APPLIED GEOMORPHOLOGY & FLOODPLAIN MANAGEMENT IN THE SOUTHWEST

Applied Geomorphology and Floodplain Management in the Southwest

A seminar presented to the
Arizona Floodplain Management Association
1994 Winter Meeting

Presented by

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AFMA 1994 Winter Meeting

Distributary-flow areas and flood hazard evaluation on piedmonts in Arizona

By
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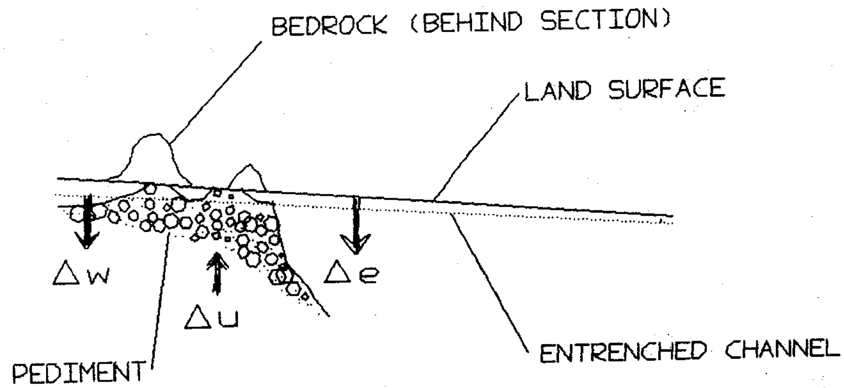
(Based on work performed from 1972-92 while employed by the U. S. Geological Survey and under contract from 1993-94 with the Flood Control District of Maricopa County)

OUTLINE

Introduction
- Purpose and scope
- Distributary-flow areas
- Geomorphology

Movement of flow paths and channel stability
- Vegetation
- Channel movement
- Hydraulic geometry
- Appearance of channels
- Soil characteristics (Soil surveys, younger and older soils, soil surveys)
- Interfluves(height)
- Desert Varnish
- Size of distributary-flow area
- Channel links
- Degree of flood hazard(Hjalmarson and Kemna, 1991)



$$\frac{\Delta u}{\Delta t} \leqslant \frac{\Delta w}{\Delta t} \geqslant \frac{\Delta e}{\Delta t}$$

EXPLANATION

Δu CHANGE OF PEDIMENT UPLIFT FOR Δt

Δw CHANGE OF PEDIMENT-CHANNEL DOWNCUTTING FOR Δt

Δe CHANGE OF DFA EROSION FOR Δt

Δt PERIOD OF TIME

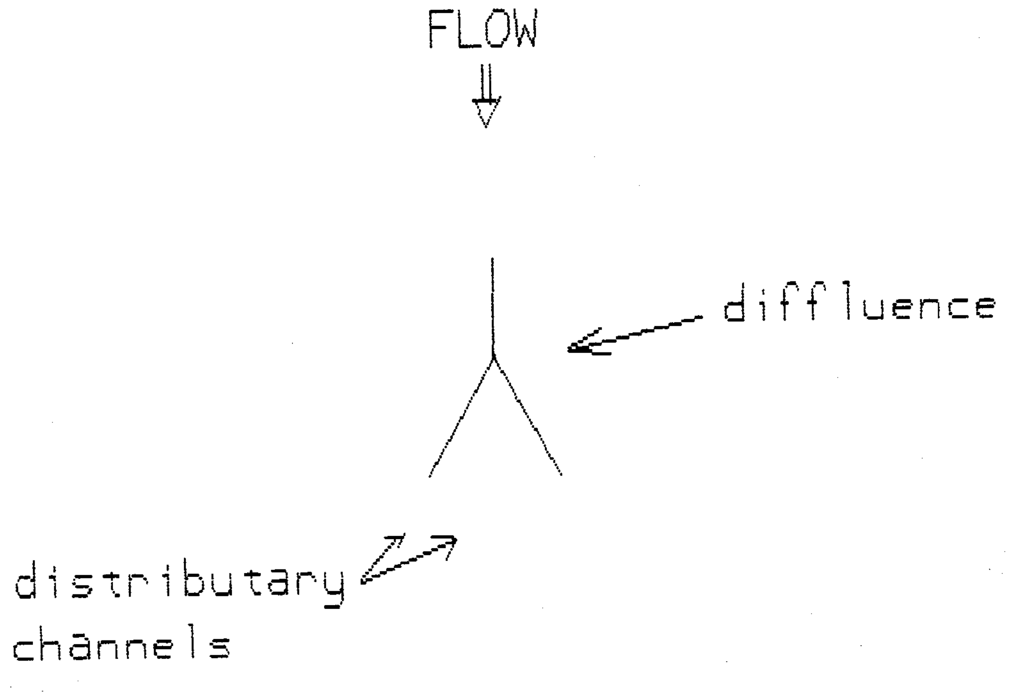
MODIFIED FROM BULL(1977, PAGE 249)

FIGURE [redacted] --SKETCH OF CROSS-SECTION SHOWING UPLIFT AND EROSIONAL CONDITIONS THAT FAVOR CHANNEL ENTRENCHMENT AT SITE 6A.

(2)

DISTRIBUTARY FLOW

DIFFUSE FLOW WITH AT LEAST ONE DIFFLUENCE AT THE OUTFLOWING BRANCH OR FORK OF A STREAM WHERE TWO OR MORE CHANNELS ARE FORMED.



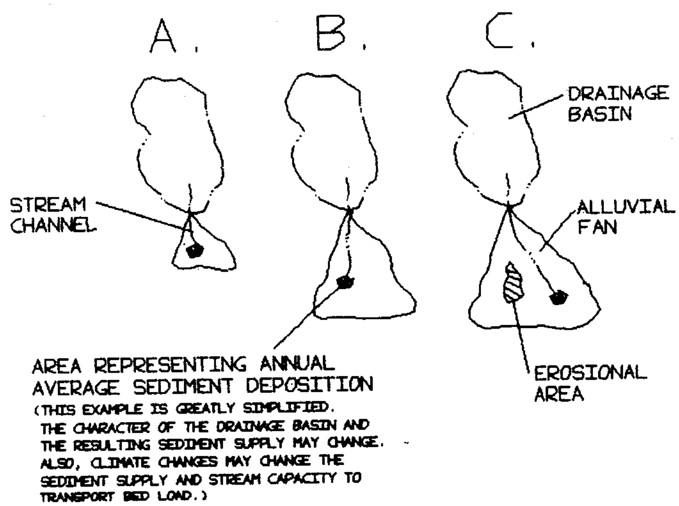


FIGURE [redacted].--STAGES OF ALLUVIAL FAN DEVELOPMENT

[redacted]

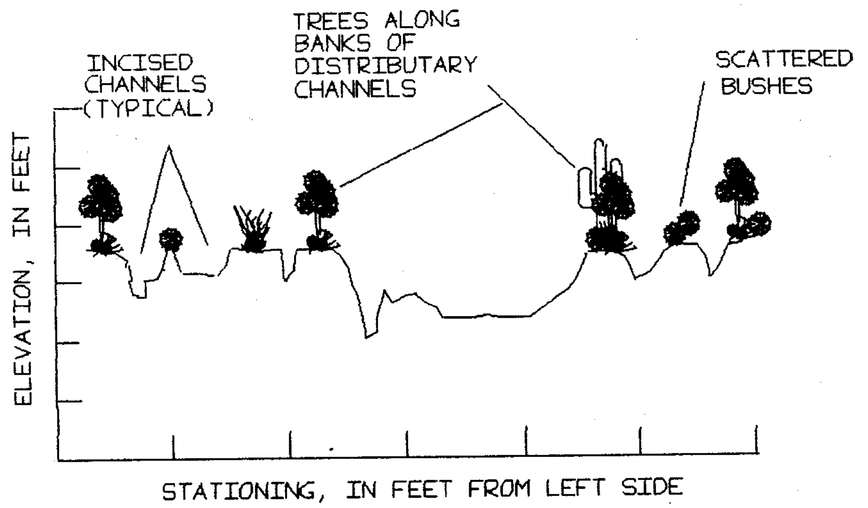


FIGURE [redacted].--SKETCH OF CROSS SECTION AT EQUAL DISTANCES FROM THE DIFFLUENCE OF SITE 6A.

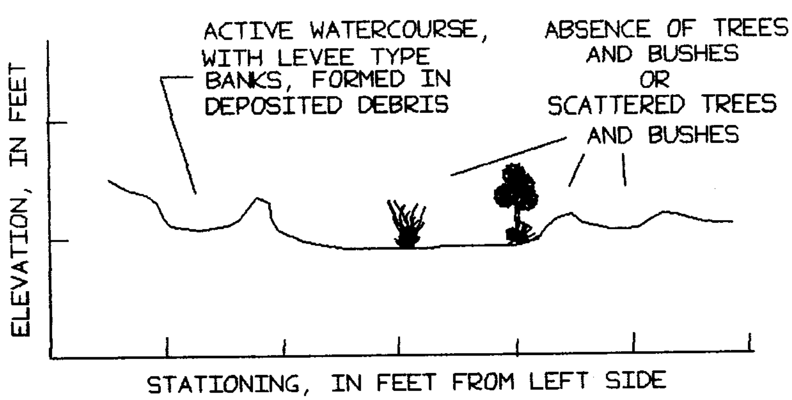
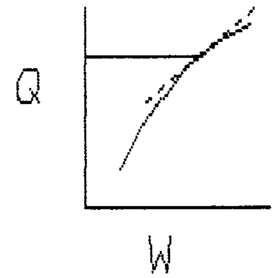


FIGURE [redacted].--SKETCH OF CROSS SECTION AT EQUAL DISTANCES FROM PRIMARY DIFFLUENCE OF AN AGGRADING ALLUVIAL FAN.

HYDRAULIC GEOMETRY

SURVEY CROSS SECTION

COMPUTE W vs Q relation



$$W = C_W Q^b$$

HYDRAULIC GEOMETRY

$Q = WDV$

W = width of channel
D = mean depth of channel
V = mean vel. of Q that formed channel

To represent the geometry of a uniform channel

$$Q = kQ^bQ^fQ^m$$

where $b + f + m = 1$

$$k = C_wC_bC_v$$

$$W = C_wQ^b \qquad D = C_bQ^f \qquad V = C_vQ^m$$

		b	f	m
Emperical values	Cohesive banks	.25	.43	.32
	Noncohesive banks	.50	.27	.23
Assumed values	Used for FEMA method	.40	.40	.20
Computed values	Avg. for 13 sites in Maricopa Co.	.27	.44	.29
	Avg. of 15 cross sections at site 2	.30	.44	.26

[redacted]--Computed hydraulic-geometry exponents and soil type for channels cross sections in [redacted] Site 2

Site (elevation, in ft.)	Exponents			Soil* type
	Width	Depth	Velocity	
1843	.20	.48	.32	3
1850	.25	.45	.30	3
1866	.31	.44	.25	3
1872	.40	.49	.11	3
1874	.16	.51	.33	3
1960	.39	.35	.26	3
1998	.38	.37	.25	3
2191	.22	.47	.31	6
1755	.20	.47	.33	90
1808	.44	.37	.19	90
1876	.30	.47	.23	90
1969	.29	.44	.27	90
2002	.30	.42	.28	96
2006	.41	.34	.25	96
1763	.21	.50	.29	98
Mean	.30	.44	.26	
Standard deviation	.084	.053	.055	

* From maps of soil types in Camp(1986).

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Paleoflood Hydrology: Principles and Applications in Arizona

Paleoflood Hydrology Defined

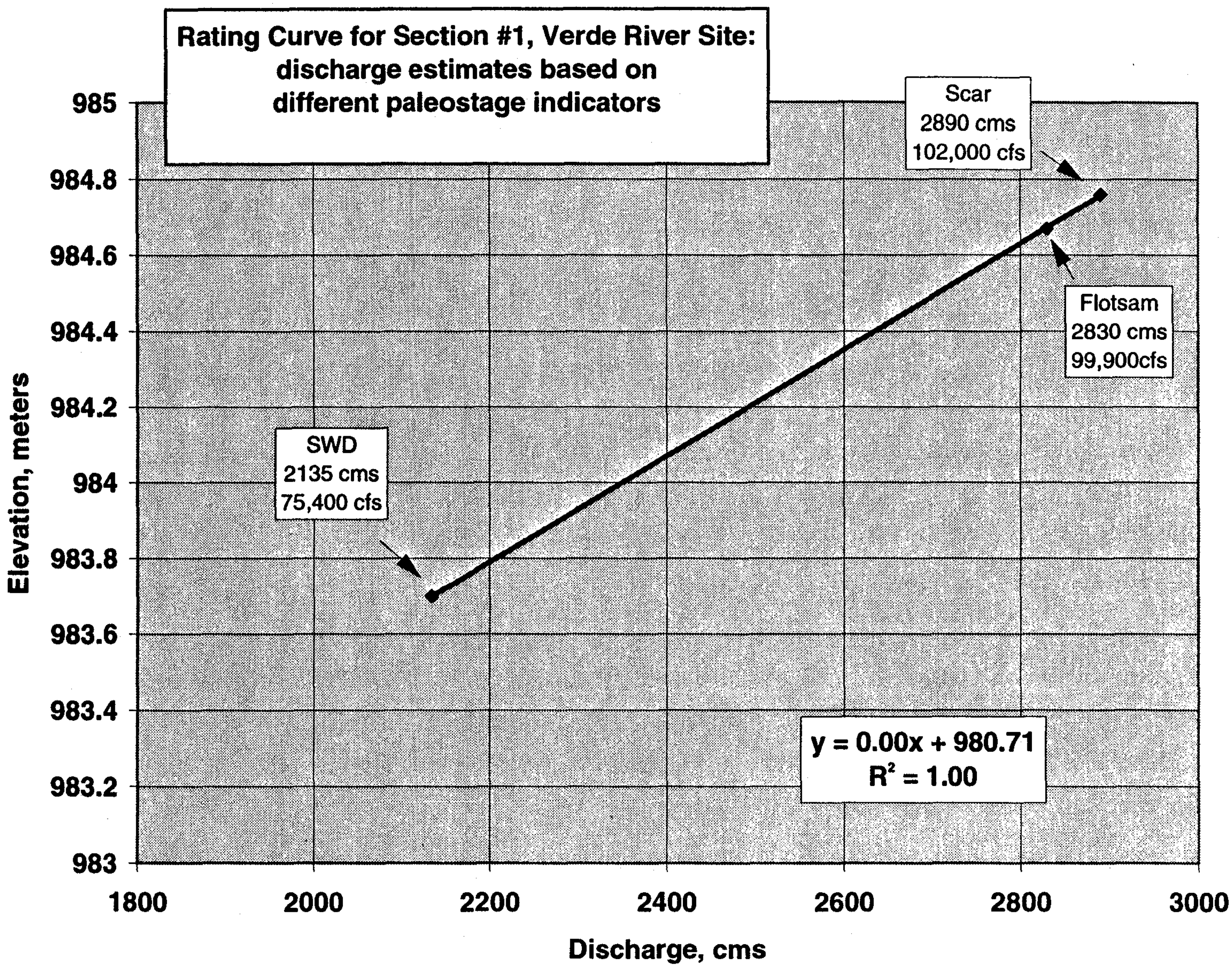
- Different conventional methods of flood discharge determination
  - gaging
  - modelling/prediction
- Geological flood studies
  - slackwater deposit-paleostage indicator method (SWD-PSI)

Philosophical background of paleoflood hydrology

- Is it esoteric, academic hogwash?
  - real data vs. prediction from small samples
  - real data vs. model calibration from small flows
- Is it new and different?

The SWD-PSI Method: How does it work?

- Goals
- Definitions
  - slackwater deposits
  - other paleostage Indicators
- Step-by-Step Description of field and office methods
  - site selection criteria
  - geological analysis
  - topographic survey
  - hydraulic modeling
  - deposit age-estimation


Rating Curve for Section #1, Verde River Site: discharge estimates based on different paleostage indicators
Scar
2890 cms
102,000 cfs
Flotsam
2830 cms
99,900cfs
SWD
2135 cms
75,400 cfs
y = 0.00x + 980.71
R² = 1.00
985
984.8
984.6
984.4
984.2
984
983.8
983.6
983.4
983.2
983
Elevation, meters
1800
2000
2200
2400
2600
2800
3000
Discharge, cms

Discharge Comparisons: Verde and Salt Rivers

	Verde River	Salt River
Q100		
USGS	164,000	208,000
MLE1	110,000	110,000
MLE2	126,000	119,000
1993 Peak Q		
USGS	127,000	144,000
SWD-PSI	106,000	134,000
Yc	150,000	N/A
PMF		
COE	676,000	1,008,000
USBR	994,000	683,000
Largest Paleoflood	176,500-230,000	162,500-172,200

notes:

USGS Q100 from 1991
MLE1 from 1986
MLE2 from 1994--incorporates uncertainties
USGS 1993 estimates are preliminary
PMFs for Salt River include Tonto Creek drainage area
Paleoflood record lengths at least 1000 years for Salt and Verde

The Character of Flood Flow and Channel Stability
on Active Alluvial Fans in Arizona

by Philip A. Pearthree, Ph.D.
Arizona Geological Survey

1) Introduction, purpose and scope

2) Review of physical characteristics of active alluvial fans

active fans are fundamentally depositional systems
distribute water and sediment
laterally extensive, geologically very young deposits evidence of fan activity
minimal topographic relief perpendicular to flow direction
usually associated with distributary drainage networks

3) Character of flow during alluvial-fan floods

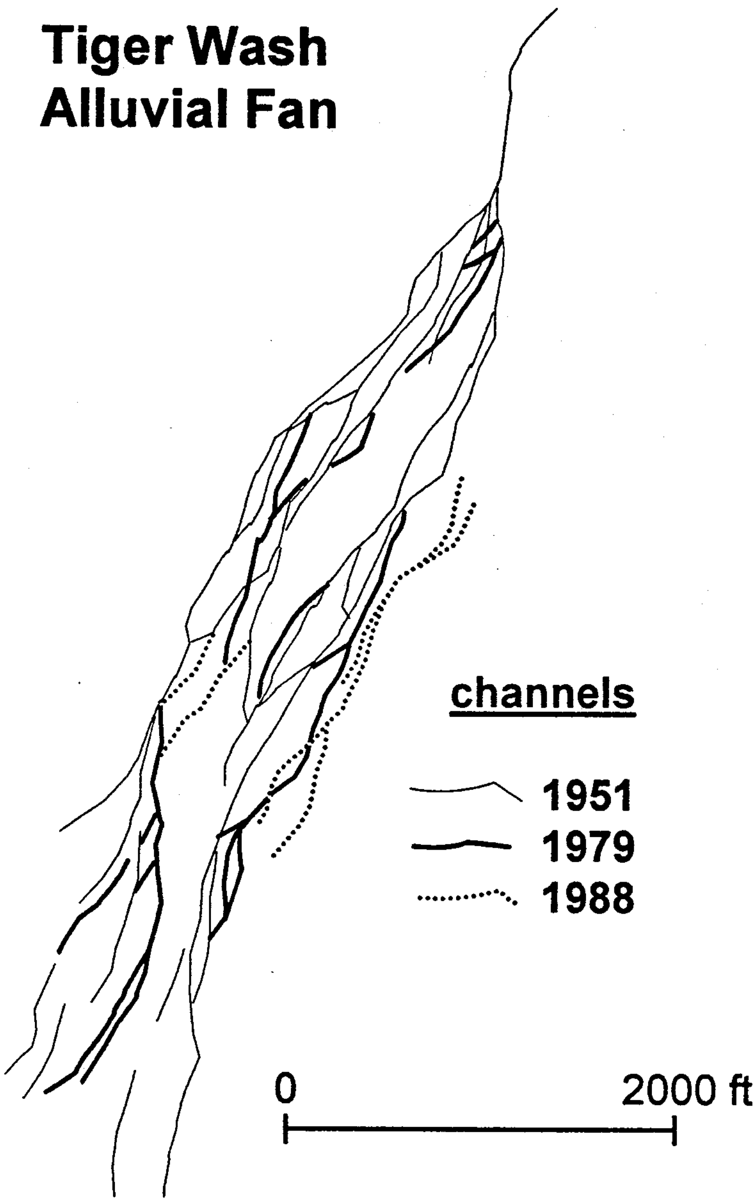
evidence from extreme alluvial-fan flood on Wild Burro Wash in 1988
detailed peak-flow reconstruction and analysis using flood debris
flow patterns very complex
deep (channelized) flow restricted in extent, shallow flooding areally important
alternation from confined (channelized) to unconfined (expansion) reaches observed in many places and at all scales
changes in channel slope associated with width changes
relatively deep, high velocity flow modeled in channelized reaches
no substantial changes in channel position during this flood

4) Frequency of changes in channel positions on active fans

historical aerial photos document channel changes on several active alluvial fans
substantial additions to distributary channel networks; incorporation of tributary drainage networks locally
abandonment or diminution of other channels
trenches across fans reveal hundreds of years of fan history
some dramatic shifts in loci of deposition have occurred
bottom line is changes in channel locations seem to occur fairly frequently on active fans

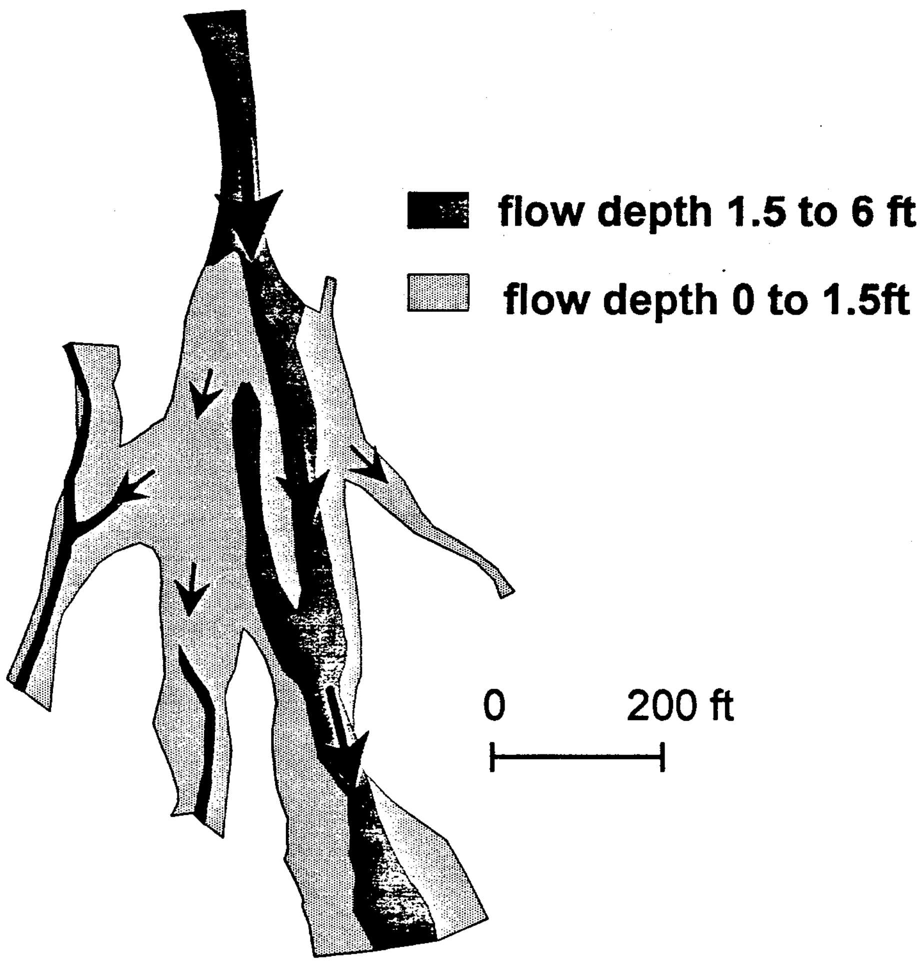
5) Mechanisms of channel change on active fans

diversions in lower portions of expansion reaches
    miminal topographic confinement, flows may exploit different paths
overbank flow developing into piracy of preexisting dendritic channel networks
    small channels rapidly enlarged by much larger flows from distributary system
local aggradation creating unstable topographic situation
    loci of flow and deposition higher than surrounding areas, flow may "slip off"

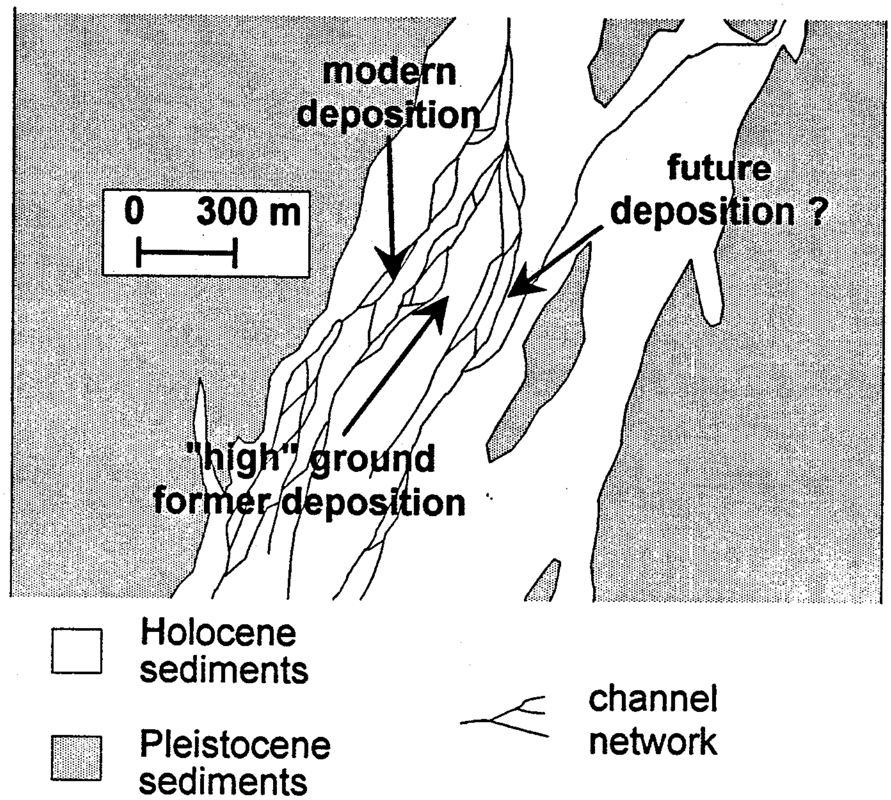


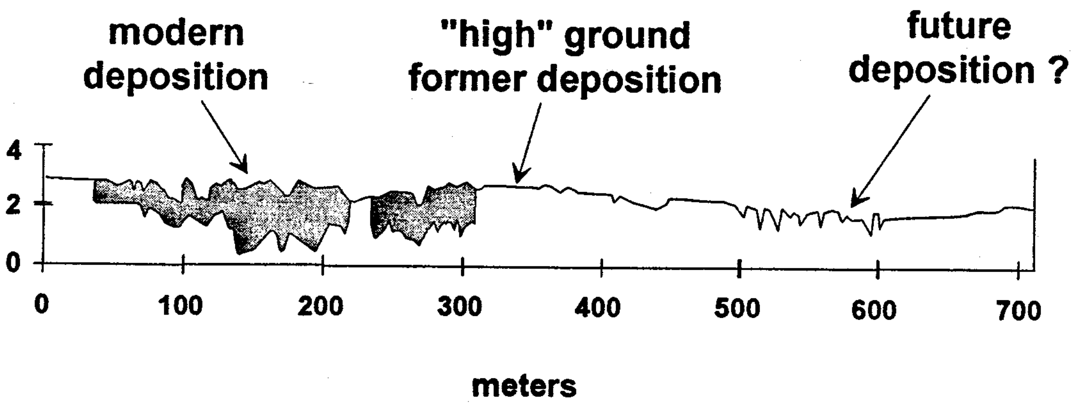
modified from J.E. Fuller, CH2MHILL, 1992

Wild Burro Flood Expansion Reach and Potential Flow Diversions



Aggradation and Topographic instability





Geomorphologic Approach to Assessing Stream Stability

AFMA - February 10, 1994

Overview

- Introduction
- Perspective
- Typical Approaches
- Geomorphologic Approach
- Recommended Approach

Introduction

- 3 Main Flood Hazards
  - Inundation
  - Transportation
  - Erosion = Instability?

- Instability Problems
  - Loss of Channel Capacity
  - Bank Erosion at Structures
  - Degradation at Structures
  - Environmental Concerns

Introduction

- **Definition of Stream Stability**
  - Static Equilibrium
  - Dynamic Equilibrium
  - Change not = Instability
  - Sediment Movement
  - Floods are Natural

- **Definition of Instability**

  - Refers to Man's Activities
  - Non-natural change?

- Disclaimers:
  - Time Limit/Scope
  - Non-academic
  - Hyperbole

Threshold of critical power in streams

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ABSTRACT

Stream power is the power *available* to transport sediment load, and it may be defined as γQS, where γ is specific weight of water, Q is stream discharge, and S is slope. Critical power is the power *needed* to transport sediment load. The threshold of critical power is where stream power/critical power = 1.0. Where stream power exceeds critical power during long time spans, additional sediment load is obtained by vertical erosion that cuts V-shaped cross-valley profiles in bedrock. The threshold is approached asymptotically during downcutting, and high-order streams approach the threshold more rapidly than do low-order streams. High discharges cause net lateral erosion in reaches near the threshold. Straths and flood plains form under such conditions. Where stream power is less than critical power, selective bedload sedimentation decreases sediment load and size and therefore the critical power. Such deposition is self-enhancing because of concurrent decreases in slope. Thus, it is unlikely that aggrading reaches attain the threshold, but the tendency to attain the threshold may keep stream and critical power roughly the same. Reaches of streams at the critical-power threshold are sensitive to changes in climate, base level, and the impact of humans; these may change stream and/or critical power and result in aggradation or degradation.

INTRODUCTION

Although a model may be selected by a geomorphologist with the intent of making an efficient study and obtaining reasonable results, the background and biases of the investigator are important in determining the selection of a problem and the approach used. Gilbert (1877, 1914) chose to emphasize geomorphic processes. Davis (1899, 1902) chose to emphasize landform morphologies. Schumm and Lichty (1965) pointed out that time and space considerations (1) influence one's viewpoint regarding attainment of equilibrium in geomorphic systems, and (2) vary greatly between a study that emphasizes interaction of variables along a reach of a stream during several hours and a study that emphasizes morphologic changes of a drainage basin during millions of years.

Streams develop morphologies that depend on the frequency and magnitude of discharge of sediment and water from the hillslope subsystem. Some workers have regarded this interaction between form and process as an approximate equilibrium between the variables of the stream subsystem (Gugliemini, 1867; Surell, 1841; Dausse, 1872 — all cited in Rouse and Ince, 1957, p. 71; Davis, 1902; Mackin, 1948; Rubey, 1952; Hack, 1960. Other workers have emphasized the tendency toward adjustment between interdependent variables (Gilbert, 1914; Kesseli, 1941; Leopold and Maddock, 1953; Bull, 1975).

Most workers consider the concept of the graded stream as an equilibrium situation where, over a period of years, the hillslope subsystem supplies a uniform discharge of water and sediment to the stream subsystem. Because of the absence of long-term trends in discharge characteristics, the alluvial channel that has achieved a graded condition has developed a morphology so that the stream velocity is sufficient to transport the imposed sediment load (Mackin, 1948). Davis (1902) believed that grade was achieved only after a long time and that it was attained only in the mature and late stages of his "cycle of erosion." Knox (1976), who is interested in climatic change and humans as causes for ungraded streams, defined a graded stream as "one in which the relationship between process and form is stationary and the morphology of the stream remains constant over time." In contrast to the viewpoint of Davis, Knox believes that adjustment to a graded condition occurs rapidly. Leopold and Bull (unpub.) prefer to emphasize more than slope and velocity by defining equilibrium conditions in terms of stream power. They have stated that "a graded stream is one in which, over a period of years, slope, velocity, depth, width, roughness, pattern and channel morphology delicately and mutually adjust to provide the power and efficiency necessary to transport the load supplied from the drainage basin without net aggradation or degradation of the channels." This definition also includes the concept of how a graded stream differs from one that is not graded.

