Chapter 5
Evaluation of Stability

5-1. General

a. The purpose of this chapter is to provide assistance in evaluating the stability of existing or proposed channels that form part of a flood control project. The meaning of stability as used herein is defined in paragraph 1-1.

b. A stability evaluation of some type should be conducted early in project planning 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 long-term viability of a project. Once key planning decisions have been made, it may be difficult to modify the project sufficiently to avoid serious stability problems.

c. There has been a tendency in the past to defer treatment of stability problems to postconstruction 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.

d. Stability evaluation will normally be directed toward 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. When stability evaluation indicates a need for detailed studies of sediment yield, transport, or deposition, reference should be made EM 1110-2-4000. The appropriate level of detail for a particular evaluation depends on the status of the study, the perceived seriousness of potential problems, the scale of the project, and the resources available.

5-3. Technical Approaches and Their Application

a. Approaches and techniques that have been used for quantitative evaluation of channel stability include allowable velocity, allowable shear stress, stream power, hydraulic geometry relationships, sediment transport analysis, and bank slope stability analysis. Most of those techniques do not provide a complete solution, and are best regarded as aids to judgment rather than self-sufficient tools. For example, available analytical techniques cannot determine reliably whether a given channel modification will be liable to meander development, which is sensitive to difficult-to-quantify factors like bank vegetation and cohesion. Locally or regionally developed approaches and data that have been found to give satisfactory results should normally be preferred over the more general approaches described herein.

b. The erosional and depositional stability of mobile-boundary channels is a complex multidimensional problem. Analytical knowledge is not as thorough as that for nonerodible 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. Caution should be observed against relying on a single method. The analytical tools applied should be appropriate to the anticipated forms of instability.

c. Adequate resistance to erosion does not necessarily result in freedom from instability or sedimentation if the channel has substantial inflows of bed material. The simpler methods such as 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 2-20). Modified or more complex methods are required to take account of sediment inflows. In flood control channels, avoidance of sediment deposition may be as important as avoidance of erosion.

d. Simple formulas for computing values of specific parameters - 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.

5-4. Allowable Velocity and Shear Stress

The concepts of allowable velocity and allowable shear stress are closely linked. They have been used mainly to design channels free from boundary erosion. In channels transporting sediment, however, design should ensure that sediment outflow equals sediment inflow. Modifications of allowable velocity or shear stress to allow for sediment transport have been proposed in a few references, but are of limited applicability. The information provided below is in summary form. More extensive information on allowable velocity and shear stress concepts is available in numerous textbooks and manuals on mobile boundary hydraulics and sediment transport.

a. Allowable velocity data.

(1) The concept of allowable velocities for various soils and materials dates from the early days of hydraulics. An example of simple velocity data is given by Table 5-1, which is provided as a guide to nonscouring flood control channels in EM 1110-2-1601. In the reference, the table is supplemented by graphical data for coarse gravel and boulder materials.

(2) Another example is Figure 5-1, which shows data provided by the Soil Conservation Service (U.S. Department of Agriculture (USDA) 1977). This discriminates between "sediment-free" and "sediment-laden" flow. Adjustment factors are suggested in this reference for depth of flow, channel curvature, and bank slope. In this context, "sediment laden" refers to a specified concentration of suspended sediment.

b. Allowable shear stress data.

(1) By the 1930's, boundary shear stress (sometimes called tractive force) was generally accepted as a more appropriate erosion criterion. The average boundary shear stress in uniform flow (Figure 5-2) is given by

$$\tau_0 = \gamma RS \tag{5-1}$$

where

γ = specific weight of water

R = hydraulic radius

S = hydraulic slope

Table 5-1
Example of Simple Allowable Velocity Data
(From EM 1110-2-1601)

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

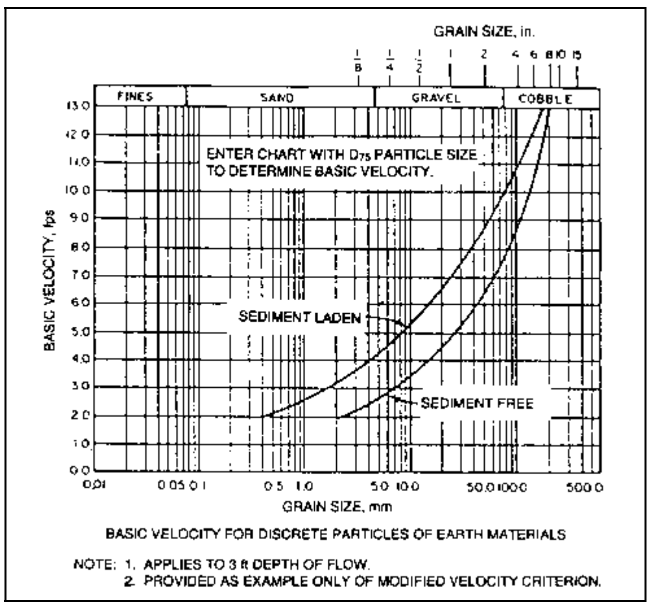


Figure 5-1. Example of allowable velocity data with provision for sediment transport (USDA 1977)

