Chapter 2
Channel Stability Principles

Section 1
Characteristics of Channels in Erodible Materials

2-1. Geomorphic Context

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

b. In general terms, a drainage basin can be divided into three main zones: an upper erosional zone of sediment production, a middle zone of sediment transport with simultaneous erosion and deposition, and a lower zone of sediment deposition (Figure 2-1). The actual situation is often more complex, because local geological controls or other factors can produce local depositional zones in the upper basin or local erosional zones in the lower basin. Flood control projects are more common in the middle and lower zones where the stream overflows frequently onto agricultural or urban land. Methods of estimating sediment production or yield are described in Chapter 3 of EM 1110-2-4000.

c. In the general case, the longitudinal profile of the stream system tends to flatten through time by degradation in the upper reaches and aggradation in the lower reaches (Figure 2-2). In most natural systems this process is slow enough to be of little engineering concern; but where the stream system has been interfered with in the historical period, profile flattening may be proceeding at noticeable rates. In some channelization projects, response of this type has been dramatic (see Chapter 3 for examples).

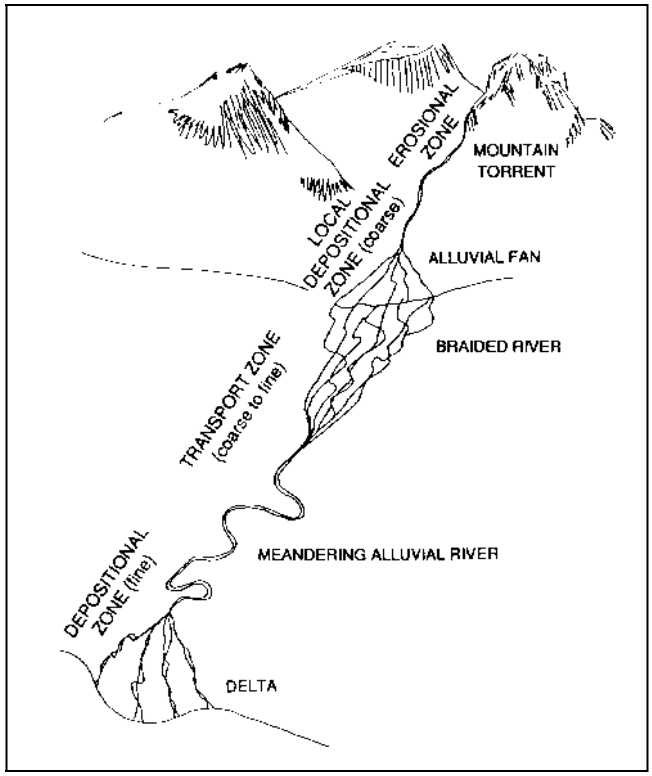


Figure 2-1. Drainage basin zones and some channel types

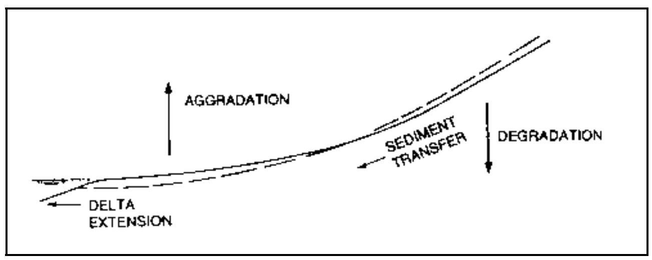


Figure 2-2. Typical longitudinal stream profile and direction of change through time

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

e. Selected references on the geomorphology and hydraulics of stream systems are listed in Appendix A.

2-2. Common Channel Types

A number of common channel types and their characteristic stability problems are described below and summarized in Table 2-1.

a. Mountain torrents. These are high-velocity streams on steep slopes, often exhibiting a sequence of drops and chutes controlled by large boulders, fallen timber, etc. (Figure 2-3). Erosion and deposition are sometimes confined to severe flood events. Some mountain torrents on very steep slopes are subject to the phenomenon of "debris flows" or "debris torrents" whereby under severe flood conditions the bed becomes fluid and a virtual avalanche of boulders and gravel runs down the mountainside.

b. Alluvial fans.

(1) Alluvial fans generally occur where a stream emerges from a mountain valley onto relatively flat land (Figure 2-4). They are depositional features usually characterized by coarse alluvial materials and unstable multiple channels subject to frequent shifts or "avulsions." The main channel is often "perched" on the highest ground. Sometimes the alluvial fan is inactive depositionally, and the stream is eroding into earlier deposits. They are usually easily recognizable on aerial photographs and sometimes on topographic maps. In wooded country they are not always easily recognized on the ground.

Table 2-1
Some Stream Channel Types and Their Characteristic Stability Problems

Channel Type	Typical Features	Stability Problems
Mountain torrents	Steep slopes Boulders Drops and chutes	Bed scour and degradation Potential for debris flows
Alluvial fans	Multiple channels Coarse deposits	Sudden channel shifts Deposition Degradation
Braided rivers	Interlacing channels Coarse sediments(usually) High bed load	Frequent shifts of main channel Scour and deposition
Arroyos	Infrequent flows Wide flat channels Flash floods High sediment loads	Potential for rapid changes in planform, profile, and cross section.
Meandering rivers	Alternating bends Flat slopes Wide floodplains	Bank erosion Meander migration Scour and deposition
Modified streams	Previously channelized Altered base levels	Meander development Degradation and aggradation Bank erosion
Regulated rivers	Upstream reservoirs Irrigation diversions	Reduced activity Degradation below dams Lowered base level for tributaries Aggradation at tributary mouths
Deltas	Multiple channels Fine deposits	Channel shifts Deposition and extension
Underfit streams	Sinuous planform Low slope	Meander migration
Cohesive channels	Irregular or unusual planform	Variable

Figure 2-3. Mountain torrent

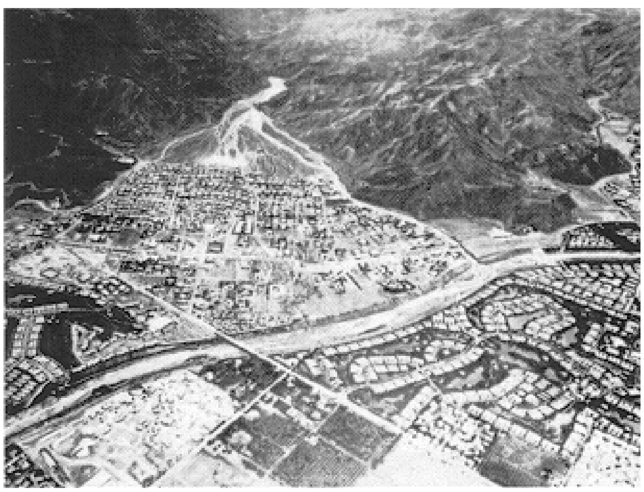


Figure 2-4. Alluvial fan

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

c. Braided rivers. Braided rivers consist of a network of interlacing channels with unstable bars and islands (Figure 2-5). They generally occur in the upper and upper-middle zones of a basin. Bed materials are usually gravels or cobbles, but braided sand rivers are found occasionally. Bed material transport tends to be high, at least in flood periods. Stability problems include how to maintain the channel through transport of the bed material load and how to avoid serious disturbances of the longitudinal profile. Points that require consideration are the planned cross section, the alignment in plan, and provision for future shifting and erosional attack.

Figure 2-5. Braided river

d. Arroyos. Arroyos are streams in deserts and arid areas that are dry much of the time but carry large discharges and heavy sediment loads under occasional flood conditions (Figure 2-6). The channel may be deeply incised into the terrain in some reaches and liable to frequent overspill in others. Because of the heavy sediment loads, infilling by deposition can occur very quickly if velocities are reduced by enlargement, weirs, or other works.

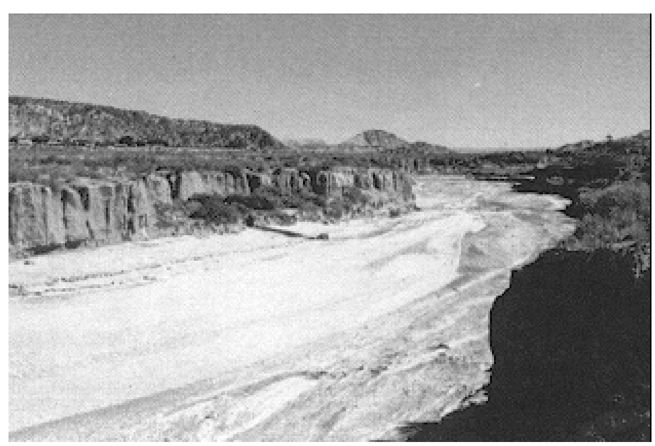


Figure 2-6. Arroyo

e. Meandering alluvial rivers.