Although a tendency toward equilibrium conditions exists in streams, the attainment of graded conditions for long periods of time may be unlikely for many reaches of streams. Changes in independent variables of the fluvial system, such as climate, total relief as affected by tectonic movements, the erodibility of the surficial materials, and the human impacts create conditions conducive to change instead of equilibrium in fluvial systems. The time needed for changes in the above variables to affect the operation of the hillslope subsystem ranges from 10^6 yr for the effects of tectonic uplift in arid fluvial systems to 10 yr for the impact of humans where vegetation is cleared from hills in humid regions. Long time lags of response and adjustment for hillslope subsystems result in long time spans for stream subsystems to approximate graded conditions. Most fluvial systems now are responding to several changes in independent variables, each with its own time lag needed to approach a new equilibrium condition. Other landforms — such as deposits and topographic inversion — do not even tend toward equilibrium configurations (Bull, 1976a).

This study focuses on geomorphic thresholds, rather than on the concept of equilibrium, to explain the interrelations between process and form in fluvial systems. A geomorphic threshold is a transition point or period of time that separates different modes of operation within part of a landscape system. Adjustments within fluvial systems are further complicated by feedback mechanisms that interact with thresholds and produce complex responses within the system to perturbations (changes

Geological Society of America Bulletin, Part I, v. 90, p. 453–464, 11 figs., May 1979, Doc. no. 90508.

in independent variables). The interrelation between a threshold and feedback mechanism is outlined in Figure 1, A. Change in base level affects the gradient, and thereby stream power; which, in part, determines whether only sediment transport, or net aggradation or degradation, occurs at the foot of a hill.

The differences between the threshold and equilibrium concepts are illustrated in Figure 1, B. Geomorphic equilibrium occurs when self-regulating feedback mechanisms cause an adjustment among the variables of a system, or part of a system, such that changes in landscape morphology do not occur with time. Points in time that separate reversals in modes of operation are thresholds, but they are not equilibrium conditions unless an adjustment to a time-independent landform assemblage has occurred. Periods of equilibrium are thresholds when they separate different modes of operation of the system.

PURPOSE AND SCOPE

An important threshold — the threshold of critical power — separates the modes of net deposition and net erosion in fluvial systems. My purpose here is to analyze the critical-power threshold and to demonstrate the widespread application of the threshold approach to the understanding of the interrelations between processes and landforms.

First, the components of the threshold are analyzed, then the types of landscapes associated with downcutting and nondowncutting modes of operation of stream systems are outlined. Variations of stream systems in time and space as affected by the threshold are demonstrated by three markedly different examples. First, the responses of a fluvial system to tectonic uplift of a mountain front (a local perturbation) which

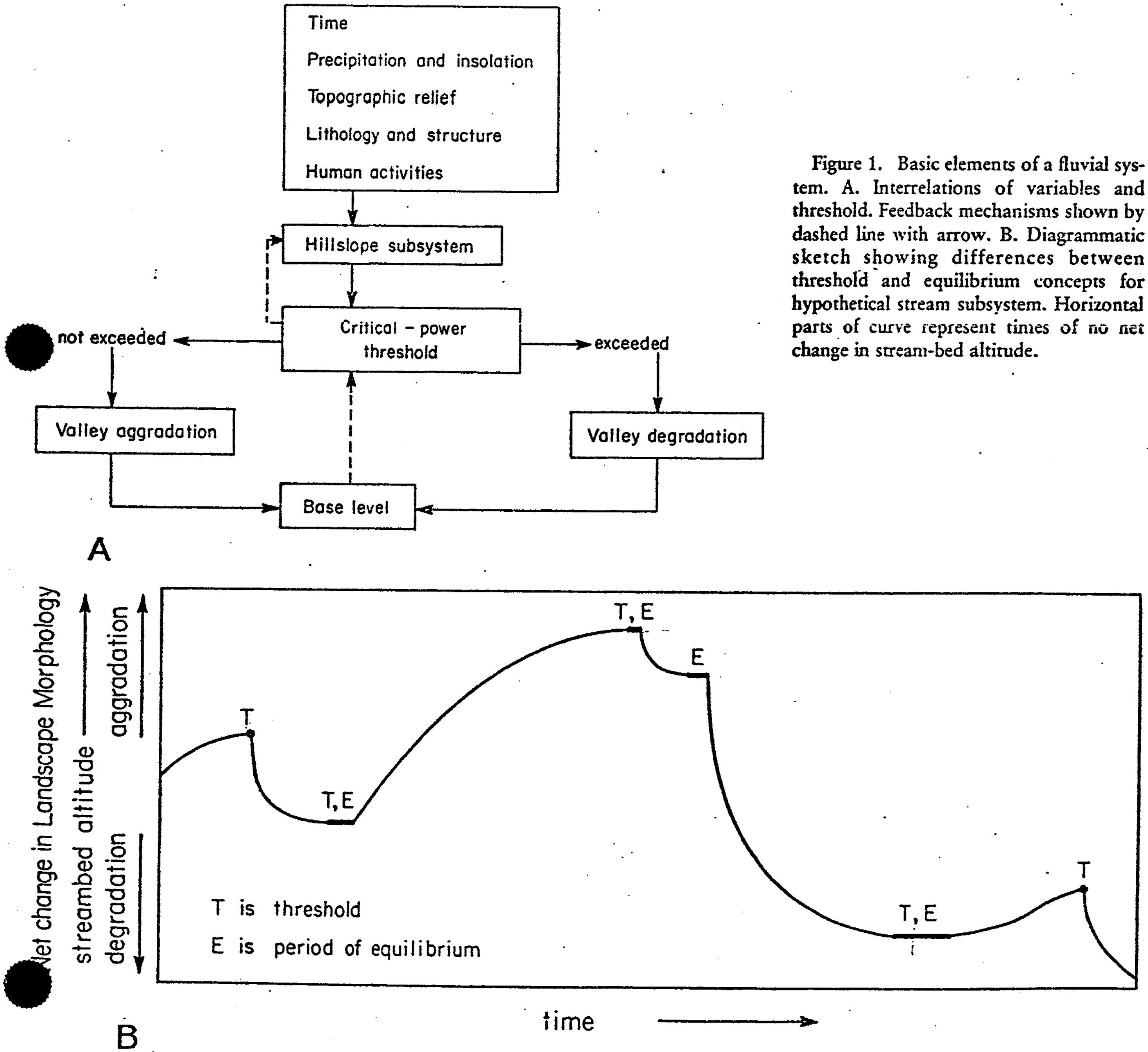


Figure 1. Basic elements of a fluvial system. A. Interrelations of variables and threshold. Feedback mechanisms shown by dashed line with arrow. B. Diagrammatic sketch showing differences between threshold and equilibrium concepts for hypothetical stream subsystem. Horizontal parts of curve represent times of no net change in stream-bed altitude.

involve geologic time spans (10^5 to 10^6 yr) are outlined. Second, the Pleistocene-Holocene climatic change that affects entire drainage basins but for shorter time spans (10^4 yr) are analyzed. Third, the impact of humans is considered, in the context of arroyo cutting, involving small spaces and time intervals (10 to 10^2 yr).

THRESHOLD OF CRITICAL POWER

Useful threshold concepts include those that stress adjustment to changing variables. The critical-power threshold separates the modes of erosion and deposition in streams and is dependent on the relative magnitudes of power needed to transport the average sediment load and on the stream power available to transport the load.

Streams may be regarded as sediment-transporting machines and may be analyzed in terms of the availability of stream power to do work (Bagnold, 1973, 1977; Emmett and Leopold, 1977). Stream power is dissipated in maintaining fluid flow against flow resistance and in doing work by moving the saltating bedload. Where stream power is more than sufficient to transport an imposed sediment load, scour of alluvium on the streambed, and perhaps of bedrock, may occur. Where stream power is insufficient, part of the saltating load will stop and the bed of the stream will aggrade. Bagnold described the kinetic power along a stream channel as γQS, where γ is the absolute density mass per volume, Q is discharge, and S is the gravity gradient. γ is assumed to be roughly constant, although it is recognized that sediment concentrations are decreased by ground-water additions to perennial streams and are increased by infiltration of ephemeral streams. It is useful to consider the total power supply per unit area of streambed, ω where

$$\omega = \gamma QS/\text{width} = \gamma dSu = \tau u, \qquad (1)$$

where d is the mean flow depth, u is the mean flow velocity, and τ is the mean boundary shear stress.

Stream power as defined by Bagnold places an emphasis on the availability of power to transport bedload. Definitions of power that emphasize flow velocity and slope (Yang, 1971; Stall and Yang, 1972) may be useful for analyses of meanders and pools and riffles but are not as useful as the Bagnold equation for the analysis of an erosion-deposition threshold.

The stream power *available* to transport sediment is one component of the critical-power threshold and consists of those variables that if increased favor transportation of the sediment. Stream power was selected as one component of the threshold because sediment transport is highly sensitive to changes in discharge and slope of water (for example, see Baker, 1973, Fig. 54).

The importance of discharge on stream power is dramatically revealed by the marked increases in sediment concentration that occur with increasing discharge at a station. Suspended sediment transport rates (G) may increase by the large exponential factor of about 2.5 with increase in discharge (Q) (Leopold and others, 1964, p. 220–221):

$$G = p\,Q^{2.5}. \qquad (2)$$

The other component of the threshold is critical power. Critical power is the stream power *needed* to transport the average sediment load supplied to a reach of a stream and consists of those variables that if increased favor deposition of the sediment. Critical power changes with variations in sediment load and size and with hydraulic roughness. The term "critical power" is a shorthand expression (through the continuity equation, $Q = wdv$) for variables such as width, depth, and velocity that affect hydraulic roughness and channel morphology. All of these variables interact to determine the capacity and competence of the stream to transport sediment.

Both stream and critical power change with time. Changes in stream power during short time spans generally are the result of changes in discharge. Rates of change of slope tend to be more conservative. Relatively rapid changes in slope occur with the changes in sinuosity that result from changes in stream-channel pattern. Downcutting or backfilling changes slope at a slower rate. Critical power may change rapidly with the amount and size of sediment load derived from the hillslope subsystem and with changes in hydraulic roughness. Changes in streamflow characteristics such as the ratio of water depth to sediment size (Bagnold, 1973, 1977) also affect the amount of power needed to transport bedload, but this type of change is in order to achieve maximum efficiency as a stream tends toward a graded (equilibrium) condition.

The threshold of critical power is defined as

$$\frac{\text{stream power}}{\text{critical power}} = 1.0 \qquad (3)$$

The components of the threshold described by equation 3 differ in their ease of measurement. Stream power may be estimated by measurements of discharge and stream gradient. Energy grade lines parallel the longitudinal profiles of the water surfaces for reaches of small streams that are more than 100 m long (Leopold and others, 1964, p. 304; Baker, 1974). Critical power includes hydraulic roughness, and, like the useful concept of hydraulic roughness, it cannot be measured directly in the field. Despite this apparent drawback, the ratio definition of the threshold is substantially more versatile than erosion-deposition thresholds stated merely in terms of available channel slope.

A simple application of the critical-power threshold is shown in Figure 2, which depicts a stream that has been affected by the emplacement of a road berm and a culvert north of Tucson, Arizona. The culvert was installed slightly higher than the stream bed and constitutes a minor local base-level rise. Reach A of the stream has local scour and backfill but no net aggradation or degradation, and thus it may be regarded as approximating a threshold (graded) condition. Aggradation postdating culvert emplacement has occurred in reach B, where stream power has become insufficient to transport the sediment load, as a result of decrease in slope (which is due partly to ponding during peak discharges). Critical power also increased in reach B as the aggrading area became more vegetated, thereby increasing hydraulic roughness. Reach C is not in equilibrium because much of the bedload has been trapped upstream from the culvert. This reduction in critical power has resulted in active channel downcutting of reach C, despite the concurrent decreases in slope downstream from the plunge pool associated with the culvert. Thus, in a distance of less than 1 km, reaches of a stream may be found that are at, are less than, and exceed the threshold of critical power.

Substantial philosophical differences exist between the threshold and graded-stream conceptual frameworks. The graded-stream approach seems most applicable for large spaces and long time spans, but the threshold concept may be applied to problems that vary greatly in both time and space. Both approaches consider the interaction between process and form, but the threshold concept emphasizes the possibility of change in a fluvial system. Those using the threshold approach are more likely to be interested in when and where change occurs in fluvial systems and the reasons for change, rather than searching for approximations of equilibrium. The graded-stream approach generally encourages study of self-regulating feedback mechanisms, but the threshold approach generally encourages study of self-enhancing feedback mechanisms. The graded-stream approach assumes that after a perturbation a stream will return to an equilibrium longitudinal profile. The critical-power threshold approach encompasses the equilibrium concept, but it emphasizes how far removed a stream is from equilibrium and recognizes that the behavior of both the stream and hillslope subsystems are dependent in part on the extent of deviation from the critical-power threshold (that is, the graded condition).

The ratio of vertical to lateral cutting during floods in alluvial stream channels is determined largely by how close the stream is to the critical-power threshold. In most cases, stream-bed scour is followed by backfilling during the waning stages of a flow event. These short-term changes are chiefly the result of changes in discharge and load. Where changes in slope occur, they are only temporary, because permanent changes in slope in a reach approximating the threshold might change the stream power sufficiently to cross the threshold. In reaches where stream power exceeds critical power, vertical erosion predominates, but lateral erosion predominates where a stream is close to the threshold. Lateral erosion tends to be permanent, as indicated by the presence of straths and flood plains.

Perennial streams may scour or backfill their channels during large flows, but low flows are times of reworking of those stream-bed materials that can still be transported. Ephemeral streams characteristically aggrade their channels during low flows because streamflows infiltrate into the channel before reaching the mouth of a drainage basin. Major flows may cause net scour of the channels of ephemeral streams as the accumulated sediment is flushed out of a given drainage net.

Long-term variations (> 1,000 yr) in critical power are the result of changes in amount and size of sediment discharge from the hillslope subsystem. Such changes most commonly are the result of climatic or base-level changes, although the impact of humans is important in many parts of the world.

For either long or short time spans, the interrelations of materials, processes, and landforms can be evaluated by using the allometric-change approach in which landscape elements are viewed as changing at different rates (Bull, 1975). The allometric approach allows for either graded or changing conditions. The critical-power threshold is defined allometrically in equation 3 because the relative power of the two components determines the threshold. Defining thresholds by using the format of equation 3 is advantageous (Bull, 1979). The components of the threshold are identified and compared to each other. The numerical index defines the relative conditions that must be met in order to cross the threshold and change the mode of system operation.

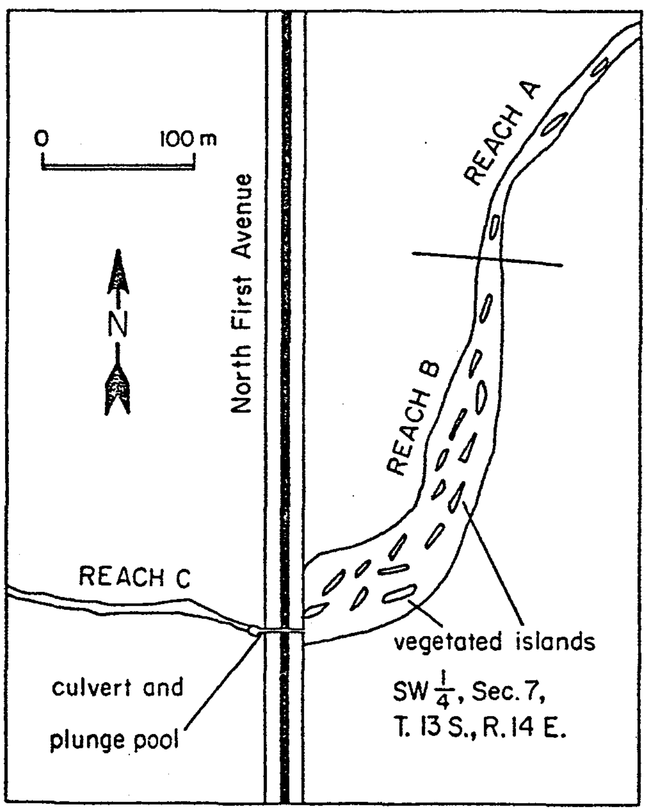


Figure 2. Sketch map showing variations in width of active channel of stream that has been affected by emplacement of road embankment and culvert; north of Tucson, Arizona.

PROCESSES AND MORPHOLOGIES

Three possible interrelations between stream and critical power are shown in Figure 3. The figure is not to scale and may be regarded either as variations that characteristically occur with stream order or as a common situation along trunk stream channels.

The hypothetical situation depicted in Figure 3 portrays the effects of local thunderstorm rainfall of 20 mm in 30 min falling on barren granitic hillslopes in the headwaters of a large drainage basin in an arid region. Stream power decreases with increasing distance from the headwaters. Maximum values of discharge and slope occur in reach A, but overall slope decreases downstream, and discharge decreases downstream as flow infiltrates into the dry steam bed. Discharge, and stream power, decrease to zero in reach C. Critical power increases in reach A as sediment load is picked up from the hillslopes and stream beds, decreases in reach B because of decreases in hydraulic roughness, and decreases in reach C because of decreases in load.

Changes in power for ephemeral and perennial streams can be compared by using the average exponents of the downstream hydraulic geometry equations (Leopold and others, 1964, p. 244). For the ephemeral stream system depicted in Figure 3, $w \alpha Q^{-0.5}$, $d \alpha Q^{-0.3}$, $u \alpha Q^{-0.2}$, and $S \alpha Q^{-0.8}$.

Total stream power, Ω, decreases markedly:

$$\Omega \alpha wduS, \quad (4)$$

$$\Omega \alpha Q^{(-0.5-0.3-0.2-0.8)},$$

$$\Omega \alpha Q^{-1.8}, \quad (5)$$

and stream power per unit width, ω, also decreases:

$$\omega \alpha duS \quad (6)$$

$$\omega \alpha Q^{-1.3} \quad (7)$$

Discharge increases downstream in perennial streams, and $w \alpha Q^{+0.5}$, $d \alpha Q^{+0.4}$, $u \alpha Q^{+0.1}$, and $S \alpha Q^{-0.8}$.

Total stream power increases,

$$\Omega \; \alpha \; Q^{(+0.5+0.4+0.1-0.8)}$$

$$\Omega \; \alpha \; Q^{+0.2},$$

but stream-power per unit width decreases:

$$\omega \; \alpha \; Q^{-0.3}. \qquad (9)$$

Headwaters streams in most mountainous regions generally exceed the critical-power threshold. Stream power is much more than is needed to transport the sediment load and overcome roughness in reach A of Figure 3, part A. Cross-valley morphologies of such reaches characteristically are V-shaped because the stream obtains additional sediment by vertical erosion into bedrock. All downcutting reaches, however, have a tendency to approach the threshold of critical power.

Stream power is less than the critical power in reach C of Figure 3 — a ratio of less than 1. Both steep and gentle reaches may occur in locally aggrading reaches. In Figure 4, deposition of sand has occurred in a locally aggrading section of a bedrock channel. In reach X the mode of operation is to alluviate the channel and valley floor and represents the situation depicted in reach C of Figure 3. Increases in flow width, infiltration capacity, and vegetation all act as self-enhancing feedbacks that promote additional alluviation. Stream power in reach X does not tend to remain less than critical power, because selective sedimentation decreases sediment load and size, thereby reducing the critical power and tending to re-establish the critical-power threshold. In order to achieve the threshold, the decrease in sediment load must be sufficient to compensate for the concurrent decrease in stream gradient caused by alluviation. It is unlikely that aggrading reaches attain the threshold, but the tendency to attain the threshold may result in roughly similar values of stream and critical power.

The deposition of the patch of alluvium illustrated in Figure 4 also results in the formation of reach Y, which is inherently unstable because the stream slope is steep. Channel entrenchment into the alluvium may occur, particularly at high discharges. The formation of channels tends to concentrate flow, and this is a self-enhancing feedback that tends to destroy the patch of alluvium.

Thus, local aggradation may result in reaches that either exceed or are less than the critical-power threshold and where the relative rates of change of processes and landforms are dependent on two offsetting self-enhancing feedback mechanisms. Alluviation will be temporary in a bedrock channel such as illustrated in Figure 4, and where streams debouch onto a permanent depositional area, such local alluviations are redistributed over the surface of the deposit.

Stream power and critical power are equal, but changing, in reach B, which is in equilibrium. Stream power is decreasing because of decreases in discharge and slope. Sediment load is constant or may even increase, but, by definition, it cannot decrease until reach C. Hydraulic adjustments act as self-regulating feedback mechanisms to maintain graded conditions in reach B despite decreases in discharge. If dune bedforms and highly turbulent flow are present in reach A, they may give way to the planar beds of reach B. The resulting decreases in hydraulic roughness cause decreases in critical power and provide an example where

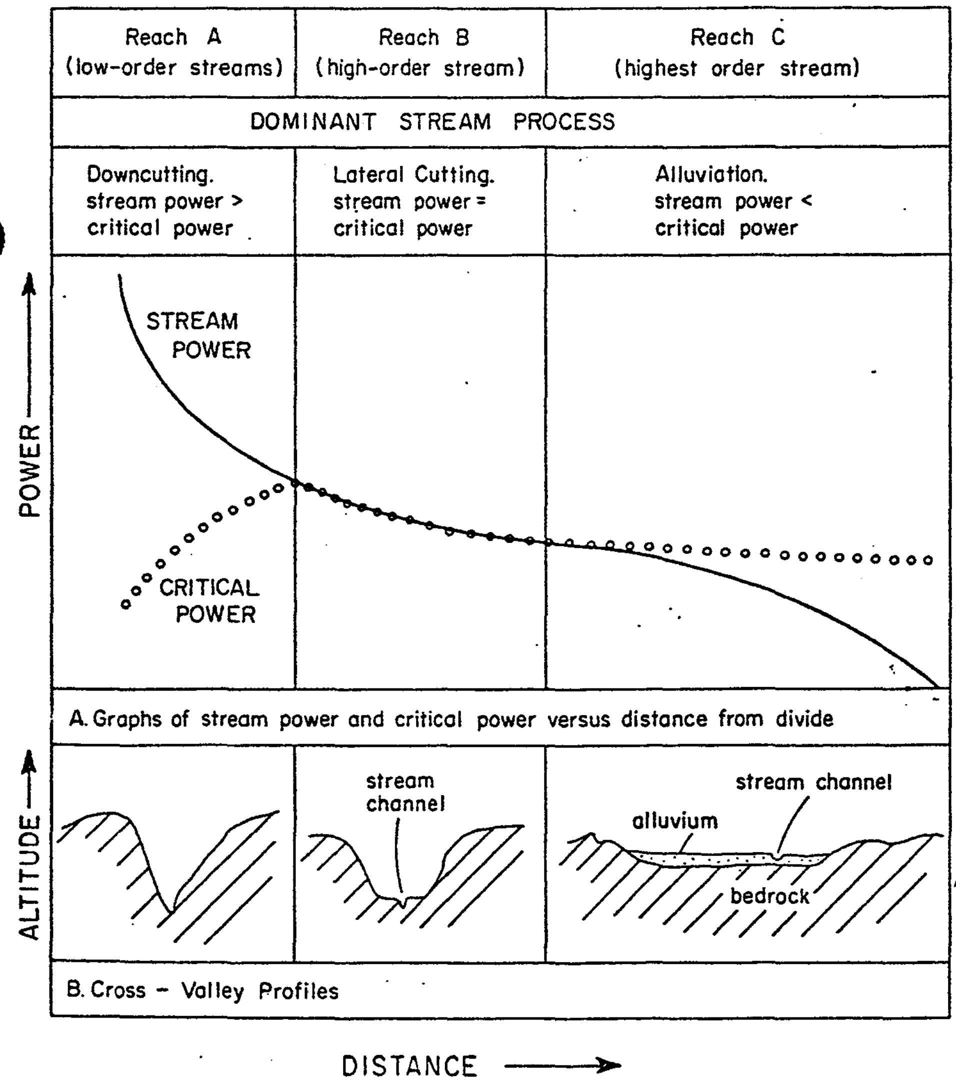


Figure 3. Diagrammatic sketches and graphs of stream power and critical power for arid rocky drainage basin.

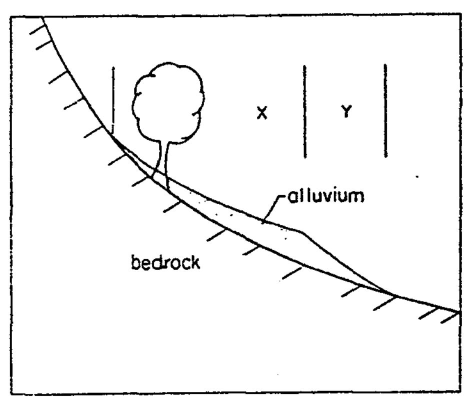


Figure 4. Diagrammatic sketch of stream profile showing adjacent alluvial reaches that are more gentle (X) and steeper (Y) than pre-existing bedrock channel.

hydraulic adjustments are sufficient to maintain a graded-stream condition despite concurrent changes in several variables. In reaches A and C of Figure 3, part A, the hydraulic adjustments are insufficient to allow attainment of graded streamflow.

A reach where stream power is more than the critical power will tend to erode down to the threshold of critical power. High-order streams achieve the threshold condition more rapidly than do low-order streams because of their greater capacity. The rate of downcutting decreases asymptotically, and lateral erosion and deposition become more important as the threshold is approached. Minor downcutting or deposition may occur in a reach, but such local processes are temporary and commonly are offset by the presence of the opposite process within the same reach, as in a point-bar environment. Straths form under such conditions. This concept was first stated by Gilbert (1877, p. 126): "Downward wear ceases when the load equals the capacity for transportation. Whenever the load reduces the downward corrasion to little or nothing, lateral corrasion becomes relatively and actually of importance."

A variety of field evidence may indicate that a given reach of a stream is close to the critical-power threshold. The presence of alluvium in amounts that exceed that scoured by large discharges suggests that net vertical erosion is minimal. In downcutting reaches, stream width at peak discharges equals valley-floor width; but when lateral cutting becomes predominant over downcutting, the floodplain is narrower than the valley-floor width. Measurements that show neither net erosion nor deposition indicate threshold conditions. For time spans of 1 to 100 yr, measurements of erosion and deposition can be made in the field. For longer time spans, radiogenic dating of stratigraphy may be used. The threshold has been passed if accelerated downcutting occurs as a result of minor steepening of the channel due to base-level fall or local alluviation. Parallel stream terraces may be suggestive of a return to similar threshold conditions after adjustments to perturbations. The evidence that many depositional settings were close to the threshold is found in stratigraphies that contain numerous temporary small hiatuses.

Reaches of streams at the critical-power threshold are highly susceptible to accelerated downcutting or alluviation because of changes in either stream or critical power. For the situation depicted in reach B of Figure 3, part B, a moderate increase in the critical power may result in alluviation. A moderate decrease in critical power may accelerate the rate of channel downcutting. Changes in the critical power that result from changes in the independent variables are a major cause of passing the threshold, which results in alluviation or terracing of streams. The situation is different for reach A, where even a large increase in critical power can occur and the stream will continue to downcut. For reach C, changes in critical power may (1) accelerate the rate of alluviation, (2) return the mode of operation to equilibrium conditions, or (3) cause the threshold to be crossed, thereby initiating entrenchment of the channel into the alluvium.

The concept that streams tend toward the minimum gradients needed to transport their sediment loads has been recognized by many workers (such as Leopold and Langbein, 1962; Yang, 1971, p. 243) and is an important part of the graded stream and critical-power threshold conceptual frameworks. A graded stream would be one that has attained and remained at the critical-power threshold. Knox (1976) would consider a stream to be graded even if long-term net erosion or deposition were taking place. Knox's approach pertains to those streams that remain on one side or the other of the critical-power threshold or those that remain at the threshold.

VARIATIONS IN TIME AND SPACE

In this section the critical-power threshold is used to evaluate time lags in arid fluvial systems that have responded to perturbations of greatly different character and duration. The topics include the assessment of the impact of tectonic uplift, climatic change, and human actions.

Responses to Tectonic Perturbations

Differential vertical uplift at a mountain front is a perturbation that first affects the fluvial system adjacent to the front. Headcut migration steepens the drainage net and then the hillslopes. The ridge crests in the headwaters of the drainage basin will be the last landscape element to adjust to the increase in relief caused by the uplift.

Uplift rates of mountain fronts are not uniform. Periods of rapid uplift are separated by periods of minimal tectonism, when stream erosion is the chief local base-level process. After substantial uplift, the critical-power threshold may be exceeded along an entire drainage net, indicated by lack of net alluviation in narrow V-shaped valleys. Straths formed during periods of tectonic quiescence will become terraces with the onset of the next period of accelerated uplift, which steepens the slope of the active stream channel.

An example of a stream that has repeatedly returned to the critical-power threshold after pulses of differential uplift of the mountain front is the Wadi Saada, which discharges onto a large alluvial fan along the coast of the east-central Sinai Peninsula. The differential uplift appears to be chiefly downfaulting of the rift valley to the east. Most of the drainage basin is underlain by coarse-grained granitic rocks, and hydrolytic weathering and salt splitting

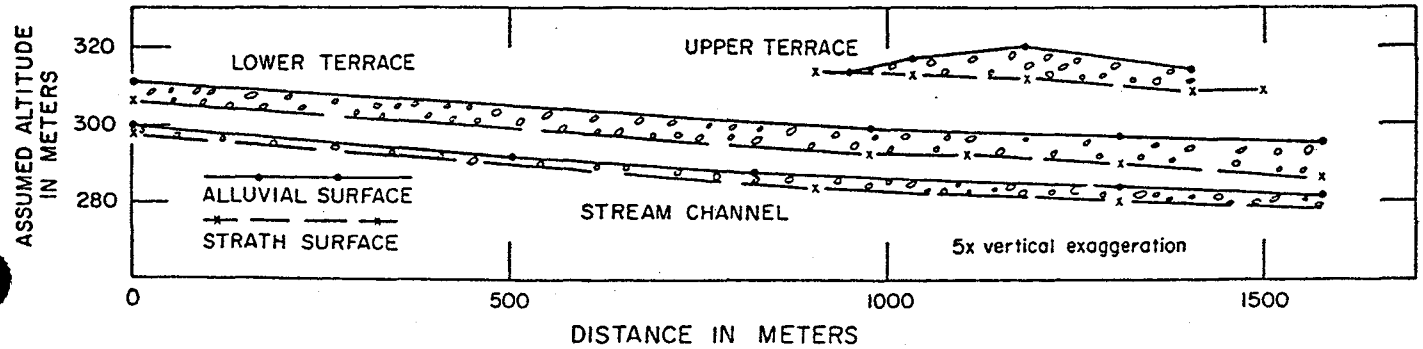


Figure 5. Longitudinal profiles of strath terraces of Wadi Saada, east-central Sinai Peninsula.

are important processes that produce large amounts of grus.

Although the width of the Wadi Saada exceeds 100 m at the mountain front, it is a strath that is overlain by 3 m of bouldery gravel. Figure 5 shows remnants of two similar ancestral straths now preserved under terrace gravels at about 10 and 30 m above the wadi strath surface.

Although a net increase in the total relief of the watershed has occurred as a result of the uplifts, permanent steepening of the stream gradient apparently has not occurred in the reach immediately upstream from the fault scarp. Differential uplift of the mountain front caused headward erosion in the reach upstream from the fault and establishment of a steeper and a narrower valley than before faulting. Then, during a period of tectonic inactivity, fan deposition constituted a base-level rise in the reach downstream from the fault. The stream cut down to the critical power threshold upstream from the mountain front, and lateral erosion widened the valley floor. The presence of three straths suggests that long periods of tectonic quiescence occurred between uplifts of 20 and 10 m. The mean discharge of water and sediment from the hillslopes may not have changed much during the long time spans represented by the suite of terraces. The similarity of terrace slopes may reflect similar sizes of the coarse-grained bedload (Leopold and Bull, unpub.).

