual and alluvial soils over weak bedrock.
Hills wooded; valley in mixed woodland and farms, history of clearing, recent encroachment of residential acreages associated with nearby town.
Surface erosion from areas of recent logging in upper basin; high bank erosion in some tributary hill streams.

Channel system. In project area, stream flows through mixed farm land and residential subdivisions in broad alluvial valley. Channel partly single and partly double with islands. Floodplain on both sides except for occasional impingement on valley margins. River probably underlain in most places by considerable depths of alluvium.

Upstream of project length, main stem and tributaries are mainly incised, with occasional bedrock outcrops. Some tributaries deliver substantial quantities of coarse and fine sediment. No storage reservoirs. Minor irrigation diversion with weir just upstream of project length.

Downstream of project length, channel gradually changes to meandering sand river and discharges to larger river after 20 miles.

Hydrology. No hydrometric data. Simulation results not available. Based on regional correlations, mean annual flood should be in order of 1200 cfs and 50-year flood in order of 3500 cfs. Very large flood 1952, most recent overbank flood 1984.

The 1952 flood resulted in $10 million damage to crops and buildings. The 1984 flood caused $20 million damage, mainly to residences. There was extensive development of residential subdivisions between 1952 and 1984.

Project length. Irregular meanders with frequent splitting around islands. Comparison of 1984 and 1950 airphotos indicates substantial shifting and trend to wider channel with more exposed bars.

Average topographic slope about 8 ft per mile. Sequence of pools and gravel riffles at low flow, no indication of rock rapids or drops. Narrow bridge near lower end of project length may cause backwater at high flows.

Typical single-channel bankfull section about 70 ft x 4 ft, but quite variable. Total width around islands about 100 ft. Total floodplain width from 500 to 1500 ft, about 40% lawns or grazing, 30% crops, 30% trees. Overbank flow about once every two years, alleged to have increased in frequency. No existing flood protection.

Boundary materials. Bed material: sand and gravel to about 50 mm max. Channel bars vary considerably in form and surface constitution. Bank materials stratified - 1 to 2 ft overbank deposits of silt and fine sand overlying medium sand and gravel. Banks mostly cleared of vegetation, but treed through wooded areas. Protected locally by timber piles and jetties or old car bodies - effectiveness limited. Complaints of accelerated erosion in some properties as a result of bank protection on neighboring properties.

Evident instability. In cleared land, outer banks of bends sloughing at angle of repose. Residents allege losses as high as 10 ft per year locally; airphotos indicate longterm rates at worst locations average about 5 ft per year. In wooded areas, banks are fairly stable. No indications of bed degradation or aggradation.

Other features. Water clear at low flows, turbid in floods. Active movement of gravel on bars. Considerable accumulations of log debris on some bars and islands. Allegations of adverse effects from timber harvesting in upper basin. Some winter ice but no evidence of stability effects. No significant boat use.

No local example of flood control channelization on a similar stream.

Step 2 - Classification and assessment of existing instabilities

Drainage basin. It is possible that basin changes are causing increase of flood peaks and sediment loads and that apparent trend of increasing channel instability may continue. There are no known plans for control of basin erosion, which overall is not considered to be a major problem.

Channel system. Channel system outside of the project area has not been examined in detail. Superficially, there appear to be no upstream instabilities having major implications for the project area. Any increase or reduction in sediment deliveries to downstream lengths would be of concern or interest to fisheries authorities.

Project length. There is substantial lateral instability evidenced by eroding banks, loss of land and growth of channel bars. Exchange of bed sediment between eroding areas and bars is maintained by a supply of coarse sediment from upstream sources.

There is no evidence of instability in the longitudinal profile. Bridges built some 40 years ago near the downstream end of the reach and above the upstream end show no evidence of bed aggradation or degradation.

Comparison of airphotos indicates some increase in average width over the last 40 years. This may be due to reduced bank stability resulting from land clearing, or higher flood peaks resulting from basin changes, or both.

In summary, bank erosion with channel shifting in the floodplain is the dominant form of existing instability. Only local individual efforts have been made to resist it. With respect to cross-section and slope, the channel appears to be more or less in equilibrium with present inflows of water and sediment.

Step 3 - Identification of project features with stability implications

The initial concept is simply to construct levees on the floodplain on both sides of the channel, to contain floods up to a 50-year return period. Riparian owners wish these to be constructed as close to the river as possible, and would also like to see bank erosion reduced. No details of the project have been determined.

Step 4 - Assessment of potential instability - flood control channel

General. The effect of levees close to the river will probably be to increase substantially flood flows carried by the channel, as wide areas of floodplain flow and storage will be eliminated. If the levees are set farther back, this effect will be reduced, but any acceptable levee location is likely to entail higher in-channel flows and an increase in channel-forming discharge. Extensive surveys and hydraulic analyses would be required to quantify these effects.

Lateral instability. The existing lateral instability will be aggravated by increased in-channel flows. Bank erosion and loss of land can be expected to become more severe. Consideration should therefore be given to erosion protection of the levees and to the potential downstream consequences of increased sediment from bank erosion.

Profile stability. With increased in-channel discharges, the channel can be expected to flatten its slope over the long term by upstream degradation and downstream aggradation. Given the wide range in bed-material sizes and the active lateral shifting, such effects may not be of much significance for many years. Extensive field investigations would be needed to model this process.

Cross-sectional instability. There may be a tendency for cross-sections to both widen and deepen. In the absence of substantial riparian developments, this is unlikely to be of serious concern in itself.

Step 5 - Conclusions and recommendations

Conclusions. A flood problem exists and a workable scheme for flood protection can be developed. The existing channel is laterally unstable. Meander shifting is liable to encroach on levees built close to the existing channel. The project is likely to increase the rate of meander shifting and to result in a somewhat enlarged cross-section and a flatter slope in the long term. Potential maintenance problems include provision of bank protection to safeguard the levees and removal of downstream sediment produced by increased bank erosion. No specific measures for controlling instability have so far been proposed.

Recommendations. A feasibility report should be prepared examining a range of solutions to the flooding problem. Any solution that includes levees should take into consideration the existing channel instability, the possibility of project aggravation of this instability and the need to safeguard the levees against channel encroachment.

5.6 Example of more quantitative evaluation

The following fictional example illustrates a partly quantitative stability evaluation that utilizes some of the technical criteria reviewed in Sections 2.3 and 5.3. It demonstrates the advisability of using more than one approach. The project length encompasses a considerable proportion of the total length of the stream. In order to simplify the presentation, numerical values and stability analyses given here refer only to the downstream portion of the project length.

VARMINT CREEK AT ROADAPPLE - project length 30 miles

Step 1 - Description of existing channel system

Drainage basin. 320 sq. miles to downstream end of project. Generally flat slopes throughout. Sandy soils with no rock outcrops. Upstream of project length, land is in crops and pasture. Through the project length, wooded floodplain extends almost to basin boundaries both sides. This floodplain land is being developed into low-density subdivisions on margin of large metropolitan area.

Channel system. Creek has single channel with irregular sinuous planform. One major tributary enters near upstream end of project length. Varmint Creek discharges to a lake 5 miles downstream of termination of project. No existing storage reservoirs, flood control or bank protection works.

Hydrology. Mean annual rainfall 45 inches, mean monthly temperatures 50 to 80 degrees F. 45 years of continuous streamflow records near downstream end of project give following flood frequency estimates:

2-year flood	4500 cfs
10-year flood	12500 cfs
50-year flood	26000 cfs

Largest known peak (1929) estimated 26000 cfs. Largest recent flood (1984) 10,000 cfs.

Project length. No indications of significant bank erosion or channel shifting where natural bank and floodplain vegetation is intact. Where bank vegetation has recently been cleared locally, bank failures are occurring. Slope 2.5 ft/mile (0.00047). Typical cross-section near downstream end: bottom width 50 ft, bankfull width 170 ft, bankfull depth 12 ft, effective width of floodplain 1500 ft. Estimated return period of bankfull flow: 2 years approximately.

Boundary materials. Medium to coarse sand on bed, fine to medium sand on banks. Considerable grass and low brush in bankfull channel beyond limits of a low-water channel approximately 20 ft wide. Large trees on floodplain. Estimated roughness (n) of bankfull channel 0.04, of floodplain 0.08.

Sediment transport. 10-year record of suspended sediment concentrations indicates mean annual yield 48,000 tons/year or 150 tons/sq.mi/year. Bed load unknown. Channel exhibits sandy point bars but no indications of high bed transport.

Step 2 - Classification and assessment of existing instabilities.

Drainage basin. No serious basin erosion or point sources of sediment. Changes in land use are not expected to affect sediment yield appreciably.

Project length. No significant instabilities except bank failures at local clearings.

Step 3 - Identification of project features with stability implications.

The basic proposal is to widen and deepen the channel, following existing alignments, to accommodate a 10-year flood without overbank flow. The proposed cross-section has 200 ft bottom width, side slopes 3:1 (H:V), and 16 ft depth. Flood frequencies will be altered because existing extensive floodplain storage will be eliminated at lower floods and reduced at higher floods. Estimated post-project flood frequencies as determined by hydrologic routing studies are as follows:

2-year flood	15,000 cfs
10-year flood	24,000 cfs
50-year flood	42,000 cfs.

It is proposed to retain a 50-ft strip of existing floodplain tree cover along both sides of the enlarged channel, to help protect the banks. Estimated roughness (n) of enlarged channel = 0.03.

Step 4 - Evaluation and assessment of potential instability - proposed project channel compared with existing channel

(1) Velocities

Existing channel at 2-year flood: mean V by Manning at bankfull depth (12 ft) = 3.2 ft/s. Check bankfull Q = 110 x 12 x 3.2 = 4224 cfs, close to quoted 2-year flood. At 10-year flood, channel V = 4.0 ft/s.

Check Figure 5.3.3: for D_{50} estimated 0.5 mm, computed mean V is at or below threshold value. It therefore appears that significant bed movement would occur only at higher floods.