(1) These generally occur in the middle and lower zones of a basin. The single channel follows a characteristic sinuous planform and is normally eroding into the floodplain on one bank and creating new floodplain by deposition on the opposite bank. Bed material is usually sand or sand and gravel. In undisturbed natural systems, future shifting of the channel is often predictable from comparison of sequential maps or aerial photographs. In many cases the traces of former channel locations are detectable on aerial photographs (Figure 2-7).

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

f. Modified streams.

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

(2) A particular regional type of modified stream is exemplified by the incised channels of northern Mississippi (Figure 2-8). These are hill streams in erodible soils that often have a long history of response to widespread basin erosion following land-use changes, channelization, and/or altered base levels. Planning of flood control works on a stream of this type should take into account its present state of evolution toward a new equilibrium.

g. Regulated rivers. These are generally streams where the flood discharges have been reduced and the low flows increased by upstream storage reservoirs (Figure 2-9). Such streams often exhibit a reduction in morphologic activity compared with previous natural conditions, and the cross sections of their channels may have been reduced by deposition of sediment and encroachment of vegetation. But if the stream under natural conditions carried substantial loads of bed material, trapping of sediment in reservoirs may initiate slope changes downstream. The effects of regulation on stability are thus complex and depend on the previous characteristics of the stream as well as on the degree and mode of regulation.

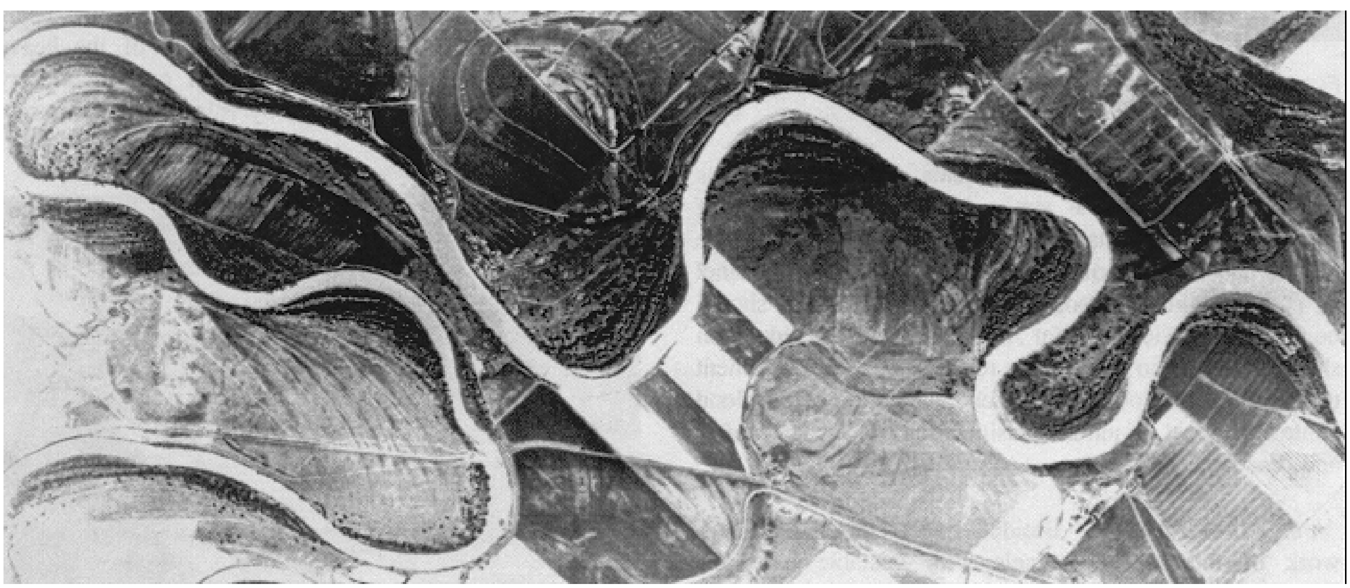


Figure 2-7. Meandering alluvial river

Figure 2-8. Incised channel

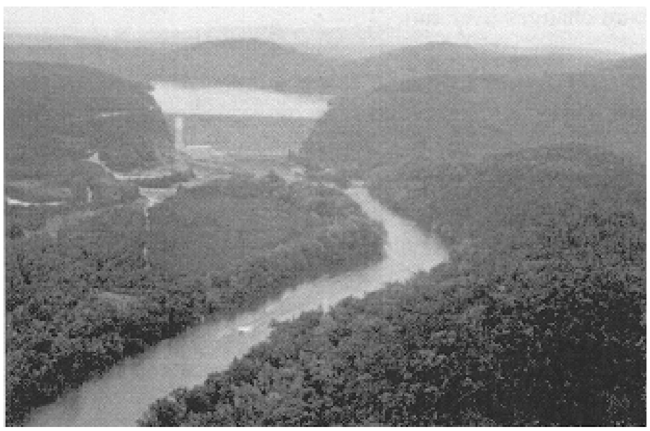


Figure 2-9. Regulated river

h. Deltas. Deltas somewhat resemble alluvial fans but occur on flat slopes where a river discharges into still water and deposits its sediment load (Figure 2-10). Under natural conditions the river splits into a number of distributaries, whose bed levels rise over time as the delta extends into the water body. Flood control levees adjacent to deltas can require periodic raising, particularly if the river is confined artificially to a single channel. The potential for channel avulsions upstream of the works requires consideration.

i. Underfit streams.

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

Figure 2-10. Delta

(2) Underfit streams are also found throughout the country in abandoned river courses and as a result of flood control works such as levees and reservoirs. Underfit streams can sometimes be realigned and shortened without creating instability problems. However, there are also many instances in which shortening might cause severe instability problems.

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

2-3. Channel Geometry and Processes

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

a. Planforms.

(1) Stream planforms were once roughly classified as braided, meandering, and straight; but a wide variety of natural forms are now recognized. Figure 2-11 shows a more extended set of descriptions with associated environmental conditions.

(2) Relationships between planform and other aspects of geometry and processes are difficult to systematize, although often appreciated intuitively from long experience of river observation. For example, braided rivers are usually wide and shallow, and the limits of the braided area tend to remain relatively stable. Certain types of sinuous planform generally indicate a systematic process of down-valley meander migration, while others indicate a process of periodic bend cutoffs. Streams with highly contorted meandering planforms tend to have relatively flat slopes and low width-to-depth ratios. Figure 2-12 attempts to summarize available information on channel pattern, type, and associated variables, and Figure 2-13 illustrates various forms of meander shifting. The total length of most natural streams does not change appreciably over time despite dynamic changes in planform and channel location. For example, local shortening produced by occasional meander bend cutoffs is usually compensated for by gradual lengthening of other bends. Where overall shortening is imposed, the stream often responds by attacking banks and developing new meanders in an attempt to restore the original length.

b. Cross sections.

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

(2) The process of cross-section enlargement by erosion is easy to visualize. The mechanism of shrinkage is less easy to visualize and varies considerably (Figure 2-14). In a more or less straight channel, it can occur as a result of deposition of suspended sediment on the banks and subsequent colonization by vegetation. In a shifting meandering channel, shrinkage will occur if the rate of deposition on the inner bank of bends exceeds rate of erosion on the outer bank.

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

(4) When hydraulic computations of channel capacities and water surface profiles are made for active mobile-boundary streams, it is important to realize the transitory nature of cross sections. Although the average channel cross section over a long reach may be similar under low-water and flood conditions, individual cross sections may change substantially according to the stage of flow. For example, bends and scour holes in meandering channels normally deepen in floods, and points of inflection (“crossings”) tend to shoal. When water surface profiles are modelled using standard computational procedures based on fixed boundaries, boundary mobility must be considered and a sensitivity analysis performed if necessary.