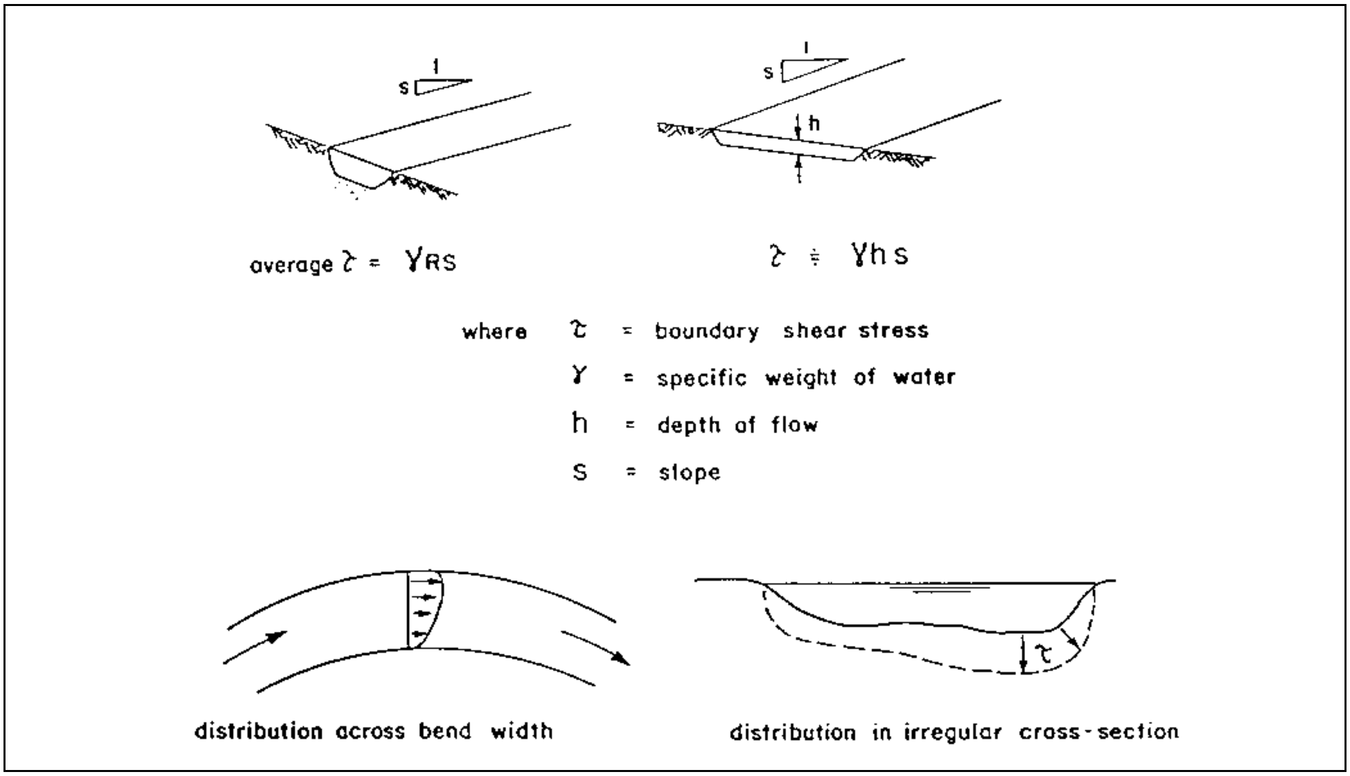


Figure 5-2. Boundary shear stress in uniform flow

Values for incipient erosion (or initiation of motion) of noncohesive materials are usually presented in nondimensional form.

(2) Figure 5-3 shows a modified version of the well-known Shields diagram for initial movement or scour of noncohesive uniformly graded sediments on a flat bed. The diagram is applicable theoretically to any sediment and fluid. It plots the Shields number (or mobility number), which combines shear stress with grain size and relative density, against a form of Reynolds number that uses grain size as the length variable. For wide channels with hydraulic radius approximately equal to depth, the relationship can be expressed as

$$\frac{\tau_0}{\gamma_s' D} = \left[\frac{dS}{(s - 1)D}\right] = f\left(\frac{V_* D}{\nu}\right) \qquad (5\text{-}2)$$

where

γ_s' = submerged specific weight of sediment

D = grain size

d = depth of flow

s = dry relative density of sediment

V_* = shear velocity defined as $\sqrt{\tau_0/\rho}$

ρ = fluid density

ν = kinematic viscosity

(3) For sediments in the gravel size range and larger, the Shields number for beginning of bed movement is essentially independent of Reynolds number. For wide channels the relationship can then be expressed as

$$\frac{dS}{(s-1)D} = constant \qquad (5\text{-}3)$$

The constant is shown as 0.06 in Figure 5-3, but it is often taken as 0.045, or even as low as 0.03 if absolutely no movement is required. For widely graded bed materials, the median grain size by weight (D_{50}) is generally taken as the representative size, although some writers favor a smaller percentile such as D_{35}.

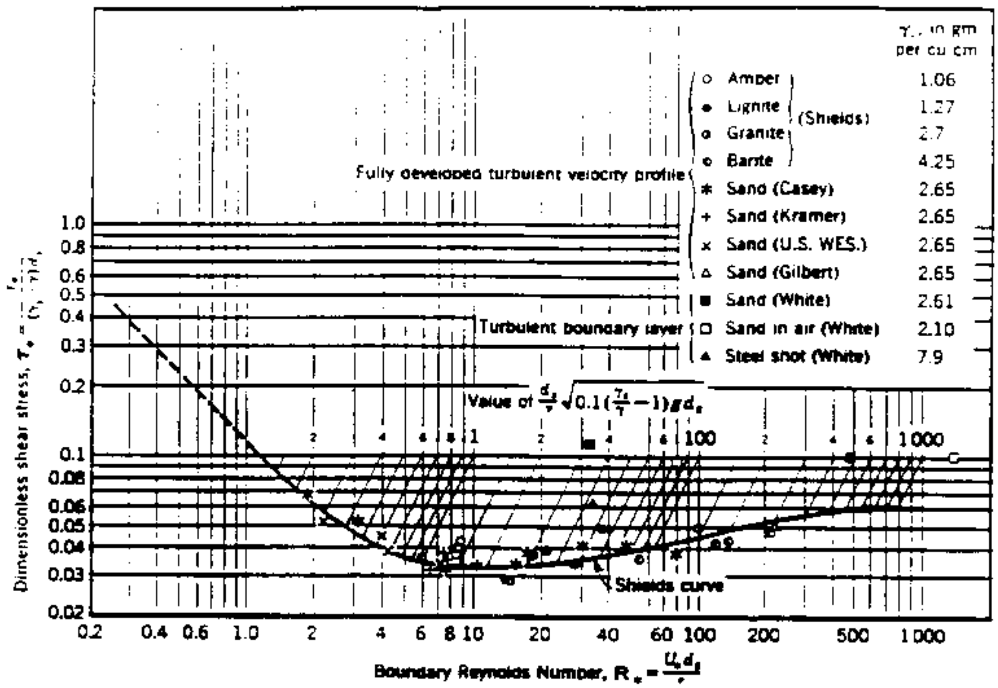


Figure 5-3. Shields diagram: dimensionless critical shear stress

(4) The allowable shear stress concept has also been applied to semicohesive and noncohesive soils, but values do not correlate well with standard geotechnical parameters because erosional resistance is affected by such factors as water chemistry, history of exposure to flows, and weathering (Raudkivi and Tan 1984). Analysis of experience with local channels and hydraulic testing of local materials are generally recommended. Figure 5-4 gives an example of allowable shear stresses for a range of cohesive materials, but where possible, values should be compared against the results of field observation or laboratory testing.

c. Allowable velocity-depth relationships. Theoretical objections to use of velocity as an erosion criterion can be overcome by using depth as a second independent variable. An example of a velocity-depth-grain size chart is shown in Figure 5-5. This particular chart is intended to correspond to a small degree of bed movement rather than no movement. Its derivation is explained in Appendix B. It should be taken as indicative of trends only and not as definitive guidance for the design of flood control channels.

d. Cautions regarding allowable velocity or shear stress. The following limitations of the allowable velocity

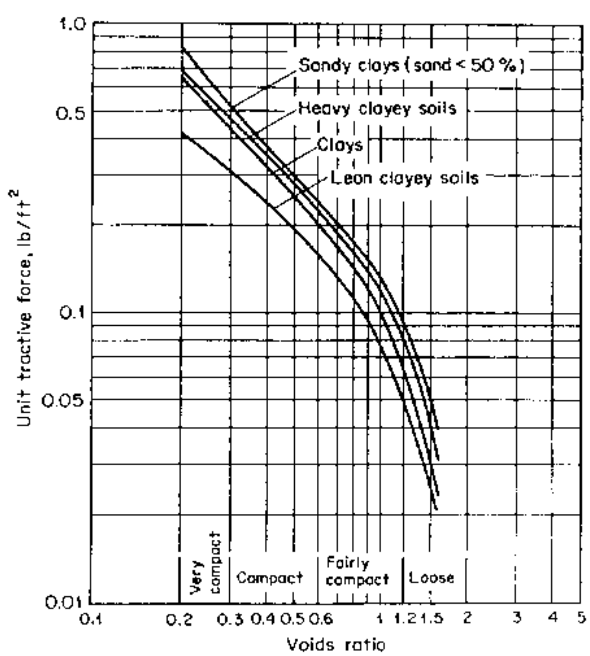


Figure 5-4. Example of allowable shear stresses ("tractive forces") for cohesive materials (Chow 1959; courtesy of McGraw-Hill)