Project channel: for n = 0.03 and proposed cross-section, new 2-year flood (15,000) cfs flows at depth of 12.3 ft and mean V of 5.2 ft/s. New bankfull (10-year) flood (24,000 cfs) flows at 16 ft depth and 6 ft/s. Velocity at 2-year flood is increased by 62% unless slope is reduced by grade controls or roughness is increased.

(2) Shear stresses

Existing channel at bankfull (2-year): shear stress in centre of channel =

62.4 x 12 x 0.00047 = 0.35 lb/sq.ft.

Project channel at 2-year flood: practically no change in depth and therefore no change in shear stress.

Project channel at 10-year flood (bankfull): depth 16 ft, shear stress 0.5 lb/sq.ft.

(NOTE: because the enlargement involves mainly widening, central shear stresses are not much altered although cross-sectional mean velocities are considerably increased.)

(3) Hydraulic geometry

Reference should be made to Figure 5.6.1.

Width: existing top (bankfull) width of 170 ft at 2-year flood 4500 cfs plots slightly below Curve 3. Project top width (296 ft) plots similarly for new "channel-forming" flood of 15,000 cfs. Width enlargement therefore seems compatible with stable width considerations.

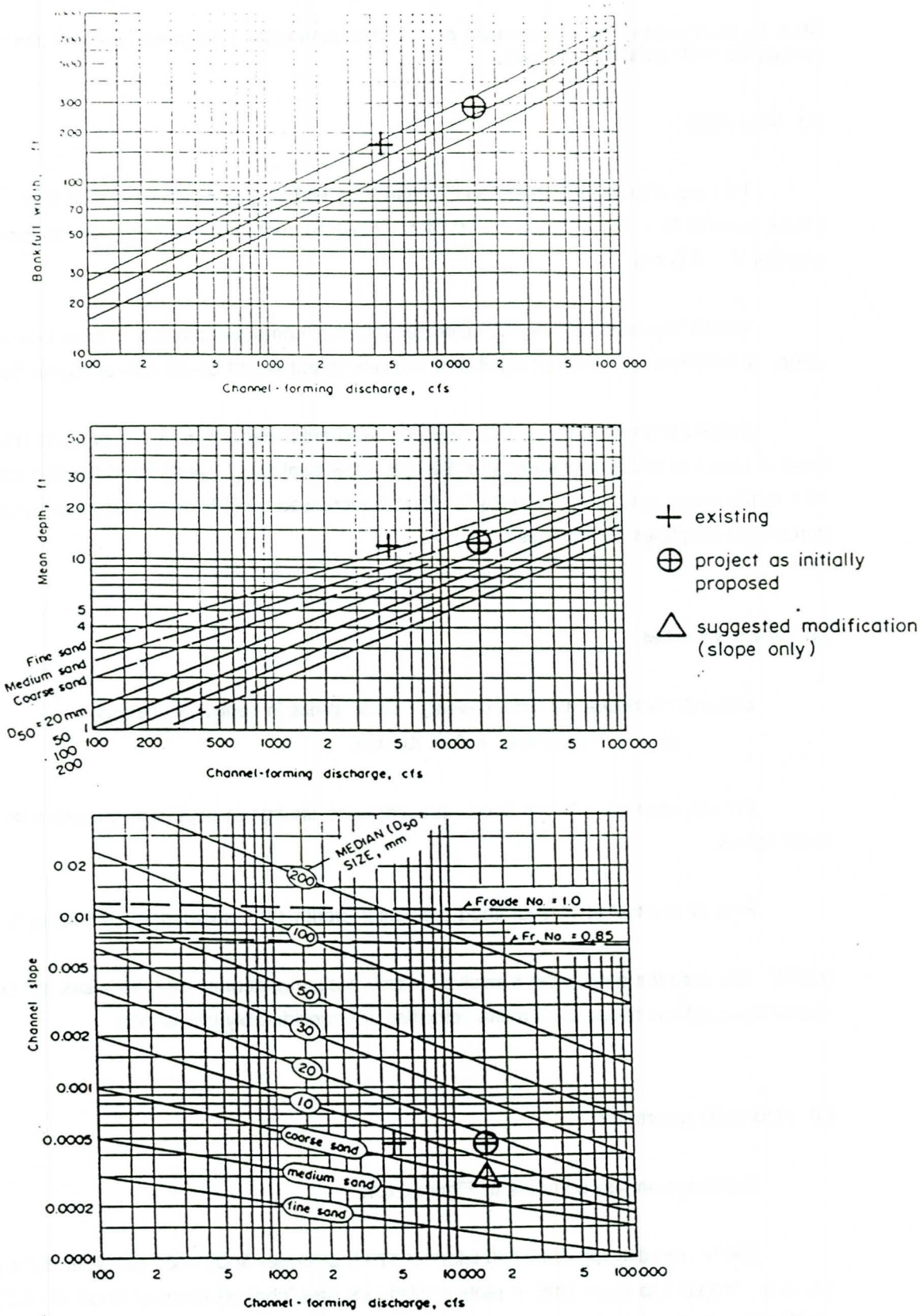


Figure 5.6.1 Hydraulic geometry checks for example of Section 5.6.

Depth: existing bankfull depth of 12 ft plots high in relation to curves. Project depth for 2-year flood 15,000 cfs (12.3 ft) is more compatible. (Depth of existing channel reflects high roughness due to vegetation.)

Slope: existing slope (0.00047) at channel-forming 4500 cfs is high for sand bed, possibly because of high roughness due to vegetation. Initial project slope, if maintained at 0.00047, is very high for new channel-forming Q of 15,000 cfs, indicating potential for considerable bed-sediment transport and slope flattening.

(4) Assessment

On the basis of the above analyses and of previous experience in the vicinity, the substantially increased in-channel velocities indicate potential for bank erosion, initiation of active meandering, active bed-material transport and probably bed degradation by head-cutting. Velocities could be reduced by grade controls or added roughness.

Step 5 - Conclusions and recommendations

Conclusions

The existing channel is stable in plan, profile and cross-section. The proposed enlargement, mainly by widening on the existing sinuous alignment, avoids drastic changes in stability parameters. However, substantially increased velocities create potential for bank erosion and channel meandering even although protective strip of floodplain vegetation is retained. Gradual slope flattening by headcutting is also a potential concern.

Recommendations

(1) Consider provision of grade controls to reduce effective slope to around 0.0003.

(2) Consider re-planting of vegetation on banks to restore or improve erosional resistance.

(3) If stabilization by vegetation is not practical, consider toe riprap at least around outer banks of bends.

5.7 References (Chapter 5)

Ackers, P. 1988. Discussion on "Frictional characteristics of alluvial streams in the lower and upper regimes" by White et al, Proc. Inst. Civ. Engrs. part 2, Sept. 1988, pp. 577-580.

ASCE 1989. Hydraulic Engineering, Proc. National Conf. on Hydraulic Engineering, New Orleans.

Colby, B.R. 1964, a. Practical computation of bed-material discharge. Journal Hydr. Div. ASCE, March pp. 217-246.

Colby, B.R. 1964, b. Discharge of sands and mean-velocity relationships in sand-bed streams. Prof. Paper 462-A, U.S. Geol. Survey.

Meyer-Peter, E. and Muller, R. 1948. Formulas for bed load transport. Intern. Assoc. Hydraulic Research, 2nd meeting, Stockholm, pp. 39-64.

Toffaleti, F.B. 1966. A procedure for computation of total river sand discharge and detailed distribution bed to surface. Report to Committee on Channel Stabilization USACE.

U.S. Army Corps of Engineers 1970. Hydraulic design of flood control channels. Engineer Manual 1110-2-1601.

U.S. Army Engineer Hydrologic Engineering Center 1977. Users Manual HEC-6, scour and deposition in rivers and reservoirs.

U.S. Army Corps of Engineers 1989. Sedimentation investigations of rivers and reservoirs. Engineer Manual 1110-2-4000.

Williams, D.T. and Julien, P.Y., 1989. Examination of stage-discharge relationships of compound/composite channels. In Proc. Intern. Conf. on Channel Flow and Catchment Runoff, ed. B.C. Yen, Univ. of Virginia, Charlottesville.

Yang, C.T. 1973. Incipient motion and sediment transport. Journal Hydr. Div. ASCE, Oct. pp. 1679-1704.

Yang, C.T. 1984. Unit stream power equation for gravel. Journal Hydr. Div. ASCE, Dec. pp. 1783-1797.

CHAPTER 6: DESIGN FOR STABILITY

6.1 General Remarks

This chapter provides guidance and examples for various practical aspects of design for stability. The main causes of the type of instability to be controlled are reviewed briefly in each case. General principles of channel equilibrium and response are reviewed in Chapter 2. Stability problems with flood control channels are discussed in detail in Chapter 3.

From the viewpoint of minimizing channel stability problems, methods of flood control can be ranked in the following order of acceptability:

1. Non-structural flood control measures such as floodproofing, evacuation and flood warning systems.

2. Levees set back clear of the meander belt.

3. Levees within the meander belt.

4. Off-channel detention basins.

5. Upstream flood retention or detention structures.

6. Floodway or bypass.

7. Enlarged compound cross-section with existing low-flow channel left intact. (Low-flow channel carries average dry-season flow.)

8. Channel widening.

9. Channel deepening.

From a safety viewpoint, on the other hand, channelization measures like 8 and 9 tend to be more defensible than structural measures such as 2, 3 and 5. Potential conflicts between stability and safety requirements should be discussed with local interests and considered together with economic, social and environmental factors.

6.2 Alignment and planform

Earlier flood control projects often involved extensive re-alignment of pre-existing streams and channels. Sinuous or meandering channels were straightened to improve hydraulic conveyance or to eliminate eroding bends, often without sufficient consideration of potential effects on long-term stability. Severe instability in profile and cross-section often occurred in and beyond the project length, and the treated length of channel often reverted eventually to a meandering state unless expensive remedial measures were undertaken (see Figure 3.1.6).