(5) Further hydraulic difficulties with unstable cross sections arise when in-channel flows are to be systematically increased as a result of flood control, for example, by construction of floodplain levees close to the channel. If the channel is left in its natural state, it may enlarge systematically over a period of time as a result of erosion by the increased flows. Actual flood levels would then tend to be lower than those computed using existing cross sections. On the other hand, if the channel is designed to be enlarged by excavation, the cross sections provided may be partly infilled by sediment deposition, in which case actual flood levels would be higher than computed. A common error in designing modified channels for flood control is to provide too large a cross section, intended to carry a rare flood without overbank flow. Such a cross section is unlikely to maintain itself because it partly infills with sediment under more frequent flood conditions. Although a need for dredging or excavation to maintain the enlarged channel may be recognized and provided for in project agreements, experience has shown

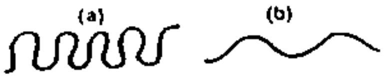
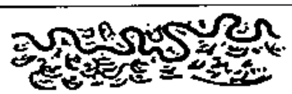
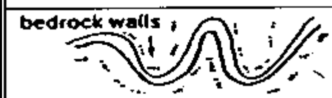
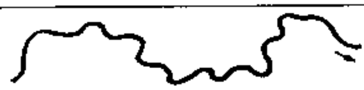
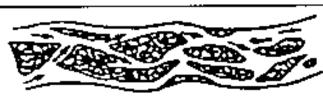
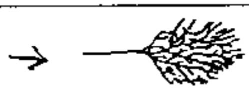
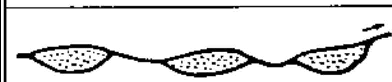
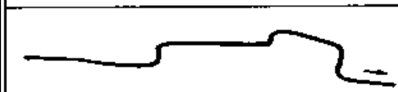
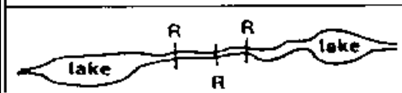
CHANNEL APPEARANCE	CHANNEL TYPE	TYPICAL ENVIRONMENT	TYPICAL BED AND BANK MATERIALS
	(a) Regular serpentine meanders (b) Regular sinuous meanders	Lacustrine plain	Uniform cohesive materials
	Tortuous or contorted meanders, no cutoffs	Misfit stream in glacial spillway channel	Uniform cohesive materials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

Figure 2-11. Some forms of stream planform (after Mollard and Janes 1984)

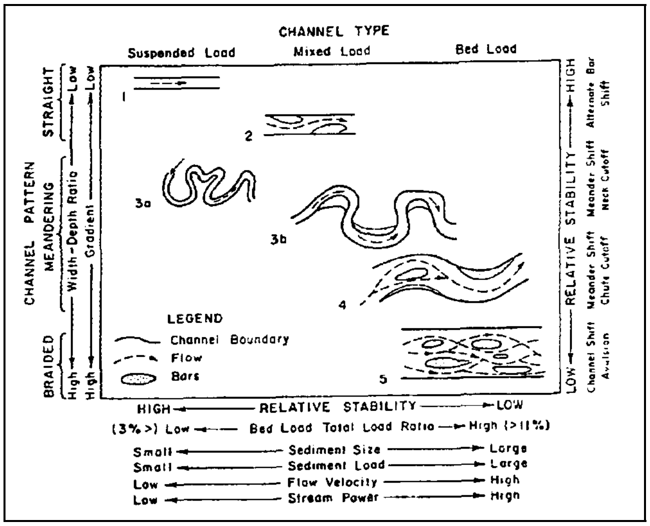


Figure 2-12. Channel classification based on pattern and type of sediment load (Schumm and Meyer 1979, courtesy of Simons, Li & Associates)

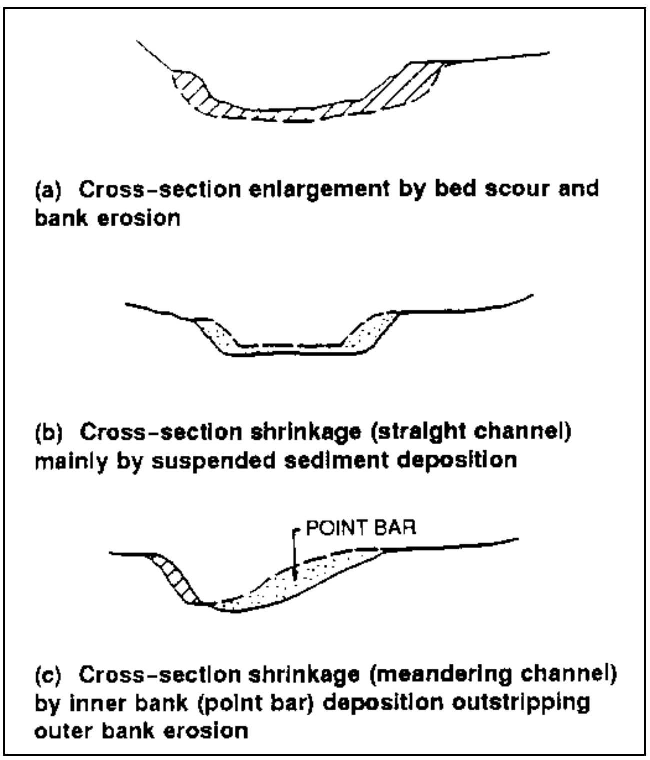


Figure 2-13. Examples of meander shifting and bank erosion (Brice 1984, courtesy of American Society of Civil Engineers)

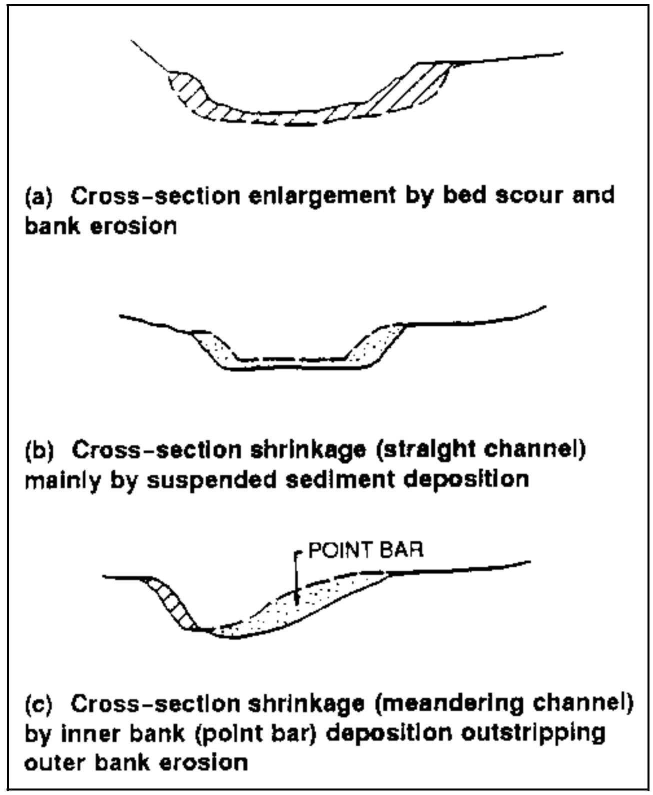


Figure 2-14. Mechanisms of cross-sectional adjustment to altered inputs of water and sediment

that it is often difficult to enforce such maintenance obligations.

c. Slopes and profiles.

(1) The longitudinal profile of a stream is only partly determined by the landscape. The channel is flatter than the valley slope unless the channel is straight. In many cases, the channel slope represents a long-term equilibrium condition. When a meandering stream is straightened, a steeper non-equilibrium slope is temporarily imposed. Responses in the form of erosion and deposition are then set in motion, in the direction of restoring equilibrium.

(2) The slope of a stream usually flattens gradually from source to mouth. However, local anomalies due to geological controls and other factors are common; for example, the slope will be flatter upstream of a bedrock sill, and steeper below a tributary that delivers quantities

of coarse sediment. Reduction of slope from head to mouth along a stream is related to changes in other characteristics; sometimes changes are relatively abrupt (Figure 2-15).

(3) Processes of channel profile change through time at rates of engineering concern are usually referred to as aggradation and degradation (Figure 2-16). For example, aggradation tends to progress upstream from a dam or grade control structure, and degradation to progress downstream from a structure that traps sediment.

(4) A process referred to as headcutting, common in channelized streams, involves degradation progressing upstream, often accompanied by aggradation progressing downstream. The upstream end of a headcut is called a nick point, or nick zone if it extends some distance along the stream.

d. Bed topography and roughness.

(1) The bed topography and hydraulic roughness of natural channels may vary greatly along the channel and also with stage of flow. The total hydraulic resistance results from a combination of grain roughness and form roughness. Form roughness can arise from bed and bank irregularities and from changes in planform. In active sand channels, bed forms may range from small ripples a few inches in height, to dunes a few feet in height, to larger waves and bars (Figure 2-17). These forms depend on flow conditions and mainly control the hydraulic roughness of the bed. Also, the bed topography at any time depends on the preceding flow history as well as on present conditions. Roughness therefore varies with stage and is not always the same at similar stages - one reason for the looped or erratic stage-discharge curves found in many alluvial streams. Other important sources of form roughness are trees and bushes, river bank protection and structures, floodplain obstructions, bedrock outcrops, bends and scour holes, and abrupt changes in cross section.