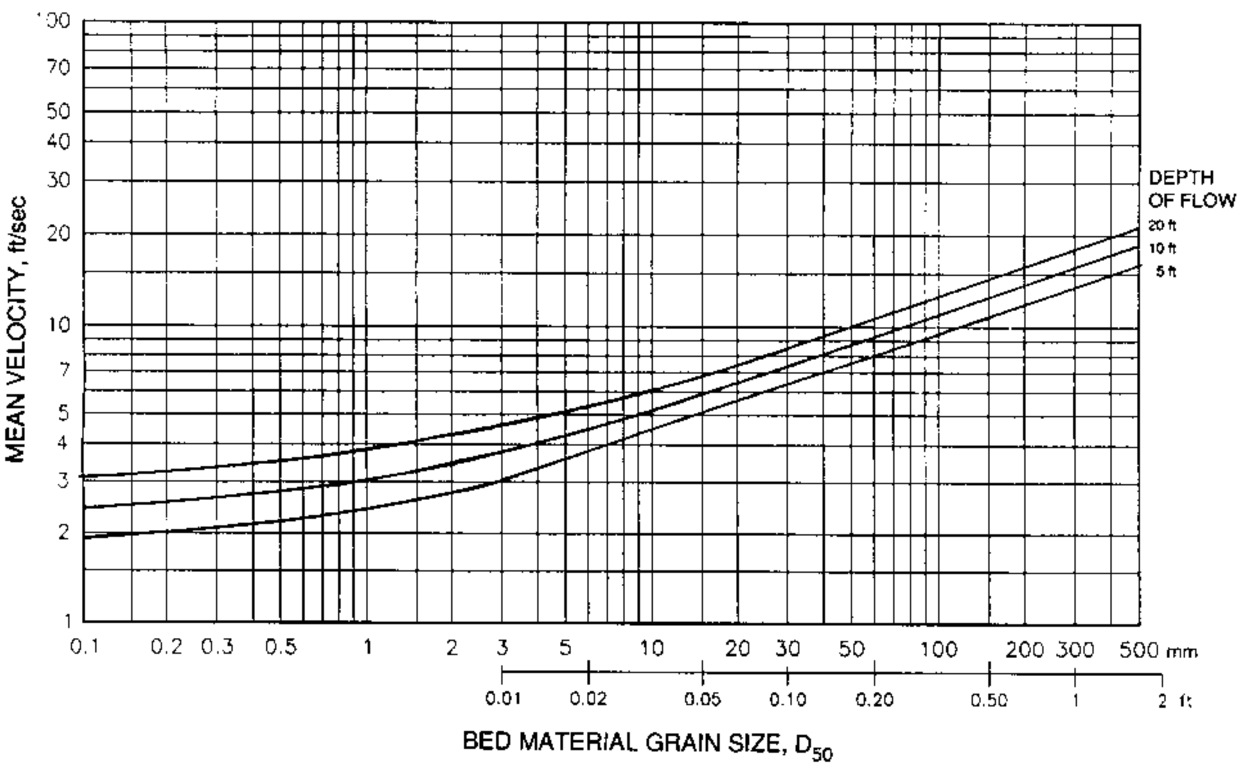


Figure 5-5. Example of allowable velocity-depth data for granular materials. For derivation see Appendix B

and allowable shear stress approaches should be recognized:

(1) For channels with substantial inflows of bed material, a minimum velocity or shear stress to avoid sediment deposition may be as important as a maximum to avoid erosion. Such a value cannot be determined using allowable data for minimal erosion.

(2) In bends and meandering channels, bank erosion and migration may occur even if average velocities and boundary shear stresses are well below allowable values. (Conversely, deposition may occur in local slack-water zones even if average values are well above maximum deposition.) Information on cross-sectional distributions of velocity and shear stress in bends is provided in EM 1110-2-1601.

(3) An allowable velocity or shear stress will not in itself define a complete channel design, because it can be satisfied by a wide range of width, depth, and slope combinations (Figure 5-6). It therefore has to be supplemented by additional guidelines for slope, width, or cross-sectional shape. In many cases of channel modification, the slope will be predetermined within narrow limits, and practicable limits of width/depth ratio will be indicated by the existing channel.

(4) The Shields relationship (Equation 5-2 and Figure 5-3) applies basically to uniform flow over a flat bed. In sand bed channels especially, the bed is normally covered with bed forms such as ripples or dunes, and shear stresses required for significant erosion may be much greater than indicated by the Shields diagram. Bed forms and irregularities occur also in many channels with coarser beds. More complex approaches have been used that involve separating the total shear stress into two parts associated with the roughness of the sediment grains and of the bed forms, of which only the first part contributes to erosion. In general, however, the Shields approach is not very useful for the design of channels in fine-grained materials.

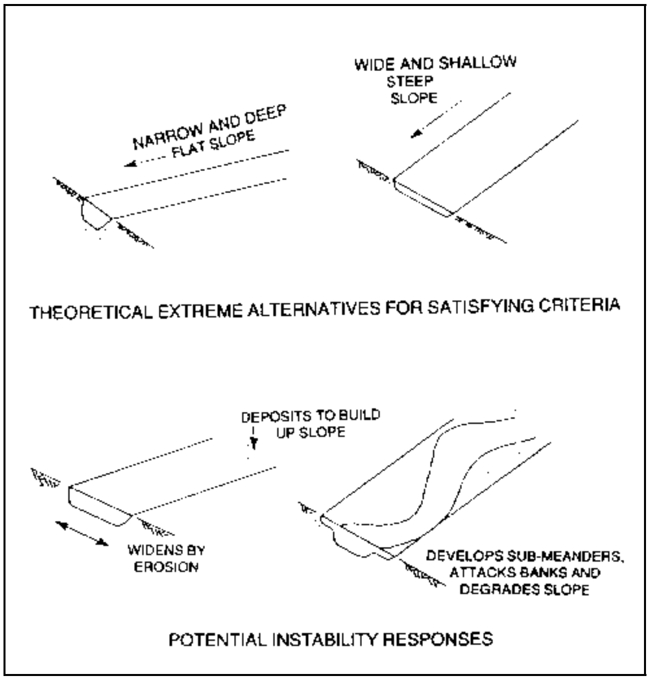


Figure 5-6. Insufficiency of allowable velocity or shear stress criterion for stability of alluvial channel

(5) Empirical data for allowable shear stress versus grain size in canals are widely published (Appendix C).

e. Guidelines for application. The following guidelines are suggested for computations and procedures using allowable velocity and shear stress concepts:

(1) Determine cross-section average velocities and/or shear stresses over an appropriate range of discharges. Under overbank flow conditions, determine in-channel values, not averages over a compound section (Figure 5-7). For existing channels, where possible use stage-discharge relations established from gaging stations or known watermarks; otherwise use hydraulic computations with estimated roughnesses. Stage-discharge relations in compound channels are reviewed by Williams and Julien (1989).

(2) A practical design approach for modification of existing channels is to match the velocity-discharge curve of the existing channel so far as possible by controlling cross section, slope, and roughness. Experience with response to local constrictions and widenings in alluvial channels generally supports this approach; these tend to scour or fill to restore more or less the natural velocity.

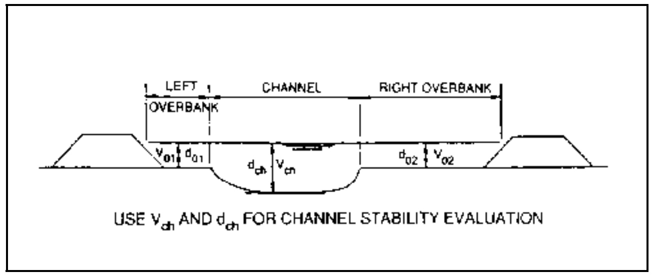


Figure 5-7. Velocities and depths in compound cross section

(3) In active alluvial streams, roughness may change appreciably between low and high stages (Figure 5-8). Bed roughness predictors (EM 1110-2-1601) can be used as a guide. For erosion checks it is conservative to estimate roughness on the low side, whereas for levee design it is conservative to estimate on the high side.