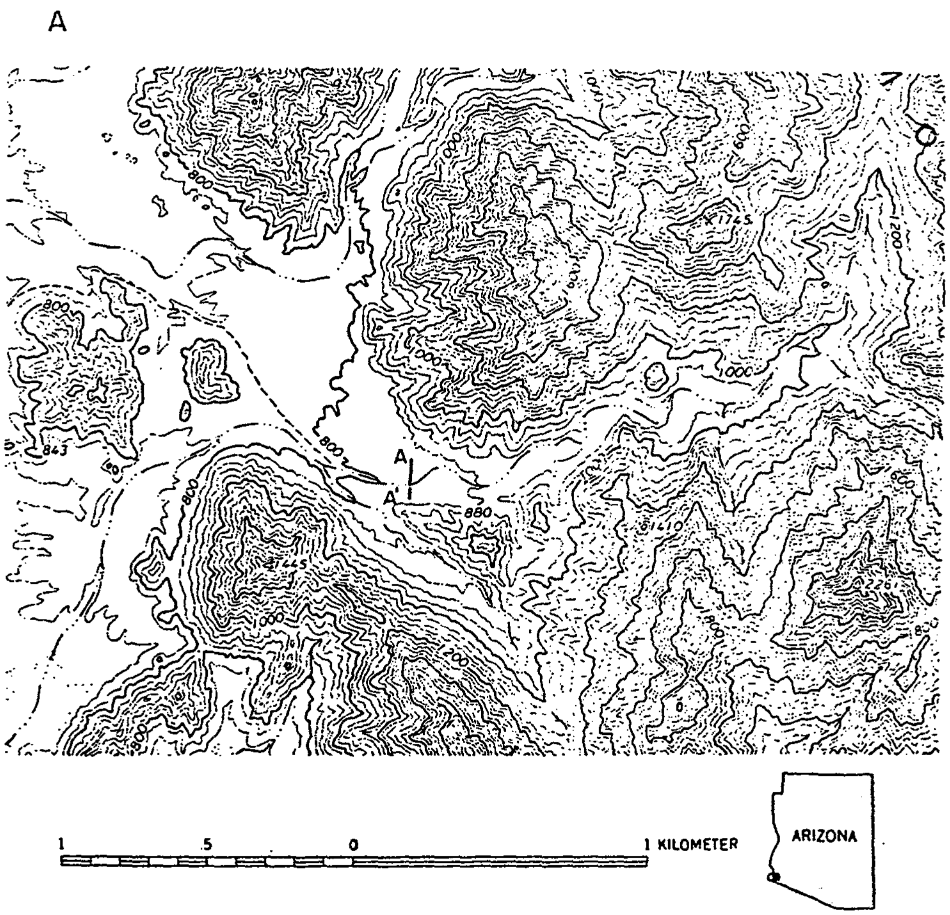
The rates of headcut migration — a type of accelerated vertical erosion — will determine the rate of upstream migration of the effects of a tectonic perturbation. The mountain-front reach is the first to approach the threshold of critical power, and the progressive increase of the ratio of lateral to vertical erosion results in valley widening near the mountain front while active downcutting is still occurring upstream.

The rate of valley-floor narrowing with distance upstream from a mountain front can be expressed by the power function

$$W = c\,L^{n}, \qquad (10)$$

where L is distance upstream from the mountain front, and W is width of the valley floor. Scatter about the regressions (Fig. 6, B) is largely the result of variations in erosional widening of the valley floors caused by nonuniform lithology and structure and changes in valley width where tributary streams join the trunk stream. The coefficient, c, is indicative of the valley-floor width at 100 m upstream from the start of the transect, which is shown by line A–A′ in Figure 6, A. The exponent, n, is indicative of the rate of valley-floor narrowing.

During the valley downcutting that occurs after mountain-front uplift, the width of the valley floor will approximate stream width at high discharges. Valley-floor width decreases upstream from the front because of the decrease in the size of the contributing watershed. During the initial downcutting of the valley, c will be an index of the magnitude of peak stream discharges at a unit distance (100 m in this case) upstream from the mountain front. With the passage of geologic time, the stream will widen its valley as it approaches the threshold of critical power. As lateral cutting becomes progressively more important, the stream will not spread over the entire valley floor during high discharges. The approximation of a threshold condition migrates gradually upstream as the upstream reaches downcut, so that the stream and critical power are roughly the same for time spans of 10^4 yr. The configurations of the plan views of the valley mouths — the pediment embayments of Figure 6, A — are functions of the rates



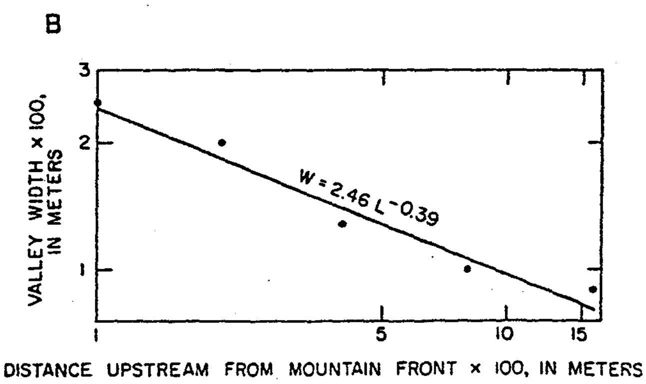


Figure 6. Pediment embayments of Gila Mountains, Arizona. A. Topographic map from Fortuna Mine quadrangle. Data for part B were collected from embayment whose mouth is marked by A–A′. Rocks are mafic gneiss, pegmatite, and quartz diorite. B. Graph showing narrowing of valley width (W) with increasing distance (L) upstream from mountain front.

of lateral cutting and/or hillslope retreat along the stream and the time elapsed since lateral erosion became predominant at the various points along the valley. More than a million years may be needed to form pediment embayments.

The values of the exponent of equation 10 commonly range from −0.1 to −1.0, but most of the exponents range from −0.1 to −0.4. These low rates of decrease of valley-floor width relative to distance upstream from the mountain front suggest that (1) the rates of migration of attainment of the threshold condition upstream from the fronts commonly have been moderately rapid (the streams' tectonically steepened gradients decreased fairly rapidly during and after cessation of uplift), and/or (2) the low rate of narrowing is controlled by structures that parallel the valley. This is not surprising, because many streams owe their locations partly to the greater ease of erosion along zones of abundant joints and shears.

Such long periods of time are needed for entire drainage nets to achieve the threshold condition that it may not happen. The adjustment time is longer for upstream reaches than reaches at the mountain front because of decreasing stream capacity in the upstream direction. In Figure 6, part A, the headwaters streams have yet to cut down to the threshold condition. Pediment-embayment development is an example of an extremely long time lag in response to progressive decrease in the stream-power component of the threshold. However, the reaches of the stream that are close to or on the erosional side of the threshold can be identified easily.

Responses to a Climatic Perturbation

In the section on pediment embayment, I discussed changes in space of the critical-power threshold during time spans of 10^6 yr, as affected by a perturbation in only a small part of the system — the zone of differential uplift at the mountain front. This section emphasizes variation of threshold conditions during 10^4 where the perturbation of Pleistocene-Holocene climatic change occurred throughout arid fluvial systems.

The change to Holocene climates in the hot deserts of the Middle East and the American Southwest can be generalized by stating that precipitation decreased and/or temperature increased. These changes in the independent variables caused the following postulated sequence of changes in the arid fluvial systems. Both climatic changes reduced the moisture available for plant growth. Reduction of vegetative density decreased infiltration rates and exposed more soil to erosion, resulting in increases of sediment concentration and runoff of water (Fig. 7) for a precipitation event of a given amount and intensity. Increases in sediment load and size greatly increased the critical power. The increase in critical power was

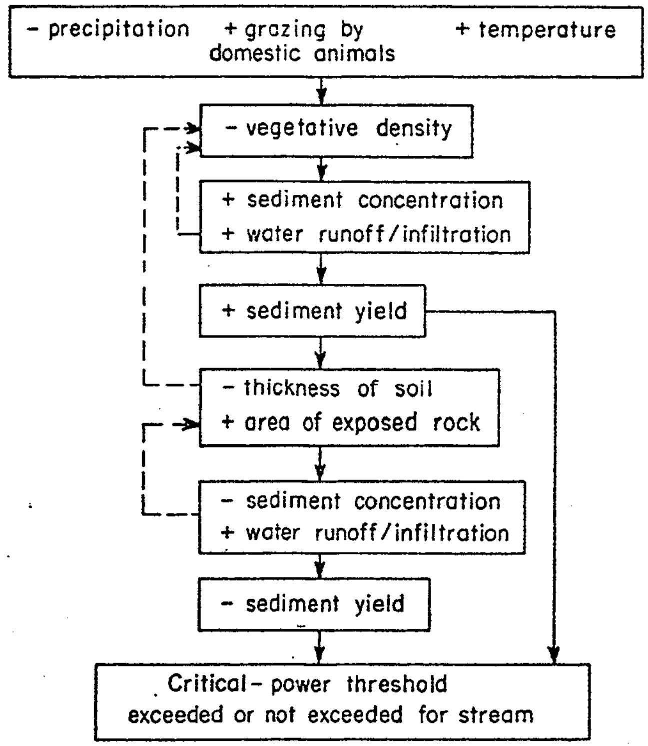


Figure 7. Increases (+) and decreases (−) in elements of hypothetical arid hillslope subsystem. Self-enhancing feedback mechanisms are shown by dashed line with arrow.

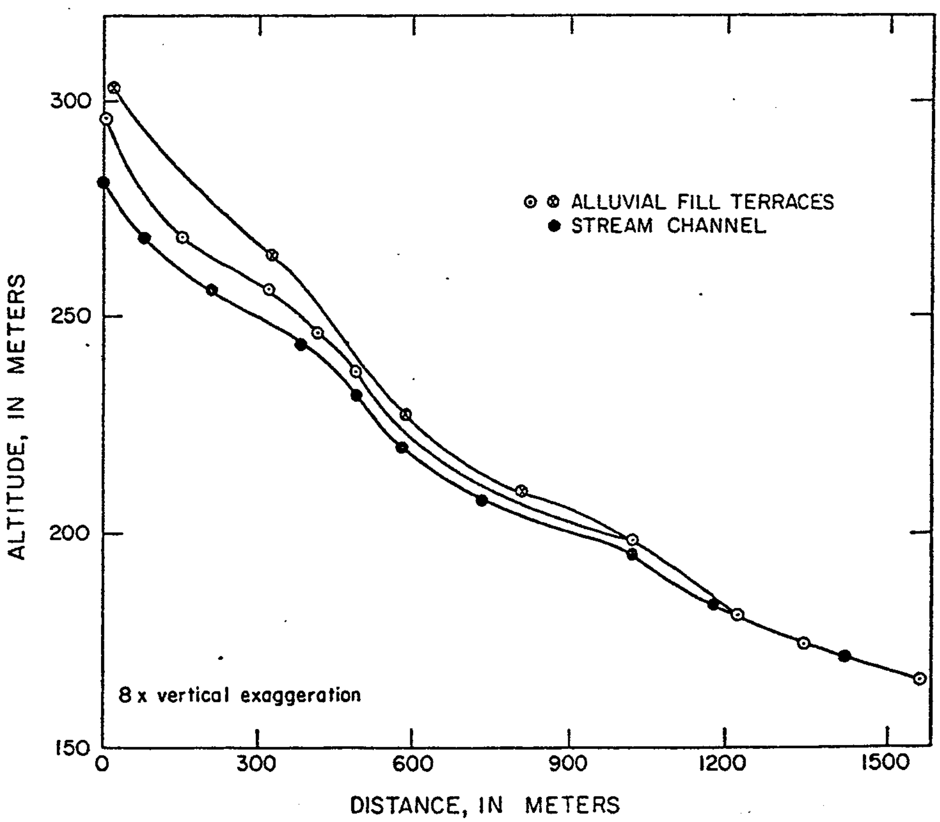


Figure 8. Longitudinal profiles of converging fill terraces in Riverside Mountains, California.

sufficient to maintain a condition where the critical-power threshold was not exceeded, despite increases in some stream gradients caused by valley alluviation. Decrease in soil thickness and concurrent increase in area of exposed bedrock caused still more rapid runoff of water, and the sediment concentration decreased as more bare rock was exposed (Fig. 7). The resulting decrease in sediment yield reduced the critical power, but the stream power had been increased by the deposition of the steep valley fill. The critical-power threshold was crossed as a result of the changes occurring in the hillslope subsystem, and erosion of the valley fill began. Three self-enhancing feedback mechanisms tended to perpetuate the net removal of soil from the slopes (Fig. 7). Increased flashiness of runoff continued to decrease soil thickness, which resulted in continued decrease in vegetative density.

Fill terraces, such as those of Figure 8, occur in the arid parts of the Mojave and Sonoran Deserts of Arizona and California. Valley fills were 6 to 30 m thick, but nearly all the streams now are downcutting into bedrock. The widespread occurrence of three Holocene terrace levels reflects climatic variations during Holocene time, but these have been minor compared to the Pleistocene-Holocene climatic change. Plants collected and stored by pack rats (*Neotoma* sp.) provided Van Devender (1973, 1977) abundant fossils from plant communities, and materials to date the times of climatic change. For western Arizona he concluded that starting about 8,000 yr ago annual precipitation decreased about 50%, that most of the decrease occurred during the winter rainy season, and that the mean annual temperature increased about 3 °C.

The fluvial systems have been changing as a result of the climatic change. The single major perturbation resulted in consecutive valley alluviation and downcutting as self-enhancing feedback mechanisms changed stream and critical power. The stream subsystem changed modes of operation in a classic example of what Schumm (1973) has referred to as complex response of fluvial systems. Holocene alluviation temporarily increased stream gradients in the Mojave Desert by as much as 25%. Although the changes in stream discharge and gradient caused large changes in stream power, the changes in critical power resulting from changes in sediment load and size were even larger and occurred more rapidly.

Response to Impact of Humans

The response to grazing — or other impacts such as short climatic variations — is most pronounced in semiarid stream systems underlain by fine-grained, easily eroded materials. Changes in sediment load and hydraulic roughness are large and commonly occur during time spans of 10 to 100 yr.

The critical-power threshold separates the two modes of operation of such stream systems (Fig. 9). Where the threshold is exceeded for a stream such as reach Y of Figure 4, decreases in valley vegetative density and flow width, and increases in flow depth and velocity all tend to act as self-enhancing feedbacks to perpetuate the downcutting mode. Increase in sediment load and decrease in slope tend to offset the effects caused by changes in the above four variables. Most entrenching streams downcut rapidly, approximate threshold conditions for a while, and then backfill or renew downcutting in response to new changes in the independent variables or to complex responses (Schumm, 1973) of the system. The valley aggradation mode (Fig. 9) has changes in dependent variables that are opposite those of the downcutting mode. For either mode, changes in base level directly affect the critical-power threshold.

An example of the sensitivity of such streams to the impact of humans is provided by the Dead Mesquite Wash study area (Packard, 1974) near Tucson, Arizona. A discontinuous ephemeral stream supports a lush growth of trees, bushes, and grass where streamflow spreads out on channel fans that are sites of valley aggradation. Self-enhancing feedbacks promote vegetative growth where vegetation greatly spreads and reduces velocity of streamflow, thereby causing deposition of additional clayey soil and prolonged infiltration of streamflow. Grazing, fire, or encroachment by headcuts in the adjacent downstream reach cause the critical-power threshold to be exceeded and establish an opposite self-enhancing feedback mechanism. The change is particularly pronounced in clay-rich soils because the initiation of any minor channel greatly decreases residence time of ephemeral sheet flow and, thereby, the infiltration of water to support the vegetation. Within decades lush growth is trans-

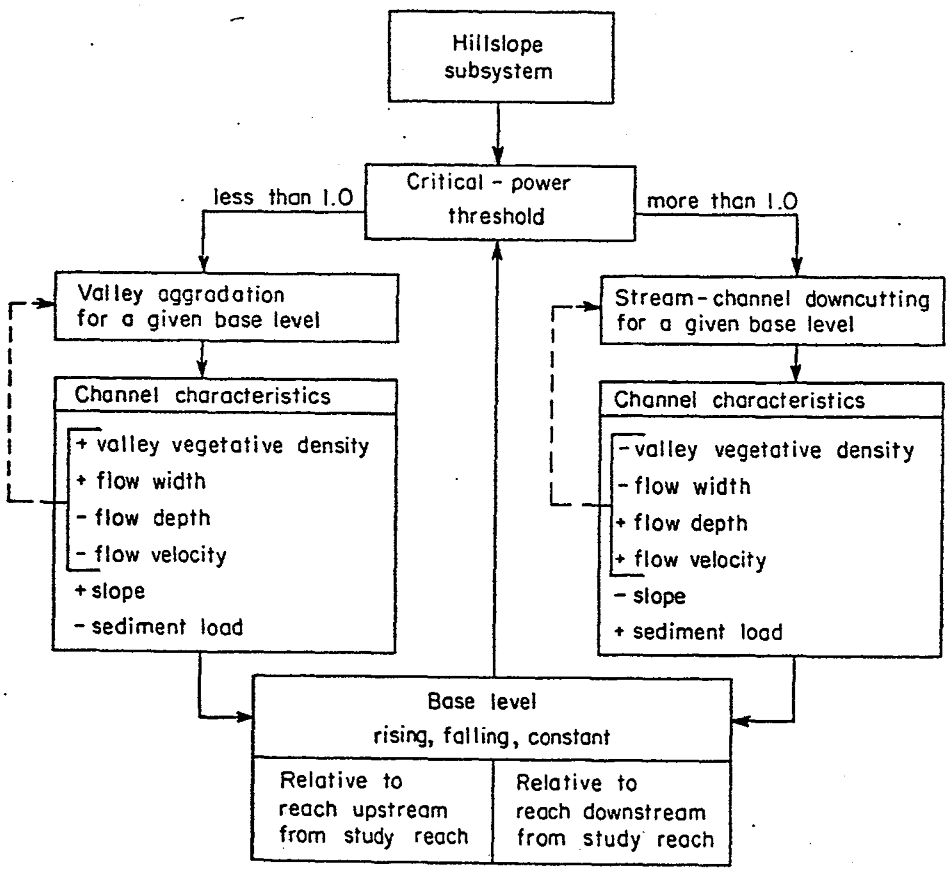


Figure 9. Increases (+) and decreases (−) in elements of hypothetical semiarid stream subsystem. Self-enhancing feedback mechanisms are shown by dashed line with arrow.

A

B

Figure 10. Threshold relations for discontinuous ephemeral stream. Dead Mesquite Wash study site, Arizona. A. Densely vegetated reach at critical-power threshold. B. Barren reach adjacent to reach shown in A. Critical-power threshold has been exceeded for this reach.

formed into badlands studded with bleached tree trunks (Fig. 10).

Patton and Schumm (1975) studied discontinuous gullies in the Piceance Basin of northwestern Colorado, where they found sandstone, siltstone, and marlstone to be the most common hillslope rock types. They compared slopes and drainage areas (a proxy for discharge) of gullied and ungullied reaches (Fig. 11), and their work showed that channel entrenchment occurred when, for a given drainage area, alluviation steepened the reach of a stream above a threshold slope in much the same manner as for reach Y of Figure 4.

In Figure 11, Patton and Schumm's plot has been divided into three groups of points in order to demonstrate the relative importance of the two components of the critical-power threshold: stream power and the critical power. The solid line is an approximation of the critical-power threshold for the different stream reaches of the Piceance Basin. Variations in stream power dominate the threshold for the points in areas A and B. None of the reaches of area B has sufficiently steep gradients that the threshold is exceeded, and virtually all of the reaches in area A are entrenched. Critical power does not vary much for the reaches of areas A and B, thereby allowing a clear relation between valley slope, discharge (basin area), and the presence of entrenched or unentrenched streams.

The relation between valley slope and basin area does not hold for area C, which consists of steep reaches with source areas of less than 20 km^2. There is a good reason for the critical power to vary more in the reaches of area C, and therefore be a more important determinant of whether or not entrenchment has occurred in the reaches of area C. The denser hillslope and valley-floor vegetation of those small basins dominated by north-facing slopes (Patton and Schumm, 1975, p. 89) has increased the hydraulic roughness and decreased discharge so that critical power is larger than stream power. Thus, the mode of operation of some, but not all, of the small basins has been alluviation instead of entrenchment of the valley floors.

Figure 11 is useful for analysis of potential impact of humans on their environment. The critical-power threshold is identified for a study area, and the relative importances of critical and stream power for different reaches of the fluvial system can be determined. Individual reaches such as point S are identified; they appear to be especially sensitive to increases in the stream power or decreases in critical power and, thereby, are likely to be entrenched.

CONCLUSIONS

The concept that streams tend toward uniform and minimum expenditure of power needed to transport their sediment loads (Leopold and Langbein, 1964) is an important part of the conceptual frameworks that emphasize equilibrium (the graded stream) or change in fluvial systems (the threshold of critical power). Some of the differences in emphasis of the two approaches are as follows. (1) Thresholds can be used in studies involving investigations that range from minutes to millions of years and for spaces of equally great contrast, but the graded-stream concept applies primarily to long times and large spaces. (2) The threshold approach tends to focus attention on those variables and complex responses that are likely to cause the mode of system operation to change. (3) The threshold approach generally encourages study of self-enhancing feedback mechanisms, whereas the graded-stream approach generally encourages study of self-regulating feedback mechanisms.

Identification of thresholds in studies of fluvial systems promotes versatility of approach and emphasis of those variables that are likely to cause the mode of system operation to change. The use of thresholds encourages study of the relative rates of change of variables — allometric change — and de-emphasizes consideration of situations that may be unlikely, such as the attainment of equilibrium (steady state) for long periods of time.

Two conditions relating to the critical-power threshold can be recognized easily in the field: (1) reaches where the threshold has been exceeded, and (2) reaches that approximate the threshold or where the critical power exceeds the stream power. Active downcutting by the stream and lack of evidence for alluviation are clear evidence that the threshold is being exceeded. The following field situations indicate that a stream is close to the critical-power threshold: (1) the presence of alluvium in amounts that exceed that scoured by large discharges, (2) a floodplain that is narrower than the valley-floor width, (3) measurements of dated alluvial sequences that indicate neither net erosion nor deposition for a reach, (4) parallel fill, or strath, terraces, which suggest fluctuating conditions and periodic return to similar threshold conditions, and (5) numerous, small hiatuses of a temporary nature in the stratigraphy of a valley fill.

It is desirable to use ratios when defining thresholds. The critical-power threshold is where stream power/critical power = 1.0. Such a ratio is an allometric approach, because the relative importances of two aspects of the system are used to define the threshold. The ratio format clearly defines the relative conditions needed to change the mode of system operation.

The critical-power threshold occupies a key position in the complex interactions between the hillslope and stream subsystems, and it is affected by feedback mechanisms and complex responses operating in either subsystem. Recognition of how far removed a stream is from the critical-power threshold should aid in better understanding of both landscape morphologies and processes, as well as their interrelations.

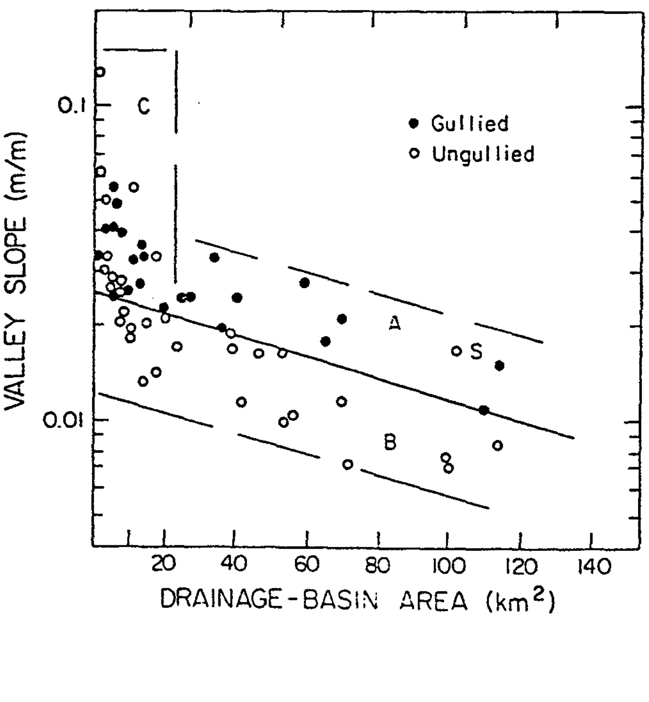


Figure 11. Relation of valley slope to drainage-basin area for gullied and ungullied reaches of discontinuous ephemeral stream in Piceance Creek Basin, Colorado (modified from Patton and Schumm, 1975, Fig. 2). Solid line is critical-power threshold and separates reaches that have exceeded threshold (A) from reaches that have yet to exceed threshold (B). Small watersheds of area C have mixed characteristics due to greater variability of critical power. Point S is ungullied reach that is considered to be especially susceptible to channel entrenchment.

ACKNOWLEDGMENTS

I am particularly indebted to Luna Leopold for his helpful discussions and suggestions during the course of development of this threshold concept. Although the preliminary versions (Bull, 1976b) included factors such as hydraulic roughness and discharge, there was an undue emphasis on stream energy gradient. Leopold's suggestion to recast my thoughts in terms of stream power has resulted in a more realistic and flexible conceptual framework. The stream-power approach is especially relevant because nonequilibrium processes, such as aggradation or degradation, directly involve the availability of stream power to transport bedload.

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Typical Approaches

- **Engineering**
- **Regulatory**
- **Environmental**
- **Geomorphologic**

Engineering Approach

Basic Characteristics

- Empirical Equations
- Continuity Based
- Desk-top Methods

Advantages

- Design Data
- Compare Alternatives
- Relative Results
- Fast
- Impressive

DRAFT

Jon Fuller
[redacted]

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

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  - Sediment Accounting

JON FULLER

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15 December 1989

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Sedimentation Investigations of Rivers and Reservoirs

ENGINEER MANUAL

Fluvial Processes in River Engineering

Howard H. Chang
San Diego State University

A WILEY-INTERSCIENCE PUBLICATION
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US Army Corps
of Engineers
Hydrologic Engineering Center

GENERALIZED COMPUTER PROGRAM

HEC-6

Scour and Deposition in Rivers and Reservoirs

User's Manual

June 1991

Approved for Public Release. Distribution Unlimited.

CPD-6

1.5 Theoretical Assumptions and Limitations

HEC-6 is a one-dimensional continuous simulation model using a sequence of steady flows to represent discharge hydrographs. There is no provision for simulating the development of meanders or specifying a lateral distribution of sediment load across a cross section. The cross section is subdivided into two parts with input data; that part which has a movable bed, and that which does not. The movable bed is constrained within the limits of the wetted perimeter and other limitations that are explained later. The entire wetted part of the cross section is moved uniformly up or down; an option is available, however, which causes the bed elevation to be adjusted in horizontal layers when deposition occurs. Bed forms are not simulated except that 'n' values can be functions of discharge which indirectly permits consideration of the effects of bed forms if the user can determine those effects from measured data. Density and secondary currents are not simulated.

There are three constraints on the description of a network system for which sediment transport is to be calculated:

a. Sediment transport in distributaries is not possible.
b. Flow around islands, i.e., closed loops, cannot be directly accommodated.
c. Only one junction or local inflow point can occur between any two cross sections.

1.6 Single Event Analysis

HEC-6 is designed to analyze long-term scour and deposition. Single event analyses must be performed with **caution.** HEC-6 assumes that equilibrium conditions are reached within each time step (with certain restrictions explained later); however, the prototype is often influenced by unsteady non-equilibrium conditions during flood events. Equilibrium is never achieved under these conditions because of the continuously changing hydraulic and sediment dynamics. If these situations predominate, single event analyses should be performed only on a qualitative basis. For gradually changing sediment and hydraulic conditions, such as for large rivers with slow rising and falling hydrographs, single event analyses may be performed with confidence.

USER'S MANUAL FOR

BRI-STARS

(BRIdge Stream Tube model for Alluvial River Simulation)

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

PROJECT NO. HR15-11

by

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Generalized Computer Program

FLUVIAL-12

Mathematical Model for Erodible Channels

Users Manual

prepared by

Howard H. Chang, Ph.D., P.E.

San Diego, California

August 1986

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)

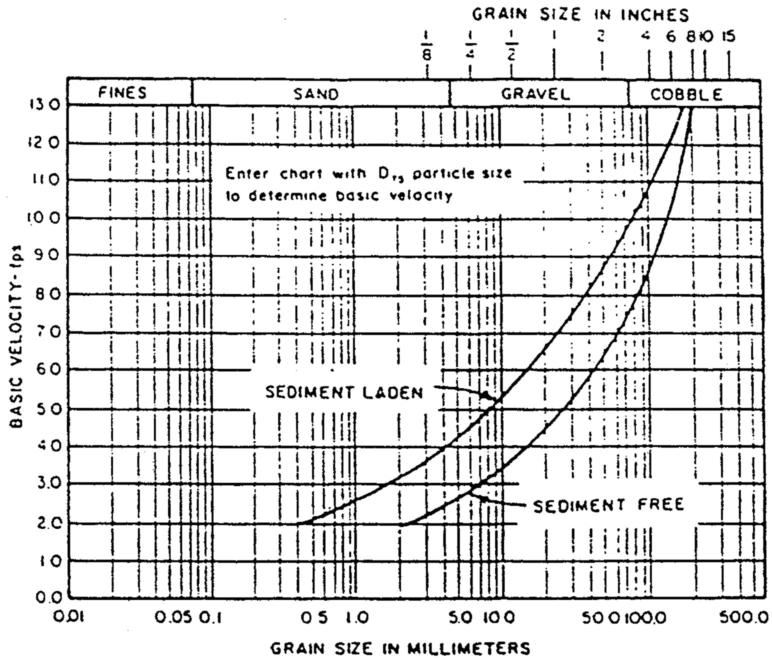
Channel Material	Mean Channel Velocity, fps
Fine sand	2.0
Coarse sand	4.0
Fine gravel††	6.0
Earth	
Sandy silt	2.0
Silt clay	3.5
Clay	6.0
Grass-lined earth (slopes less than 5%)‡	
Bermuda grass - sandy silt	6.0
- silt clay	8.0
Kentucky Blue Grass - sandy silt	5.0
- silt clay	7.0
Poor rock (usually sedimentary)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

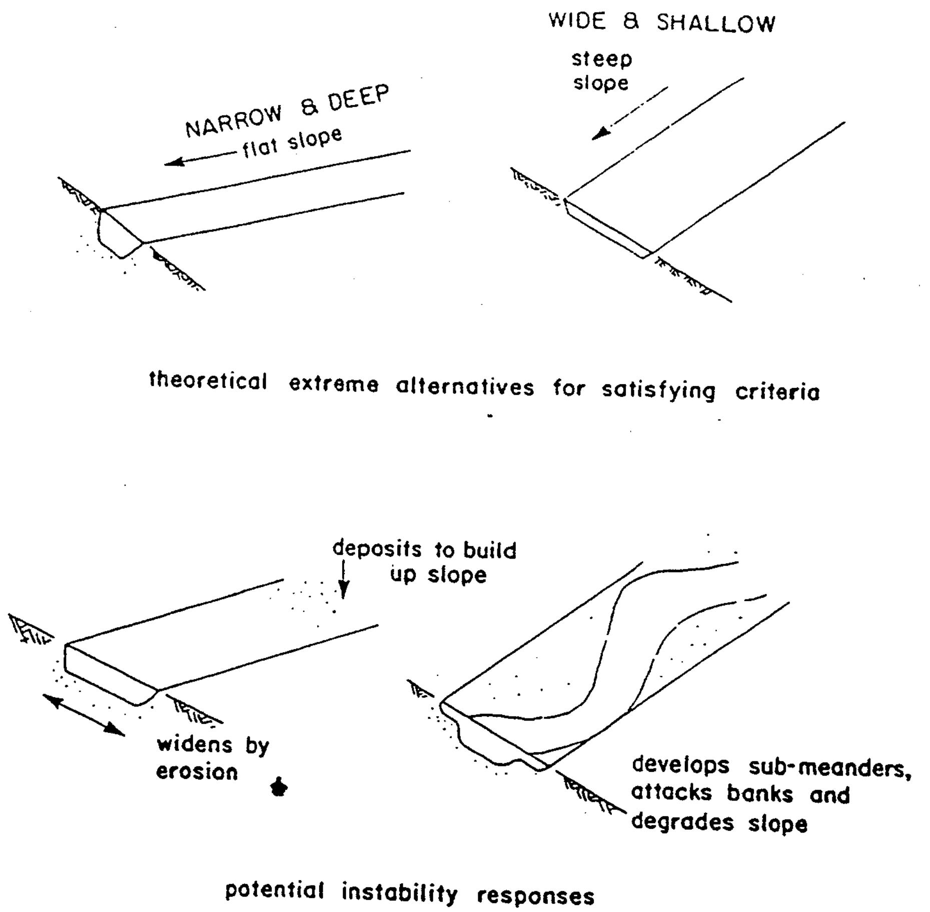


Figure 2.3.2. Insufficiency of allowable velocity or shear stress criterion for stability of alluvial channel.