(2) Channels formed in coarser sediments have different and often more stable forms of bed topography than sand-bed channels. In gravel-bed streams, the dominant form of bed topography tends to be an alternation of pools and riffles: the pools are characterized by flatter local slopes and finer bed materials, and the riffles by steeper slopes and coarser materials. Bar characteristics and flow resistance in coarse-bed streams are described by various authors (Hey, Bathurst, and Thorne 1982). Armoring, whereby the material on the bed surface is coarser than the underlying material, is described in a related publication (Thorne, Bathurst, and Hey 1987). Some of the features of natural gravel rivers tend to develop in channelized rivers and artificial channels. Armoring is common in regulated streams downstream of storage reservoirs.

(3) When discharges are augmented by flood control works, the prevailing type of bed topography may alter significantly. For example, steep sand streams with high sand transport undergo an abrupt change at a certain flow threshold, whereby the bed forms “wash out” and a more or less flat bed with reduced roughness results (Figure 2-18). This phenomenon tends to reduce flood levels, but to increase velocities with adverse consequences for channel stability. It may cause abrupt anomalies in stage-discharge curves. In some sand-bed channels, bed topography and roughness may also respond to changes in water temperature at a constant flow.

Section II
Principles of Channel Equilibrium and Response

2-4. Basic Concepts

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

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

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

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

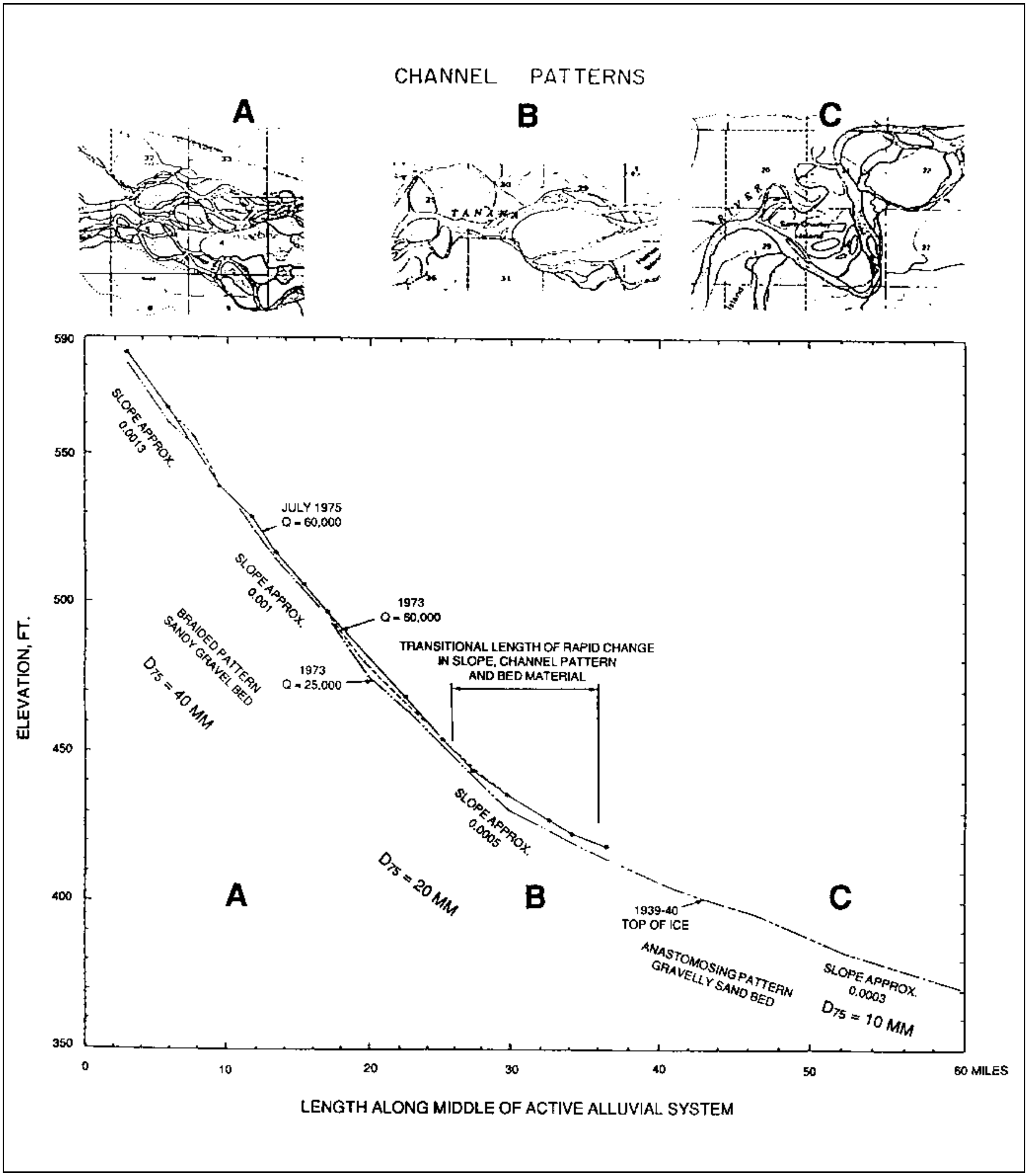


Figure 2-15. Associations between slope, planform, and bed material, Tanana River near Fairbanks, Alaska (from Buska et al. 1984)

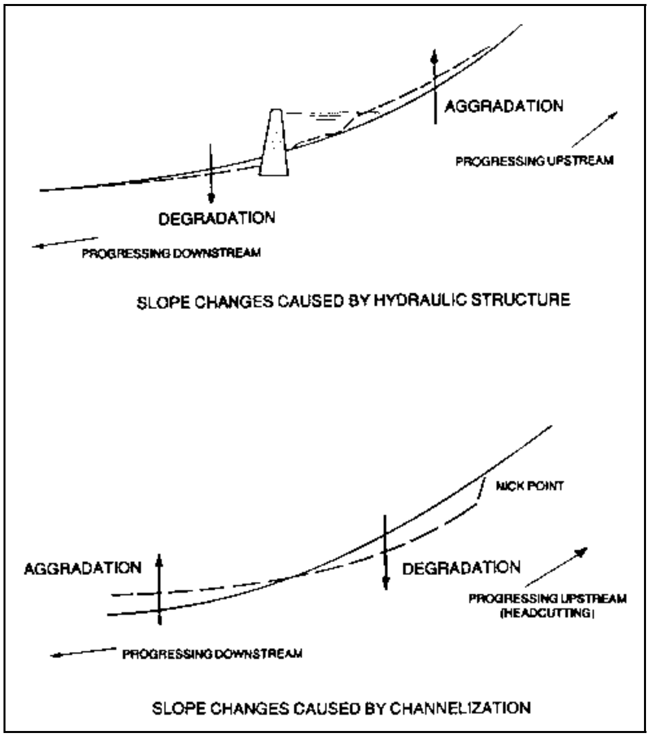


Figure 2-16. Processes of channel slope change

b. The equilibrium or regime concept has been tested against sets of river and canal data from various parts of the world (see Graf 1984, Mahmood and Shen 1971, Nunnally and Shields 1985). Channel widths, depths, and slopes are usually plotted independently against a characteristic discharge. Plots are sometimes stratified according to bed material size or other factors. Curves or equations are fitted and recommended for various analysis and design purposes. The general trend of plots by various investigators is illustrated in Figure 2-19.

c. The regime concept to stability assessment and channel design is essentially empirical. It has been regarded cautiously by many hydraulic engineers because of lack of theoretical verification and sometimes because relationships derived from one region did not fit experience elsewhere. Stevens and Nordin (1987) criticize various aspects of the traditional approach, but conclude: "Lindley's regime concept that an alluvial channel adjusts its width, depth and slope in accordance to the amount of water and the amount and kind of sediment supplied remains unchallenged here. Regime channels are those flowing in their own sediment."

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

e. The term stable channel has been used extensively in the engineering literature but is also subject to confusion. It is often used to mean a channel that has attained stability of width, depth, and slope. Such a channel, however, may be actively meandering, in which case it is not stable in planform. To avoid confusion, the term is generally avoided in this EM.

2-5. Applicability to Flood Control Projects

a. Reduced to essentials, the equilibrium concept implies that stable width, depth, and slope (and perhaps planform) can be expressed as functions of controlling variables: discharge, boundary materials, and sediment supply (Figure 2-20). Hydraulic geometry relationships may be useful in the planning stages of a flood control project for comparing alternatives and assessing certain stability problems.

b. The concept of degrees of freedom is sometimes useful for visualizing forms of potential instability in erodible channels caused by changes in controlling variables. As a general case, a channel may have at least four degrees of freedom; that is, it can adjust its planform, width, depth, and slope. Other factors such as roughness, bank line shift rates, and sediment transport may also adjust.

c. Some features and difficulties of the equilibrium concept are discussed as follows:

(1) Hydraulic geometry relationships (Figure 2-19) usually deal with width, depth, and slope, but not planform. Stability problems related to planform, for example, whether meanders will develop in an initially straight channel, therefore seem to be outside the scope of traditional equilibrium concepts. Meander geometry is discussed in paragraph 5-9.