6.2.1 Single-channel streams. Most existing channels are sinuous to some degree. Current practice is generally to retain existing alignments where practicable. Even where an entirely new channel is to be constructed, arguments can be made for a sinuous rather than a straight alignment. Keller and Brookes (1983) state "Consideration of meandering in channelization projects should be encouraged wherever feasible because meandering channels often have a more consistent pattern of sediment routing, are morphologically more stable, have more hydrological and biological diversity, and aesthetically are more pleasing". Similar comments are made by Nunnally and Shields (1985) Flood control channels stabilized on meandering alignments are shown in Figures 6.2.1 and 6.2.2

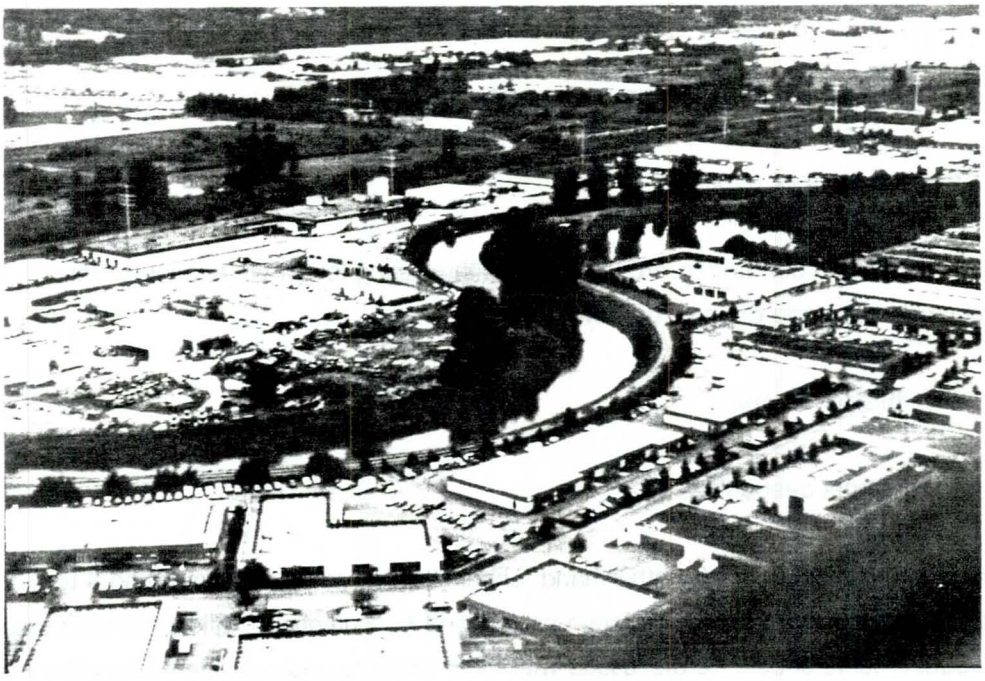
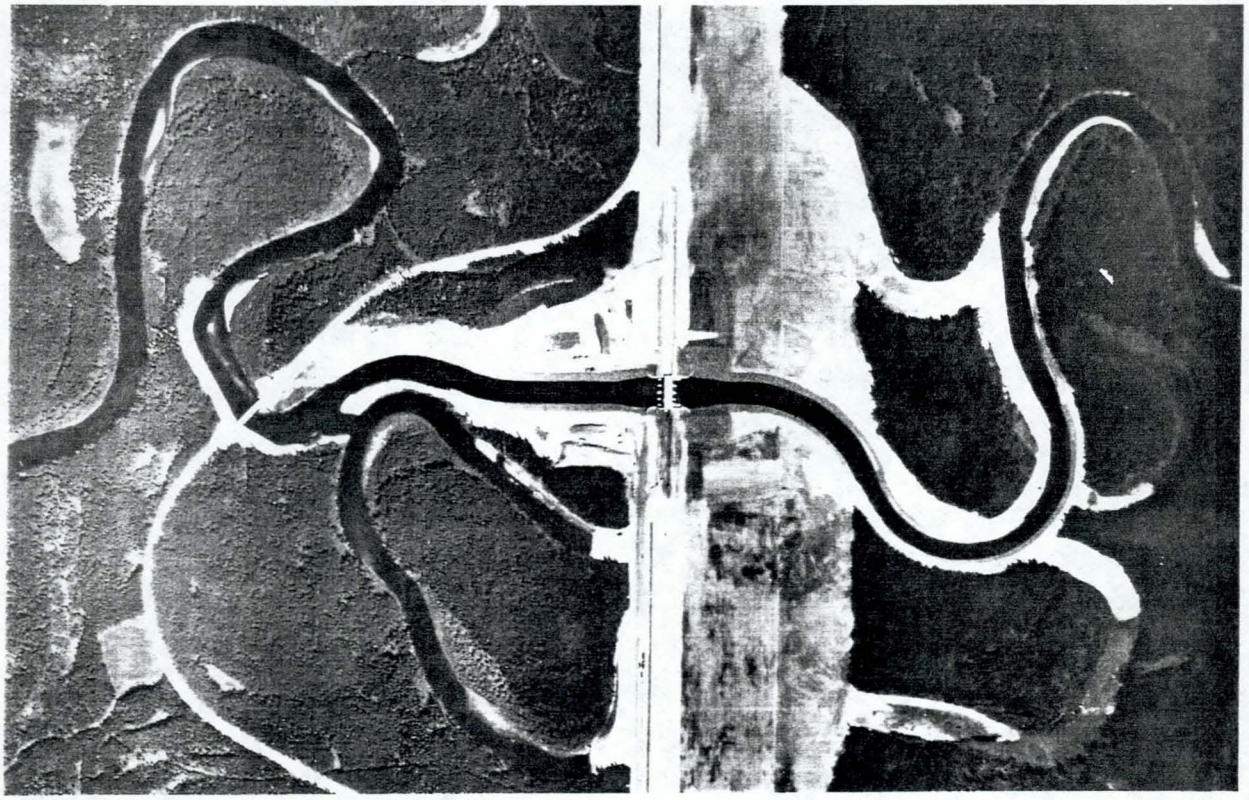


Figure 6.2.1 Regulated river with levees on meandering alignment.

(a) before project: natural meanders



(b) after project (diversion structure and channel): controlled meanders

Figure 6.2.2 Construction of a meandering alignment

Points that can be made in support of sinuous alignments include the following:

(1) Retention of a sinuous alignment avoids problems of excessive slope associated with straightening.

(2) Straight channels transporting bed sediment tend to form alternating side bars that induce sub-meandering in the low-flow channel (see Figure 3.4.1). This may eventually lead to resumption of full-scale meandering.

(3) Sinuous channels have greater local variability of depth, velocity and cross-sectional shape, which is attractive for fish habitat.

While retaining a sinuous alignment, however, it may be appropriate to eliminate or improve severe bends that are subject to rapid bank erosion and flow disturbances due to separation (Figure 6.2.3). Where the channel is widened by side cuts on alternating sides, the sinuosity can thereby be reduced to some degree (see Figure 3.1.3).

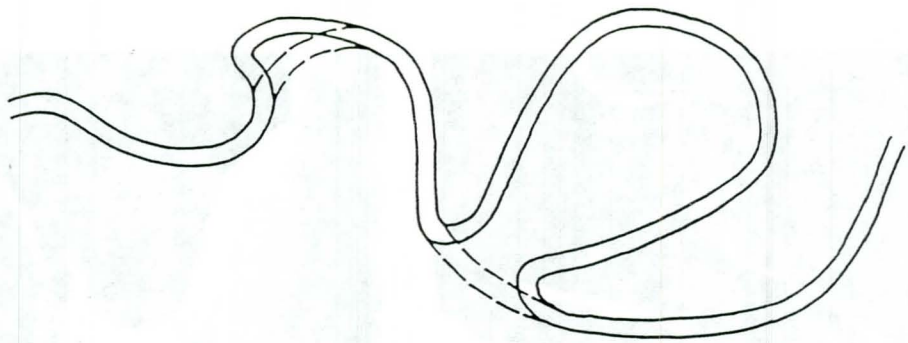


Figure 6.2.3 Limited alignment modifications to improve or eliminate troublesome bends.

Generally accepted standards for the layout of new sinuous channels are not available. A general principle that can be followed is to match the wavelength to that of a corresponding natural meandering channel, that is, a stream in similar soils with similar channel-forming discharges. Relationships between meander wavelength and channel width are discussed in Section 2.3.9. A suggested relationship between meander wavelength and bankfull (channel-forming) discharge is shown in Figure 6.2.4. In the absence of generally accepted guidelines for radius of curvature and deflection angle, it is suggested that where possible, radius of curvature should be at least 5 x channel width, and that the deflection angle of a single bend should not exceed 90 degrees.