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:

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

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*.

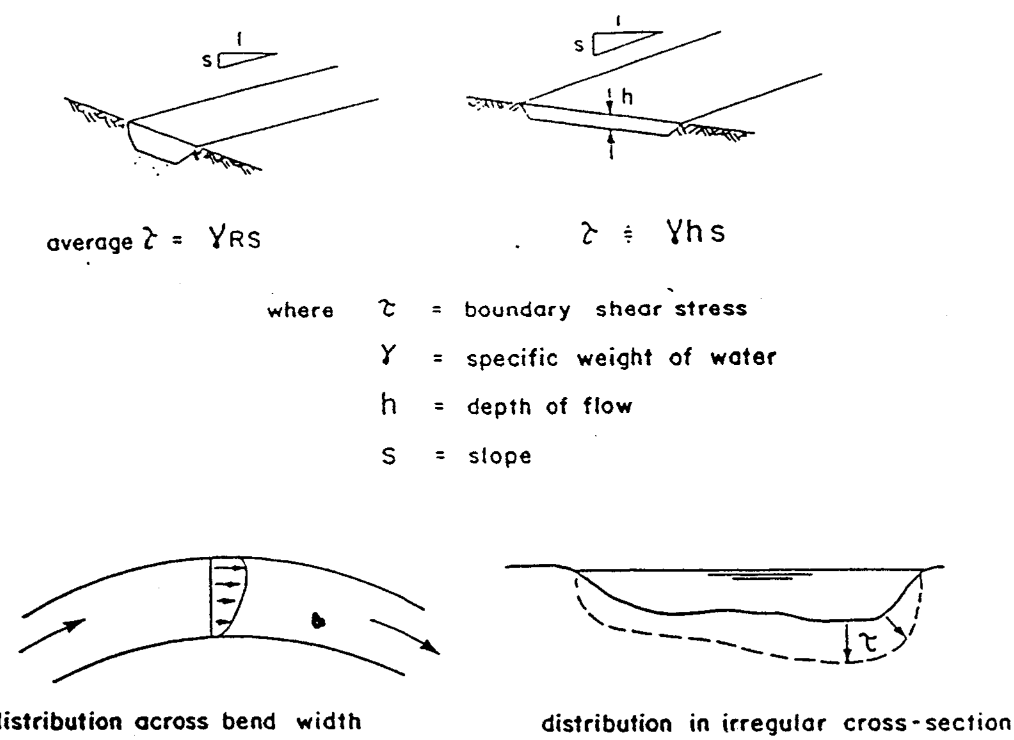


Figure 2.3.3. Boundary shear stress in uniform flow.

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:

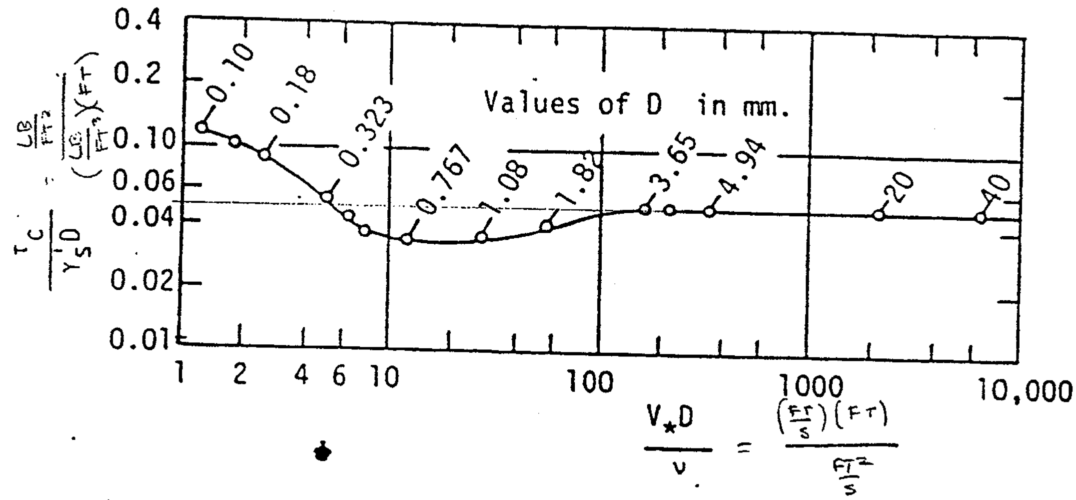
$$\tau = \gamma h S \qquad \text{(Eq. 2.3.3)}$$

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.

ORDINATES ARE DIMENSIONLESS



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).
TR 25?

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).

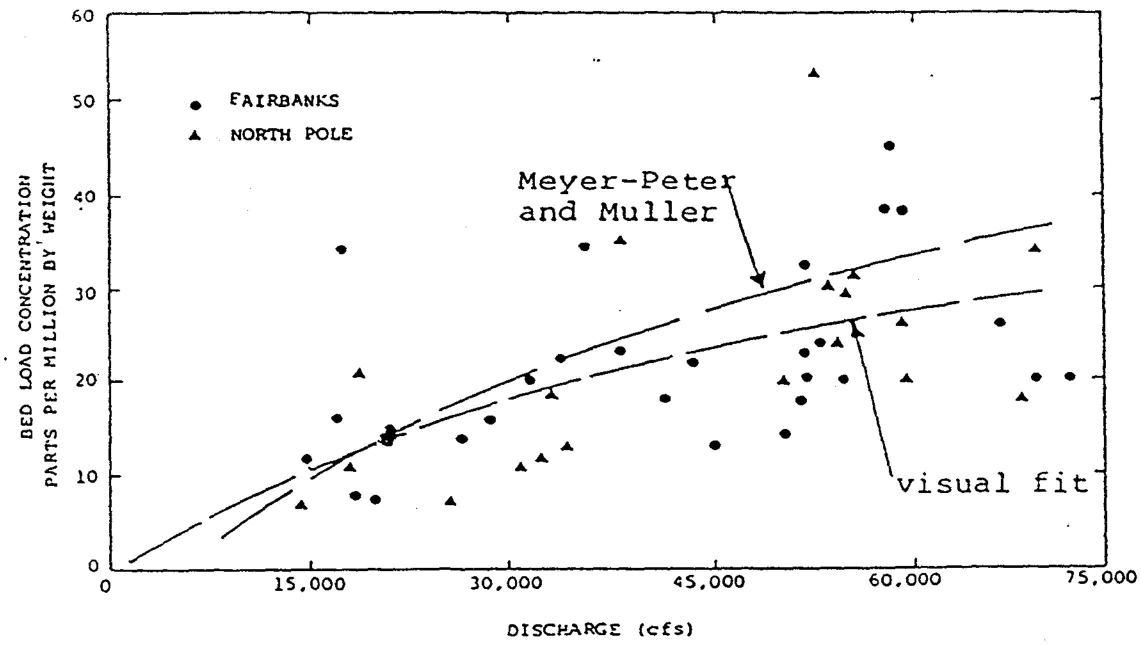


Figure 2.3.6. Comparison of computed and measured bed load (CRREL 1984).

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

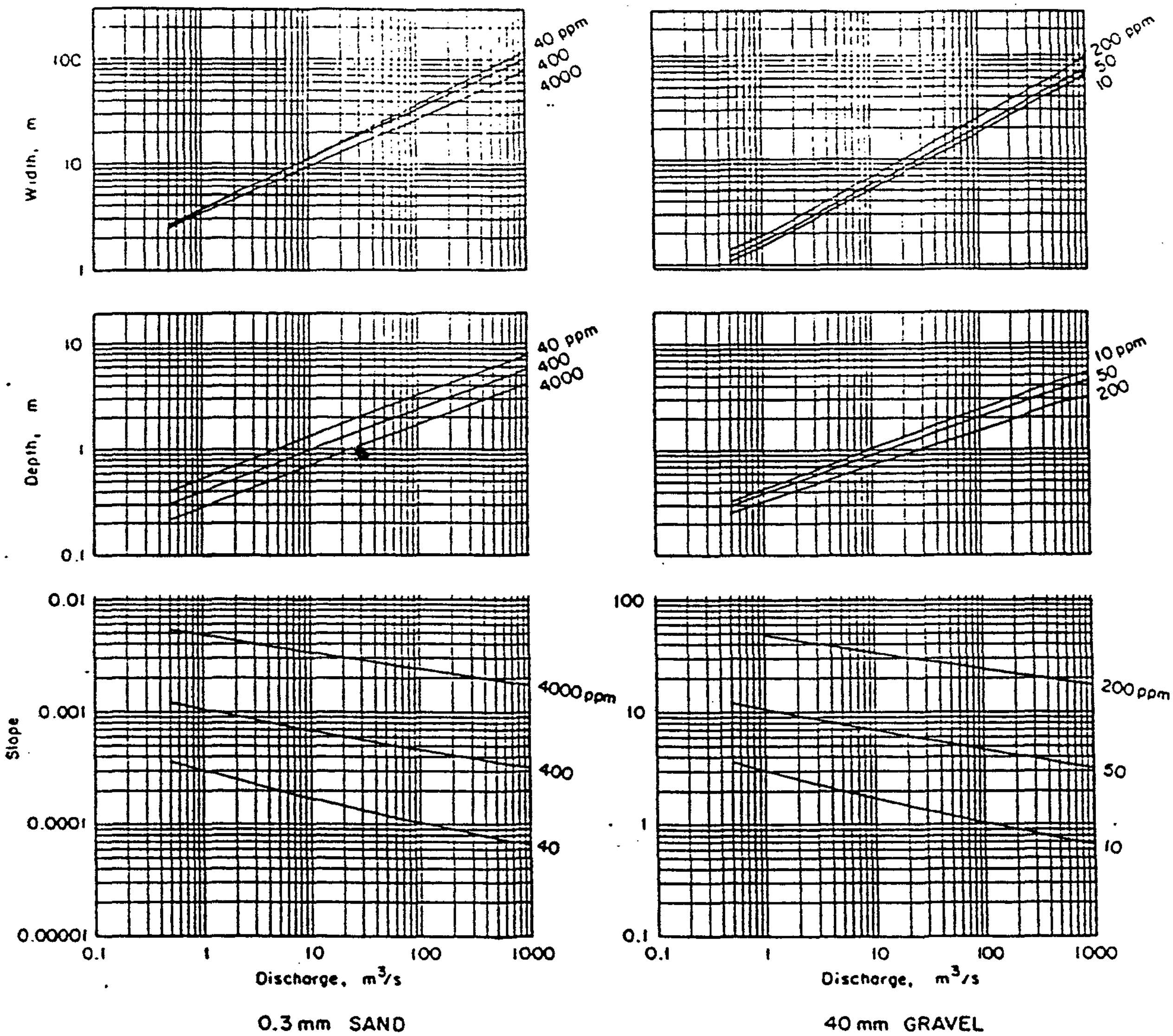


Figure 2.3.7. Effects of bed-sediment concentration on hydraulic geometry of alluvial channels, on basis of tables by White et al (1981).

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

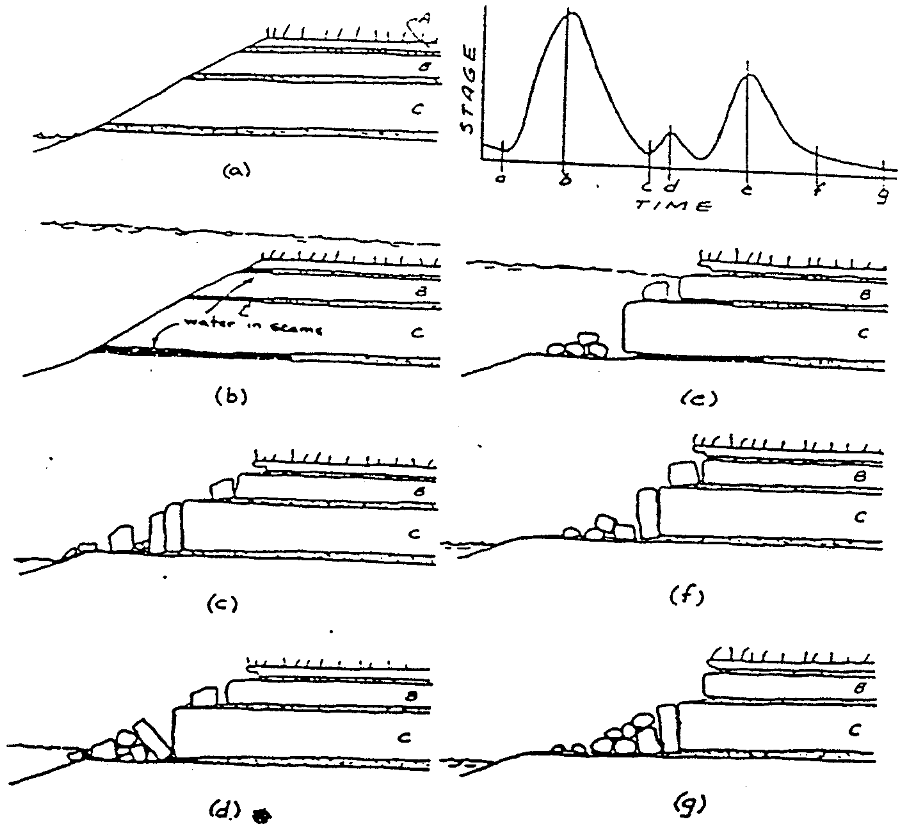
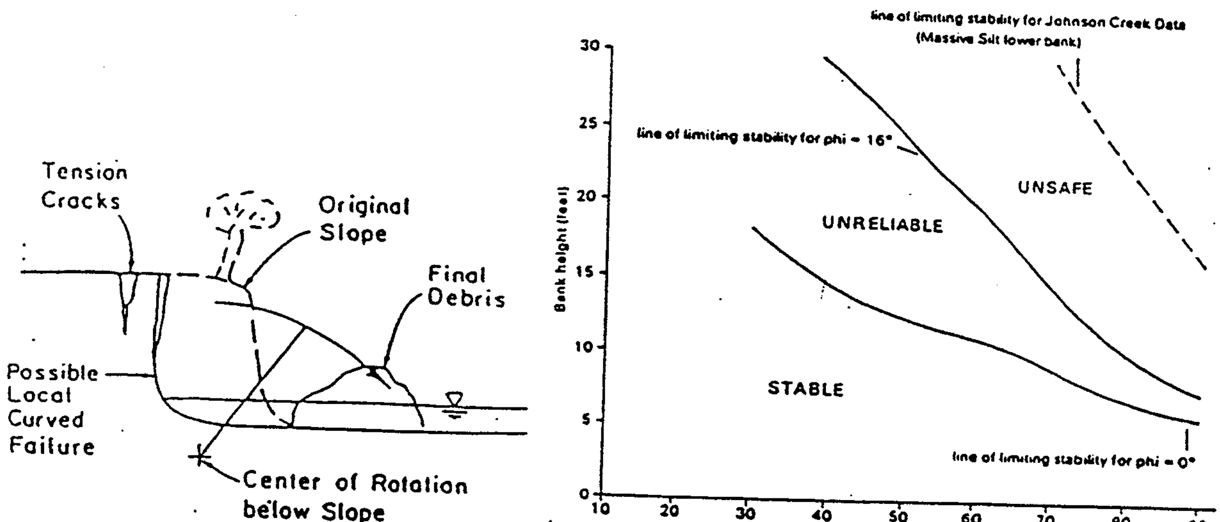


Figure 2.3.8. Mechanism of bank failure by "internal erosion" (Hagerty et al 1986).



(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).

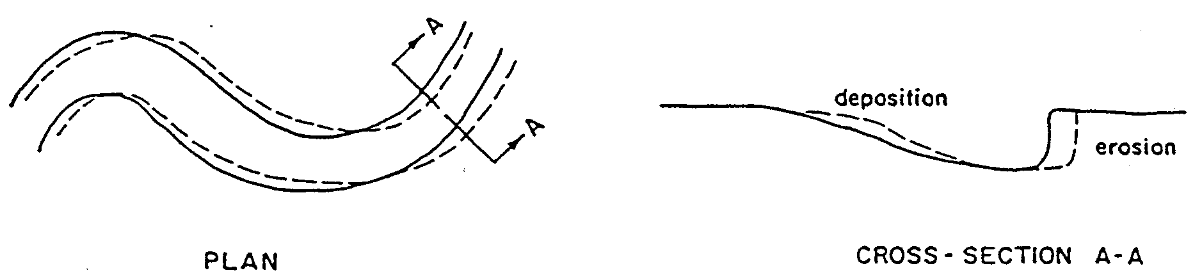


Figure 2.3.10. Natural maintenance of channel width in shifting meanders.

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.

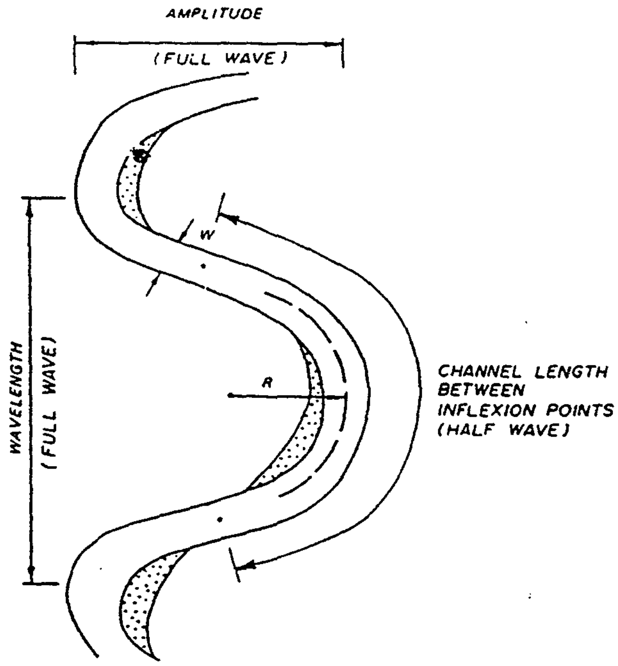


Figure 2.3.11. Meander geometry (after Nunnally & Shields 1985).

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.

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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.

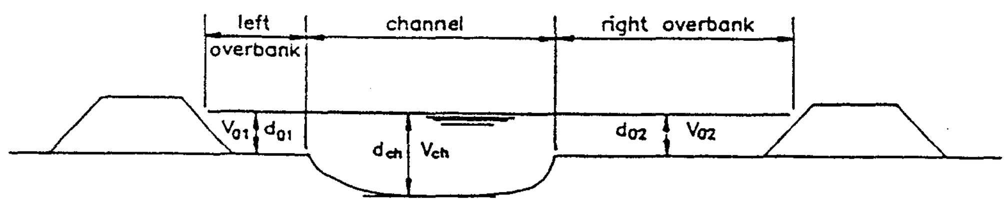
The erosional and depositional stability of mobile-boundary channels is a complex multi-dimensional problem. Analytical knowledge is very incomplete compared with that for non-erodible channels. Previous experience with the behavior and response of similar channels in a similar environment is an invaluable 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.

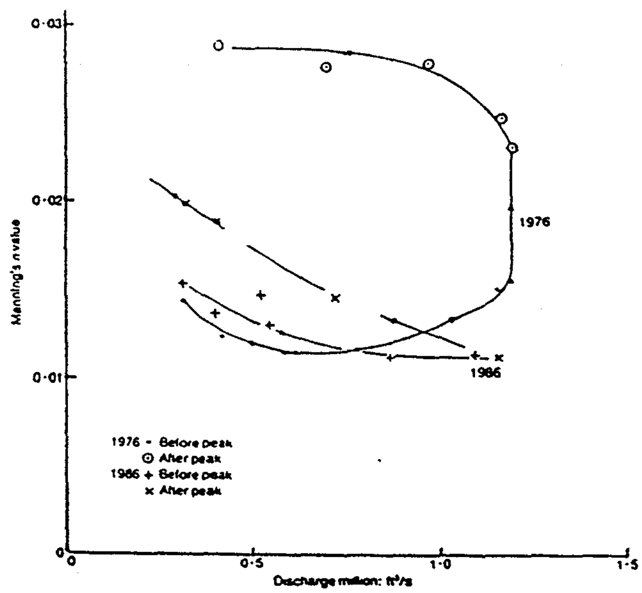


Figure 5.3.2. Roughness changes in a large sand-bed river during floods (from Ackers 1988).

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.

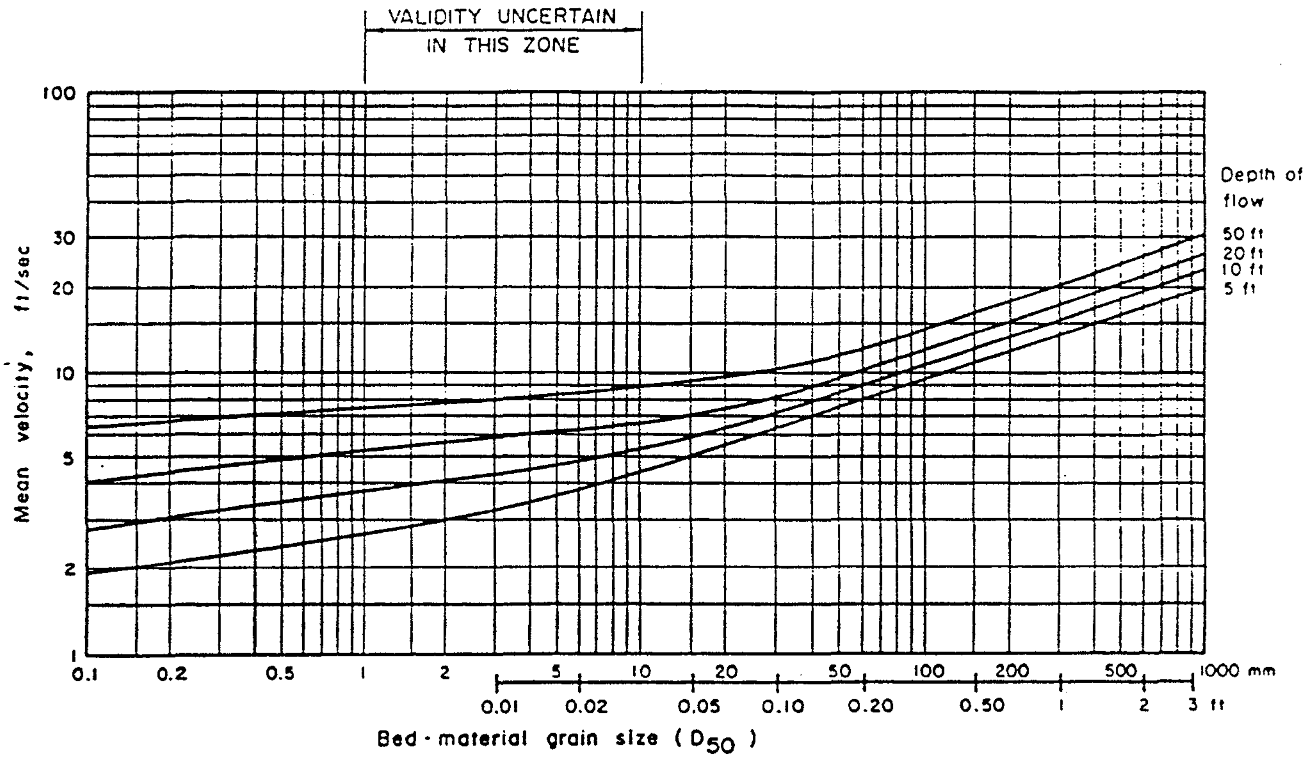


Figure 5.3.3 Approximate threshold velocities for bed movement of granular materials.

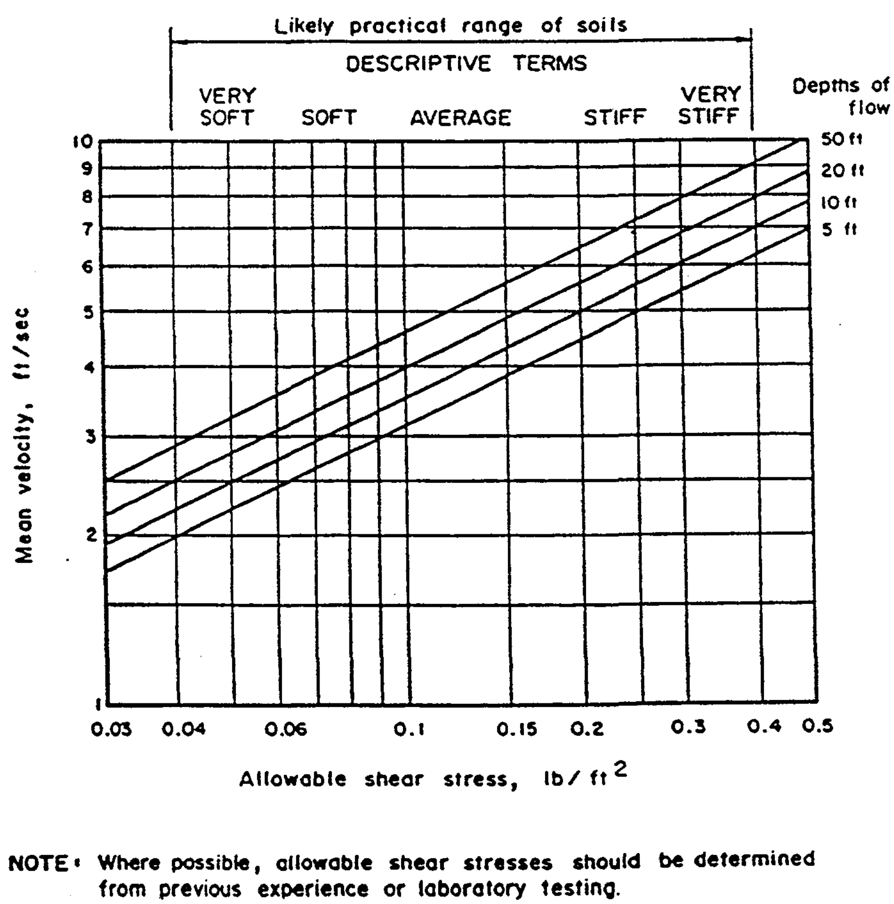


Figure 5.3.4 Approximate threshold shear stresses and velocities for erosion of cohesive materials.

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.

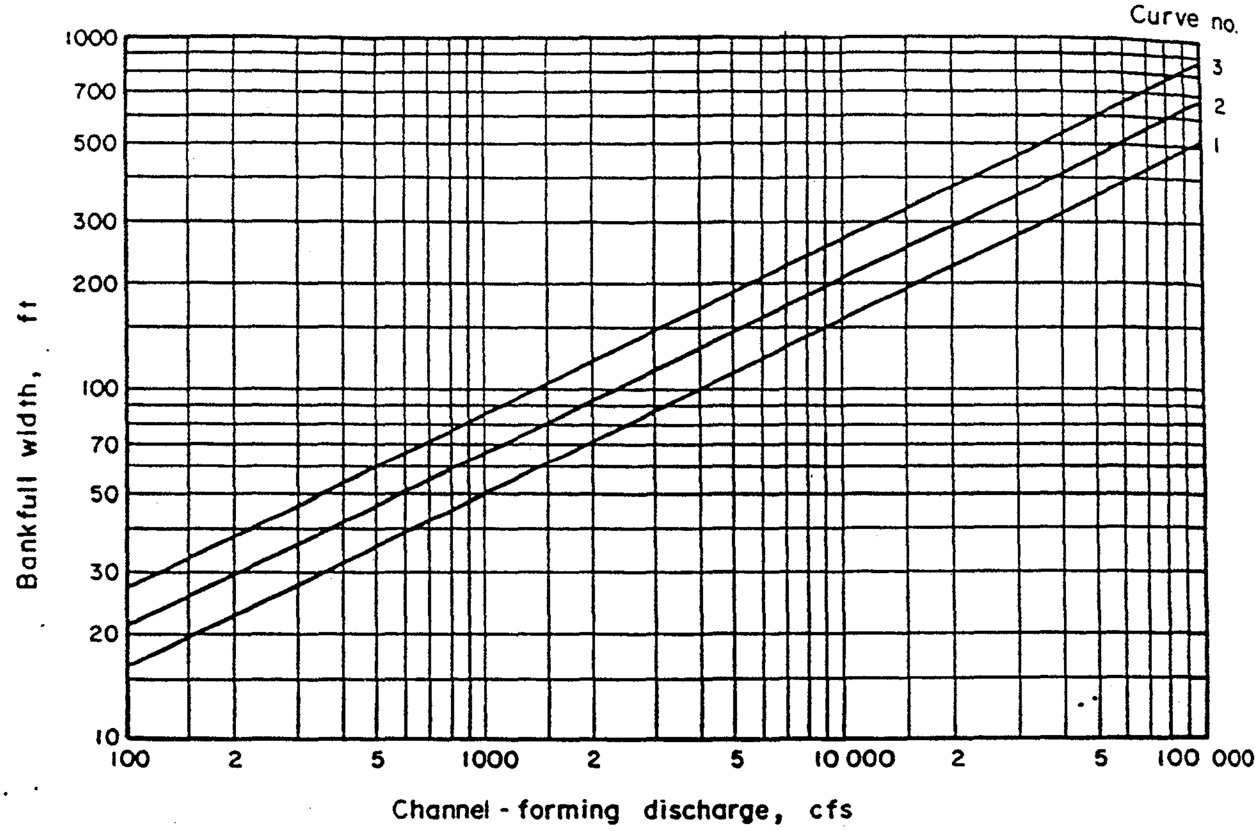
Reach-averaged values of bankfull width, bankfull depth and channel slope should be plotted against estimated bankfull discharge. Where bankfull discharge is not determinable, an alternative estimate of channel-forming discharge can be used (see Section 2.2.5). If locally or regionally developed charts 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.