(2) Most hydraulic geometry relationships use a single characteristic discharge, intended to be representative of the actual varying discharges, as a primary independent variable. In natural streams this is often taken as the

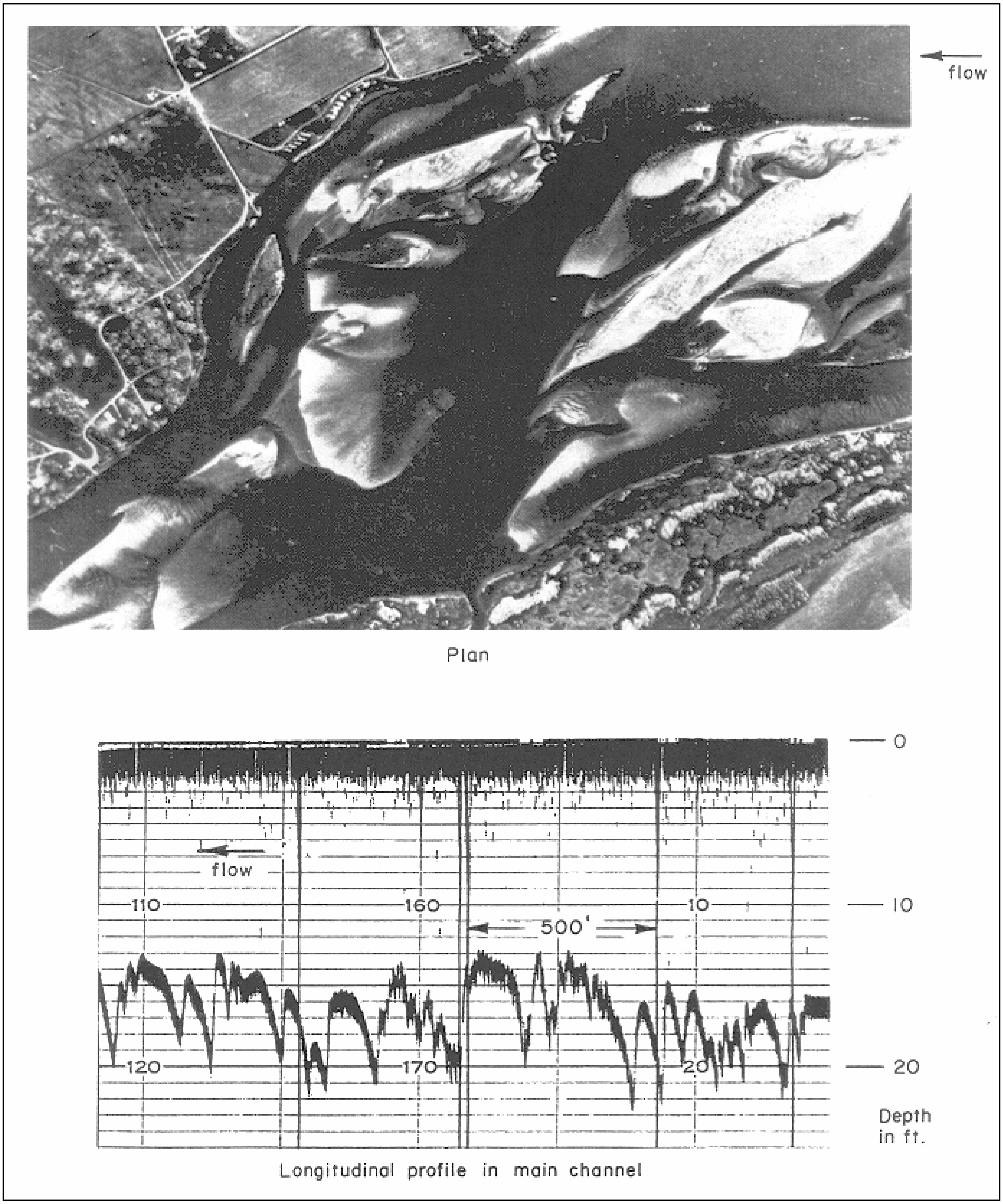


Figure 2-17. Bed forms in sand (Missouri River)

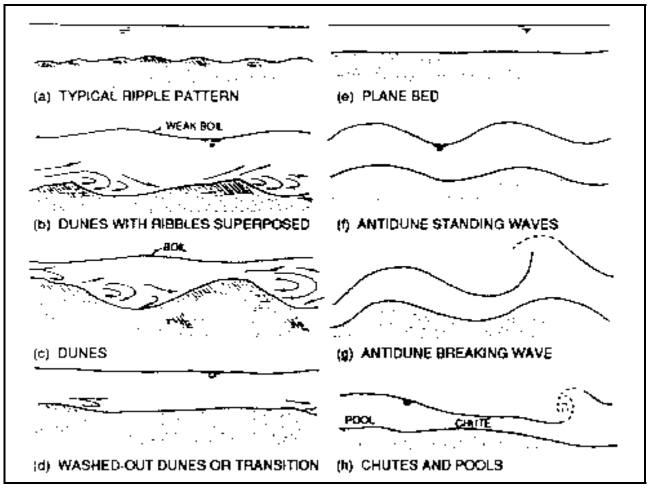


Figure 2-18. Response of bed forms in sand to increasing discharge (a through h) (after Simons and Richardson, 1961)

bank-full discharge, or a more or less equivalent flood-frequency parameter. The terms channel-forming and dominant discharge have been widely used in the literature, and are discussed further in paragraph 2-8.

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

(4) The earlier hydraulic geometry relationships did not explicitly consider sediment transport, and were applicable mainly to channels with relatively low bed material inflows. Equilibrium slopes indicated by such relationships may be too flat to maintain transport of sediment in channels with substantial bed material inflows. Some hydraulic geometry relationships incorporating sediment transport as an input variable have been published (e.g., White, Paris, and Bettess 1981a); but the difficulty remains that at the planning stage of a project, actual sediment inflows are seldom known. Information on assessing sediment inflows can be found in EM 1110-2-4000.

d. A method of applying equilibrium concepts that avoids acceptance of relationships established in unfamiliar or distant environments is to develop local or regional hydraulic geometry relationships for the class of channels of interest. Derived relationships can then be applied to estimate flood control channel dimensions or responses in a particular stream. For example, the consideration of possible width adjustments resulting from augmentation of flood discharges would use a locally developed width-discharge plot rather than a published plot derived from another region. Figure 2-21 shows an example.

2-6. Response of Channels to Altered Conditions

a. Instability and sedimentation have two aspects with respect to flood control channels: the impact of existing processes on the project, and the impact of project changes on the stream system both within and beyond the project length. This section is concerned mainly with the second aspect.

b. If the controlling variables or boundary properties (see Figure 2-20) are altered, the stream or channel will respond by altering cross section, slope, or planform.

c. It is often difficult to determine to what extent observed postproject instability represents a response, or whether it might have occurred in any case as a result of preproject processes. This is especially difficult where the stream has a history of successive modifications from a long-ago natural state. In some cases, long-term

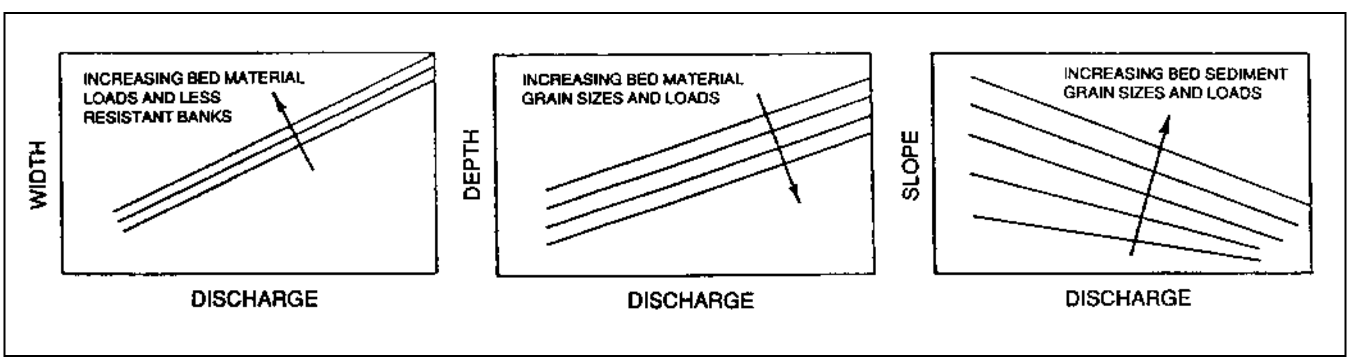


Figure 2-19. General trend of hydraulic geometry plots for channels in erodible materials