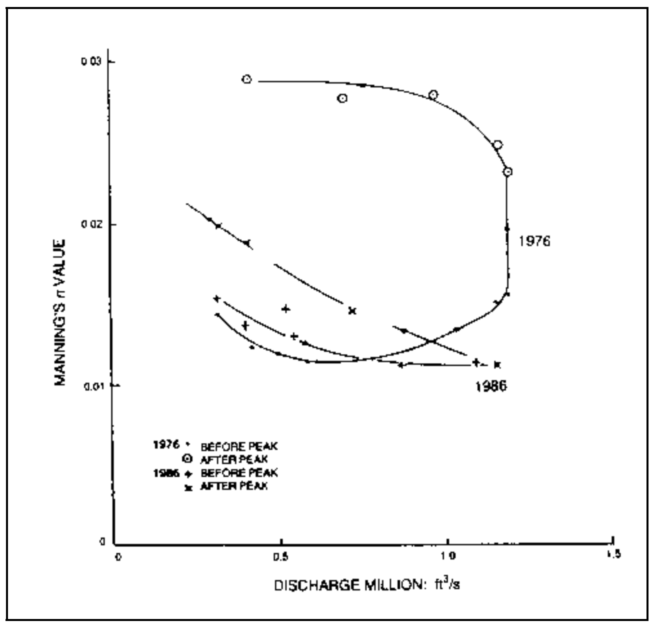


Figure 5-8. Roughness changes in a large sand bed river during floods (Ackers 1988; courtesy of Institution of Civil Engineers)

(4) If cross sections and slope are reasonably uniform, computations can be based on an average section. Otherwise, divide the project length into reaches and consider values for small, medium, and large sections.

(5) Determine the discharge for incipient erosion from the stage-velocity or discharge-velocity curve, and determine its frequency from a flood-frequency or flow-duration curve. This may give some indication of the potential for instability. For example, if bed movement has a return period measured in years, which is the case with some cobble or boulder channels, the potential for extensive profile instability is likely to be negligible. On the other hand, if the bed is evidently active at relatively frequent flows, response to channel modifications may be rapid and extensive.

5-5. Empirical Relationships for Channel Properties

a. Concepts of channel equilibrium (or regime) and hydraulic geometry are explained in Section II, Chapter 2. Empirical relationships expressing the width, depth, and slope (or velocity) of alluvial channels as separate functions of a dominant or channel-forming discharge were developed by (among others) Lacey (1929-30), Blench (1957), and Simons and Albertson (1963). References covering more recent developments, applications, and criticisms include Hey and Thorne (1986), Stevens and Nordin (1987), and White (1988). Relationships of this type may be useful for preliminary or trial selection of channel properties.

b. In considering flood control channels for a specific location, it is best to use locally or regionally developed relationships for hydraulic geometry, for example, Figure 2-21. If this is not possible, Figures 5-9, 5-10 and 5-11 show tentative relationships that may be useful as rough guides for selecting values of width, depth and slope, respectively, as functions of channel-forming discharge and bed material. Background on the development of those charts is provided in Appendix B. The following guidelines and limitations should be observed:

(1) Where possible, reach-averaged data for existing channels should be plotted and compared with the indications of the charts, using bank-full discharge as channel-forming. If bank-full discharge is not determinable, an alternative discharge parameter can be used (paragraph 2-8*a*). This comparison can indicate how compatible the stream system is with the assumptions of the charts. The trends of the charts can then be used to estimate changes appropriate for the modified project channel, particularly for modifications that involve increased in-channel flows, for example, as a result of close-set levees or floodwalls.

(2) The charts are likely to be most compatible with single-channel sand or gravel systems with relatively low bed material transport. A multichannel system, which usually indicates higher bed material transport, will tend to have greater overall widths and slopes but smaller depths, although individual branches may fit the curves reasonably in relation to their partial bank-full discharges.

(3) If bed material transport is high, the slopes indicated in Figure 5-11 may be much too low and the depths in Figure 5-10 may be too high. This is especially true of channels with sand beds and of ephemeral channels where much of the flow occurs as flash floods with very high sediment transport. In perennial-flow gravel rivers with single channels, slopes are unlikely to be more than three times greater than those indicated by Figure 5-11. Width is fairly insensitive to bed material transport unless the stream is multichanneled or braided. If bed material transport is high, it is preferable to use a sediment budget analysis of the type referred to in paragraph 5-7*b*.

(4) Actively aggrading and degrading channels can go through a complex cycle of response. In some stages of the response, they may exhibit large departures from normal hydraulic geometry relationships. For example, a channel in the earlier stages of active degradation (incision) may be abnormally narrow.

(5) The use of all three charts does not permit explicit selection of roughness and allowable velocity or shear stress. An alternative hybrid approach involves determining channel properties using three relationships: the width-discharge relationship of Figure 5-9; the Manning formula with a roughness estimate based on guidelines or experience; and an allowable velocity or shear stress.

5-6. Analytical Relationships for Channel Properties

a. Several investigators have proposed that stable channel dimensions can be calculated analytically by simultaneous solution of the governing equations. These methods consider discharge, sediment transport, and bed material composition as independent variables and width, depth, and slope as dependant variables. Three equations are required to solve for the three unknown variables. Equations for sediment transport and hydraulic resistance can be chosen, from among several that are available, for two of the required equations. Chang (1980) proposed that minimum stream power could be used as the third