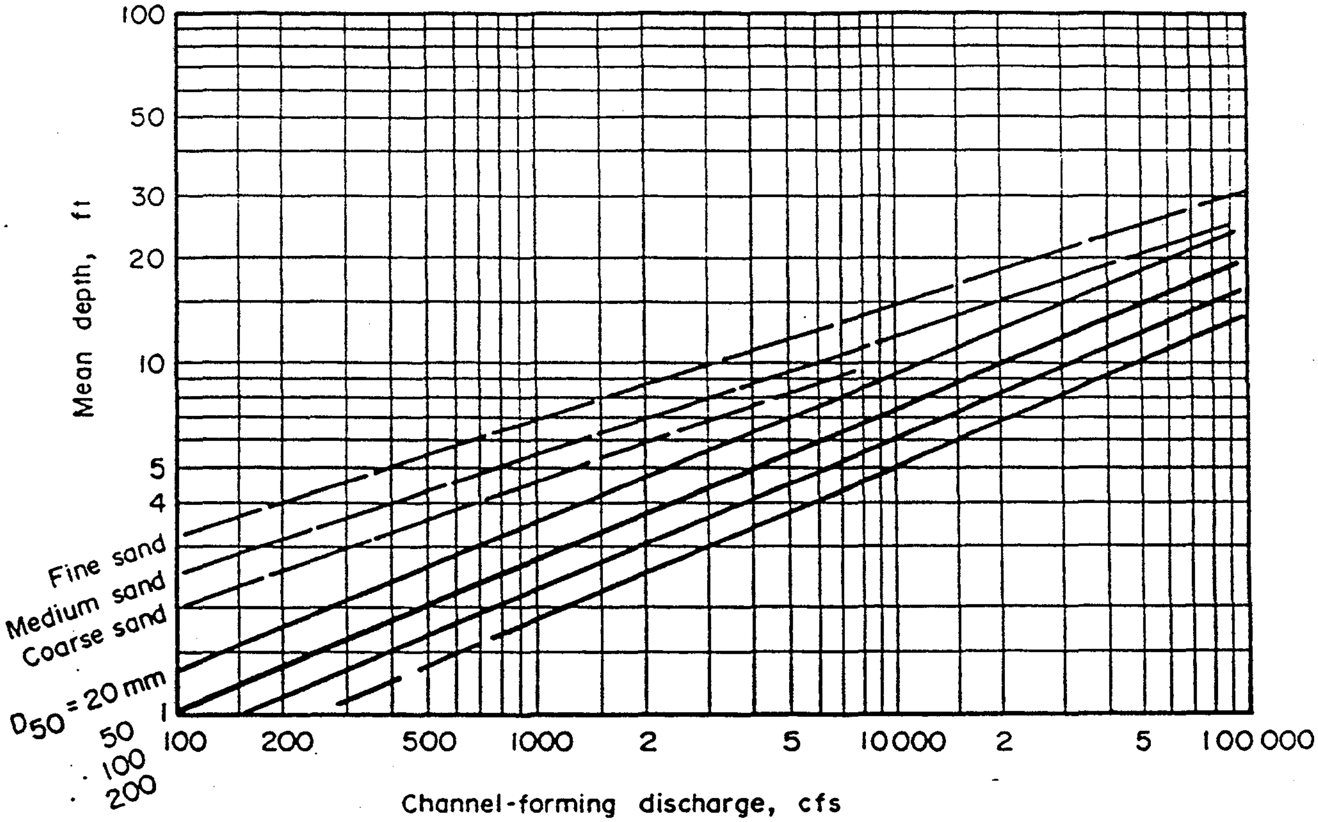
Tentative guidance: Curve 1 : stiff cohesive or very coarse granular banks.
Curve 2 : average cohesive or coarse granular banks.
Curve 3 : sandy alluvial banks.

See section 5.3.3 of text for limitations.

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

ENTER WIDTH, COMPARE Q TO Q_2 · $Q_{BANKFUL}$

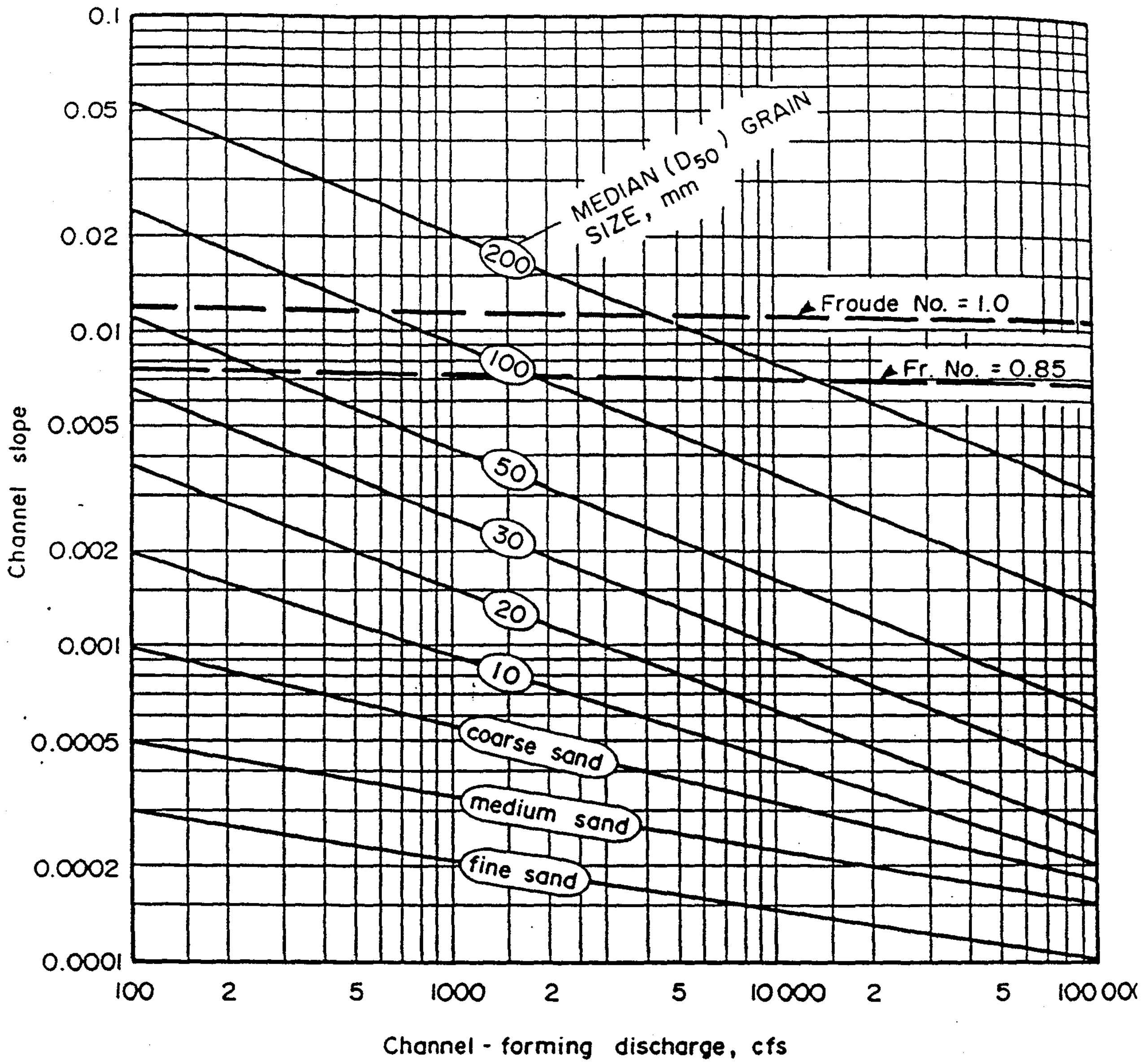
Figure 5.3.5 Hydraulic geometry: bankfull width versus channel-forming discharge.



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.

D50 REFERS TO BED MATERIAL

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.

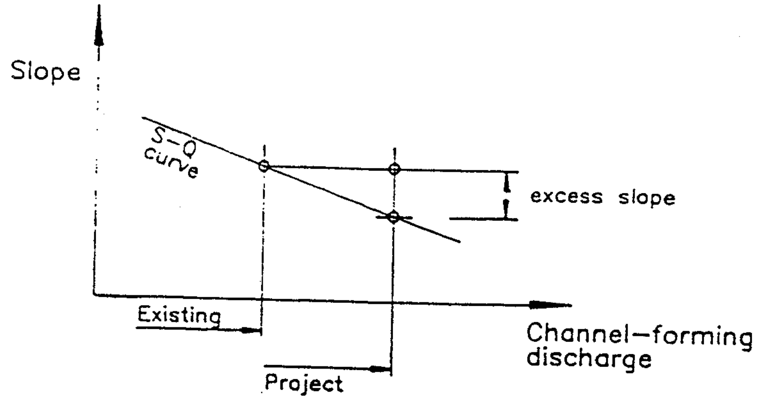


Figure 5.3.8. Excess slope due to increased channel-forming discharge.

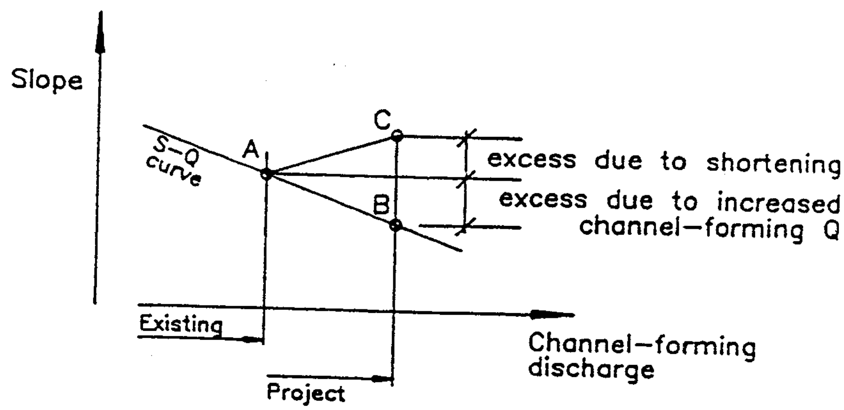


Figure 5.3.9. Excess slope due to shortening plus increased channel-forming discharge.

(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.

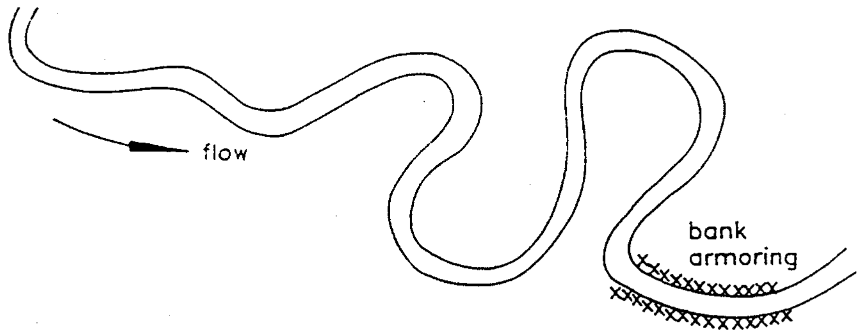


Figure 5.3.10. Distortion of meander pattern upstream of protected length.

5.4 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.

Riverbank Stability Analysis. I: Theory

By Akode M. Osman[1] and Colin R. Thorne,[2] Affiliate Member, ASCE

Abstract: In this paper, a slope stability analysis for steep banks is used in conjunction with a method to calculate lateral erosion distance, to predict bank stability response to lateral erosion or bed degradation. The failure plane angle, failure block width, and volume of failed material per unit channel length may be calculated for the critical case. These parameters define the bank geometry following failure and form the starting point for subsequent analyses. The calculation procedure is illustrated by a worked example. Following mass failure slump, debris accumulates at the bank toe. The debris is removed by lateral erosion prior to further oversteepening or degradation generating further mass failures. Any process-based model for channel width adjustment must account for the combined effects of lateral erosion and mass instability in producing bank instability. The approach adopted here represents a marked improvement over earlier work, which does not account for changes in bank geometry due to lateral erosion prior to mass failure. The engineering applications are presented in a companion paper.

Introduction

Instability of cohesive riverbanks due to bed degradation and lateral erosion is analyzed herein. These are the two processes that most commonly cause bank instability. The process of lateral erosion increases the bed width of the channel and results in steepening of the bank, which reduces its stability. Bed lowering increases the bank height, which also decreases stability. The relative amounts of vertical and lateral erosion are a function of bank material properties, bank geometry, type of bed material, and the flow characteristics.

The stability of the bank with respect to mass failure depends on soil properties and bank geometry. Soil shear strength is proportional to cohesion c' and angle of friction ϕ' (Taylor 1948; Lamb and Whittman 1969). The stability of the banks increases with an increase in c' and ϕ'. An increase in the specific weight γ, bank height H, or the slope angle i, results in decreasing stability of the bank since the driving force that causes bank failure is directly proportional to γ, H, and i. The stability relations developed here on the basis of these parameters can be used to predict the height and the bank geometry at which the banks become unstable due to bed degradation, lateral erosion, or a combination of both these processes.

First, we present a method of using the results of experiments on the erosion of cohesive soils to estimate the rate of lateral erosion of riverbanks and the change in the channel bed width. Second, bank stability relations are derived to predict the critical height, the angle between the

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Piping/Sapping Erosion. II: Identification-Diagnosis

By D. J. Hagerty,[1] Member, ASCE

Abstract: Although erosion of streambanks and other shorelines by emergent seepage is widespread, this erosion mechanism (termed *piping* or *sapping*) has not been recognized as important to the overall erosion process. The mechanism is complex, and interactions with other bank and shore processes tend to mask the effects of piping/sapping. Direct evidence (water emerging from a soil face and carrying away soil particles) is rarely encountered. Several types of indirect evidence are presented and illustrated in this paper, including cavities formed by piping, deposits of dislocated particles below piping zones, blind gullies, staining produced by persistent seepage outflow, and particular types of localized failures (slab toppling, block shearing, and tensile falls caused by undercutting due to piping/sapping). The interactions of this erosion mechanism with other erosion-deposition processes are described. The purpose of this paper is to facilitate identification and evaluation of piping/sapping erosion, particularly for relatively inexperienced field investigators.

Introduction

Although bank and shoreline erosion by piping and sapping is widespread, little recognition has been given to this mechanism. Seepage outflow can remove soil particles in the exfiltration zone, causing the formation of tubular "pipes" or lenticular cavities, which, in turn, can remove support from overlying soil layers (Hagerty 1991). Piping/sapping has been identified in many localities throughout the world and in many geologic/hydrologic settings, but the mechanism is complex and may not be recognized. Interactions between piping/sapping and other bank and shore processes tend to mask piping cavities and/or to remove features characteristic of piping/sapping activity. For these reasons, it is important to present categories of evidence that indicate that piping/sapping is or was active on a site. The purpose of this review is to assist investigators, particularly those with little experience of erosion mechanics and processes, to diagnose piping/sapping on the basis of visual observations.

Direct Evidence of Piping/Sapping

It is possible to obtain first-hand proof that piping/sapping is operating on a site; outflow of water and soil grains from an exfiltration face can be observed directly. Holes are the end product of such flow. "Dirty water" is the fundamental indicator of piping action (Casagrande 1936). The soil and water shown in Fig. 1 were in motion at the time the photograph was taken. However, such direct evidence is unlikely to be obtained.

In some cases, the outflow of soil and water occurs below stream or lake

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Note. Discussion open until January 1, 1992. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 6, 1990. This paper is part of the *Journal of Hydraulic Engineering*, Vol. 117, No. 8, August, 1991. ©ASCE, ISSN 0733-9429/91/0008-1009/$1.00 + $.15 per page. Paper No. 26067.

ν = kinematic viscosity of water;
ρ = density of water;
ρ_a = density of air; and
τ_0 = wall shear stress.

Criterion Delineating the Mode of Headcut Migration

By O. R. Stein,[1] Associate Member, ASCE, and P. Y. Julien,[2] Member, ASCE

Abstract: Two modes of headcut migration are generally recognized: (1) Rotating headcuts that tend to flatten as they migrate; and (2) stepped headcuts that tend to retain nearly vertical faces. A mathematical description of the sediment detachment potential immediately upstream and downstream of the headcut is used to delineate these modes of migration. The delineating parameter is the ratio of the time required to erode the headcut face from above to the time required to undermine the headcut face from below. This erosional time-scale ratio is a dimensionless function of flow, sediment, and geometry parameters. For the limiting case of homogeneous cohesive soils, the time-scale ratio is a simple function of a Froude number and the aspect ratio of drop height to normal flow depth. This relationship is calibrated using original laboratory experiments of headcut migration in initially vertical headcuts and verified by independent field experiments of headcuts propagating in four different homogeneous cohesive soils.

Introduction

A headcut is a natural, nearly vertical drop in channel bed elevation. The dissipation of flow kinetic energy at the drop causes excessive erosion and results in headcut upstream migration, which deepens and tends to widen the channel. Headcuts migrating in gullies may undermine upstream structures and, on a smaller scale, often define the breakpoint between overland and channel flow, and therefore play an important role in drainage network evolution. Headcuts propagating in small channels called rills contribute significantly to total upland soil losses due to erosive storms (Nearing et al. 1989). Several investigations (Blong 1970; 1985; Egboka and Okpoko 1984; Piest et al. 1975; Patton and Schumm 1975; Daniels and Jordan 1966; Kohl 1988) have focused on headcut migration in the field. Most data were collected after erosive storms and indicated that a nearly vertical face is maintained; however, information on the flow characteristics representing headcut migration was not reported. Therefore, understanding of the physical processes governing the formation, propagation, and degradation of headcuts as they migrate is very limited.

Several laboratory flume studies have observed headcut migration in specific bed materials. A knickpoint, which is a headcut in noncohesive sand, becomes indistinguishable from the rest of the channel as it propagates upstream, as shown by Brush and Wolman (1960). The data of Leopold et al. (1964) reveal the same result for cohesive soil, provided that the ratio of initial headcut drop height to flow depth in subcritical flow is less than one. Using stratified cohesive and noncohesive bed material, Holland and Pickup (1976) defined two headcut migration modes: (1) Rotating headcuts

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Note. Discussion open until June 1, 1993. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on August 20, 1992. This paper is part of the *Journal of Hydraulic Engineering*, Vol. 119, No. 1, January, 1993. ©ASCE, ISSN 0733-9429/93/0001-0037/$1.00 + $.15 per page. Paper No. 1888.

Engineering Approach

Weaknesses:

- Over-simplification
  (Not Real)

- Lack of Calibration
  (Digital WAG)

- Range of Sediment Sizes
  (Boulders, clays)

- Bank Erosion
  (Generally doesn't work)

- Accuracy
  (50% is good?)

Regulatory Approach

Types

- **Erosion Hazard Setbacks**
- **FEMA Maps will Add Erosion**

Regulatory Approach

- Advantages
  - Good Start
  - Simple

- Disadvantages
  - Non-Scientific
  - Arbitrary
  - Defensible?

FLOODPLAIN AND EROSION HAZARD MANAGEMENT ORDINANCE NO. 1988-FC2

FOR PIMA COUNTY, ARIZONA

PASSED AND ADOPTED BY THE BOARD OF SUPERVISORS

SITTING AS THE BOARD OF DIRECTORS OF THE

PIMA COUNTY FLOOD CONTROL DISTRICT

DECEMBER 6, 1988

DEPARTMENT OF TRANSPORTATION AND FLOOD CONTROL DISTRICT

1313 S. MISSION ROAD

TUCSON, ARIZONA 85713

WILLIAM T. HOWELLS

DIRECTOR AND COUNTY ENGINEER

purpose of the fee is to provide a method for off-site improvements necessary to mitigate the effect of urbanization and to provide a systematic approach for the construction of public flood control improvements. If such a system is adopted it shall demonstrate that the fee will in some manner benefit the property from which the fee is collected and be applied equitably to all property in proportion to floodwaters generated by urban use of the property. The fees will also be restricted to providing flood control improvements necessary for the allowed use of the properties from which the fee is collected, and the fees shall be reasonably related to the actual cost of providing flood control improvements beneficial to the site or surrounding area. The fees will be reviewed by the Flood Control District Advisory Committee prior to action by the Board of Directors of the Pima County Flood Control District.

ARTICLE XII

EROSION HAZARD AREAS AND BUILDING SETBACK REQUIREMENTS

In erosion hazard areas where watercourses are subject to flow related erosion hazards, building setbacks are required as follows:

A. Major Watercourses

For major watercourses, with base flood peak discharges of 2,000 cfs or greater, the following building setbacks shall be required where approved bank protection is not provided:

1. Along the following major natural watercourses where no unusual conditions exist, a minimum building setback, as indicated below, shall be provided at the time of the development unless an engineering analysis which establishes safe limits is performed by an Arizona Registered Professional Civil Engineer and is approved by the County Engineer. Unusual conditions include, but are not limited to, historical meandering of the watercourse, large excavation pits, poorly defined or poorly consolidated banks, natural channel armoring, proximity to stabilized structures such as bridges or rock outcrops, and changes in the direction, amount and velocity of the flow of waters within the watercourse.

8435 2407

a. The building setback shall be five-hundred feet along the Santa Cruz River, Rillito Creek, Pantano Wash, Tanque Verde Creek and the Canada del Oro Wash downstream of the confluence with Sutherland Wash.

b. The building setback shall be two-hundred and fifty feet along major watercourses with base flood peak discharges greater than 10,000 cfs.

c. The building setback shall be one-hundred feet along all other major watercourses with base flood peak discharges of 10,000 cfs or less, but more than 2,000 cfs.

2. Along major watercourses where unusual conditions do exist, building setbacks shall be established on a case-by-case basis by the County Engineer, unless an engineering study which establishes safe limits is performed by an Arizona Registered Professional Civil Engineer and is approved by the County Engineer. When determining building setback requirements the County Engineer shall consider danger to life and property due to existing flood heights or velocities and historical channel meandering. Unusual conditions include, but are not limited to, historical meandering of the watercourse, large excavation pits, poorly defined or poorly consolidated banks, natural channel armoring, proximity to stabilized structures such as bridges or rock outcrops, and changes in the direction, amount, and velocity of the flow of waters within the watercourse.

B. Minor Washes

For minor washes with a base flood peak discharge of 2,000 cfs or less, the following building setbacks shall be required where approved bank protection is not provided.

1. Along minor watercourses where no unusual conditions exist, a minimum setback of fifty feet shall be provided at the time of development unless an engineering analysis which establishes safe limits is performed by an Arizona Registered Professional Civil Engineer and is approved by the County Engineer. Unusual conditions include, but are not limited to, historical

meandering of the watercourse, large excavation pits, poorly defined or poorly consolidated banks, natural channel armoring, proximity to stabilized structures such as bridges or rock outcrops, and changes in the direction, amount, and velocity of flow of the waters in the watercourse.

2. Along minor washes where unusual conditions do exist, building setbacks shall be established on a case-by-case basis by the County Engineer, unless an engineering study which establishes safe limits is performed by an Arizona Registered Professional Civil Engineer and is approved by the County Engineer. When determining building setback requirements, the County Engineer shall consider danger to life and property due to existing flood heights or velocities and historical channel meandering.

ARTICLE XIII

ACCESS REQUIREMENTS

A. Purpose

It is recognized that private vehicular access may become impassable to ordinary and emergency vehicles during times of flooding. It is the intent of this Article to allocate the responsibility for private vehicular access which crosses a regulatory floodplain.

B. Application of Article

This Article shall apply in all situations where private vehicular access crosses any regulatory floodplain located between the point where the private access leaves a paved, publicly maintained roadway and the end of the private access.

C. Requirements for Private Vehicular Access

In all situations where private vehicular access crosses a regulatory floodplain located between the point where the private access leaves a paved, publicly

00000046

STANDARDS MANUAL FOR DRAINAGE DESIGN AND FLOODPLAIN MANAGEMENT IN TUCSON, ARIZONA

PREPARED FOR
CITY OF TUCSON
DEPARTMENT OF TRANSPORTATION,
ENGINEERING DIVISION

PREPARED BY
SIMONS, LI & ASSOCIATES, INC.

DECEMBER, 1989

$$SB \geq 2\ (Q_{p100})^{0.5}, \text{ for } r_c/T_w \geq 10\ ; \qquad (7.7a)$$

or, $$SB \geq 3.4\ (Q_{p100})^{0.5}, \text{ for } 5 < r_c/T_w < 10\ ; \qquad (7.7b)$$

or, $$SB \geq 5\ (Q_{p100})^{0.5}, \text{ for } r_c/T_w \leq 5\ . \qquad (7.7c)$$

Where:

SB = Minimum setback, in feet, measured from the top edge of the highest channel bank or from the edge of the the 100-year water-surface elevation, whichever is closer to the channel centerline;

Q_{p100} = Peak discharge of 100-year flood, in cubic feet per second;

r_c = Radius of curvature of channel centerline, in feet; and,

T_w = Top width of channel, in feet.

The determination of the ratio of the centerline radius of curvature of a channel to channel top width (i.e., r_c/T_w) can be determined by use of the procedure described in Chapter VIII of this Manual.

For all other watercourses (i.e., watercourses which have drainage areas less than 30 square miles in size, or times of concentration less than three hours during a 100-year flood) use:

$$SB \geq 1.0\ (Q_{p100})^{0.5}, \text{ for } r_c/T_w \geq 10\ ; \qquad (7.8a)$$

or, $$SB \geq 1.7\ (Q_{p100})^{0.5}, \text{ for } 5 < r_c/T_w < 10\ ; \qquad (7.8b)$$

or, $$SB \geq 2.5\ (Q_{p100})^{0.5}, \text{ for } r_c/T_w \leq 5\ . \qquad (7.8c)$$

Where all terms are as previously defined.

Lesser setbacks than those determined from Equations 7.7 and 7.8 *may* be allowed, but only if they can be justified by use of one of the following methods, listed in order of preference, which would indicate that a lesser setback is appropriate:

1. A detailed sediment-transport analysis, prepared by an Arizona Registered Professional Civil Engineer; or,

2. The Allowable-Velocity Approach, Tractive-Stress Approach, or Tractive-Power Approach, any or all of which must indicate that the channel banks are *not* erosive for the flow conditions associated with runoff events up to and including a 100-year flood on the affected watercourse.

Extremist Approach: STAY OUT

- Advantages
  - Simple
  - Effective

- Disadvantages
  - Property Rights
  - Expensive
  - Continuity
  - Watershed Impacts

Geomorphic Approach

Basic Characteristics:

- Process Oriented
- Understand Natural System
- Field Data
- Broad Results
- Reality Check

The University of Connecticut

INSTITUTE OF WATER RESOURCES

APPLIED FLUVIAL GEOMORPHOLOGY

by

James Grant MacBroom

REPORT NO. 31

March 1981

This publication was supported in part by funds provided by the Office of Water Research and Technology, U. S. Department of the Interior, Washington, D.C., as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

Channel Changes of the Gila River in Safford Valley, Arizona 1846-1970

By D. E. BURKHAM

GILA RIVER PHREATOPHYTE PROJECT

GEOLOGICAL SURVEY PROFESSIONAL PAPER 655-G

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1972

Geomorphic Approach

Types:

- **Historical Review**
- **Field Assessment**
- **Classification Schemes**
- **Geo-Equations (Engimorphology?)**

Historical Review

Summary: Past conditions reveal existing trends

Sources of Data:

- Aerial Photographs (1930's)
- Topographic Maps (1878)
- Historical Surveys (1860's)
- Historical Societies
- Public Archives
- As-Built Plans

Multiobjective Approaches to Floodplain Management

Proceedings of the Sixteenth Annual Conference of the Association of State Floodplain Managers

May 18-22, 1992
Grand Rapids, Michigan

Use of Historical Data and Engineering Methods for Channel Design

Jonathan E. Fuller
CH2M HILL

Introduction

Channel design is becoming more complex. The design professional of the 1990s is not only a hydrologist and hydraulic engineer, but is also a sedimentation expert, geomorphologist, environmentalist, real estate appraiser, planner, and lawyer. Technology, for the most part, has kept pace with the needs of the designer. Occasionally, unique channel characteristics or unusual design requirements go beyond the capabilities of state-of-the-art engineering methods, or the cost of applying these technologies exceeds available financial resources.

Using historical data in place of, or in addition to, traditional engineering analyses may provide a simple, accurate, cost-effective means to assess the feasibility of proposed designs, evaluate alternatives, and provide a context for selecting appropriate engineering methodologies. Historical data was used as a key element in a Sedimentation Engineering Investigation (SDI) and preliminary design of a Corps of Engineers channel design project on Coyote Creek near San Jose, California.

Limitations of Engineering Methods

Traditional engineering analyses are appropriate for most channel design projects. However, engineering methods have several limitations. First, many empirically derived techniques have a limited range of applicability. This is particularly true for sediment transport equations where appropriate equations may not be available for some stream conditions. Second, because most engineering methods use simplifying assumptions or coefficients, they rely on engineering judgement, which results in a wide range of possible "correct" answers. Practitioners who use detailed engineering methods to get more precise results often fail to recognize the scatter in data used to derive these methods. Third, the expense of using complex technology may realize only marginal gains of design information. Fourth, the complexity of many "real world" applications exceed the capabilities and the theoretical bases of engineering models. Finally (and ironically), many engineering models recommend calibration using historical data prior to application. The users manuals for these models tacitly assume that if verified historical data contradicts the results of mathematical modeling, the designer should trust the historical data. This tacit assumption should make designers question if traditional engineering methods are always needed when historical data are available.

Types of Historical Data

For channel design several types of historical data are useful. First, historical maps that show channel planform may be used to indicate rates of meander movement, locations of past diversions and tributary confluences, and occurrences of channel realignment. Channel planform data may also be obtained from original Bureau of Land Management (BLM) section line surveys, assessors maps, sketches in journals of early explorers, as well as from more standard map references. Photographs can also be used to monitor changes in planform, and to locate areas of bank erosion. Most areas in the U.S. have historic aerial coverage dating to the 1930s. Older ground photographs usually can be found at local historical societies.

Second, topographic data can be used to determine historical channel bed elevation changes. Continuous channel topography may be difficult to locate, although floodplain studies, Corps of Engineers surveys, or drainage reports for private development are common sources of these data. Topographic point data may be obtained from as-built plans for road and utility crossings, outdated U.S. Geological Survey (USGS) topographic quadrangles (which may date back to the 1800s), or original BLM section line surveys. Topographic data is usually available from public works records departments, local university map collections, and historical societies.

Third, zoning and development data for the watershed, when correlated with the data described above, can help determine historical channel responses. These data may also be used in conjunction with geomorphologic relationships to determine future changes likely to occur on the watercourse.

Finally, accounts of historical flooding reveal a channel's normal response to flooding; proposed channel design must account for these historical flood processes. A quick survey of local newspapers on dates of regional storms usually uncovers some flood data. Excellent information can also be obtained from road, channel, or river park maintenance supervisors who have cleaned up after floods, or who may keep records of maintenance activities. If the expertise is available, extension of the historical flood record through interpretation of the fluvial geomorphic record is extremely useful.

Using Historical Data

Correct interpretation is the key to successful use of historical data in channel design. Channel processes that occurred in the past are likely to occur in the future. For instance, if floods deposited sediment on roads and in flooded homes, the proposed channel design should account for the sediment load. Alternatively, if flood damage reports record episodes of bank collapse and bridge failure, grade control and bank protection may be important components of design. In general, past channel behavior may be expected to continue.

Past channel behavior, however, should be interpreted in light of information regarding regional impacts or changes within the watershed. For instance, if the historical record reveals that an episode of channel entrenchment has occurred, it may be related to a specific event such as in-stream mining. If mining is no longer occurring, extrapolation of entrenchment rates is not appropriate. If recent development has changed a watershed's flood characteristics, historical data from that watershed is less useful than data from nearby developed watersheds with similar channelization projects.

Case History: Coyote Creek

Coyote Creek is a 350 square mile watershed that drains the mountain slopes and urbanized valley of Santa Clara County, California, and flows into San Francisco Bay (Figure 1). Coyote Creek is a complex stream, with steep perennial mountain reaches impounded by two major reservoirs, meandering perennial valley reaches, ephemeral gravel and sand bed reaches, sinuous reaches with natural and constructed levees with flow from groundwater seepage and irrigation return flows, and meandering tidally influenced deltaic channel reaches near its mouth. The creek also has a complex history of diversions, channelization, and other flood control improvements.

An SDI was required as part of preliminary channel design for a reach extending 7.6 miles upstream from San Francisco Bay. The proposed design

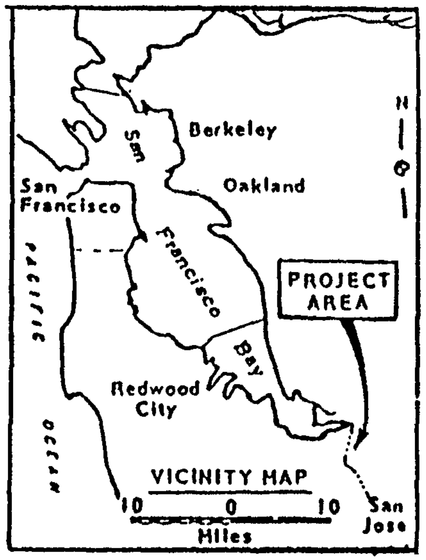


Figure 1
Coyote Creek Project Area

retained the natural flood levees that have the capacity for an approximated 5-year flood, and added an overflow channel for containing a 100-year flood. The overflow channel is hydraulically isolated from the main channel, except where it crosses the main channel at seven locations within the project limits. In pre-design conditions, overbank flooding does not return to Coyote Creek. Complex channel hydraulics and geomorphology limited the potential accuracy of traditional sediment engineering analyses. First, flow is not continuous with respect to the main channel. Second, bankfull capacity decreased in the downstream direction. Therefore, sediment continuity equations predicted deposition, although historical evidence indicated no history of deposition. Third, the backwater model provided probably did not adequately model crossover hydraulics. Fourth, the study reach was undergoing rapid bed degradation in response to development of the watershed. Fifth, sediment supply may have been only partially related to upstream velocities.