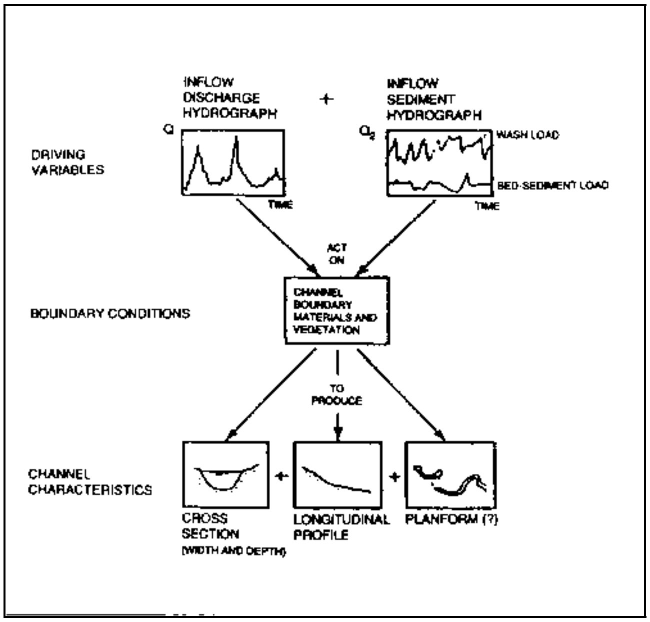


Figure 2-20. Generalized equilibrium concept for long-term formation and response of erodible channels

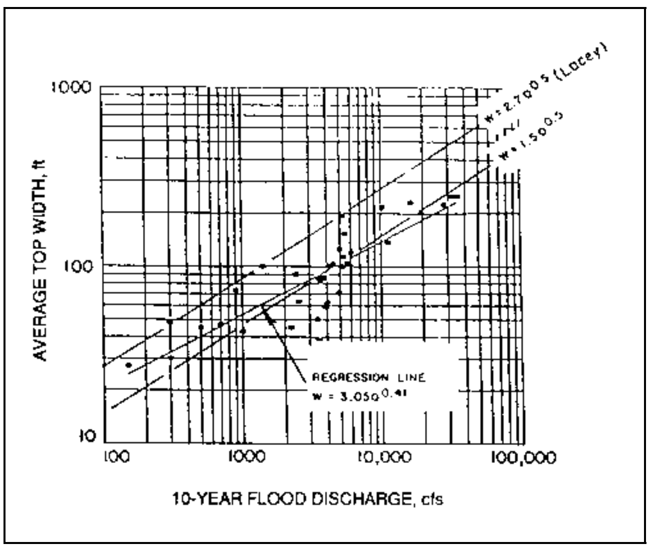


Figure 2-21. Width-discharge plot for specific local set of channels. (Note: 10-year discharge used because of special local circumstances)

responses to a historical sequence of interferences may be extremely difficult to distinguish.

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

e. Table 2-2 indicates the general direction in which channel characteristics can be expected to respond to changes in driving variables or boundary conditions (see also Figure 2-19).

f. Some additional comments are as follows:

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

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

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

(4) Depths increase with increasing discharges, but not so much as widths (Figure 2-19). Depths will generally decrease with increased bed material inflow, as slopes increase (see (5) below).

(5) Slopes vary inversely with discharges (Figure 2-19), and tend to reduce by degradation if flood discharges are increased. Slopes tend to increase by aggradation if bed material inflows are increased, and depths reduce correspondingly. Increases in discharge and in bed material input therefore have opposite effects on slope and may largely cancel out if they occur together, for example, as a result of upstream deforestation.

(6) The most widely known geomorphic relationship embodying slope and the equilibrium concept is known as Lane's (1955) principle and can be expressed in the form:

Table 2-2
Expected Response of Channel Characteristics to Changes in Driving Variables or Environmental Conditions (see Figure 2-19)

Variable Subject to Imposed Change	Nature of Change	Expected Change in Channel Characteristics (Exceptions May Occur)				
		Width	Depth	Slope	Platform Type	Bank Erosion
Discharges	Increased	Increased	Increased	Reduced	No marked change	Increased
	Reduced	Reduced or unchanged[1]	Reduced	Increased or unchanged[1]	No marked change	Reduced
Bed-sediment inflows	Increased	Unclear	Reduced	Marked increase	Increased bars and channel splitting	May increase
	Reduced	Unclear	Increased	Reduced	Less channel splitting	May reduce
Bed-sediment grain size	Increased	Insignificant	Reduced	Marked increase	Unclear	Unclear
	Reduced	Insignificant	Increased	May reduce	Unclear	Unclear
Bank conditions	Add bank protection	May reduce	May increase locally	No marked change	As imposed	Reduced locally, may increase downstream
	Removal of woody vegetation	Increased	May reduce	No change	Increased bars	Marked increase

[1] Depending on availability of sediment for deposition.

$$QS \sim Q_s\, D_{50} \qquad (2\text{-}1)$$

where

Q = discharge, ft^3/sec

S = slope, ft/ft

Q_s = bed material discharge, tons/day

D_{50} = median sediment size, ft

This form of relationship indicates that imposed increases in slope lead to an increase in sediment transport assuming the water discharge and sediment size remain constant. If a sinuous channel is straightened, an increased slope is imposed, and increased bed material transport occurs out of the straightened reach, causing degradation upstream and aggradation downstream. The channel thereby attempts to reestablish the original slope.

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

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

2-7. Channel Evolution and Geomorphic Thresholds

a. The sequence of responses to certain imposed changes, for example channelization, can be quite complex. An initial profile response may involve temporary aggradation while a later or final condition may involve degradation below original levels (Figure 2-22).

Similarly, bed degradation may undercut high banks and deliver quantities of sediment that temporarily halt or reverse degradation at downstream points. The equilibrium concept generally refers to a supposed final condition following response to a change. In some cases, however, intermediate conditions during the evolution to an eventual equilibrium may be of equal interest.

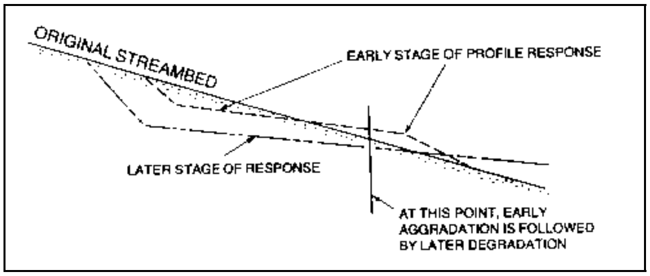


Figure 2-22. Example of complex profile response to channelization

b. Conceptual models of evolutionary response to certain types of channel modification have been developed from field studies. Figure 2-23 shows a scheme developed for incised channels in northern Mississippi, where a complex sequence of responses has occurred as a result of historic basin erosion and sedimentation, past flood control channelization, and alteration of main stem base levels (Schumm, Harvey, and Watson 1984). The model considers cross sections and slopes, but not planforms. The illustrated sequence of cross-sectional types represents a down-channel progression at a point in time, but can also represent time-dependent progression at a point on the channel.

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

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

e. Various sets of data have been analyzed to discriminate between single and braided channels on the basis of discharge, slope, and in some cases bed material grain size (Leopold, Wolman, and Miller 1964; Ferguson 1984; Struiksma and Kloassen 1988; Kellerhals and Church 1989). These show that for a given bed material and characteristic discharge, braiding is associated with higher slopes. This suggests that if a single channel is subjected to increasing bed material inflows that cause slope to increase, a point will be reached at which braiding develops; however, this may not be possible if the channel is confined by resistant banks. Figure 2-24 shows a composite plot of braiding criteria.

2-8. Hydraulic and Geotechnical Controls

The main driving variables and boundary properties that affect channel characteristics and response are discussed further below (see also Figure 2-20 and Table 2-2):

a. Discharge.

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

(2) In natural streams the channel-forming discharge can often be taken as equivalent to the bank-full discharge. In terms of flood frequency, a return period of around 2 years appears to be common in the eastern half of the United States. In most cases a return period between 1 and 10 years is appropriate. The question of altered channel-forming discharge under project conditions is referred to in paragraph 5-5.

b. Sediment inflows.