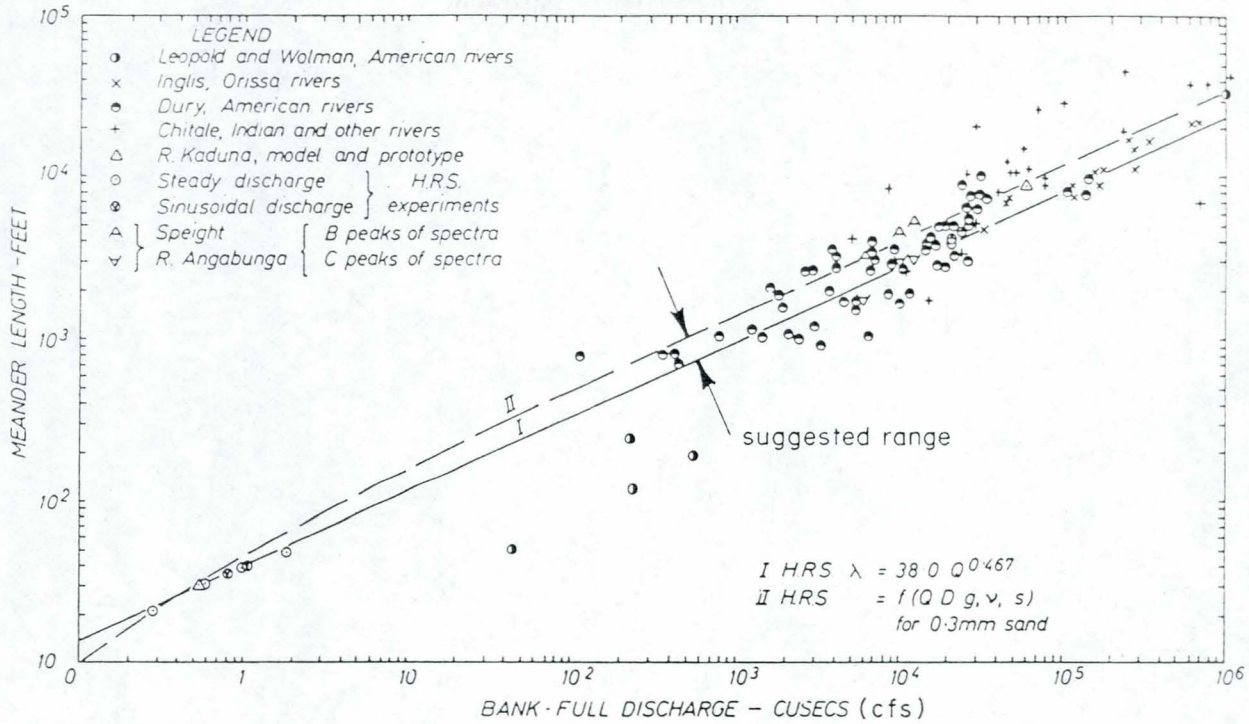


Figure 6.2.4 Suggested relationship between bankfull (channel-forming) discharge and meander wavelength for layout of new channel. (After Ackers and Charlton 1970).

6.2.2 Multi-channel streams. Some streams consist of two or more sub-channels over substantial parts of their length. Examples include the Snake River near Jackson Hole, Wyoming as described in Section 3.2.4 and the Tanana River at Fairbanks, Alaska as described in Section 3.2.9. Braided rivers (Figure 2.1.5) constitute a limiting case.

In utilizing a multi-channel stream for flood control conveyance, it is usually more economical to avoid interference with the stream itself. Levees set back clear of the active channel shift zone are preferred. Alternative locations for levees in such a situation are illustrated in Figure 3.2.6 in the context of a discussion of bank protection in the Snake River.

6.2.3 Alluvial fans. The general characteristics of alluvial fans are described in Section 2.1.2. A typical development on an alluvial fan in California is illustrated in Figure 2.1.3. It is important to determine whether the fan is actively aggrading or in a stable or degrading state. If the fan is

generally unvegetated and the principal channel is "perched" in relation to ground at equal distances from the apex (Figure 6.2.5), the fan is likely to be actively aggrading. On the other hand, if the fan is generally vegetated and the main channel is somewhat entrenched, it may be stable or degrading.

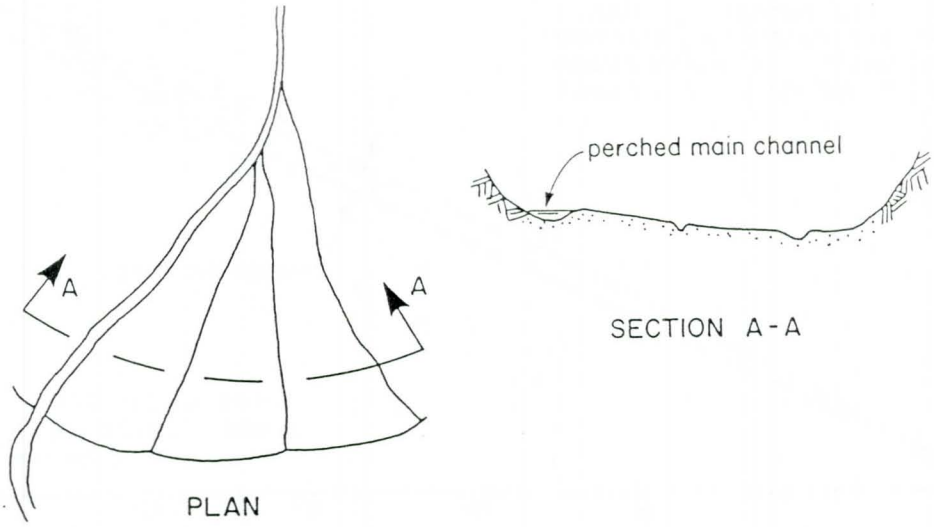


Figure 6.2.5 Perched channel on aggrading alluvial fan.

Developments requiring flood protection on aggrading alluvial fans should in many cases be discouraged. It is difficult to keep the main flow in its existing channel without expensive special measures. The channel may plug with the bedload during a flood and the main flow may divert to a lower route.

One workable although expensive method of flood control is to build a debris basin at the head or apex of the fan with provision for period cleanout (Figure 6.2.6). Deprived of bed load, the channel then tends to entrench and degrade to a flatter slope. To avoid excessive erosion it is generally necessary to line the flood control channel with concrete or riprap (Figure 6.2.7) or to provide grade control structures. Before committing to a debris basin at the apex, however, it is advisable to confirm that the main supply of coarse sediment is derived from the upstream channel or gorge and not from terrace erosion farther downstream, as is sometimes the case (Figure 6.2.8).

In some places where development has occurred on closely adjacent alluvial fans all issuing from the same mountain range, cross-slope interceptor channels have been used to pick up flows from a series of fans (Figure 6.2.9). Debris basins are located at the head of each fan.

Figure 6.2.6 Debris basin and dam at head of alluvial fan.

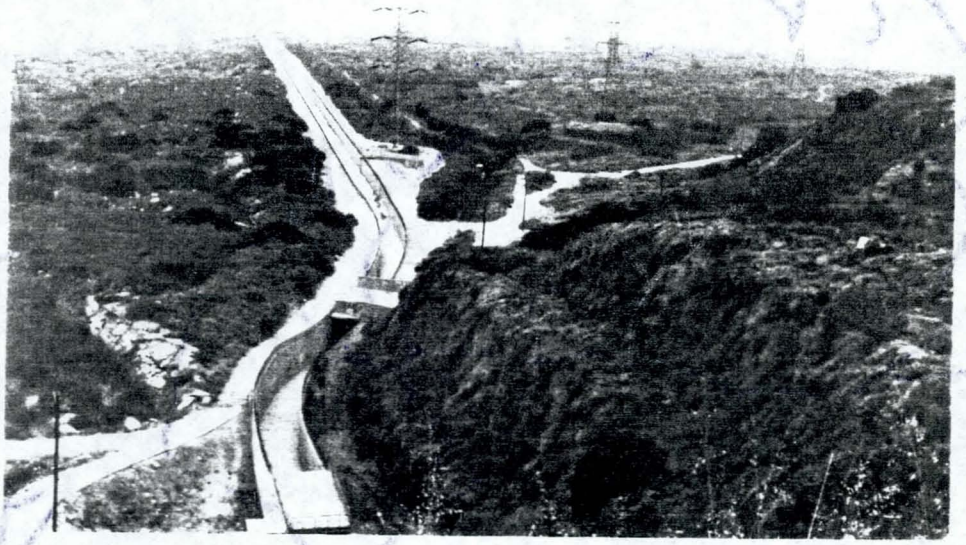


Figure 6.2.7 Concrete-lined channel on alluvial fan below debris dam.

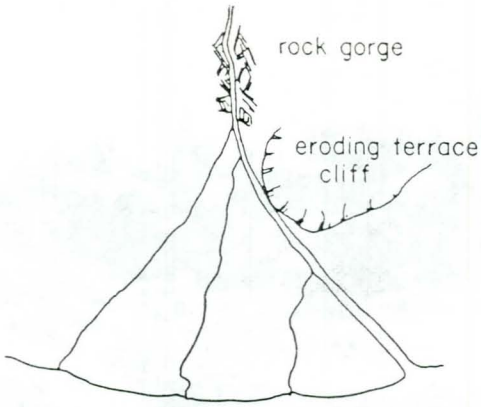


Figure 6.2.8 Principal active source of fan bed load may be downstream of apex.