In contrast to the mathematical modeling, historical data provided a clear picture of the probable channel response to the proposed design. Topographic data dating to 1899 was used to estimate bed degradation rates at key points within the reach, and to calibrate sediment yield estimates. Channel maps were used to confirm the stream's very high lateral stability and low potential for bank erosion. Anecdotal accounts of numerous flood episodes supported the conclusion that sediment transport was extremely limited. Watershed development rates were used to assess likely future impacts on sedimentation. Adjacent channel reaches were examined to determine their response to channelization. Historical data indicated that sedimentation would not significantly impact the proposed design.

Conclusion

Historical data provide an alternative to more traditional engineering methodologies. As engineering methods become more complex and expensive, use of historical data has become more attractive. Historical data may be used to narrow design options, determine project feasibility, and evaluate potential impacts of proposed designs when more detailed methods are not required.

Historical Review

Advantages:

- Simple
- Cost Effective
- Realistic
- Actual Events

Disadvantages:

- Time Gaps
- System Changes

Field Assessment

Summary:

Identify River Characteristics
Review Field Check List

Advantages:

- Necessary
- Reality Check

Disadvantages:

- Expense
- Access
- Specialized Training
- Opportunistic

APPENDIX E

FIELD RECONNAISSANCE PROCEDURE FOR SEDIMENT STUDIES

2

E-1. Preparation for Field Reconnaissance. Prior to the actual field trip an investigation of data readily available in the office should be conducted. Knowledge of various historical, hydraulic and sediment parameters will make the field investigation easier and more efficient Figure E-1 shows a suggested sequence of preparation for field reconnaissance.

E-2. Field Reconnaissance. The following is a suggested check list of tasks and observations to be made during the field reconnaissance.

a. Checklist.

(1) Verify topographic maps.

(2) Note boundary conditions.

(3) Note bed and bank material slope.

(4) Note slope of stream in general and any break points.

(5) Obtain representative samples of the bed material.

(6) Note condition of banks, whether stable or caving, and the type of material found in the stream bed and banks, particularly any lenses.

(7) Record the conditions by locations.

(8) Record drift accumulations, debris.

(9) Estimate the percent of the bed that is naturally armored.

(10) Note problem areas and attempt to ascertain the cause.

(11) Note changes in bed gradation and take representative samples for the sediment study.

b. Observations.

(1) Note channel mining activities.

(2) Note tributary entry points, the amount of flow, turbidity of flow, condition of the tributary.

(3) Note diversion points.

(4) Note natural grade controls such as rock outcrops.

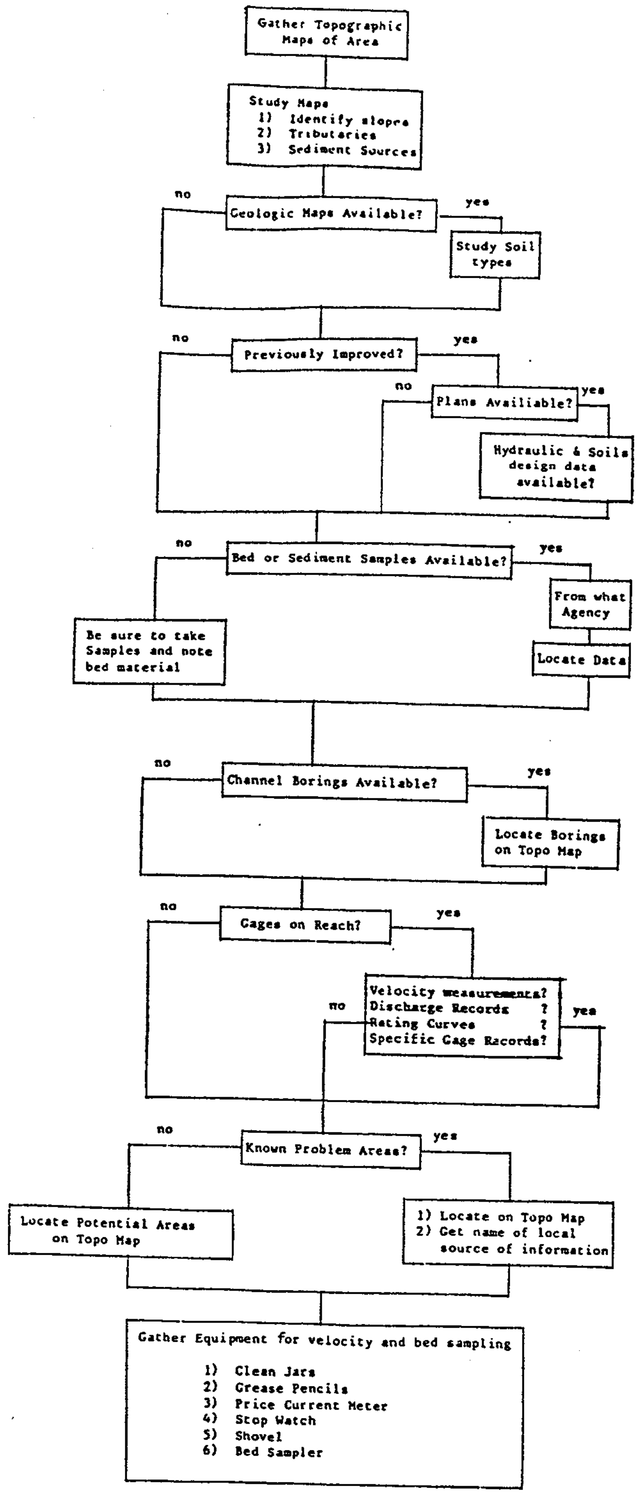


Figure E-1. Preparation for Field Reconnaissance

(5) Note presence of protection measures, their size, why they were placed.

(6) Note gage locations, type of gage.

(7) Note structural feature locations and observe bank and bed conditions in the vicinity of the structures.

(8) Note existing similar projects on same or adjacent streams - how they are performing.

(9) Note overbank conditions - areas of scour or deposition - If deposition exists - obtain samples and measure depth & note extent on map.

(10) Take velocity measurements at several locations using surface floats, pacing and a stop watch.

(11) Talk with locals to identify problem areas, get an estimate of time of problem. Also, inquire as to local land use history - when urbanized, cleared, etc.

E-3. Post Reconnaissance Activities.

a. Once the field reconnaissance is completed the engineer should have a good idea of the existing problems, the likely impacts of the proposed improvements, and which parameters may be the most sensitive to change. The engineer should also be able to outline a plan of study. The complexity of the study and quality of the results will likely depend on the availability of historic and contemporary data. Based on the data available in the office and additional field observation the engineer should be able to ascertain the following:

(1) The present stability of the stream. On a stable reach there should be little or no evidence of significant overbank deposition or recent bank erosion. The presence of large, vertical trees established on a presently stable bank indicate that the bank has been in that position for as long as it took them to grow.

General observations can be made as to the suspended sediment load. If the stream reach is unstable, it will characteristically display actively caving banks, large amounts of drift in the channel with existing trees leaning toward the channel and/or significant overbank deposition.

(2) The adequacy of present structural features.

(3) The adequacy of past channel improvements and/or alignment changes.

b. Depending on the availability of historic data, the engineer may able to ascertain the following:

(1) Long term stability trends.

(2) Stream response to land use changes.

(3) Stream response to past improvements.

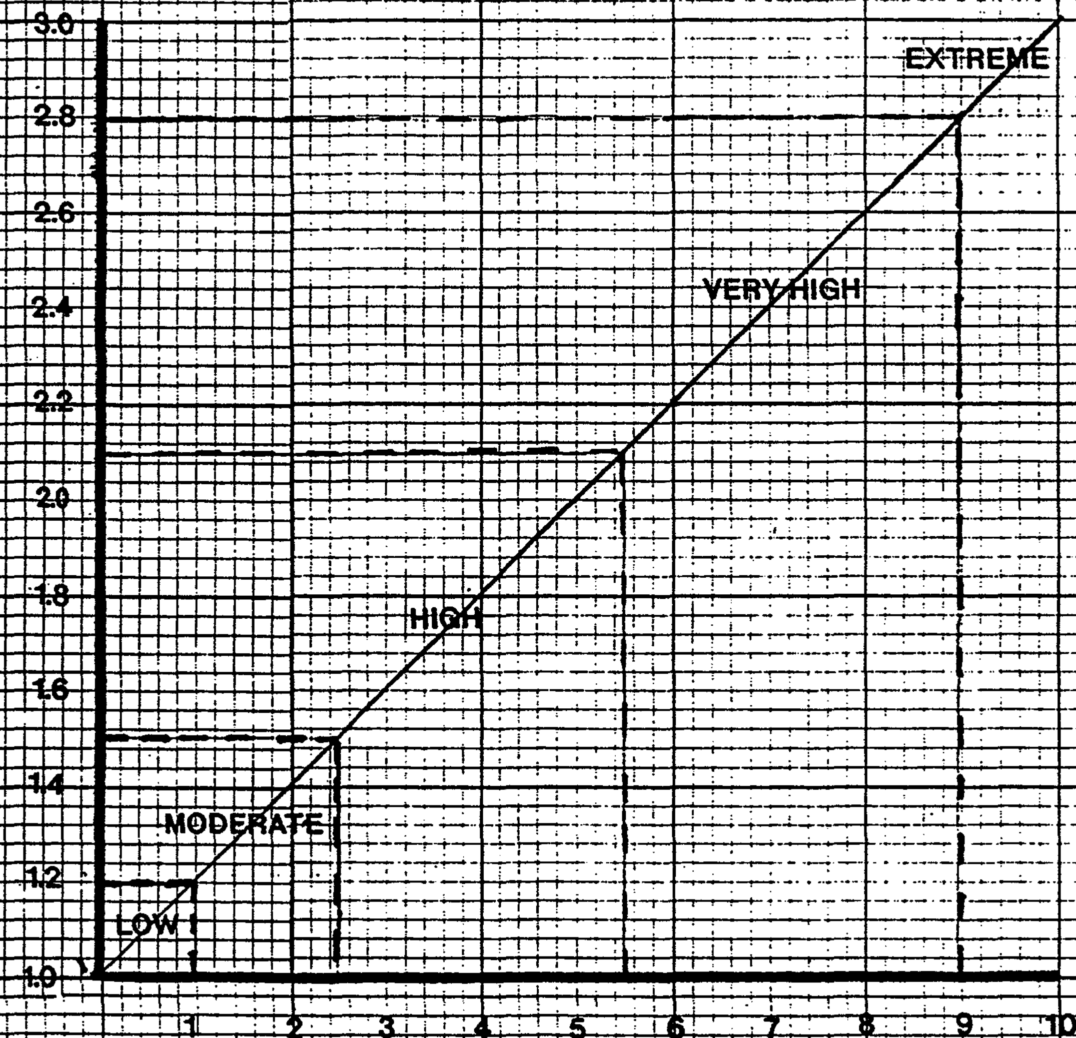
c. Depending on the availability of historic and contemporary hydrau hydrologic, topographic and sediment data the engineer should be able, ei qualitatively or quantitatively, to evaluate:

(1) Future long term stability with and without the proposed improvem

(2) Future maintenance requirements with and without the project.

(3) Design alternatives that address the interaction of sedimentation all other project considerations in order arrive at the "best" design.

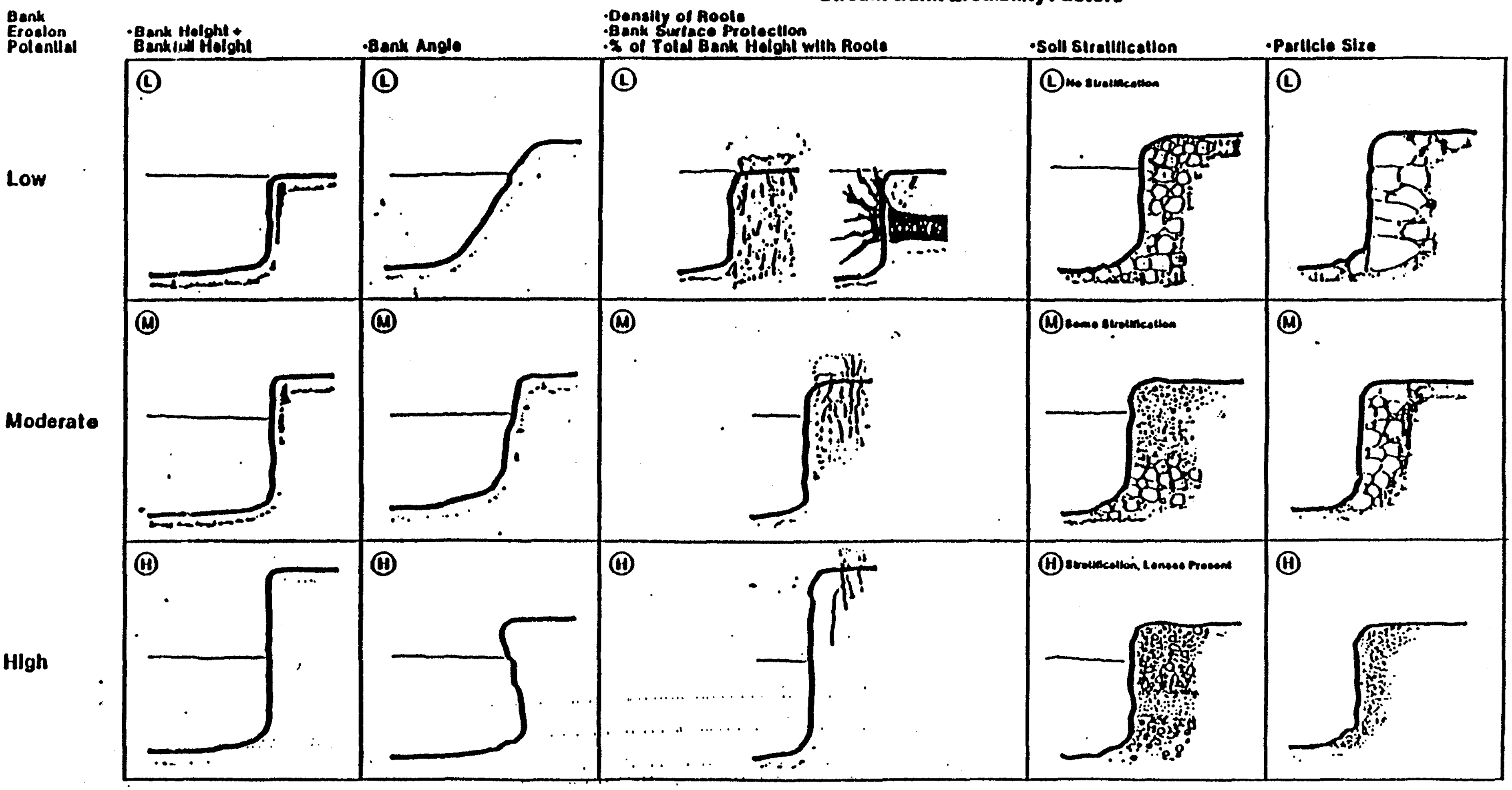
RATIO OF TOTAL BANK HEIGHT TO BANKFULL HEIGHT



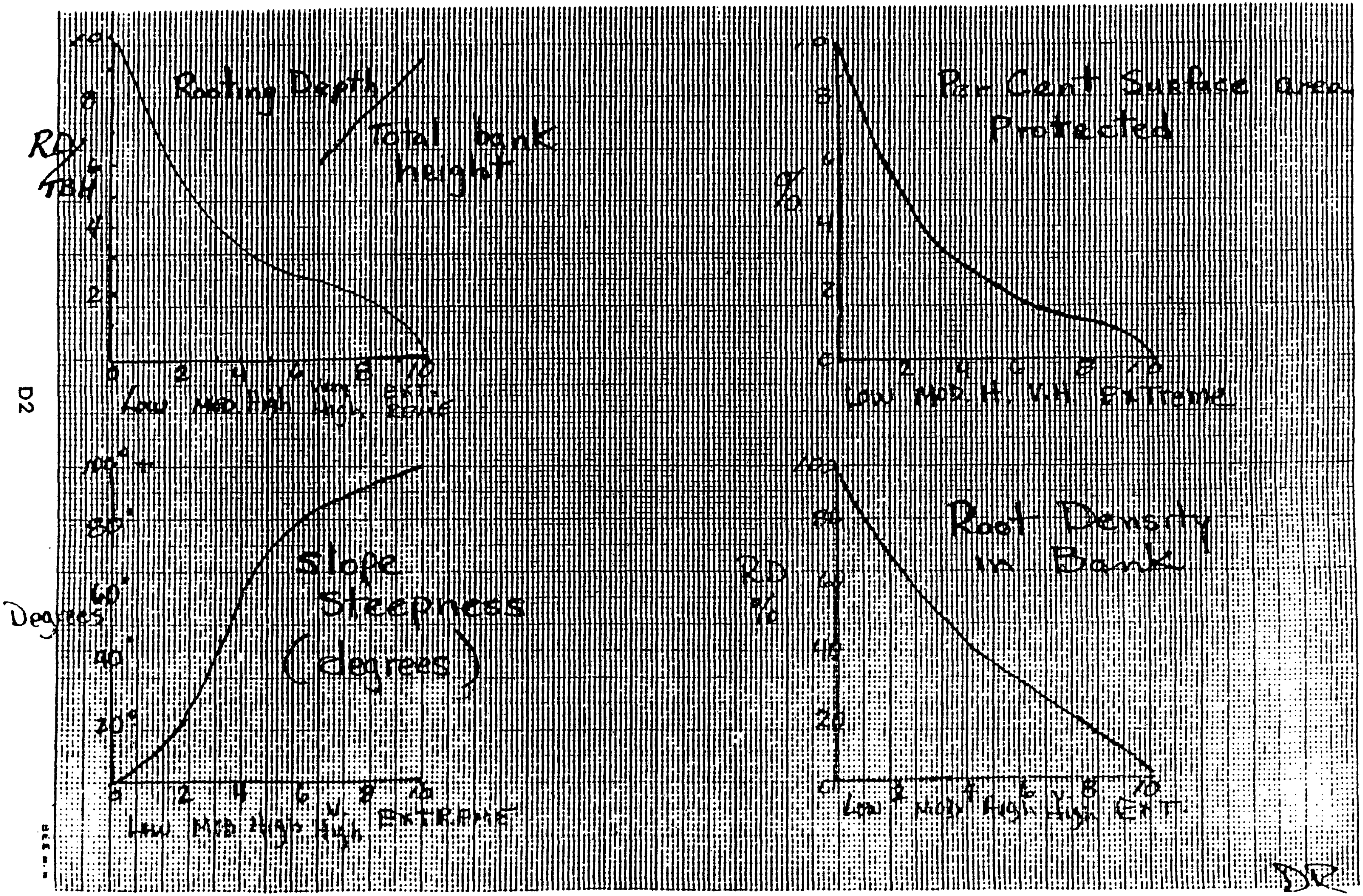
BANK EROSION POTENTIAL

DR
5/6/92

Stream Bank Erodibility Factors



BANK EROSION POTENTIAL



D2

Table 2. Summary of Delineative criteria for broad Characterization level classification.

Stream Type	Entr. ratio	W/d ratio	sinu.	slope	Landform/soil features
Aa+	< 1.4	<12	1.0-1.1	> 0.10	very high relief erosional, bedrock, or depositional features with debris flow potent. deeply entrenched streams
A	< 1.4	<12	1.0-1.3	0.04-.10	High relief, erosional, depositional or bedrock forms. Entrenched streams, step/pool morphology.
B	1.4-2.2	>12	> 1.2	.02-.039	Colluvial deposition and/or residual soils moderate relief, mod. entrenchment and w/d ratio, narrow, gently sloping valleys, stable riffle dominated riffle/pool morphology
C	> 2.2	>12	> 1.4	< .02	Broad valleys, terraces in assoc. w/floodplains Lacustrine, plains, etc. slightly entrenched, riffle/pool, meandering
D	N/A	>40	N/A	< .04	Broad valleys, alluvial and colluvial fans, Glacial debris Depositional features Braided morphology, laterally unstable.
DA	N/A	>40	N/A	<.001	Broad, flat valleys fine alluv. a/or Lacust. Anastamosed (braided morphology) geol. control creating fine deposition, well veg. bars, laterally stable
E	> 2.2	<12	>1.5	<.02	Broad Valley, meadow, Alluvial w/floodplain highly sinuous, stable stable banks, well veg. Riffle/pool morphology
F	< 1.4	>12	>1.4	<.02	Entrenched, meandering incised in highly weathered material on gentle gradients, high w/d ratio, unstable. riffle/pool morphology
G	< 1.4	<12	>1.2	<.04	"Gulley" step/pool on moderate slopes with low width/depth, narrow valleys or deeply incised in alluvial, colluvial, including fans, deltas. grade control prob., unstable

	BANK EROSION POTENTIAL											
CRITERIA	VERY LOW		LOW		MODERATE		HIGH		VERY HIGH		EXTREME	
	VALUE	INDEX	VALUE	INDEX	VALUE	INDEX	VALUE	INDEX	VALUE	INDEX	VALUE	INDEX
Bank Ht/Bkf Ht	1.0-1.1	1.0-1.9	1.0-1.19	2.0-3.9	1.2-1.5	4.0-5.9	1.6-2.1	6.0-7.9	2.1-2.8	8.0-9.0	>2.8	10
Root Depth/Bank Ht	1.0-0.9	1.0-1.9	0.89-0.50	2.0-3.9	0.49-0.30	4.0-5.9	0.29-0.15	6.0-7.9	1.14-.05	8.0-9.0	.05	10
Root Density (%)	80-100	1.0-1.9	55-79	2.0-3.9	30-54	4.0-5.9	15-29	6.0-7.9	5-14	8.0-9.0	<50	10
Bank Angle (Degrees)	0-20	1.0-1.9	21-60	2.0-3.9	61-80	4.0-5.9	81-90	6.0-7.9	90-119	8.0-9.0	120+	10
Surface Prot. (%)	80-100	1.0-1.9	55-79	2.0-3.9	30-54	4.0-5.9	15-29	6.0-7.9	10-15	8.0-9.0	<10	10
TOTALS												
		5-9.5		10-19.5		20-29.5		30-39.5		40-45		46-50
Numerical Adjustments												

BANK MATERIALS:

BEDROCK: BANK EROSION POTENTIAL ALWAYS VERY LOW
BOULDERS: BANK EROSION POTENTIAL LOW
COBBLE: DECREASE BY ONE CATEGORY UNLESS MIXTURE OF GRAVEL/SAND IS OVER 50%, THEN NO ADJUSTMENT
GRAVEL: ADJUST VALUES UP BY 5-10 POINTS DEPENDING ON COMPOSITION OF SAND
SAND: ADJUST VALUES UP BY 10 POINTS
SILT/CLAY: NO ADJUSTMENT

STRATIFICATION: 5-10 POINTS (UPWARD) DEPENDING ON POSITION OF UNSTABLE LAYERS IN RELATION TO BANKFULL STAGE

Classification Schemes

Summary:

Stream type indicates processes
Review classification schemes

Advantages:

- Easy to Use
- Reality Check
- Model Selection
- Other Applications

Disadvantages:

- So What?
- Square Pegs
- Arizona Stream Types

USER'S MANUAL FOR THE

BRI-STARS Expert System for Stream Classification

by

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Table 1.1 - Stream Classification (L. Rundquist, 1975)

Classification Group	Classification Variable	Classification Variable Subclassification	Criteria	Code
Geography	Land use policy in the drainage basin	Urban	Greater than 25% of drainage basin is urban	LU1
		Rural	Greater than 45% of drainage basin is rural	LU2
		Agricultural	Greater than 35% of drainage basin is agricultural	LU3
		Conservation	Greater than 65% of drainage basin is conservation	LU4
	Vegetation in and along the channel (specify type)	Vegetation scarce in the channel	Less than 20% of bed and bank area covered	VI1
		Moderate vegetation in the channel	20-60% of bed and bank area covered	VI2
		Significant vegetation in the channel	Greater than 60% of bed and bank area covered	VI3
		Vegetation scarce along the channel	Less than 20% of bank area covered	VA1
		Moderate vegetation along the channel	20-60% of bank area covered	VA2
		Significant vegetation along the channel	Greater than 60% of bank area covered	VA3
Geology	Down valley slope	Flat gradient	$S_V < 0.0001$	VS1
		Moderate gradient	$0.0001 < S_V < 0.01$	VS2
		Steep gradient	$0.01 < S_V$	VS3
	Material in which channel is formed*	Alluvial	Visual observation	MC1
		Alluvial with rock outcroppings	Visual observation	MC2
		Bedrock	Visual observation	MC3
	Underfit stream	Is not underfit	Visual observation	US1
		Is underfit	Visual observation	US2
	Lakes on the river	Lake upstream	Map or field investigation	LR1
		Lake at site	Map or field investigation	LR2
		Lake downstream	Map or field investigation	LR3
		No lake	Map or field investigation	LR4
	Channel constriction (specify general or local)	Minor reduction	Reduced by 10%	CC1
		Moderate reduction	Reduced by 10-50%	CC2
		Major reduction	Reduced by more than 50%	CC3
		No reduction	No reduction	CC4
	Tectonic activity	Minor tectonic activity	Less than 2 ft/century	TA1
		Major uplift	Greater than 2 ft/century	TA2
		Major subsidence	Greater than 2 ft/century	TA3
	Works of man	Classify according to corresponding geological classification listed above		

Table 1.1 (continued)

Classification Group	Classification Variable	Classification Variable Subclassification	Criteria	Code
Hydrology	Mean annual flow*	Small river	Q_m < 10,000 cfs	MA1
		Large river	Q_m > 10,000 cfs	MA2
	Bank-full flow*	Small river	Q_b < 50,000 cfs	BF1
		Large river	Q_b > 50,000 cfs	BF2
	Hydrograph shape	Perennial, single peaked	Qualitative (see Fig. 2.2)	HS1
		Perennial, multiple peaked	Qualitative (see Fig. 2.2)	HS2
		Perennial, uniform	Qualitative (see Fig. 2.2)	HS3
		Intermittent	Qualitative (see Fig. 2.3)	HS4
		Ephemeral, infrequent	Qualitative (see Fig. 2.4)	HS5
		Ephemeral, single peaked annual	Qualitative (see Fig. 2.4)	HS6
		Ephemeral, multiple peaked annual	Qualitative (see Fig. 2.4)	HS7
Bed and Bank Material	Median bed material size*	Clay	d_{50} < 0.004 mm	BD1
		Silt	0.004 mm < d_{50} < 0.062 mm	BD2
		Sand	0.062 mm < d_{50} < 2.00 mm	BD3
		Gravel and cobbles	2.00 mm < d_{50} < 250 mm	BD4
		Boulders	250 mm < d_{50}	BD5
	Bed material gradation	Uniform	σ < 1.30	BG1
		Graded	1.30 < σ	BG2
	Median bank material size*	Clay	d_{50} < 0.004 mm	BK1
		Silt	0.004 mm < d_{50} < 0.062 mm	BK2
		Sand	0.062 mm < d_{50} < 2.00 mm	BK3
		Gravel and cobbles	2.00 mm < d_{50} < 250 mm	BK4
		Boulders	250 mm < d_{50}	BK5
Amount and Type of Sediment Load	Amount of total sediment load associated with bank-full discharge*	Small	C_T < 20,000 ppm	SL1
		Significant	20,000 ppm < C_T	SL2
	Type of sediment load*	Bed material load	Qualitative	TS1
		Mixed load	Qualitative	TS2
		Wash load	Qualitative	TS3

Table 1.1 (continued)

Classification Group	Classification Variable	Classification Variable Subclassification	Criteria	Code
Pattern and Stability	Stable	Sinuous	S.I. >1.1, stability determined qualitatively	SP1
		Multichannel	B.I. > 0.25, stability determined qualitatively	SP1
	Unstable	Meandering	S.I. > 1.1, instability determined qualitatively	UP1
		Tortuous	S.I. > 1.1, instability determined qualitatively	UP2
		Braided	B.I. > 0.25, instability determined qualitatively	UP3
		Straight	S.I. < 1.1, B.I. < 0.25, instability determined qualitatively	UP4

*denotes computational variable

Schumm and Meyer [32] extended this general methodology in 1979 to classify five types of alluvial channel plan forms (Figure 2.3). Allen [1] redid Schumm's work in terms of the lateral stability of channels and presented a continuum of channel forms. Mollard [22] further developed the continuum approach permitting the qualitative assessments of discharge, sediment supply, ratio of bed material load to total sediment load, channel gradient, channel sinuosity and channel stability with relation to channel pattern.

A third type of stream classification is that of Rosgen [27]. The purpose of this classification scheme and others like it is to categorize natural stream channels on the basis of measurable morphological features. This classification is summarized in Table 2.2.

Table 2.1 - Classification of Alluvial Channels (Schumm, 1963)

Mode of Sediment Transport and Type of Channel	**Channel Sediment (M) Percent**	**Bed-load (% of Total Load)**	**CHANNEL STABILITY**		
			Stable (Graded Stream)	**Depositing (Excess Load)**	**Eroding (Deficiency of Load)**
Suspended Load	>20	<3	Stable suspended-load channel. Width/depth ratio <10; sinuosity usually >2.0; gradient relatively gentle.	Depositing suspended load channel. Major deposition on banks cause narrowing of channel; initial streambed deposition minor.	Eroding suspended-load channel. Streambed erosion predominant; initial channel widening minor.
Mixed Load	5-20	3-11	Stable mixed-load channel. Width/depth >10, <40; sinuosity usually <1.3; gradient moderate.	Depositing mixed-load channel. Initial major deposition on banks followed by streambed deposition.	Eroding mixed-load channel. Initial streambed erosion followed by channel widening.
Bed Load	<5	>11	Stable bed load channel. Width/depth >40; sinuosity usually <1.3; gradient relatively steep.	Depositing bed load channel. Streambed deposition and island formation.	Eroding bed load channel. Little streambed erosion; channel widening predominant.

STREAM TYPE	GRADIENT	SINUOSITY	W/D RATIO	DOMINANT PARTICLE SIZE OF CHANNEL MATERIALS	CHANNEL ENTRENCHMENT-VALLEY CONFINEMENT	LANDRORM FEATURE - SOILS/STABILITY
A1	4-10	1.0 - 1.1	10 or less	Bedrock	Very deep/very well confined	Deeply incised, bedrock, drains poorly w/steep side slopes and/or vertical rock walls.
A1-a	10+	(Criteria same as A1)				

STREAM TYPE	GRADIENT	SINUOSITY	W/D RATIO	DOMINANT PARTICLE SIZE OF CHANNEL MATERIALS	CHANNEL ENTRENCHMENT-VALLEY CONFINEMENT	LANDRORM FEATURE - SOILS/STABILITY
A2	4-10	1.1 - 1.2	10 or less	Large & small boulders w/mixed cobble	Same	Steep side slopes w/predominantly stable materials.
A2-a	10+	(Criteria same as A2)				
A3	4-10	1.1 - 1.3	10 or less	Small boulders, cobble, coarse gravel	Same	Steep, depositional features w/predominantly coarse-textured soils. Debris avalanche is the predominant erosional process. Stream adjacent slopes are rejuvenated with extensive exposed mineral soil.
A3-a	10+	(Criteria same as A3)				
A4	4-10	1.2 - 1.4	10 or less	Predominantly gravel, sand, and some silts	Same	Steep side slopes w/mixture of either depositional landforms with fine-textured soils such as glaciofluvial or glaciolacustrine deposits or highly erosional processes. Stream adjacent slopes are rejuvenated.
A4-a	10+	(Criteria same as A4)				
A5	4-10	1.2 - 1.4	10 or less	Silt and/or clay bed and bank materials	Same	Moderate to steep side slopes. Fine-textured cohesive soils, slump-earthflow erosional processes dominate.
A5-a	10+	(Criteria same as A5)				
B1-1	1.5-4.0	1.3 - 1.9	10 or greater	Bedrock bed, banks, cobble, gravel, some sand.	Shallow entrenchment, moderate confinement	Bedrock-controlled channel with coarse-textured depositional bank materials.
B1	2.5-4.0	1.2 - 1.3	5-15	Predominantly small boulders, very large cobble	Moderately entrenched, well confined	Moderately stable, coarse-textured resistant soil materials. Some coarse river tarraces.
B2	1.5-2.5	1.3 - 1.5	8-20	Large cobble mixed w/small boulders & coarse gravel.	Moderately entrenched, moderately confined	Coarse textured, alluvial terraces with stable, moderately steep side slopes.
B3	1.5-4.0	1.3 - 1.7	8-20	Cobble bed w/ mixture of gravel & sand, some small boulders	Moderately entrenched, well confined.	Glacial outwash terraces and/or rejuvenated slopes. Unstable, moderate to steep slopes. Unconsolidated, coarse-textured unstable banks. Depositioal landforms.
B4	1.5-4.0	1.5 - 1.7	8-20	Very coarse gravel w/ cobble, mixed sand, and finer material.	Deeply entrenched, well confined	Relatively fine river terraces. Unconsolidated coarse to fine depositional material. Steep side slopes. Highly unstable banks.
B5	1.5-4.0	1.5 - 2.0	8-25	Silt/clay.	Same	Cohesive fine-textured soils. Slump-earthflow erosional processes.
C1-1	1.5 or less	1.5 - 2.5	10 or greater	Bedrock bed, gravel, sand, or finer banks.	Shallow entrenchment , poorly confined	Bedrock-controlled channel with depositional fine-grained bank material.
C1	1.2-1.5	1.5 - 2.0	10 or greater	Cobble bed with mixture of small boulders and coarse gravel.	Moderately entrenched, moderately confined	Predominantly coarse-textured, stable high alluvial terraces.
C2	0.3-1.0	1.3 - 1.5	15-30	Large cobble bed w/ mixture of small boulders & coarse gravel.	Moderately entrenched, well confined	Overfit channel, deeply incised in-coarse alluvial terraces and/or depositional features.