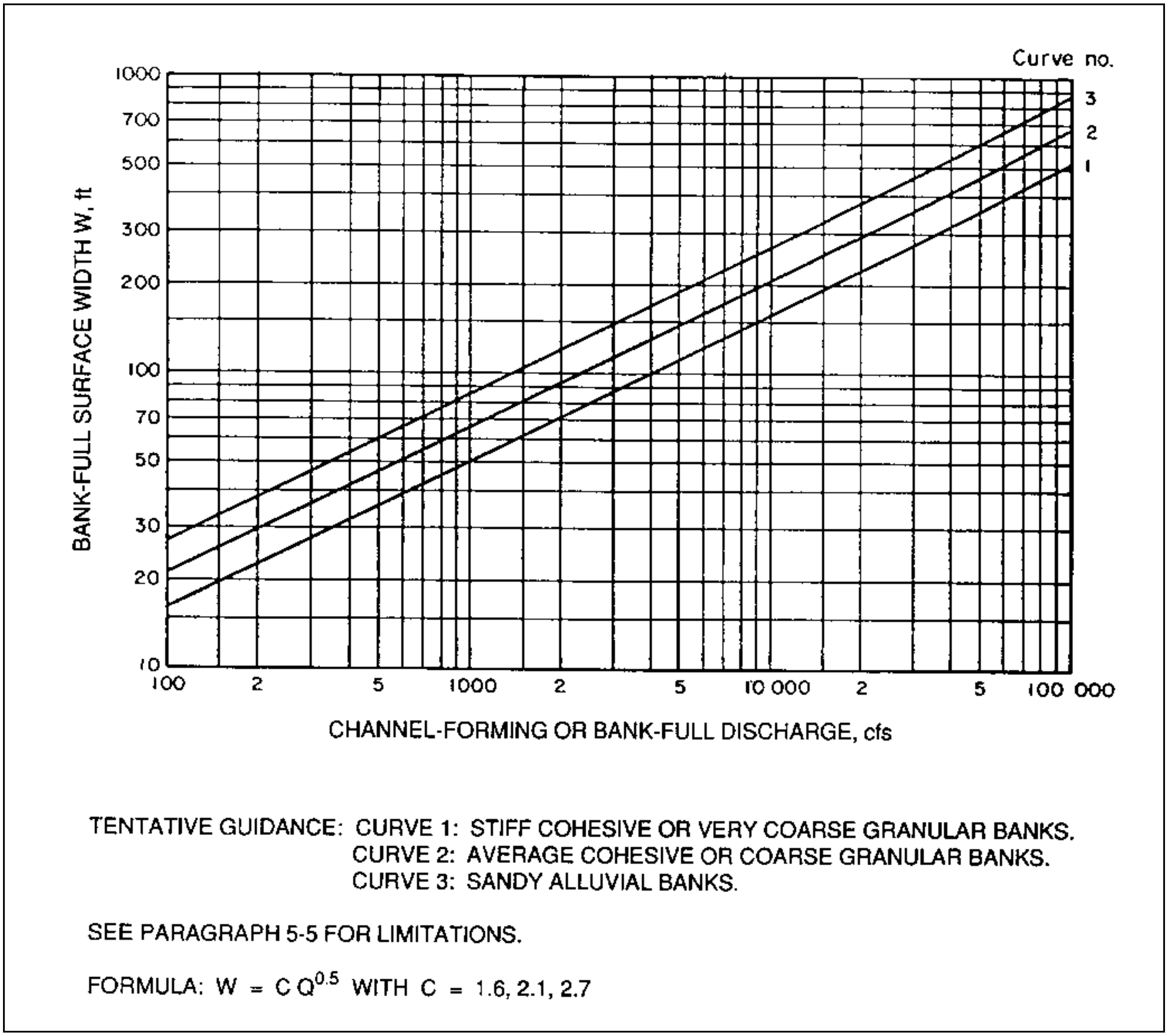


Figure 5-9. Tentative guide to width-discharge relationships for erodible channels. See Appendix B for derivation.

equation. He combined the Engelund-Hansen sediment transport and flow resistance equations with the minimum stream power equation to develop a stable channel design method. Chang's method was verified using canal and flume data with large width-to-depth ratios and low bed material transport. White, Bettess, and Paris (1982) proposed that maximum sediment transport, which they demonstrated to be equivalent to minimum stream power, could be used as a third equation. They used their own flow resistance equation and the Ackers-White sediment transport equations in their stable channel design method. Their method was also tested using sand-bed canal and flume data with low bed material transport and large width-to-depth ratios. The method did not produce acceptable results in gravel-bed streams. The White, Bettess, and Paris method is available in the U.S. Army Corps of Engineers CORPS computer program package. Sample results are shown in Appendix C. The minimum stream power concept has not been embraced by the profession, despite its apparent success in some applications.

b. Abou-Seida and Saleh (1987) used the Einstein-Brown sediment transport equation and the Liu-Hwang flow resistance equation to solve for two of the dependent

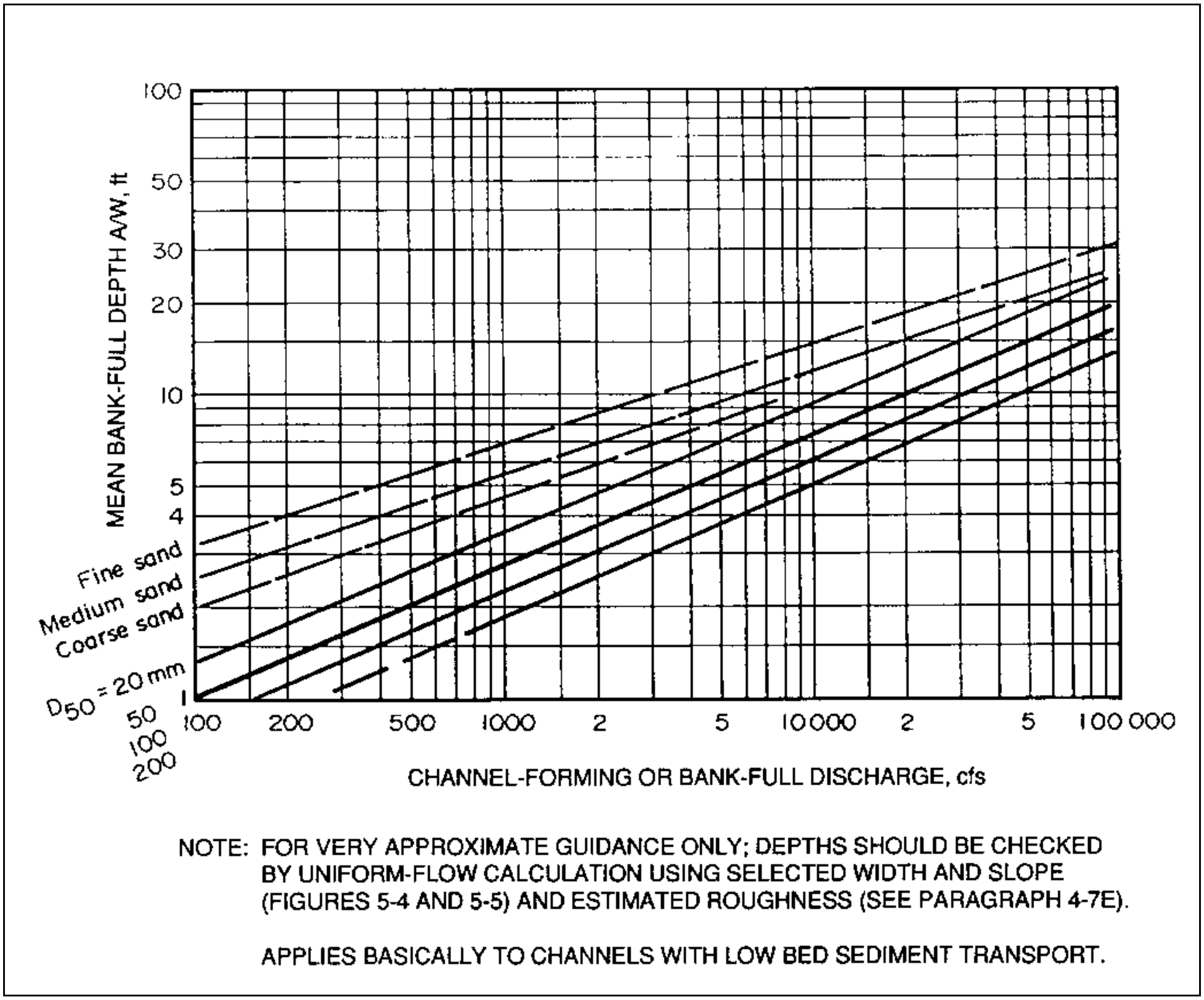
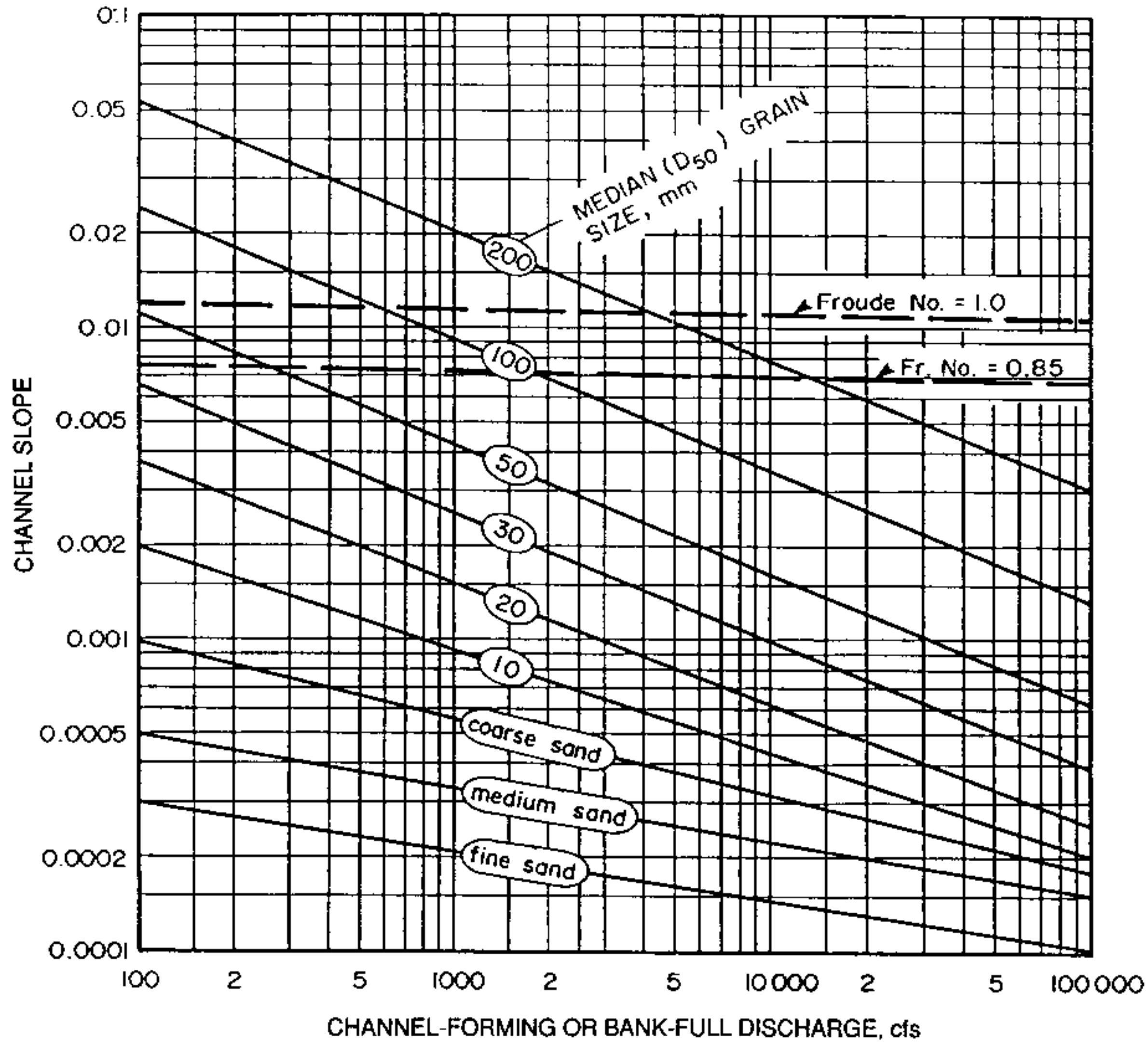