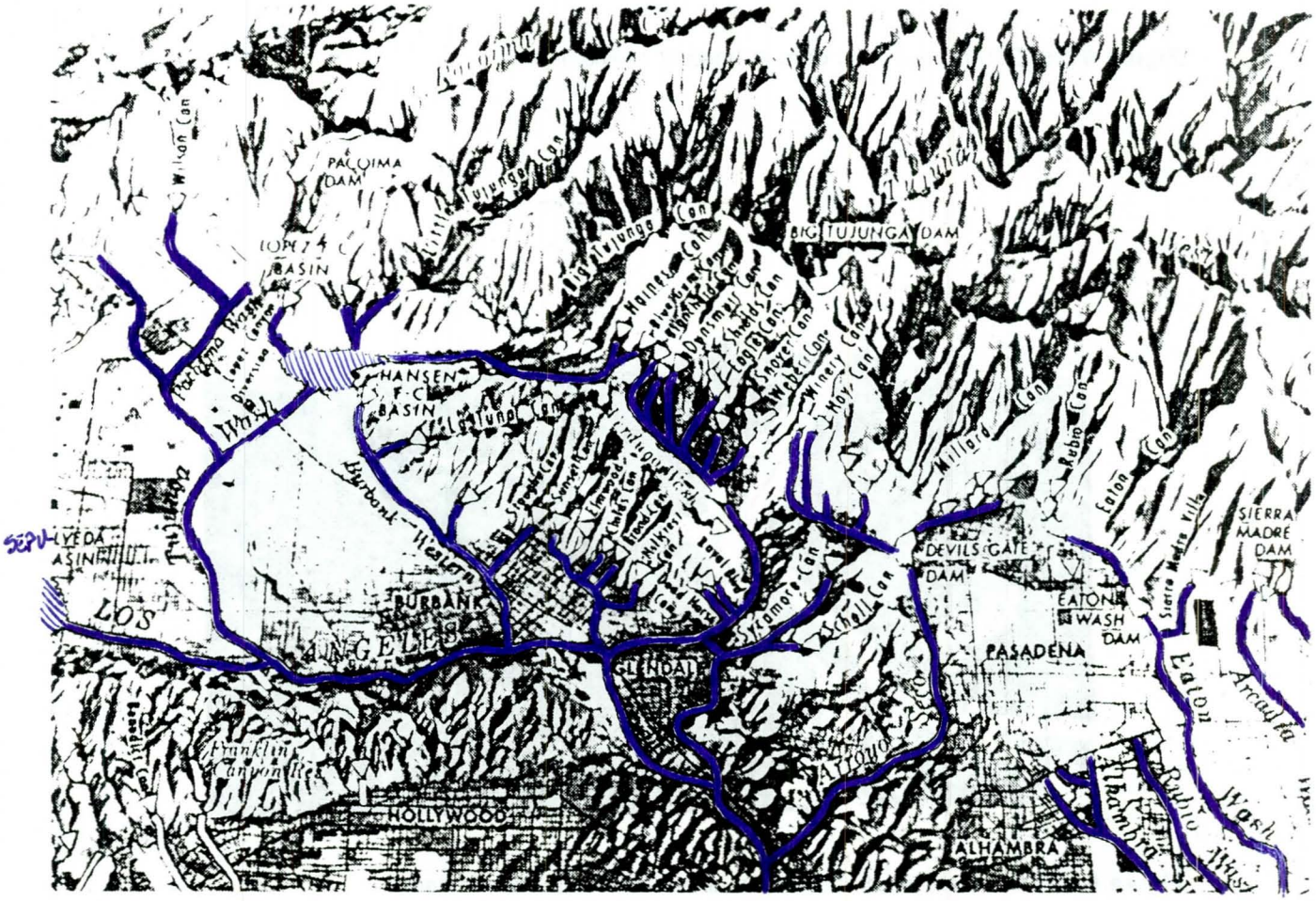


Figure 6.2.9 Cross-slope interceptor channels collecting flood flows from adjacent alluvial fans.

Problems arising from sediment in concrete-lined flood control channels are described by Williams (1990). Particular reference is made to loss of design capacity as a result of greatly increased roughness due to bed-load deposits.

6.3 Longitudinal profile and grade controls

6.3.1 Causes of profile instability. In most cases the basic longitudinal profile of a flood control channel is determined by the slope of the existing channel. Most problems of longitudinal instability arise because the existing slope is too steep for equilibrium under the modified hydraulic or hydrologic conditions of the flood control channel. The bed of the project channel then begins to degrade upstream and perhaps to aggrade downstream.

There are two main reasons why the existing gradient may be too steep for the project channel. The first reason is that discharges in the project channel are usually significantly larger than in the existing channel. As explained in Chapter 2, larger discharges require flatter slopes to maintain equilibrium with equivalent bed-sediment transport; see also Figure 5.3.7. A second reason is shortening through realignment, which was a common problem in earlier flood control projects but is now discouraged - see Section 6.2.1. A third, less common reason may be the addition of a basin or reservoir that traps bed sediment upstream of the project channel; see Section 6.2.3.

Problems of profile degradation are most common and severe in channels with beds of sand or other easily eroded fine-grained materials. Examples include many of the bluffline streams of northern Mississippi, which as a result of land-use changes and channel alterations are generally degrading into fine-grained deposits of sand, loess, silt and clay. In gravel-bed channels, the ability of the stream to armor the surface of the bed with the coarser fraction of the bed load tends to limit depths of degradation.

A less common problem of longitudinal stability is that the project channel slope is too flat and begins to steepen (aggrade) by accumulation of bed sediment. This can occur in diversion and bypass projects if the existing channel is subject to reduced discharges but continues to take a substantial part of the bed-sediment load (see also Section 3.1). It may also arise in new channel projects if the slope provided is insufficient to transport all the inflowing bed sediment.

6.3.2 Grade control structures. Channel profile degradation can be controlled by the use of grade control structures at intervals along the channel. Grade control structures provide local hard points or controlled drops so that an equilibrium slope can develop or be constructed between structures

(Figure 6.3.1). The spacing is determined so that the local degradation or drop below each structure is within acceptable limits.

Grade control structures are generally classified into two types: (1) stabilizers, and (2) drop structures (Figure 6.3.2). The distinction between the two types is not always clearcut. Design guidelines for both types are given in EM 1110-2-1601 (USACE 1990) and in Hydraulic Design Criteria 623/624, and have been expanded by Robles (1983) and Biedenharn (1987). According to Robles (1983), stabilizers as used in the Los Angeles District are "concrete or grouted stone sills built across the channel to form an artificial control point". According to Biedenharn (1987), stabilizers may be of three types: weirs, chutes or flumes, and may be constructed of a wide variety of materials. Types illustrated include a simple sheetpile weir (Figure 6.3.3) and a special flume type developed in Mississippi (Figure 6.3.4).

If the drop that develops below a stabilizer is too great - normally 2 to 4 ft depending on type - energy dissipation becomes a problem and more elaborate drop structures must be used. Drop structures are normally provided with some form of stilling basin or armoured plunge pool for energy dissipation (Figure 6.3.5). They have been used as remedial measures in cases of severe degradation, or as elements of project design where substantial slope flattening is expected. Whether to use stabilizers at relatively close spacing or drop structures at wider spacing is partly an economic question.

The rating curve of a grade control structure should normally be designed to match that of the upstream channel as closely as possible over the full range of discharges. In some cases, stepped sill crests are used to achieve a match (Figure 6.3.6).

The decision as to whether grade controls or drops should be part of the project design or whether they should be deferred until problems develop depends partly on economic and political considerations and partly on the expected severity of profile response. Previous local experience is generally valuable in this connection.

Where existing slopes are only marginally excessive, it may be possible to achieve longitudinal stability by increasing channel roughness, for example using scattered boulders. Such a solution is often favoured by fisheries interests as it provides useful resting places and shelter.

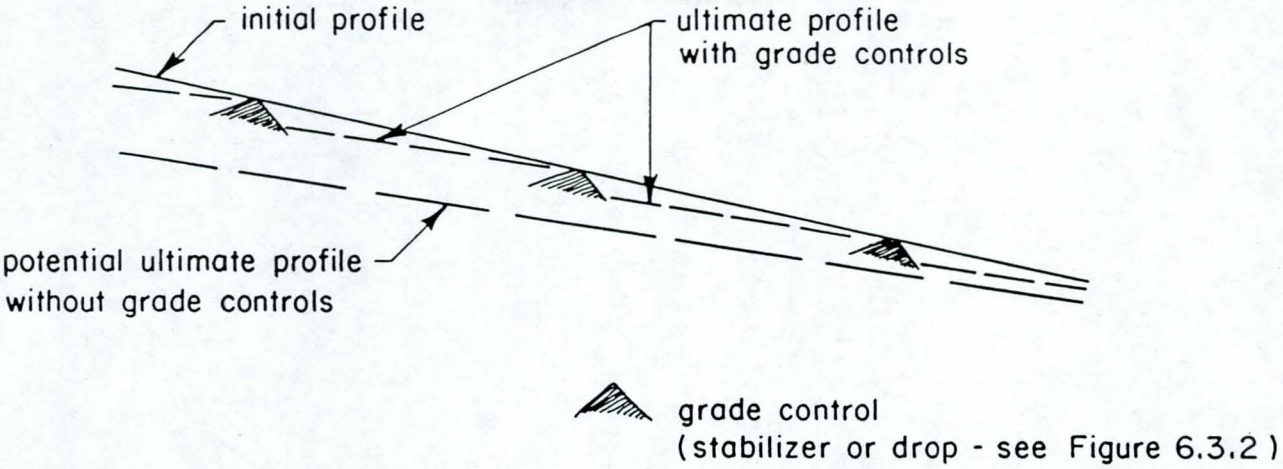


Figure 6.3.1 Use of grade controls to limit profile degradation and downstream sedimentation.