(1) Figure 2-20 treats sediment inflows as an external control on channel equilibrium, implying that the sequence of sediment discharges entering the reach of interest is independent of conditions within the reach. Part of the sediment load interchanges with the channel boundaries, and sediment can accumulate within a reach or be augmented by erosion within the reach. Sediment transport within the reach and sediment outflows from the reach are therefore affected by reach processes as well as by inflows.

(2) Sediment in streams can be divided into bed material load and wash load (Figure 2-25). Bed material

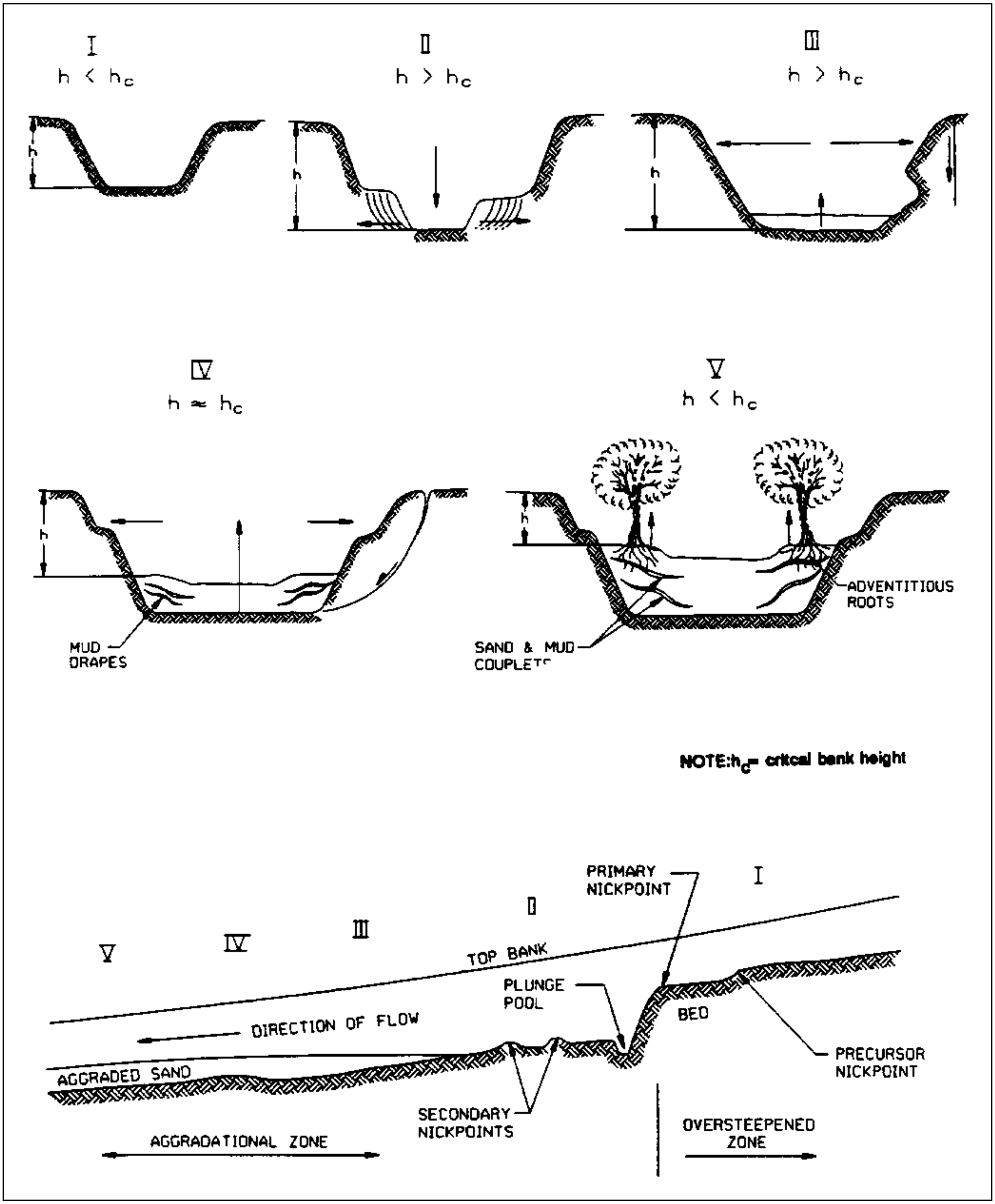


Figure 2-23. Channel evolution model for incised channels (Schumm, Harvey, and Watson 1984, Courtesy of Water Resources Publications)

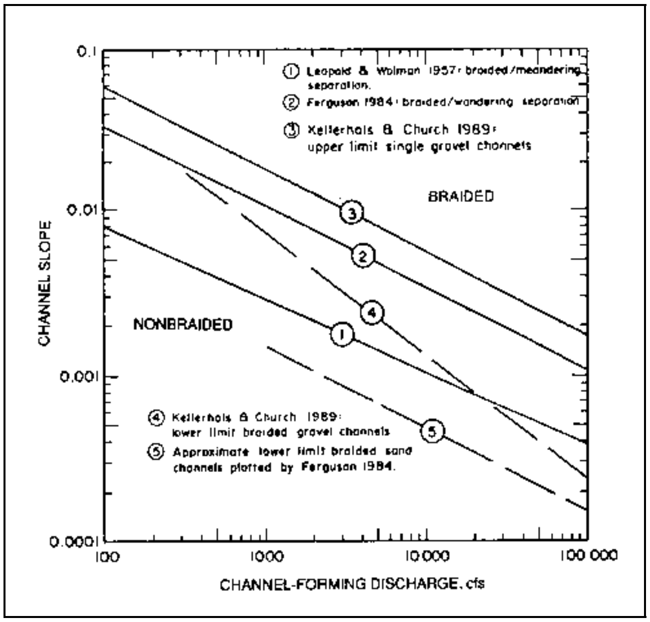


Figure 2-24. Slope-discharge chart distinguishing braided from non-braided channels

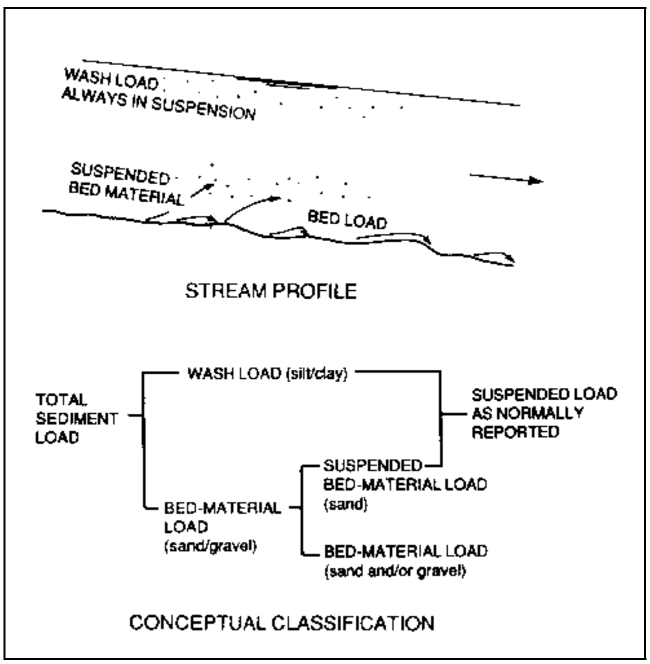


Figure 2-25. Classification of stream sediment loads

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

(3) Bed material load has an important influence on channel slope, planform, and cross section, as indicated by Table 2-2. Generally, increased bed material load tends to reduce channel stability, because it forms local deposits that divert flow against banks and so on. Increased wash load, on the other hand, may increase bank stability, because it deposits silt and clay on banks during flood recessions, which tends to increase erosion resistance and promote vegetation growth.

(4) Equation 2-2 is useful for qualitative prediction of channel response to natural or imposed changes in a river system. For example, in considering short-term response to a sudden increase in slope—as from channel straightening, and assuming the water discharge and bed material particle size remain constant, the bed material sediment discharge will increase, i.e.,

$$Q_s^- \, D_{50}^0 \sim Q_s^0 \, S^- \qquad (2\text{-}2)$$

The superscript ^{0} indicates no change. Thus, if the slope increases, denoted by S^+, then for the relationship to remain balanced, the sediment discharge Q_s must also increase as denoted by Q_s^+. In the long term, however, the slope will adjust to the long-term bed material input from the basin.

c. Bed material size.