Figure 5-10. Tentative guide to depth-discharge relationships for erodible channels. See Appendix B for derivation.

design variables of width, depth, or slope, leaving one degree of freedom for the designer. Their method was developed for lower regime flow with low bed material transport.

c. The analytical stable channel design method presented in the Corps of Engineers SAM computer package for channel design calculates a family of solutions for slopes and widths that are dependent on the imposed conditions of discharge, sediment inflow, and bed material composition. This method is similar to the Abou-Seida and Saleh method in that only two of the design variables are solved for, and the designer must choose the third design variable from a family of solutions. The SAM method uses the sediment transport and resistance equations developed by Brownlie (1981). These resistance equations account for changes in roughness due to bed forms. The SAM analytical method partitions the total roughness into bank and bed resistance in the manner proposed by Einstein (1950); thus the method is not subject to the limitation of a wide channel. More detail on application of this method is available in Thomas, et al. (in preparation). An example is given in Appendix C.



NOTE: FOR LIMITATIONS SEE PARAGRAPH 5.5. CURVES ARE BASICALLY FOR SINGLE CHANNELS WITH FULLY ALLUVIAL BED BUT LOW BED SEDIMENT TRANSPORT. SLOPES MAY BE MUCH HIGHER WITH HIGH SEDIMENT TRANSPORT, ESPECIALLY WITH SAND BEDS.

Figure 5-11. Tentative guide to slope-discharge relationships for erodible channels. See Appendix B for derivation.

5-7. Sediment Transport and Sediment Budget

a. General.

(1) Many flood control channels have substantial inflows of bed 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. If the channel is dimensioned for flood capacity without consideration of sediment transport continuity, it may undergo deposition until transport continuity is attained (Figure 5-12).

(2) Most sediment transport functions predict a rate of sediment transport for given hydraulic conditions, usually average cross section, slope, and depth of flow. It

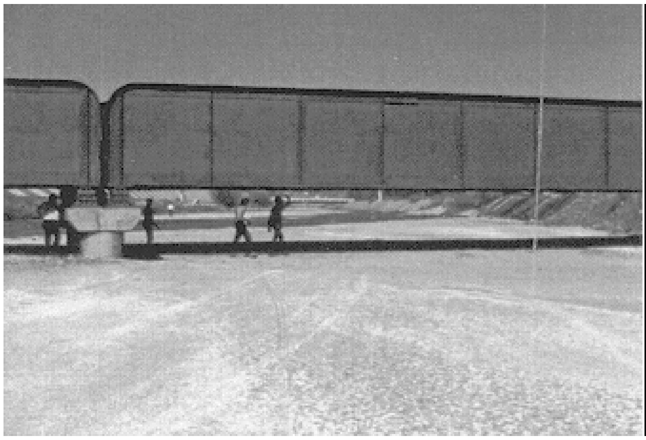


Figure 5-12. Infilling of oversized flood control channel by deposition of sand in floods

is important to know whether a given function is supposed to predict total bed material load or bed load only. 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.

(3) 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 1984, 1987).

(4) An example where computed bed load transport was compared with field measurements is shown in Figure 5-13. 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, Emmett, and Parks 1981). The data, although widely scattered, are reasonably compatible with the Meyer-Peter and Müller bed load formula, which is considered applicable to gravel channels (see Vanoni 1975).

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

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

b. Sediment budget analysis. Where field observations and checks of velocity, shear stress, or hydraulic geometry indicate a substantial degree of actual or potential bed instability and sediment transport, a sediment budget analysis may be conducted for the project reach, along the lines indicated below.

(1) Bed material transport rates are first estimated as a function of discharge using appropriate transport functions. These rates are then integrated to provide estimated total loads for two hydrologic conditions: mean annual, using the long-term flow-duration curve; and design flood, using the flood hydrograph. Each of those quantities is computed separately for both existing channel conditions and proposed project conditions. Where possible, computed loads should be checked against known quantities of erosion, deposition, or dredging over specific periods or in specific events. Otherwise, their reliability may be low.