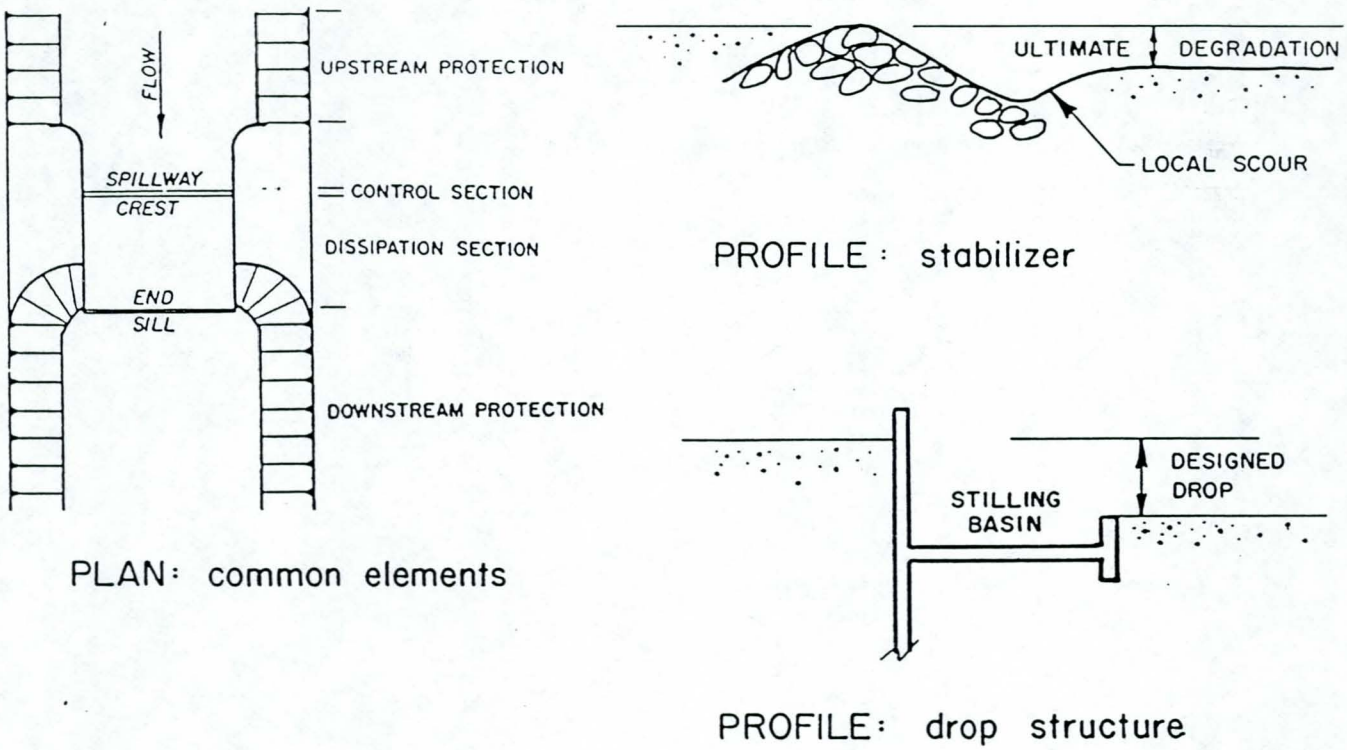


Figure 6.3.2 Classification of grade controls.

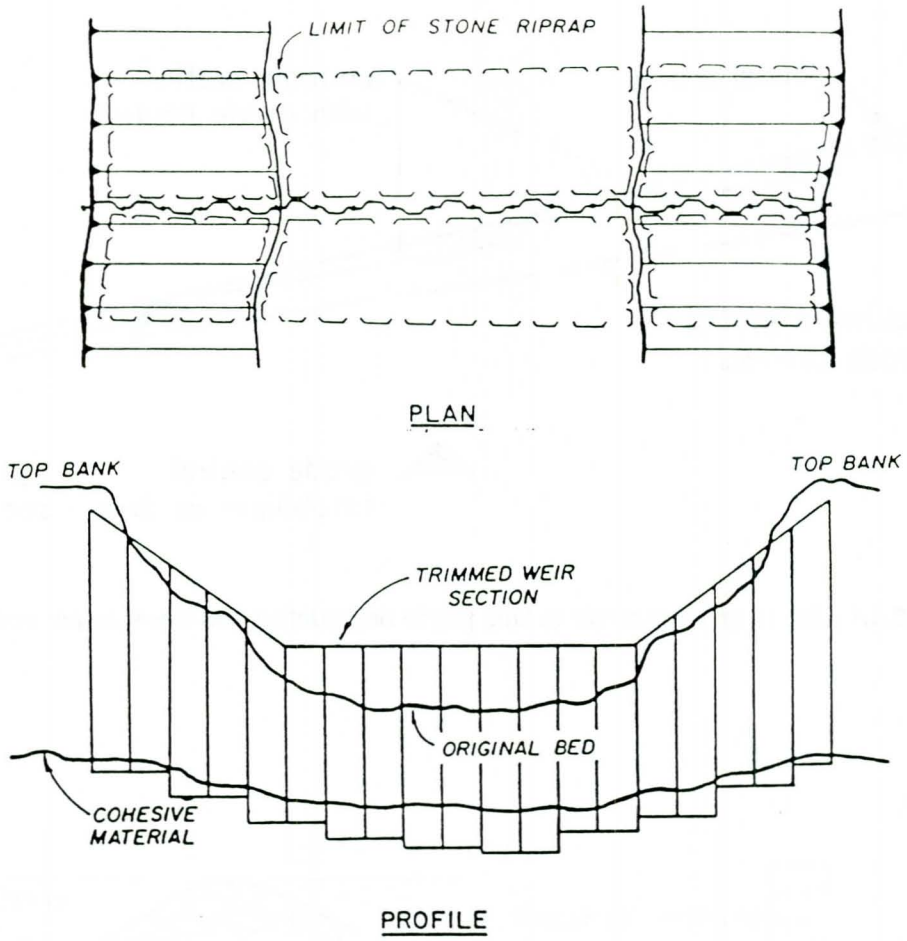


Figure 6.3.3 Sheet-pile weir stabilizer (Biedenharn 1987).

Figure 6.3.4 Flume-type grade control/gauging structure.

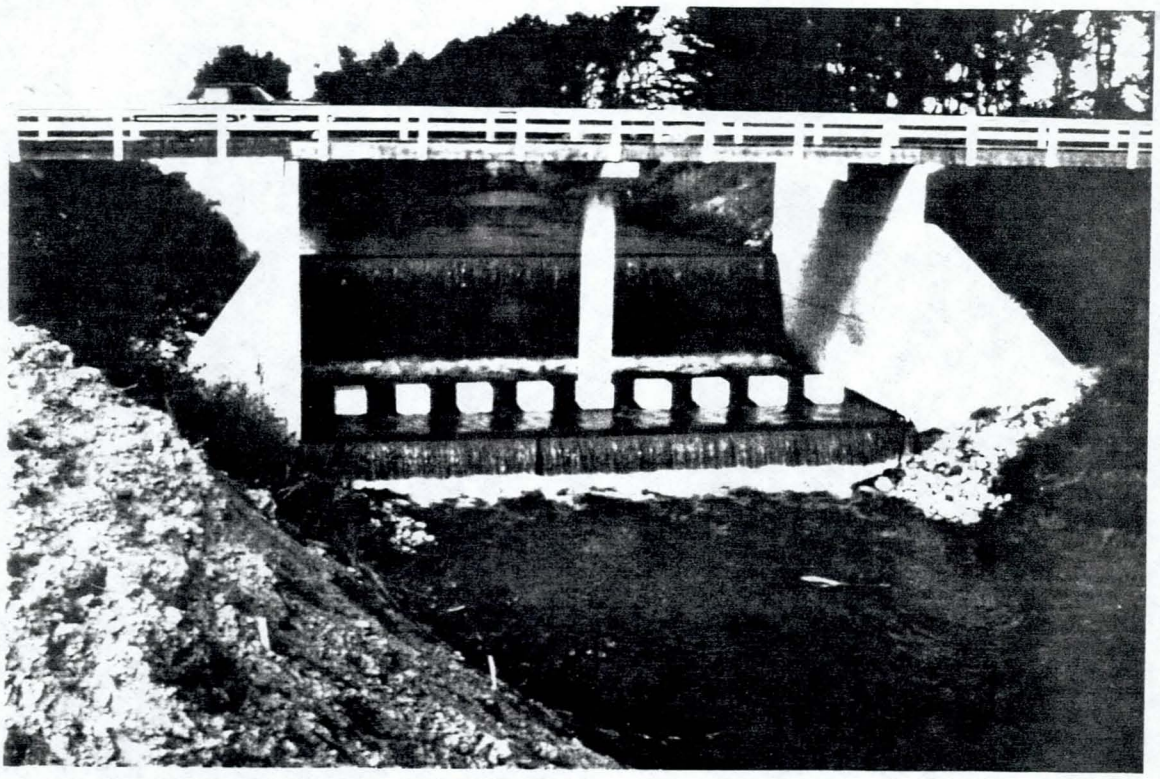


Figure 6.3.5 Drop structure with energy dissipator.

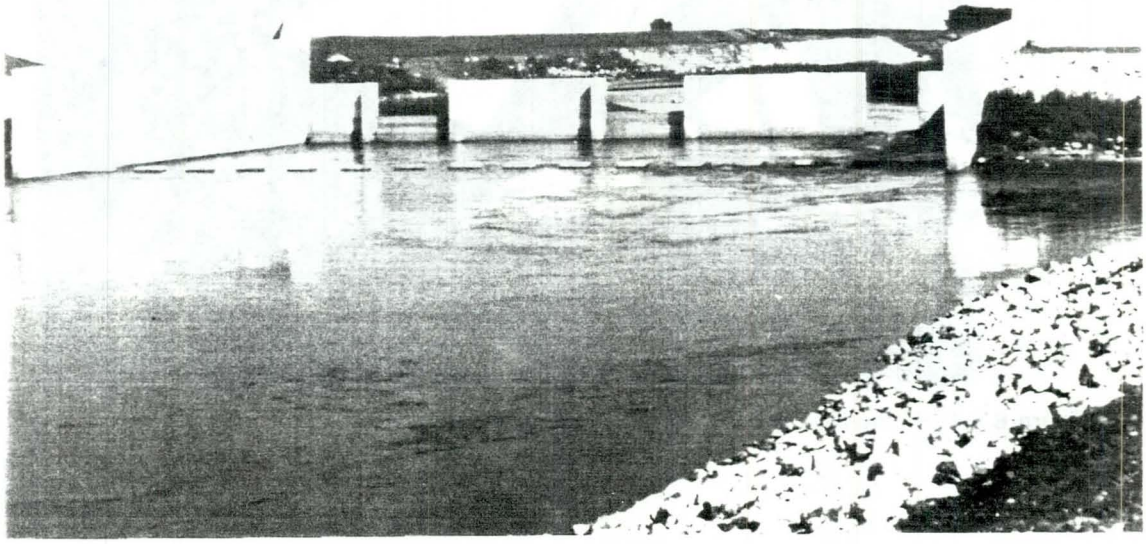


Figure 6.3.6 Use of stepped sill on grade control structure to match upstream rating curve.