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

(2) Figure 2-26a shows grain size distributions of bed material and measured bed load in a sand/gravel river. Because material in the coarse sand and fine gravel

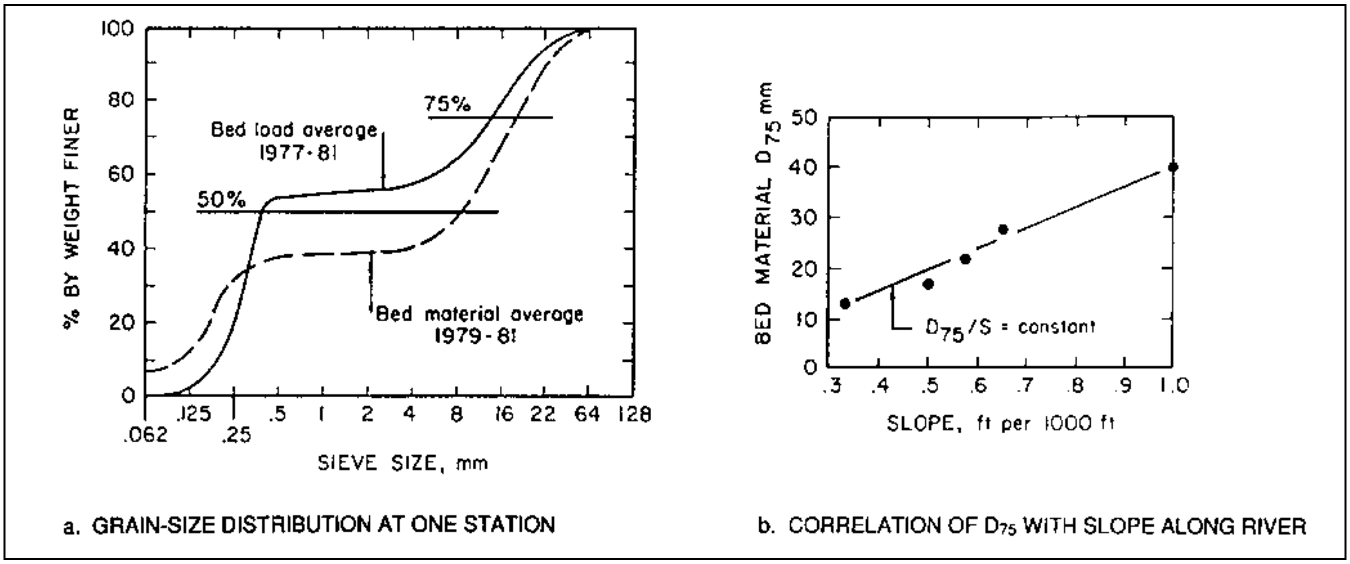


Figure 2-26. Bed material grain size distributions and correlation with slope (Tanana River near Fairbanks, Alaska) (from Buska et al. 1984).

categories is virtually absent, the two distributions show D_{50} values of 8 mm and 0.4 mm, respectively, which greatly exaggerate the overall difference. When the D_{75} size, which falls clearly into the gravel range, was used to represent the bed material distribution, a good correlation was obtained with slope variation along the river (Figure 2-26b).

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

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

(1) For fully alluvial streams flowing within an envelope of self-deposited sediments, it is debatable whether bank materials should be considered as independent factors affecting channel characteristics (Figure 2-20). Vegetation, however, is more clearly an independent factor. Instability is often triggered by the clearing of vegetation from streambanks, and sometimes by eroded and deadfall vegetation within the channel. The role of bank vegetation varies greatly with the region and type of vegetation. Vegetation established on bars during low-flow periods can have a significant effect on channel capacity and processes. Vegetation has been treated as a variable in some hydraulic geometry relationships (Hey and Thorne 1986).

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

(3) The effect of geotechnical bank stability on channel characteristics is important in some environments. River engineers have tended to regard bank instability more as a consequence than a cause of channel instability, the reasoning being that collapse of the upper bank is initiated by hydraulic scour at the toe. Geotechnical mechanisms, however, appear to be significant primary causes of alluvial bank failures within certain large drainage basins. Hagerty (1992) discusses sequences of alluvial bank failure and erosion of failed soil along streams and rivers. According to Thorne and Osman (1988), bank stability characteristics affect hydraulic geometry in both straight and meandering channels. This topic is discussed further in paragraph 5-9.

e. Ice and frozen ground.

(1) The influence of floating ice on channel characteristics and stability is relatively small except where the ice season is a large part of the year and the largest flows occur during ice breakup, as in Alaska and northern Canada. Channel characteristics in far northern regions include ice-formed features like boulder ridges and paving (Figure 2-27a), and peculiar forms of channel planform resulting from ice jamming.

(2) The direct erosive action of ice on riverbank materials is generally small compared to that of flowing water, but ice easily removes vegetation up to the normal level of ice breakup (Figure 2-27b). Ice blockages can concentrate flows and cause bank erosion and bed scour at certain locations.

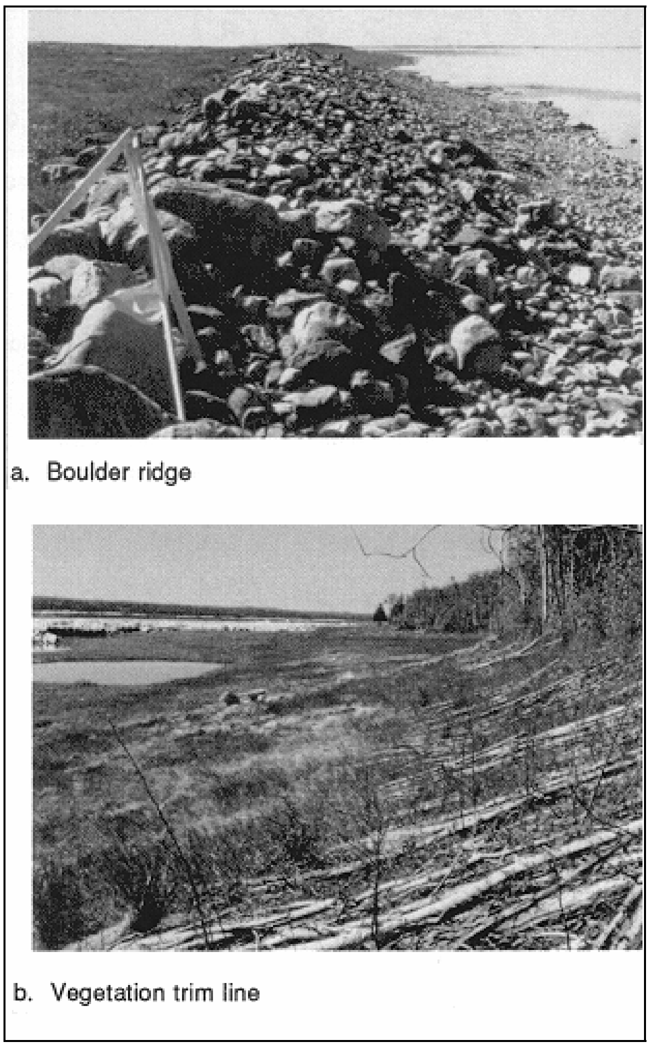


Figure 2-27. Ice effects on banks of northern rivers

(3) With regard to frozen ground, Gatto (1984) states: "The effect of permafrost on erodibility is perhaps the factor about which there is most debate.... Some investigators report that ice-rich permafrost increases bank recession.... Other investigators conclude that frozen sediments are harder to erode...." It therefore appears that frozen ground may accelerate or retard bank erosion, depending on the nature of the frozen sediments and the content of pure ice. Hydraulic geometry in cold regions does not appear to be greatly different from elsewhere, but frozen banks may exhibit unusual forms of erosion (Figure 2-28).

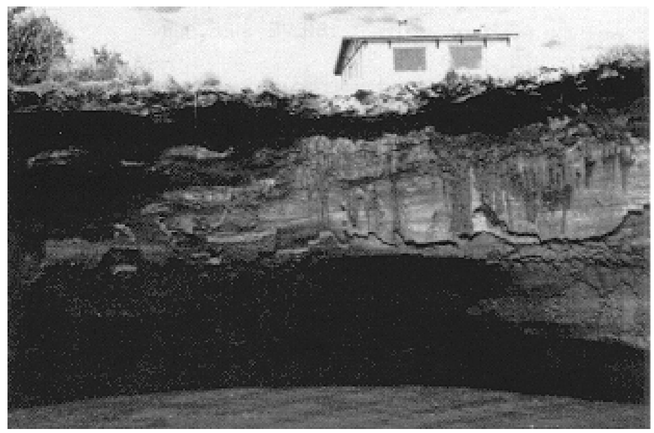


Figure 2-28. Undercut bank erosion in frozen fine-grained alluvium (Kuskokwim River, Alaska)