STREAM TYPE	GRADIENT	SINUOSITY	W/D RATIO	DOMINANT PARTICLE SIZE OF CHANNEL MATERIALS	CHANNEL ENTRENCHMENT-VALLEY CONFINEMENT	LANDRORM FEATURE - SOILS/STABILITY
C3	0.5-1.0	1.8 - 2.4	10 or greater	Gravel bed w/ mixture of small cobble & sand.	Moderately entrenched, slightly confined	Predominantly moderate to fine textured multiple low river terraces. Unstable banks, unconsolidated, noncohesive soils.
C4	0.1-0.5	2.5+	5 or greater	Sand bed w/ mixtures of gravel & silt (no bed armor).	Moderately entrenched, slightly confined	Predominantly fine textured, alluvium with low flood terraces.
C5	0.1 or less	2.5+	5 or greater	Silt/clay w/ mixtures of medium to fine sands (no bed armor).	Moderately entrenched, slightly confined	Low, fine textured alluvial terraces, delta deposits, lacustrine, l??ss or other fine textured soils. Predominantly cohesive soils.
C6	0.1 or less	2.5+	3 or greater	Sand bed w/ mixture of silt & some gravel.	Deeply entrenched, slightly confined	Same as C4 except has more resistant banks.
D1	1.5 or greater	N/A Braided	N/A	Cobble bed w// mixture of coarse gravel & sand & small boulders	Slightly entrenched, no confinement	Glacial outwash, coarse depositional material, highly erodable. Excess sediment supply of coarse size material.
D2	1.5 or less	N/A Braided	N/A	Sand bed w/ mixture of small to medium gravel & silts	Slightly entrenched, no confinement	Fine textured depositional soils, very erodable - excess of fine textured sediment.

2.1.1 Causes of Meandering and Braiding in Rivers

Meandering Rivers

River meanders have been explained in the literature using three major approaches. The first approach is that meanders are caused by secondary currents. A second opinion espouses the theory of dynamic instability. The third is a statistical argument.

The existence of secondary currents in river bends can be clearly demonstrated to have a significant effect on the growth and migration of a meander. However, for secondary currents to be the cause of meanders, an explanation is required to show that secondary currents can exist in straight channels. Eakin [9] and Neu [23] maintain that the Coriolis effect of the earth's rotation is responsible for the development of secondary currents and subsequently meandering rivers. This approach is quite unlikely since the relative effect of Coriolis effect on river channels is quite small and, as Werner [35] states, actual observed effects on stream meandering have been largely negative. Considerable support for the idea of secondary currents causing meandering has been provided in laboratory experiments by Shen [34] and Einstein and Shen [11]. Once secondary currents have been created, a bar will form on one side of the channel and a pool on the other side, enhancing meander development, as supported by Einstein and Huon Li [10] and Delleur and McManus [7].

Another school of thought believes meanders to be caused by the dynamic instability of the stream bed and banks. More formal mathematical studies have been based on this concept and were summarized by Raudkivi [25] and Callander [5]. These methods generally follow the approach that the channel bed is dynamically unstable and bed forms propagate downstream inducing bank instability and hence move a meander in a downstream direction.

A third group believes meanders to be based on statistical probability and thermodynamic analogy. They propose that the most probable path between two points defines a meander path, using a random walk analogy. This group included Leopold and Langbein [19] who use an energy loss maximation approach, Scheidigger [28] who tried to extend their argument, and Yang [36] who approaches the problem from the concept of minimum energy expenditure per unit mass along the water course.

All of the three general approaches gave some merit but perhaps Lee [18] provided the most practical conceptual framework of river meandering. He considered two phases of the process: (1) initiation of meandering, and (2) sustenance of meandering. Due to irregularity in topography and soil characteristics, flow in channels will be deflected and will tend to initiate a meandering course. Secondary currents and dynamic instability will develop once such a feature has appeared. Variations in flow

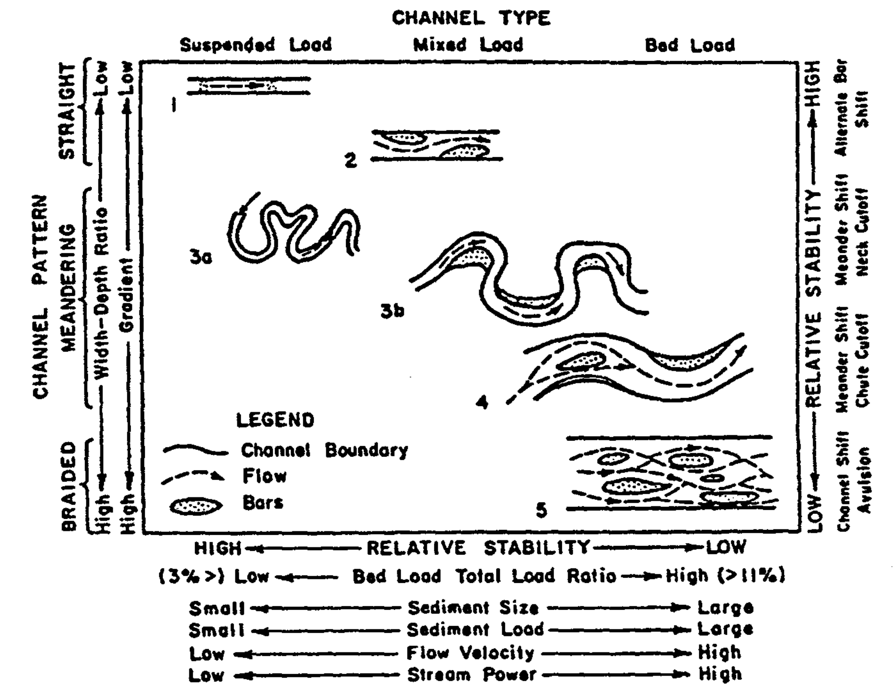


Figure 2.3 - Channel pattern stability and hazards

will then exacerbate meandering tendencies, though a meandering river will tend towards an equilibrium or perhaps most probable state based on valley slope, streamflow, and sediment discharge variations.

Braided Channels

Braided channels occur as a result of large or significant changes in slope, streamflow, or sediment load. Variations of two major independent variables in rivers, streamflow and sediment discharge can markedly change channel geometry

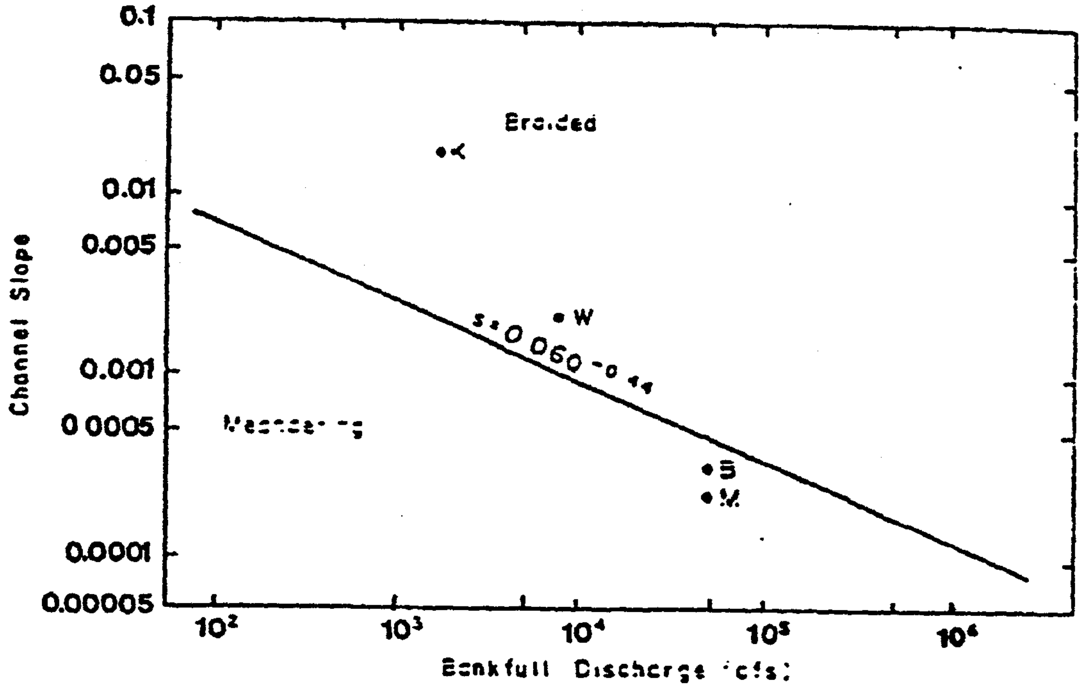


Figure 2.4 - Leopold and Wolman's (1857) patterns relation

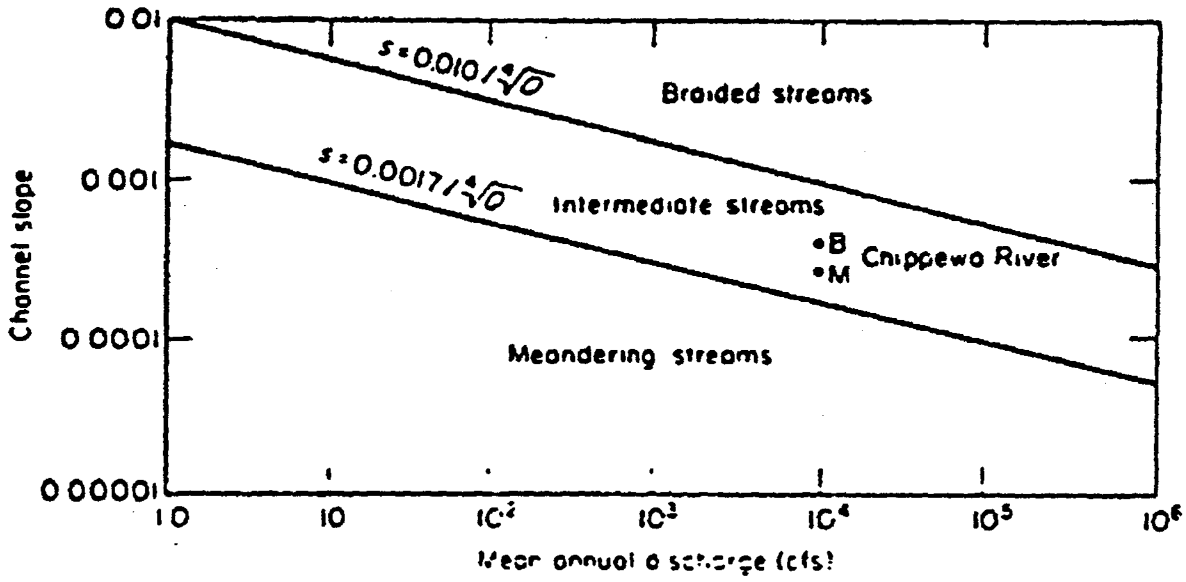


Figure 2.5 - Lane's (1957) channel pattern relation

Geo-Equations

Summary:

Predict equilibrium from measured parameters

Review sample equations

Advantages:

- Identify Trends
- Level I Analysis

Disadvantages:

- Scatter in Data
- Regional Applicability
- Arizona Applications

TABLE 2

Derived empirical equations for river-meander and channel-size features (A = bankfull cross-sectional area, W = bankfull width, D = bankfull mean depth, L_m = meander wavelength, L_b = along-channel bend length, B = meander belt width, R_c = loop radius of curvature, K = channel sinuosity, m = meters)

Equation number	Equation	Standard deviation of residuals, in percent +	Standard deviation of residuals, in percent −	Sample correlation coefficient	Number of data points	Applicable range
Interrelations between meander features						
2	$L_m = 1.25L_b$	32	24	0.99	102	$5.5 \leq L_b \leq 13{,}300$ m
3	$L_m = 1.63B$	31	24	0.99	155	$3.7 \leq B \leq 13{,}700$ m
4	$L_m = 4.63R_c$	21	17	0.99	78	$2.6 \leq R_c \leq 3{,}600$ m
5	$L_b = 0.80L_m$	32	24	0.99	102	$8 \leq L_m \leq 16{,}500$ m
6	$L_b = 1.29B$	31	24	0.99	102	$3.7 \leq B \leq 10{,}000$ m
7	$L_b = 3.77R_c$	35	26	0.98	78	$2.6 \leq R_c \leq 3{,}600$ m
8	$B = 0.61L_m$	31	24	0.99	155	$8 \leq L_m \leq 23{,}200$ m
9	$B = 0.78L_b$	31	24	0.99	102	$5.5 \leq L_b \leq 13{,}300$ m
10	$B = 2.88R_c$	42	29	0.98	78	$2.6 \leq R_c \leq 3{,}600$ m
11	$R_c = 0.22L_m$	21	17	0.99	78	$10 \leq L_m \leq 16{,}500$ m
12	$R_c = 0.26L_b$	35	26	0.98	78	$6.8 \leq L_b \leq 13{,}300$ m
13	$R_c = 0.35B$	42	29	0.98	78	$5 \leq B \leq 10{,}000$ m
Relations of channel size to meander features						
14	$A = 0.0054L_m^{1.53}$	103	51	0.96	66	$10 \leq L_m \leq 23{,}200$ m
15	$A = 0.0085L_b^{1.53}$	140	58	0.96	41	$8 \leq L_b \leq 13{,}300$ m
16	$A = 0.012B^{1.53}$	97	49	0.97	63	$5 \leq B \leq 11{,}600$ m
17	$A = 0.067R_c^{1.53}$	138	58	0.97	28	$2 \leq R_c \leq 3{,}600$ m
18	$W = 0.17L_m^{0.89}$	56	36	0.96	191	$8 \leq L_m \leq 23{,}200$ m
19	$W = 0.23L_b^{0.89}$	56	36	0.97	102	$5 \leq L_b \leq 13{,}300$ m
20	$W = 0.27B^{0.89}$	63	39	0.96	153	$3 \leq B \leq 13{,}700$ m
21	$W = 0.71R_c^{0.89}$	48	32	0.97	79	$2.6 \leq R_c \leq 3{,}600$ m
22	$D = 0.027L_m^{0.66}$	79	44	0.86	66	$10 \leq L_m \leq 23{,}200$ m
23	$D = 0.036L_b^{0.66}$	72	42	0.90	41	$7 \leq L_b \leq 13{,}300$ m
24	$D = 0.037B^{0.66}$	66	40	0.90	63	$5 \leq B \leq 11{,}600$ m
25	$D = 0.085R_c^{0.66}$	90	47	0.90	28	$2.6 \leq R_c \leq 3{,}600$ m
Relations of meander features to channel size						
26	$L_m = 30A^{0.65}$	59	37	0.96	66	$0.04 \leq A \leq 20{,}900$ m^2
27	$L_b = 22A^{0.65}$	77	43	0.96	41	$0.04 \leq A \leq 20{,}900$ m^2
28	$B = 18A^{0.65}$	56	36	0.97	63	$0.04 \leq A \leq 20{,}900$ m^2
29	$R_c = 5.8A^{0.65}$	76	43	0.97	28	$0.04 \leq A \leq 20{,}900$ m^2
30	$L_m = 7.5W^{1.12}$	65	39	0.96	191	$1.5 \leq W \leq 4{,}000$ m
31	$L_b = 6.1W^{1.12}$	85	39	0.97	102	$1.5 \leq W \leq 2{,}000$ m
32	$B = 4.3W^{1.12}$	74	42	0.96	153	$1.5 \leq W \leq 4{,}000$ m
33	$R_c = 1.5W^{1.12}$	55	35	0.97	79	$1.5 \leq W \leq 2{,}000$ m
34	$L_m = 240D^{1.52}$	142	59	0.86	66	$0.03 \leq D \leq 18$ m
35	$L_b = 160D^{1.52}$	128	56	0.90	41	$0.03 \leq D \leq 17.6$ m
36	$B = 148D^{1.52}$	115	53	0.90	63	$0.03 \leq D \leq 18$ m
37	$R_c = 42D^{1.52}$	165	62	0.90	28	$0.03 \leq D \leq 17.6$ m
Relations between channel width, channel depth, and channel sinuosity						
38	$W = 21.3D^{1.45}$	160	62	0.81	67	$0.03 \leq D \leq 18$ m
39	$D = 0.12W^{0.69}$	94	48	0.81	67	$1.5 \leq W \leq 4{,}000$ m
40	$W = 96D^{1.32}K^{-2.14}$	121	55	0.87	66	$0.03 \leq D \leq 18$ m and $1.20 \leq K \leq 2.60$
41	$D = 0.09W^{0.59}K^{1.46}$	73	42	0.86	66	$1.5 \leq W \leq 4{,}000$ m and $1.20 \leq K \leq 2$

APPENDIX D

QUALITATIVE ANALYSIS OF GENERAL RIVER RESPONSE TO CHANGE

D-1. Introduction. Sufficient hydraulic and sediment data to perform a quantitative analysis is unavailable for the vast majority of Corps' studies and projects. However, this does not preclude a sediment analysis. The analysis must, by necessity, be qualitative in nature. This requires an understanding of fluvial processes [35], [47], and [49].

D-2. General Relationships.

a. Studies conducted by [34], [31], and [48] support the following general relationships according to [49].

(1) Depth of flow y is directly proportional to water discharge Q.

(2) Channel width W is directly proportional to both water discharge Q and sediment discharge Qs.

(3) Channel shape, expressed as width to depth W/y ratio is directly related to sediment discharge Qs.

(4) Channel slope is directly proportional to water discharge Q and directly proportional to both sediment discharge Qs and Grain Size d50.

(5) Sinuosity is directly proportional to valley slope and inversely proportional to sediment discharge Qs.

(6) Transport of bed material Qs is directly related to stream power TAU and concentration of fine material CF, and inversely related to the fall diameter of the bed material d50.

b. Simons [49] developed a relationship for predicting system response to changes in the parameters listed above.

$$Qs \sim [(Gma*D*S) * W * U] / (d50/CF) = [Gma*Q*S] / (d50/CF) \qquad \text{(D-1)}$$

where:

CF = oncentration of fine material load
D = Depth of flow
d50 = Median fall diameter of bed material
Gma = Specific weight of water
Q = Water discharge
Qs = Sediment discharge
S = Channel slope
U = Average velocity
W = Channel width

By applying the relationship (D-2) to the tributary stream, it can be seen that the increase in slope must be balanced by an increase in sediment transport Qs if the discharge and fall diameter are unchanged.

$$Q * S \sim Qs * d50$$

Therefore, the new slope could induce head-cutting in the tributary stream resulting in bank instability and increased sediment transport from the tributary, an overload of sediment in the main stream, and major changes in the geomorphic characteristics of the stream system.

TABLE D-1. Impact of Change on Stream System

	Local Effects	Upstream Effects	Downstream Effects
1.	Head-cutting	Increased velocity	Increased transport to main cannel
2.	General scour	Increased transport of bed material	Aggradation
3.	Local scour	Unstable channel	Increased flood stage
4.	Bank instability	Possible change in planform of river	Possible change in planform of river
5.	High velocities		

D-5. Effects of In-Channel Structures.

a. Qualitative analysis can be used to analyze the response of reaches on two major tributaries a considerable distance upstream of their confluence. This situation is depicted in Figure D-2.

b. Upstream of Reach A, a diversion structure is built to divert essentially clear water to the adjacent tributary on which Reach B is located. Upstream of Reach B, the clear water diverted from the other channel plus water from the tributary is released through a hydropower plant. Eventually, a large storage reservoir will be constructed downstream of the tributary confluence on the main stem at point C. By altering the normal river flows, these structures initiate several responses on the river system. Through qualitative analysis, it can be seen that Reach A may aggrade due to the excess of sediment left in that tributary when clear water is diverted.

$$Q * S \sim Qs * d50$$

c. If the specific weight Gma is assumed to be constant and t concentration of fine material CF is incorporated in the fall diameter, t above relationship can be expressed as:

$$Q * S \sim Qs * d50 \quad \text{(D-}$$

d. The above relationship is identical to that proposed by Lane [3 except that the fall diameter, which includes the effect of temperature transport, has been substituted for the physical median diameter used by Lan

D-3. Application of Qualitative Analysis.

a. In order to evaluate natural or imposed changes to a river system wi the above equations, the engineer must remember that the proportionality mu remain balanced. For example, if median fall diameter and water discharge a assumed constant and a decrease in slope is proposed for a reach of strea: equation (D-2) indicates that the sediment discharge must also decrease.

b. Simons and Senturk [49] offer several good examples of the applicati of Qualitative Analysis. Two of these are characterized below.

D-4. Drop in Base Level on Main Channel. Figure D-1 shows the effect that drop in the base level on a main channel has on a tributary stream.

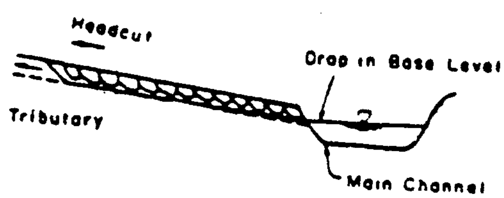


Figure D-1. Lowering base level of tributary stream

TABLE D-2. Impact of Change on Stream System

	Local Effects	Upstream Effects	Downstream Effects
1.	Reach A may be subjected to channel aggradation by diversion of clear water due to excess sediment left in the channel after the diversion and degradation in tributaries caused by lowering of their base level	Upstream of Reach A, aggradation and possible change of river form	See upstream
2.	Reach B may be subjected to degradation due to increased discharge in the channel	Upstream of Reach B--aggradation and change of river form	Construction of reservoir C could induce aggradation in the main channel and in the tributaries
3.	If a storage reservoir was constructed at C it could induce aggradation in both tributaries	Channel instabilities	
4.		Significant effects on flood stage	

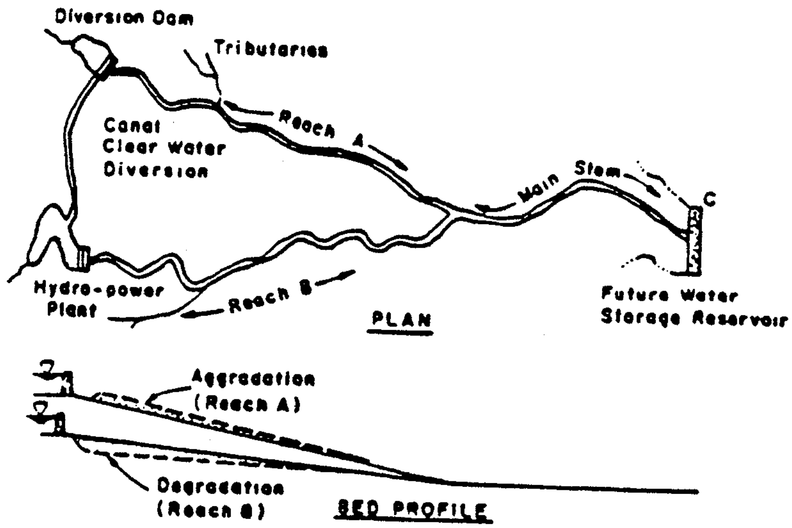


Figure D-2. Clear water diversion and release combined with dov storage

c. Initially, there may be a lowering of the channel bed downstr the diversion structure due to deposition upstream of the diversion the initial release of essentially clear water until the sediment requirement of the diversion reservoir is satisfied. Reach B is li degrade due to the increased discharge and essentially clear water rele

$$Q * S \sim Qs * d50$$

d. It is possible that the degradation in the main channel may sufficient head-cutting on tributaries of Reach B to offset add degradation. See the example of Figure D-1 above. Such changes in a system are not uncommon. A complete analysis of such a system must c the effect of each response both individually and collectively.

Recommended Approach

- Assess Needs
  - What is Purpose?
  - What Data are Available?
  - What i$ Level of Intere$t

Recommended Approach

(Level of Effort)

1. Historical Review
   - Literature
   - Map Work
2. Field Assessment

****

3. Classification
   - Applicable Methods
4. Geo-Equations
   - Identify Trends

****

5. Engineering Approach
   - If Necessary
   - Evaluate Alternatives
6. Regulatory Approach

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 fo 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

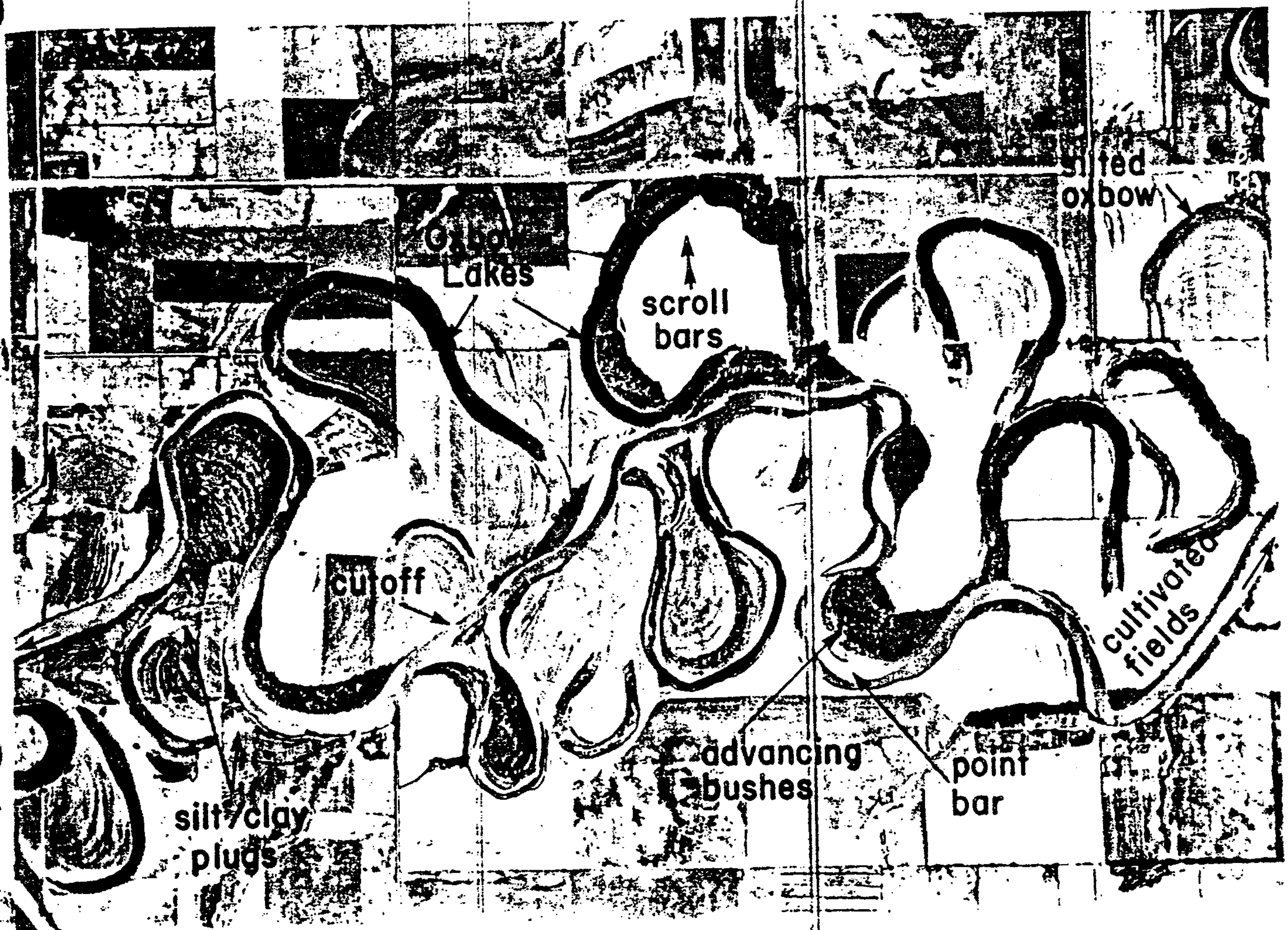


Figure 4.2.1 Airphoto of meandering river illustrating channel features.

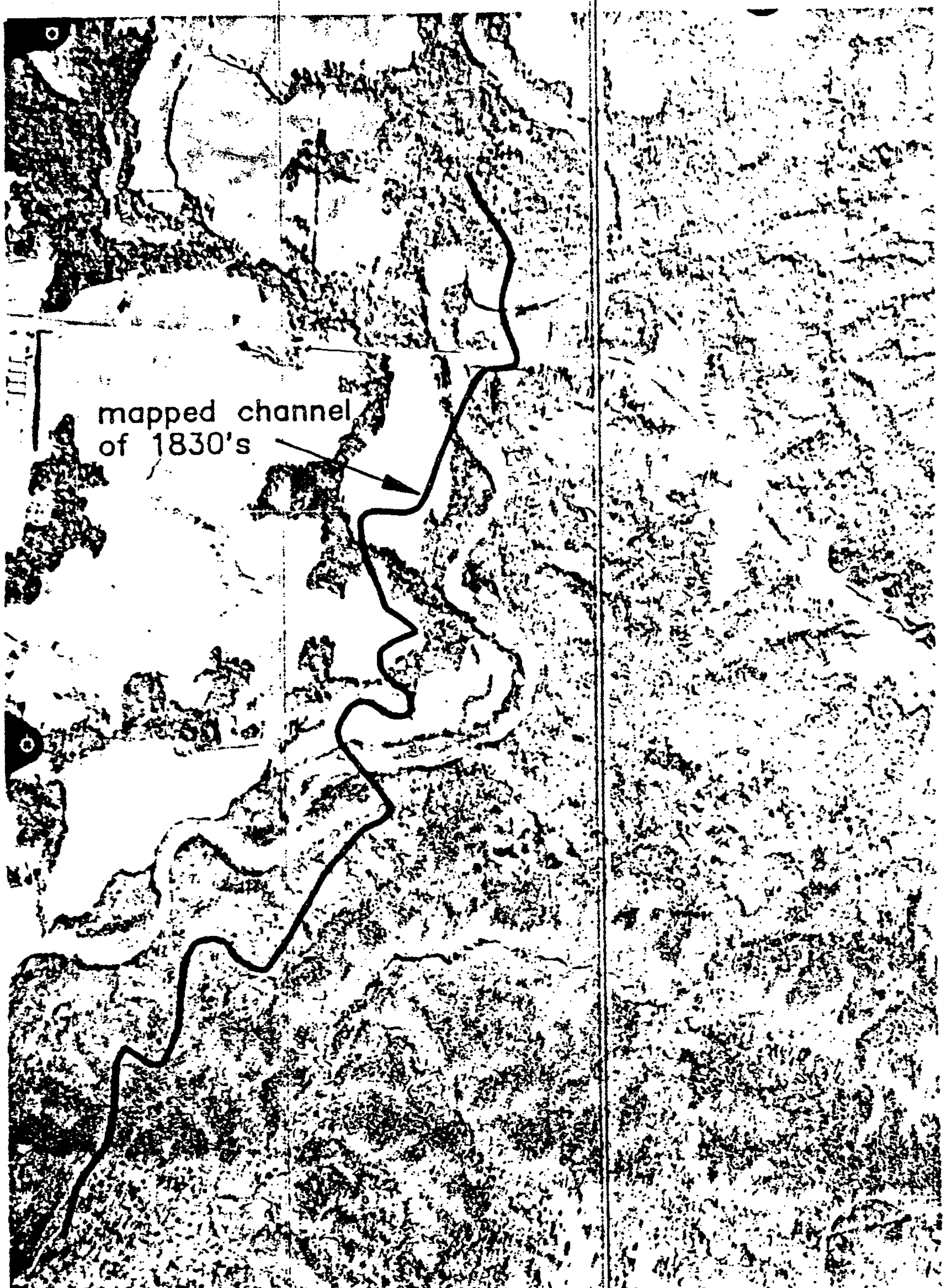


Figure 4.2.2 Comparison of modern and pre-settlement channel locations, Fannegusha Creek, Mississippi.

location of the 1830 channel was detectable from stereo viewing of the 1986 photos, being marked 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 an 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 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 ma 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 problem 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 unde ice conditions may be appropriate.