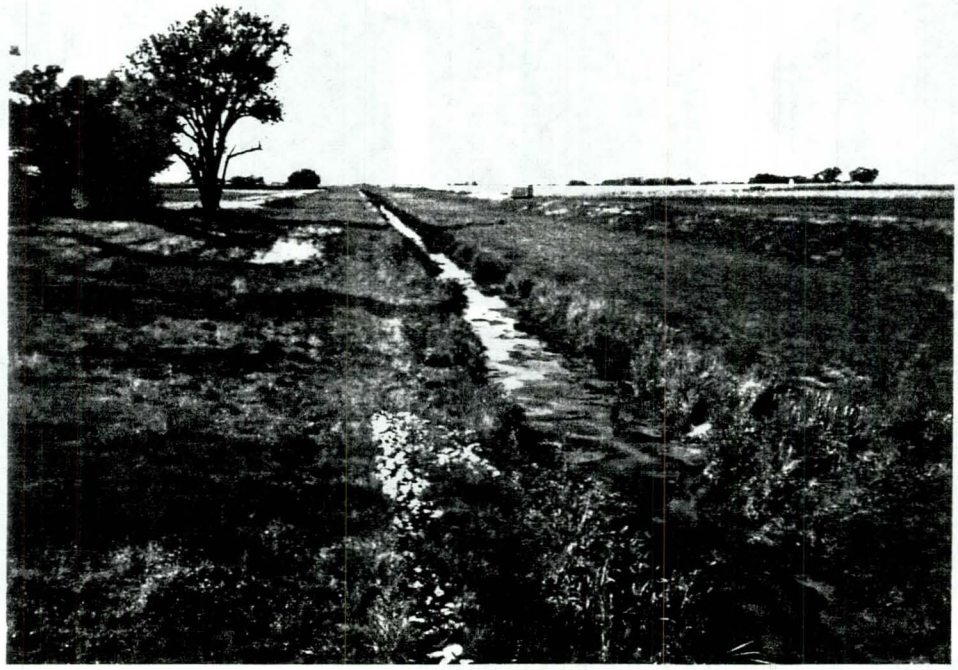


Figure 6.4.2 Compound cross-section with low-flow channel, grassed berms and levees.

6.4 Cross sections and hydraulic capacities

A wide variety of cross-sectional types and modifications have been used in flood control channel projects. The following types are illustrated in Figure 6.4.1:

(1) Existing channel retained, with wide setback levees on floodplain.

(2) Existing channel retained, with levees close to channel banks.

(3) Channel widened on one or both sides to full depth.

(4) Channel deepened and widened on one side.

(5) Channel deepened and widened to part depth (with berm).

(6) Major enlargement with retention of inner low-flow channel (Figure 6.4.2).

(7) Existing channel paralleled by separate floodway or bypass channel.

A number of these alternatives are also discussed in Sections 3.1 and 6.1. From a stability viewpoint Type I above is generally preferable, but in many cases other considerations will predominate. Type 7 is also attractive if sedimentation is not a problem - see Section 3.1.7. Generally, widened and deepened sections are the most susceptible to problems of bank erosion, channel shifting and profile degradation.

A wide variety of practice exists with respect to criteria for channel capacity and frequency of the bankfull condition, depending on the overall requirements of the project. In compound cross-sections such as Type 5, the berm level normally corresponds to a 2-year flood or greater. In Type 6, the low-flow channel may be sized for dry-season flows only.

6.5 Control of meandering

Development and migration of meanders is a major stability problem in many flood control projects. This often results from continuation or aggravation of a pre-existing situation. Tolerable pre-existing meander migration may become troublesome in a project context because it threatens flood control levees. Pre-existing meandering may be aggravated because increased channel-forming discharge tends to increase the meander wavelength and amplitude and rate of migration, or

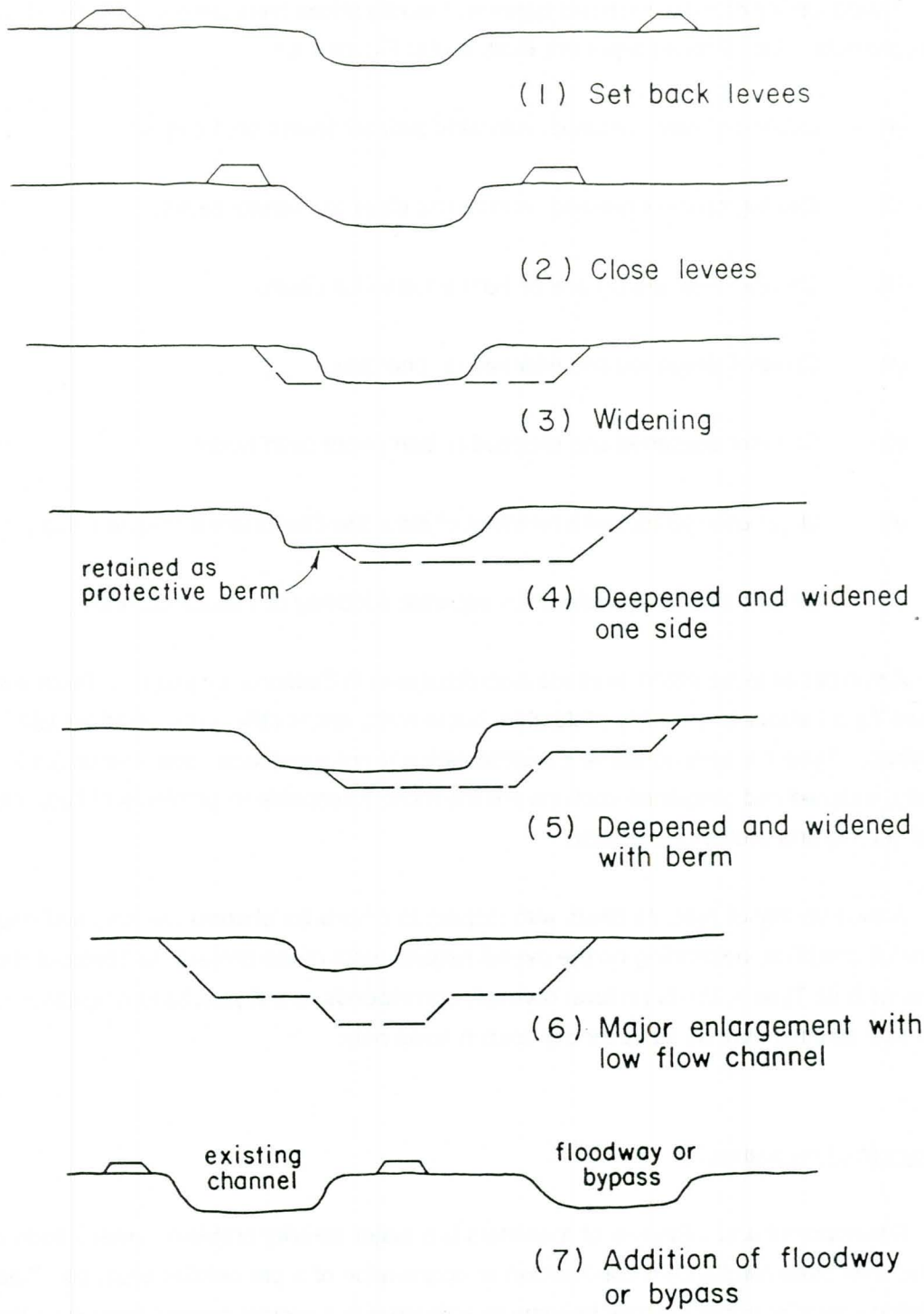


Figure 6.4.1 Various types of modified cross-sections.

because natural bank protection has been disturbed by project works or accompanying land-use changes. For example, clearing and snagging or channel enlargement often reduce the erosion resistance of stream banks and lead to accelerated meandering.

Re-development of meanders is a common problem in streams that have been straightened or re-aligned (Figures 3.7.6 and 6.5.1). If a channel is made too wide, the low-water channel may develop sub-meanders (Figure 3.4.1) that can gradually progress to full meanders by erosive attack on the banks.

Figure 6.5.1 Re-development of meanders in straightened channel following side bar development.

There is an apparent paradox about certain aspects of meandering. It might seem logical that high slopes and velocities would cause more rapid meander shifting. However, it is noticeable that streams with flat slopes and relatively low velocities often have very active meanders, and that meandering tends to be more extreme in backwater zones, for example, upstream of confluences and reservoirs.

Several points about dealing with meandering in project design and maintenance are discussed below.

(1) In the case of levees, the best solution is to locate the levees outside the meander belt. This is not always possible, however. In some cases the meander belt may occupy the entire valley bottom. In other cases the meander belt may widen after construction due to factors mentioned above. Sometimes the pattern of future meander shifting is difficult to predict.

(2) Levees can be set back as far as possible from the existing channel, and a minimum distance between the levees and eroding river banks can be specified, with an understanding that protection works will be initiated when this minimum is reached at any point. In the case of the Tanana River at Fairbanks, Alaska, a deferred construction agreement provides for construction of groins when the specified minimum setback is encroached on.

(3) Short lengths of bank revetment at points of active river attack are not usually effective in the long term. The attack usually shifts to other points and tends to outflank the short revetments. As these are extended, the end result is protection of the entire project length.

(4) An intermittent form of bank protection, such as groins, is usually more economical than continuous revetment. However, groins tend to cause local flow disturbances that are sometimes unacceptable for navigational or environmental reasons.

(5) Bank vegetation and root systems provide effective protection against rapid meander shifting in many natural streams. Vegetation should not be disturbed unless there is no reasonable alternative. In the case of channel enlargement, excavation on the inner bank only (see Figure 3.1.3) enables retention of protective vegetation on outer banks. Where existing vegetation has to be removed, it may be feasible to re-plant. However, biological restorative techniques that are successful in small streams are not always transferable to larger channels. EM 1110-2-1205 (USACE 1990) should be consulted for guidance.

6.6 Bank protection

Artificial bank protection is used to control meandering, to protect channel banks and levees against velocities and shear stresses that are too high for the bank materials, or to prevent toe scour and removal of berms that would encourage progressive bank failure due to geotechnical factors such as gravity slumping and seepage (Figure 6.6.1).