(2) A sediment balance is then estimated for the project. The computed loads for existing conditions are assumed to represent project inflow, and those for project conditions are assumed to represent project outflow. If outflow exceeds inflow (either for the mean annual or the design flood hydrologic condition), bed erosion in the project channel is indicated. If outflow is less than inflow, bed deposition is indicated. The differential quantity can be converted to an average depth of erosion or deposition using the channel dimensions. The actual erosion or deposition will not, however, be uniform along the channel, due to slope flattening or steepening.

(3) Procedures for performing the required computations are included in the computer program “Hydraulic Design Package for Channels (SAM)” (Thomas et al., in preparation). General guidance on selection of sediment transport functions is shown in Table 5-2, and more specific guidance is included in SAM.

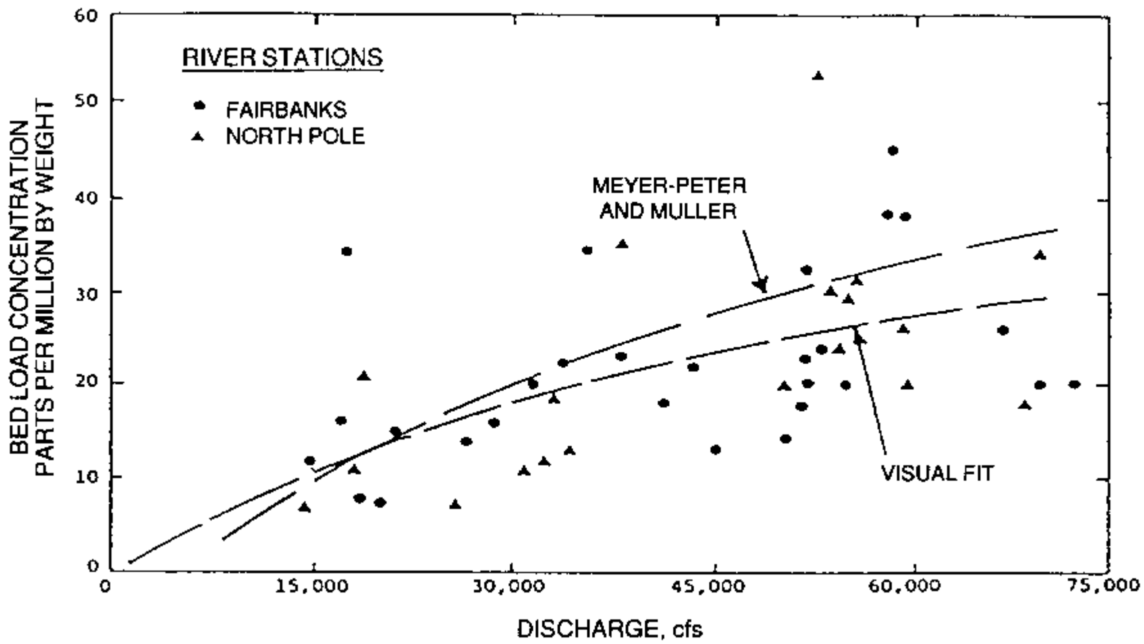


Figure 5-13. Comparison of computed and measured bed load in Tanana River near Fairbanks, Alaska (Buska et al. 1984)

Table 5-2
Sediment Transport Functions

Class of Channel	Suggested Functions	Reference
Large sand-bed rivers	Laursen-Madden Toffaleti	U.S. Hydrologic Engineering Center (1993) Toffaleti (1968)
Intermediate-size sand-bed rivers	Laursen-Madden Yang unit stream power	U.S. Hydrologic Engineering Center (1993) 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 Müller	Yang (1973, 1984) See above and below
Gravel-bed rivers	Meyer-Peter and Müller	Meyer-Peter and Müller (1948)

Note: Tentative guidance is provided below for functions most appropriate to various classes of channels. This guidance is based on experience at the U.S. Army Engineer 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 wash load concentrations where necessary. Additional guidance for selection of sediment transport functions is available in the SAM computer program package (Thomas et al., in preparation). The distinctive hydraulic variables from the user's river are compared to a large data set developed by Brownlie (1981), and a river data set is selected from a river with the most similar characteristics. The guidance program then selects a sediment transport function that best reproduces the selected data set.

(4) When application of this methodology indicates a strongly erosional or depositional situation, a more detailed sediment investigation may follow, as described in EM 1110-2-4000.

(5) Sediment budget procedures are most applicable to estimating the following types of response: profile degradation or aggradation resulting from imposed slope changes associated with realignment, or from incompatibility of existing slope with altered discharges; and erosion or deposition resulting from undersizing or oversizing of project cross sections. They are less useful for evaluating meander development and associated bank erosion and deposition.

5-8. Slope Stability

a. Bank erosion or failure often involves both hydraulic and geotechnical factors. It may be part of an overall process such as meander migration (see paragraph 2-3); it may be due to local hydraulic phenomena; or it may be due mainly to geotechnical factors like drawdown or seepage. Apparent geotechnical failure may be a delayed response to hydraulic scour at the toe. Other causes include boat-generated waves and turbulence, jams of ice or debris, and traffic of animals or vehicles.

b. Understanding of the interaction of hydraulic and geotechnical factors in streambank failure and erosion is not well developed. A number of papers under the theme “Mechanics of Riverbank Erosion” are presented in Ports (1989).

c. Mechanisms of bank slope failure in the Ohio River basin are described by Hagerty (1992). One identified process is internal erosion of sandy soil layers by groundwater outflow, followed by subsequent gravity collapse of overlying layers (Figure 5-14). Other processes referred to include erosion and infiltration of cracks by overland flow and precipitation, and river erosion of soil berms deposited by previous failures (Figure 5-15).

d. A stability analysis method for steep cohesive riverbanks (Osman and Thorne 1988; Thorne and Osman 1988) was developed from studies in the bluff-line streams of northern Mississippi but is of more general applicability. The conceived mechanism of bank failure is shown in Figure 5-15a. The analysis method is based on 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 5-15b). 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.

e. The above approach is most appropriate where bank failures are due primarily to geotechnical and geological factors. Where they result primarily from generalized channel processes, analysis of geotechnical mechanisms may be of secondary importance.

5-9. Meander Geometry

a. 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; Elliot 1984; Jansen et al. 1979; Leopold, Wolman, and Miller 1964.)

(1) Meander plan dimensions are more or less proportional to the width of the river. On maps and aerial photographs, 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 inflection points (Figure 5-16) have both shown good correlations with channel width. Hey (1984) suggests as a preferred average relationship:

$$L = 2\pi W \tag{5-4}$$

where L is the channel length between inflection points and W is width. Hey cites theoretical support based on the size of circulation cells in bends.