Electronic means of notetaking such as tape-recordings are favored by some observers, bu 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**

<u>Upstream basin conditions</u>

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

<u>Channel planform and banks</u>

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

<u>Channel profile and bed</u>

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

<u>Water surface profile and hydraulics</u>

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

<u>Downstream reaches</u>

- Prior interference
- Features susceptible to upstream changes

<u>General</u>

- 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.

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 <u>Channel and floodplain surveys</u>

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.

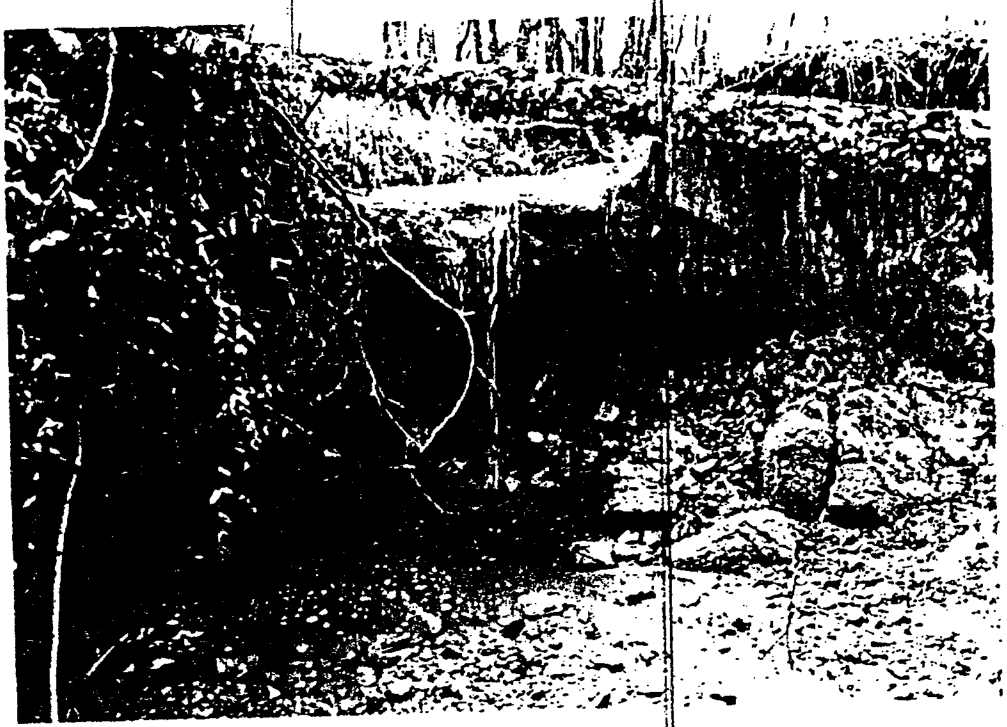


Figure 4.3.8 Mouth of perched tributary.

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.

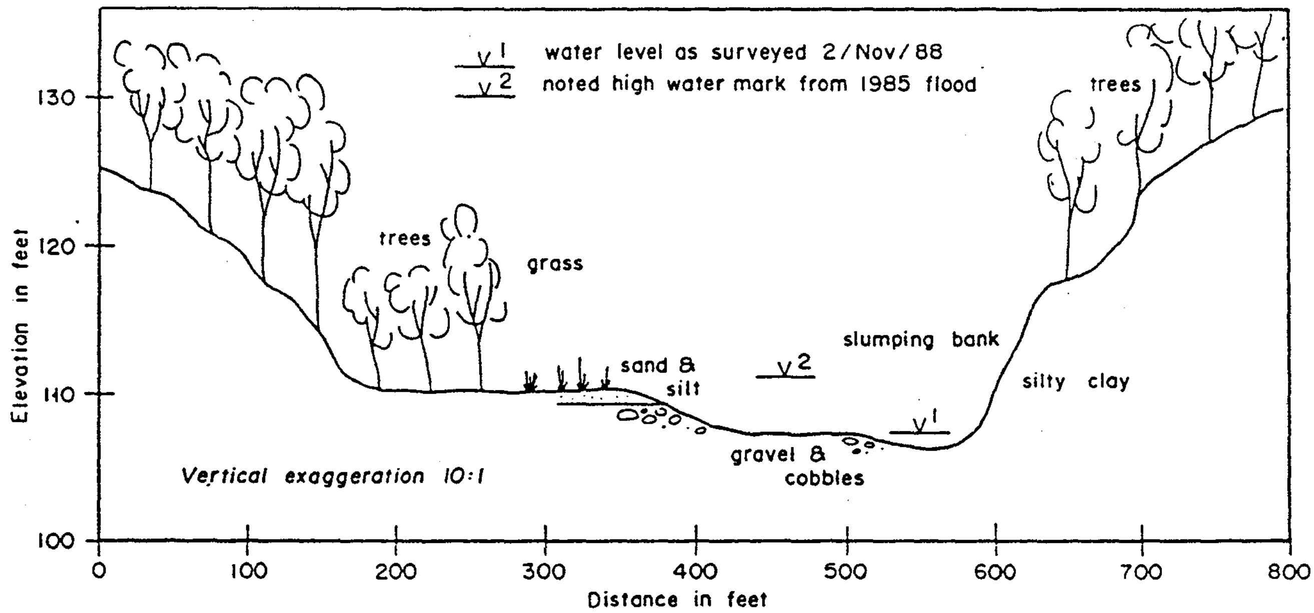


Figure 4.4.1 Example survey cross-section.

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.

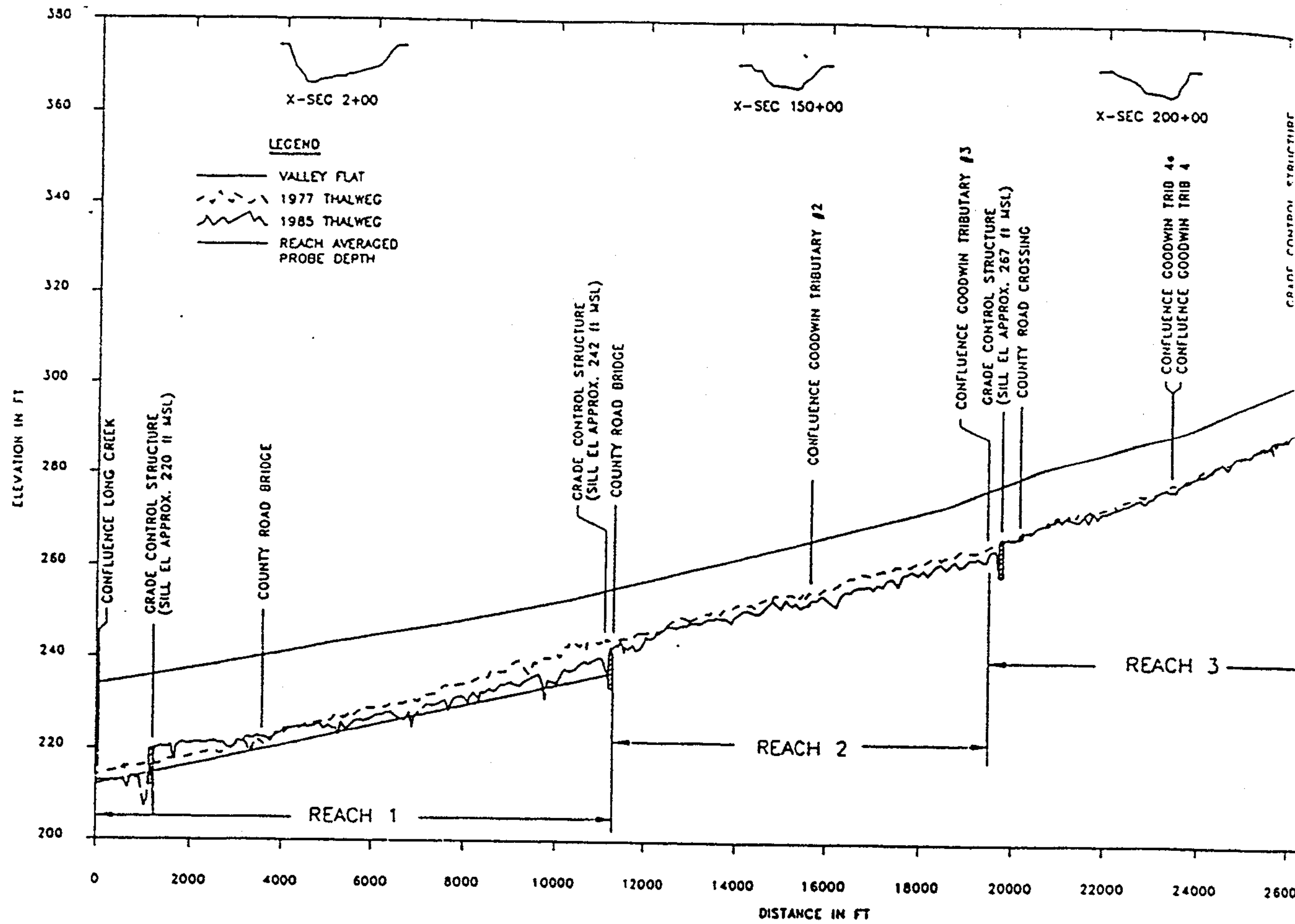


Figure 4.4.2 Example of stream profile.

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.

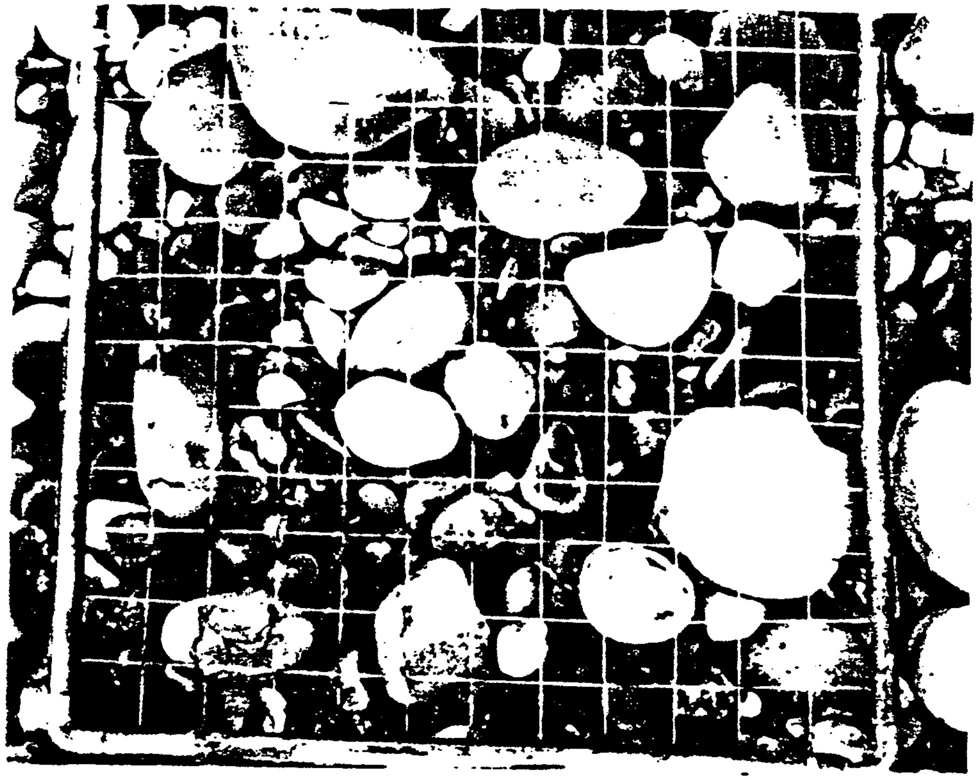
With coarse bed materials, collection of samples large enough for meaningful grainsize analysis may be inconvenient. An alternative is to photograph the surface of channel bars though a wire grid, and to analyze the surface distribution from the photographs (Figure 4.4.3). If the surface material is 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.

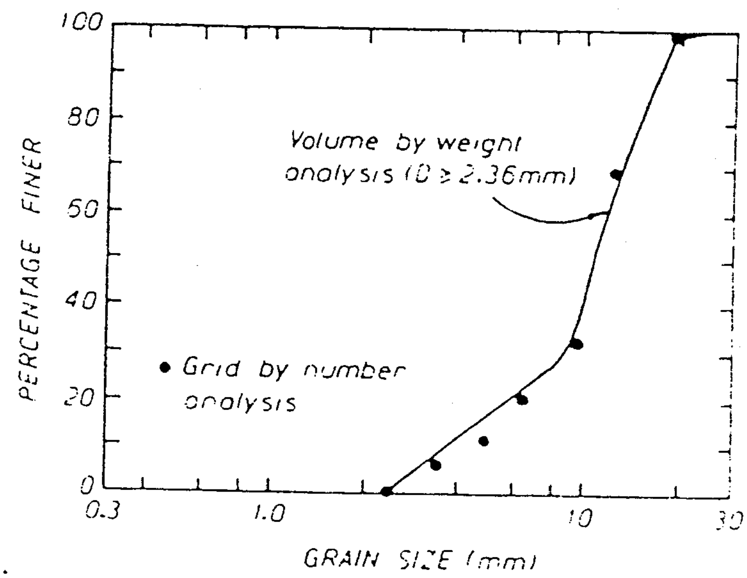
4.4.3 Bank failure and erosion. The general characteristics of bank failure and erosion will be noted in the field inspection - see Section 4.3 above. In some cases a detailed survey of erosional sites may be required in order to relate erosional severity to bank soils, heights and slopes etc. Related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

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(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 mainl 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 flo 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 <u>Geologic and geotechnical information</u>

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 198ç to which reference should be made if a full sedimentation analysis is judged advisable. In many sm 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 b judged to some extent by experienced observers from the aerial and ground features of the channe 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 wi 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. Descriptioı 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 pe 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.

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GLOSSARY

Fluvial Sediment Terms[1]

This proposed method has no status as an ASTM standard and is published on behalf of the sponsoring committee for information only for a maximum of two years. comments are solicited and should be addressed to the American Society for Testing and Materials 1916 Race St., Philadelphia, PA 19103.

accelerated erosion[2]--erosion at a rate greater than normal (see geologic erosion) for a site on the land surface or in drainageways, brought about by man, usually through reduction of plant cover or by disturbance.

accretion--a process of sediment accumulation by flowing water.

agglomeration--the coalescence of dispersed suspended matter into large flocs or particles which settle rapidly. Also called "flocculation."

aggradation--the geologic process by which stream beds, flood plains, and the bottoms of other water bodies are raised in elevation by the deposition of material eroded and transported by water from other areas.

aliquot--a fractional portion representative of the whole.

alluvial deposit--sediment deposited by the action of running or receding water.

alluvial fans--a deposit of loose-rock material shaped like a segment of a cone formed because of a sudden flattening of a stream gradient especially at debouchures of tributaries on main stream flood plains.

alluvial stream--a stream whose boundary is composed of appreciable quantities of the sediments transported by the flow and which generally changes its bed forms as the rate of flow changes.

alluviation--the process of accumulating sediment deposits at places where the flow is retarded.

antidunes--bed forms that occur at a velocity higher than that velocity which forms dunes and plane beds. Antidunes commonly move upstream, and are accompanied by and in phase with waves on the water surface.

armoring--the formation of a resistant layer of relatively large particles by erosion of the finer particles.

avulsion--a sudden natural change of a stream channel, so that the water flows elsewhere than in its previous course.

bed-load--material moving on or near the stream bed by rolling and sliding with brief excursions into the flow three or four diameters above the bed.

bed-load discharge--the quantity of bed-load passing a cross section of a stream in a unit of time.

bed-load sampler--a device for sampling the bed-load sediment.

bed material--the sediment mixture of which the stream bed is composed.

bed-material load--that part of the total load of a stream which is composed of particle sizes present in appreciable quantities in the shifting portions of the streambed

[1]This document is under the jurisdiction of Committee D.14 on Water.
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[2]Descriptive terms.

bottomset bed--fine-grained material (usually silts and clays) slowly deposited on the bed of a quiescent body of water which may in time be buried by forest beds and topset beds.

boulder (fluvial sediment)--larger than 256 mm. *See scale of particle sizes.*

braided river--a wide- and shallow-river channel where flow passes through a number of small interlaced channels separated by bars or shoals.

channel--a natural or artificial waterway that periodically or continuously contains moving water, or which forms a connecting link between two bodies of water.

channel-fill deposits--deposits of sediment within a channel, partly or completely filling the channel. (Such materials accumulate where the transporting capacity has been insufficient to remove it as rapidly as it has been delivered.)

clay size (fluvial sediment)--0.24 to 4 µm. *See scale of particle sizes.*

coagulation--the agglomeration of colloidal or finely divided suspended matter caused by the addition to the liquid of an appropriate chemical coagulant by biological processes, or by other means (see also agglomeration).

cobbles (fluvial sediment)--64 to 256 mm. *See scale of particle sizes.*

cohesive sediments--sediments whose resistance to initial movement or erosion depends upon the strength of the bond between particles.

colloids (fluvial sediment)--finely divided solids that do not settle in a liquid but which may be removed by coagulation or biochemical action. Smaller than 0.00024 mm. *See scale of particle sizes.*

colluvial deposits--unsorted or poorly sorted deposits accumulated along valley margins by slope wash and by other mass movements from the adjacent hillsides.

concentration of sediment by weight--the ratio of the weight of dry sediment in a water-sediment mixture to the weight of the mixture. This concentration when determined on a weight basis as parts per million (ppm), may be converted to milligrams per litre (mg/L) on the basis of Table 1.

concentration of sediment by volume--the ratio of the volume of dry solids in a water-sediment mixture to the volume of the mixture.

critical tractive force--the minimum force necessary to initiate movement of sediment particles in the stream bed.

degradation--the geologic process by which streambeds, floodplains, and the bottoms of other water bodies are lowered in elevation by the removal of material by water.

delivery rate--an obsolete, ambiguous term. Use sediment delivery ratio or sediment yield, whichever is meant.

delta--a sediment deposit formed where moving water is slowed by a body of standing water.

density current--the movement of fluid of one density under, through, or over another fluid of differing density.

deposition--the mechanical processes through which sediments settle out.

depth-integrating sediment sampler--a device that collects a representative water-sediment mixture at all points along the sampling vertical.

depth integration[2]--a method of sampling to obtain a representative, discharge-weighted water-sediment sample of stream verticals, except an unmeasured zone near the streambed, by continuously compositing a portion of the water-sediment mixtures as the sampler traverses the vertical at approximately a constant transit rate.

diameter-sedimentation--the diameter of a hypothetical sphere of the same specific gravity and the same settling velocity as the given particle in the same fluid.

discharge-weighted concentration--the ratio of the discharge of the dry weight of sediment to the discharge by weight of the water-sediment mixture.

dissolved load--the part of the stream load that is carried in solution.

dissolved solids[2]--the mass of dissolved constituents in water determined by evaporating a sample to dryness, heating at 105°C for 2h desiccating and weighing.

dunes (stream)--bed forms of coarse sediment generally transverse to the direction of flow, with a triangular profile having a gentle upstream slope (dunes advance downstream by the movement of sediment along the upstream slope and by the deposition of sediment on the steep downstream slope. Dunes move downstream at low velocities compared to the stream flow velocity.)

equal-discharge-increment (EDI) method[2]--a procedure for obtaining the discharge weighted suspended-sediment concentration of flow at a cross section whereby (1) depth integration is performed at the centers of three or more equal flow segments of the cross section and (2) a vertical transit rate is used at each sampling vertical that will provide equal sample volumes from all flow segments.

equal-width-increment (EDI) method[2]--a procedure of obtaining the discharge weighted suspended-sediment concentration of flow at a cross section (1) performing depth integration at a series of vertical equally spaced across the cross section and (2) using the same vertical transit rate at all sampling verticals.

fall velocity--the rate of fall or settling of a particle in a given medium.

filtration--the process of passing a liquid through a porous medium for the removal of suspended matter.

flocs or floccules--masses of solids, formed in a liquid by addition of coagulants (flocculants), or through biochemical processes, or by agglomeration of individual particles.

fluvial sediment--particles derived from rocks or biological materials that are transported by, suspended in, or deposited by streams.

foreset bed--the advancing and relatively steep frontal slope of a delta. (It progressively covers the bottomset bed and in turn is covered by the topset bed. Foreset beds represent the greater part of the volume of a delta.)

geologic or natural erosion[2]--the erosion process on or in a given land form undisturbed by activities of man and his agents.

grading--the degree of mixing of size classes in sedimentary material: Well-graded implies a more or less uniform distribution from coarse to fine; poorly graded implies uniformity in size or lack of continuous distribution (see sorting).

graded stream--a stream in which a steady state has been reached such that, over a period of time the discharge and load entering the system are balanced by the discharge and load leaving the system.

gravel (fluvial sediment)--sediment particles between 2.0 and 64 mm in size. *See scale of particle size.*

gross erosion[2]--the total of all sheet, gully, and channel erosion in a watershed, usually expressed in weight.

gully erosion--the enlargement of rills ad development of channels 300 mm or more in depth by ephemeral concentrated flow of water. (Gullies are characterized by steep walls and by steep head cuts.)

instantaneous sampler[2]--a suspended-sediment sampler that takes a representative specimen of the water-sediment mixture in a stream at a desired depth and moment of time.

lag deposits[2]--the larger and heavier particles that are sorted out and left behind in stream channels.

lateral accretion deposits[2]--sediment deposits formed along the inner (convex) sides of channel bends. See point bar.

meander--one of a series of sinuous curves, bends, or loops produced in the flood plain of a mature stream.

mean particle size or diameter ( )[2]--the weighted average of different sediment size classes by weight.

measured sediment load[2]--that part of the total sediment load that can be measured with available suspended-sediment samplers. (does not include bed load and suspended load very near the bed).

mechanical analysis[2]--a determination of the particle-size distribution of a sample by mechanical separation.

median size or diameter ( )[2]--the particle size of sediment for which 50 weight % is finer, obtained graphically by locating the diameter associated with the midpoint of the particle-size distribution. (The and are different with skewed distribution).

milligrams per litre[2]--the weight in milligrams of any substance contained in 1 L of liquid. (Nearly the same as parts per million below 16,000 ppm.)

movable bed[2]--a stream bed made up of materials readily transportable by the stream flow.

mudflow--a mass of water-sediment mixture with more than 400,000 ppm of sediment which, because of its high viscosity, moves more slowly than water.

native water[2]--untreated water from a water body that has been unaffected by sampling, handling, and preservation.

natural levee[2]--raised berms or crests above the flood-plain surface adjacent to the channel, usually containing coarser materials deposited as flood flows.

naturally dispersed sample--a sample having sediment that will not settle in about 4 h due to the character or fineness of particles and/or to the nature of the dissolved constituents.

nominal diameter[2]--the diameter of a sphere that has the same volume as the (sediment) particle.

noncohesive sediments[2]--discrete particles, the movement of which for given erosive forces depends only upon the properties of shape, size, and density, and upon the relative position of the particle with respect to surrounding particles.

oxbow lake[2]--cutoff portion of meander bends.

particle size[2]--the diameter of a particle measured by settling, sieving, micrometric, or direct measurement methods. *See scale of particle sizes.*

particle size average[2]--the average size of particles from a sediment sample, usually the averages of D_{10}, D_ and D_{90}. *See particle-size distribution.*

particle-size distribution[2]--the relative amount of a sediment sample of a range in specific sizes in terms of percentages by weight finer than a given size. D__ (Often shown on a semilog plot.)

particle-size intermediate axis[2]--the size of a rock or sediment particle determined by direct measurement of the axis normal to a plane representing the longest and shortest axes.

particle-size sorting[2]--a measure of the range of particle sizes in a distribution, as the percentile range D_{90} - D_{10}.

particle size, standard deviation--a statistical measure obtained from the formula $\frac{1}{2}(D_{84}/D_{50} + D_{50}/D_{10})$.

parts per million--parts by mass of sediment in a million parts of the water-sediment mixture.

plane bed--a sedimentary stream bed without elevations or depressions larger than the maximum size of the bed material.

point bar--one of a series of low accurate ridges of coarse sediment deposited on the inner (convex) side of river curves.

point-integrating sediment sampler[2]--a device designed to collect a representative sample of the water-sediment mixture at a selected depth in a stream vertical over a specific time period by opening and closing under water.

point integration[2]--a method of sampling to obtain the mean concentration of sediment at a point in a stream.

point sample--sample of water-sediment mixture taken at a single point, either with an instantaneous or a point-integrating sampler.

pumping sampler--a device that draws the water-sediment mixture through a pipe or hose, the intake of which is placed at the desired sampling point in a stream.

rating curve sediment--a graph of the relationship between stream discharge and sediment discharge at a stream cross section.

regimen of a stream[2]--characteristics of a stream with respect to flow duration, form of and changes in channel capacity to transport sediment and amount of material supplied for transportation.

rill erosion[2]--a process forming small well-defined incisions in the land surface less than 300 mm in depth. (It is an intermediate process between sheet erosion and gully erosion.)

ripple--small triangular-shaped bed forms that are similar to dunes but smaller.

roundness--the ratio of the average radius of curvature of the individual edges of a particle to the radius of the maximum circle that can be inscribed within the particle.

runoff--that part of precipitation appearing in surface streams.

sand size (fluvial sediment)--0.062 to 2 mm (*See scale of particle sizes).*

scale of particle sizes--after AGU (American Geophysical Union) scale (see Table 2).

scour--the enlargement of a flow section by the removal of the boundary material by the motion of the fluid.

sediment--particles derived from rocks or biological materials that are or have been transported by water.

sediment delivery--an obsolete, ambiguous term, use sediment yield.

sediment delivery ratio--the ratio of sediment yield to gross erosion expressed in percent.

sediment discharge[2]--the mass or volume of sediment passing a stream cross section in a unit of time.

(The term may be qualified as suspended-sediment discharge, bedload discharge, or total-sediment discharge.)

sediment load[2]--the weight of solid matter being moved by a stream through a cross section per unit of time. (Bed-material load plus wash load.)

sediment production--an obsolete, ambiguous term. Use erosion.

sediment sample[2]--a quantity of water sediment mixture or deposited sediment that is collected to represent some property or properties of the sampled medium.

sediment yield--the total sediment ____ from a watershed or past a given location in a specified period of time. (It includes bed load as well as suspended load and usually is expressed in weight per unit of time.)

sedimentation (a) consists of five fundamental processes: (1) weathering, (2) erosion, (3) transportation, (4) deposition, and (5) diagenesis, or consolidation into rock: (b) deposition of particles, especially in engineering.

sedimentology--the scientific study of sediment, sedimentary rocks, and the processes by which they were formed.

settling--the process of depositing by gravity matter suspended in water.

sheet erosion[2]--the more or less uniform removal of soil from an area by raindrop splash and overland flow, without the development of water channels exceeding 300 mm in depth. (Included with sheet erosion, however, are the numerous but conspicuous small rills that are caused by minor concentrations of runoff. The rills can be easily obliterated by normal field cultivation. Maximum depth of a rill is 300 mm. Larger water channels are gullies.)

sieve diameter--the size of sieve opening through which a given particle of sediment will just pass.

silt--individual mineral particles that range in diameter from 0.004 to 0.062 mm. Not a synonym of sediment.

siltation--not recommended. Use sediment deposition.

sloughs--a stagnant or sluggish channel of water occurring in a flood plain.

sorting--the dynamic process by which sedimentary particles are selectively separated from associated but dissimilar particles by flowing water.

specific weight of sediment deposits--the dry weight of sediment solids per unit volume of deposit in place. Synonym: volume weight.

sphericity--the ratio of the surface area of a hypothetical sphere of the same volume as the particle to the actual surface area of the particle. (A more convenient expression is the ratio of the diameter of a circle with an area equal to that of the projection of a grain when it rests on its larger face to the diameter of the smallest circle circumscribing this projection). (shape factor).

splay--deposits of flood debris (usually of sand) scattered on the flood plain.

standard-fall diameter--the diameter of a sphere with a specific gravity of 2.65 and the same standard-fall velocity as the particle.

standard-fall velocity--the rate of fall that a particle would finally attain if falling alone in quiescent distilled water of infinite extent and a temperature of 24°C.

standard-sedimentation diameter--the diameter of a sphere with the same specific gravity and fall velocity as the given particle.

streambank erosion[2]--the removal of bank material by flowing water.

stream discharge--the quantity of flow passing through a cross section in a unit of time.

supernate or supernatant--the liquid above the surface of settled sediment.

suspended-sediment load--the weight of suspended particles continuously supported by the water.

suspended-sediment discharge--the quantity of suspended-sediment passing through a stream cross section in a unit of time.

suspended-sediment sampler--a device that collects a representative portion of the water with its suspended-sediment load.

texture--the geometric aspects of the component particles of a sediment deposit or rock including size, shape, and arrangement.

terminal velocity--the limiting velocity reached by a particle falling under the action of gravity in a still liquid at a specified temperature.

thalweg--the line connecting the lowest or deepest points along a stream bed, valley, or reservoir, whether underwater or not.

topset bed--a layer of sediment deposited on the top surface of an advancing delta that is continuous with the landward alluvial plain.

traction--transport of debris by running water, in which the particles are swept along close to the bed of the stream by rolling, sliding, or saltation.

trap efficiency--the proportion of the incoming sediment load that is deposited, in percent.

transportation--the complex process of moving sediment particles by water. (The principal factors affecting transportation are turbulence, ratio of settling velocity to water velocity, shape, size, density, and quantity of particles, and saltation.)

turbidity--an expression of the optical properties of a sample which causes light rays to be scattered and absorbed rather than transmitted in straight lines through the sample. (Turbidity of water is caused by the presence of suspended and dissolved matter such as clay, silt, finely divided organic matter, plankton, other microscopic organisms, organic acids and dyes.)

turbulence--the irregular motion of a flowing fluid.

unsampled-sediment discharge[2]--the difference between the total-sediment discharge and the measured suspended-sediment discharge.

unsampled zone--the unsampled part of the sampling vertical: (usually, assumed to be 9° to 15° mm above the stream bed depending on the kind of sampler used).

valley trenching--gully erosion occurring in flood plains.

vertical--an approximately vertical path from water surface to stream-bed along which one or more samples are taken to define sediment concentration or distribution.

vertical accretion deposits--flood-plain deposits formed by deposition of suspended sediment from overbank flood waters.

volume-weight--see specific weight.

wash load--the portion of the stream sediment load composed of particles, usually finer than 0.062 mm, which are found only in relatively small quantities in the bed, assumes only in source bed.

water discharge--the quantity of water passing a stream cross section in a unit of time. (The native water contains both dissolved solids and sediment.) See stream discharge.

water pollution--the presence of harmful or objectionable material introduced into water by man's activity in sufficient quantities to adversely effect its usefulness.

watershed--all lands enclosed by a continuous hydrologic-surface drainage divide and lying upslope from a specified point on a stream.

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