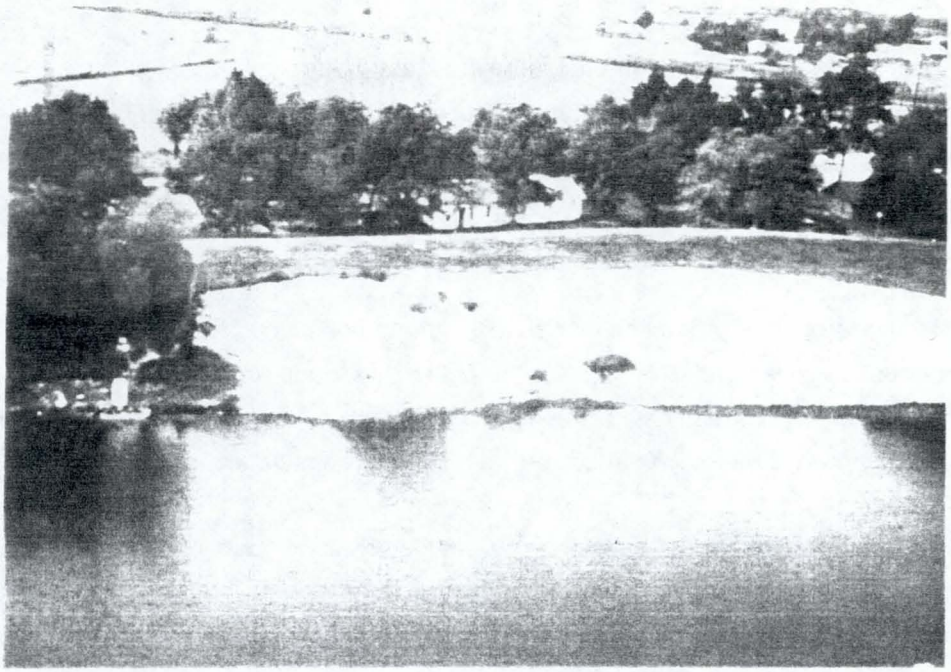


Figure 6.6.1 Revetment necessitated by encroachment of bank caving on levee.

Figure 6.6.2 Combined use of continuous toe protection and intermittent groins.

Only general comments on bank protection are made here. More extensive information is given in WES course notes on streambank protection (USACE 1989) and in Petersen (1986). Riprap bank protection is covered in EM 1110-2-1601 revised (USACE 1990). Nunnally and Shields (1985) discuss various methods from an environmental viewpoint. A set of papers in ASCE (1989) discusses various aspects of bank erosion and protection.

Methods of bank protection can be divided into continuous types like revetment and discontinuous types like groins (Figure 6.6.2). Materials include rock riprap, natural or planted vegetation, concrete, and fabricated or patented systems. Extensive experience by the Corps indicates that riprap is the only method to give reasonable assurance in highly unstable conditions.

Failure of riprap bank protection is usually due to underscouring at the toe. Galay et al (1987) give a detailed discussion of riprap protection in relation to toe scour (Figure 6.6.3). Riprap is not generally practical in channels with slope greater than about 0.005 because the required sizes and thicknesses become uneconomically large.

In meandering streams, bank protection is usually provided initially only on the outer banks. If the meanders are shifting rapidly, the protection should be extended beyond the inflection points (Figure 6.6.4).

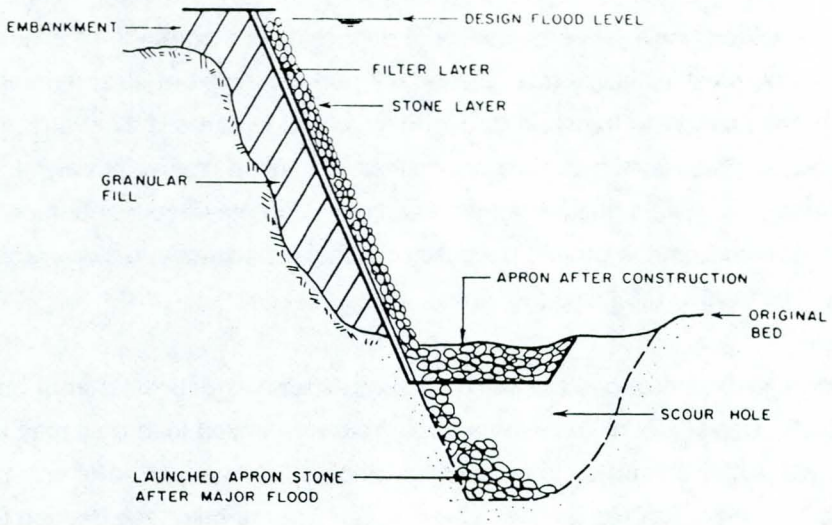


Figure 6.6.3 Use of "launching" apron to provide against toe scour below protected bank (Galay et al 1987).

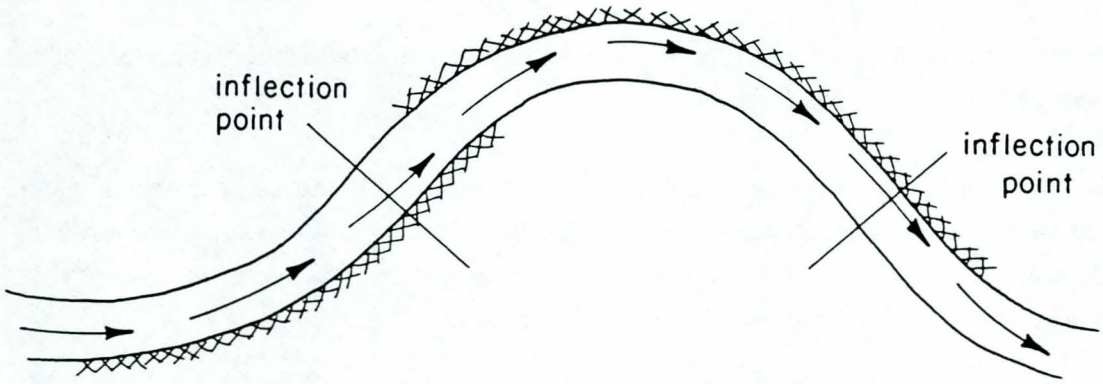


Figure 6.6.4 Extension of outer bank protection downstream of inflection points.

6.7 Control of sedimentation

Loss of designed flood conveyance by sediment deposition is a common problem. It often occurs as a result of longitudinal instability (see Section 6.2), or as a result of enlargements that reduce the capacity of the channel to transport through the project length sediment arriving from upstream. Flood diversions, high-level bypasses or offstream detention reservoirs may also reduce the sediment transport capacity of the main channel. Sedimentation may occur in unmodified channel reaches downstream from the project because of increased sediment delivery from bank erosion or bed degradation within the project length.

Most commonly, sedimentation is a problem of sandy materials deposited from bed load or suspended load or both. Deposition of fine sand and silt from suspended load only may be a problem in estuarial and deltaic channels. Loss of conveyance due to deposition of gravel is less common generally, but is a special problem with alluvial fans in hilly terrain: see Section 6.2.3. Alteration of the nature and location of sediment deposits due to upstream works may adversely affect fish habitat in gravel-bed rivers (Milhous 1982).

Methods of controlling sedimentation include the following:

(1) Debris basin at upstream end of project, designed to capture part of the bed-sediment load. It must be evacuated periodically. See EM 1110-2-1601 (USACE 1970) for details.

(2) Sediment retention structures in the headwaters and tributaries.

(3) Soil conservation measures in the watershed, including legislation to control sediment production from land use and developments.

(4) Periodic excavation or dredging of project channel. It is necessary to ensure that a single flood cannot deposit enough material to compromise the flood protection. The cleanout zone can be localized by excavating a sediment trap at one or more points. This approach may be necessary when the problem involves sedimentation downstream of the project.

In the case of levee projects, certain types of vegetation cover on the overbank (berm) areas between the channel and the levees may encourage deposition of fine sediments from suspended load. It may be necessary to keep these areas free of tall vegetation.

6.8 References (Chapter 6)

Ackers, P. and Charlton, F.G. 1970. Meander geometry arising from varying flows. Journal of Hydrology, 11,Sept. pp 230-252.

ASCE 1989. Hydraulic engineering. Proc. National Conference; New Orleans.

Biedenharn, D.S. (1987). Grade control structures. Presentation in streambank protection course, USACE Waterways Expt. Stn., Vicksburg.

Galay, V.J., Yaremko, E.K. and Quazi, B. 1987. River bed scour and construction of stone riprap protection. In Sediment Transport in Gravel-bed Rivers, ed. Thorne et al, Wiley.

Keller, E.A. and Brookes, A. 1983. Consideration of meandering in channelization projects: selected observations and judgements. In River Meandering ed. Elliott, Proc. New Orleans Conference, ASCE.

Milhous, R. 1982. Effect of sediment transport and flow regulation on the ecology of gravel-bed rivers. In Gravel-bed Rivers, ed. Hey et al, Wiley.

Nunnally, N.R. and Shields, F.D. 1985. Incorporation of environmental features in flood control channel projects. Technical Report E-85-3, USACE Waterways Expt. Stn. Vicksburg.

Petersen, M.S. 1986. River engineering. Prentice-Hall.

Robles, A. 1983. Design and performance of channel stabilizes and drop structures. Proc. Workshop Design of Headworks, ASCE and Calif. State Univ., Long Beach, November.

USACE 1989. Streambank protection. Notes for training course, Waterways Expt. Stn., Vicksburg.

USACE 1990. Engineer Manual EM 1110-2-1601 revised. Hydraulic design of flood control channels.

USACE 1990. Engineer Manual EM 1110-2-1205. Environmental engineering for flood control channels.

Williams, P.B. 1990. Re-thinking flood-control channel design. Civil Engineering (ASCE), January pp 57-59.