(3) The ratio of 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.

b. The relationships cited in *a* above refer to natural streams and are not criteria for stability of flood control channels; the planforms of many meandering systems are obviously unstable. Nevertheless, the use of

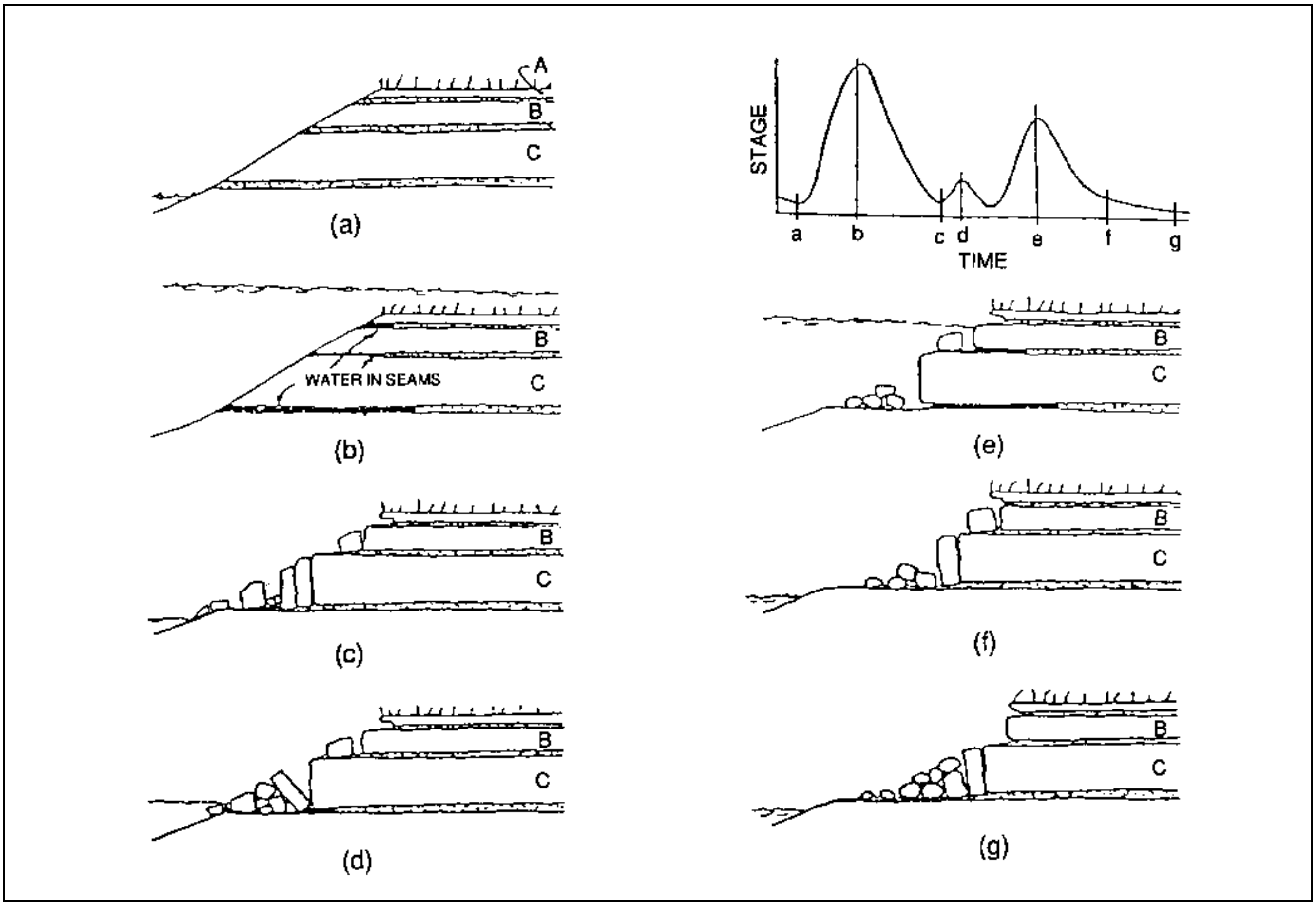


Figure 5-14. Mechanism of bank failure by internal erosion (Hagerty, Spoor, and Kennedy 1986; courtesy of University of Mississippi)

moderately sinuous rather than straight alignments is generally preferred, even where there are no existing constraints on alignment. Geometric guidelines for channel design are suggested in Figure 5-17.

c. 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, is roughly proportional to the square root of channel-forming discharge. If active meander shifting exists in the preproject 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.

d. 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 5-18). Where only intermittent bank protection is proposed, progressive distortion of the meander pattern may occur upstream of each protected length.

5-10. Basinwide Evaluation for System Rehabilitation

A systematic approach to stability evaluation, developed primarily by Vicksburg, the U.S. Army Engineer District, for rehabilitation of incised streams in hill watersheds of the Upper Yazoo Basin, Mississippi, involves analysis of the entire watershed to identify both local and systemwide instability problems and their interrelationships. Steps in the process include the following:

a. The entire watershed is investigated in the field to identify dominant geomorphic processes and features. (The type of information collected is indicated in Chapter 4.)

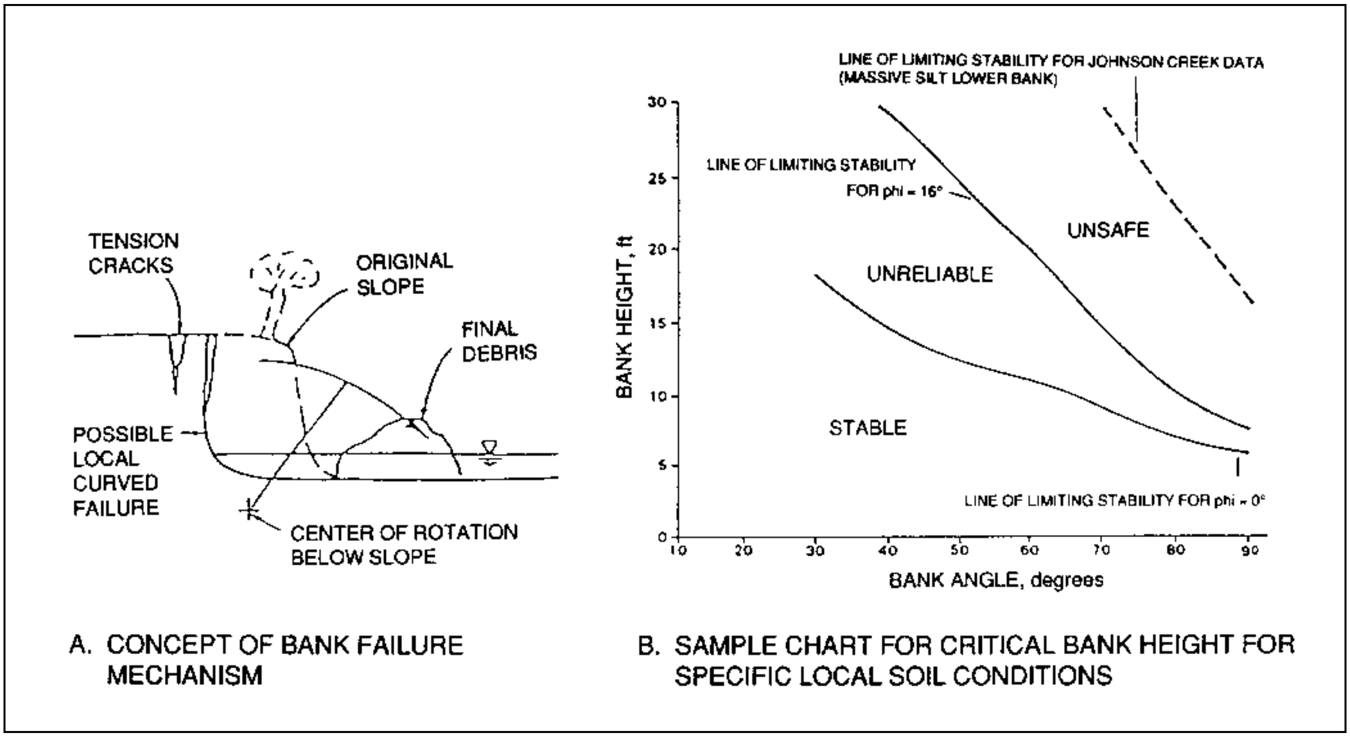


Figure 5-15. Stability analysis for steep cohesive river banks (Thorne and Osman 1988; courtesy of American Society of Civil Engineers)

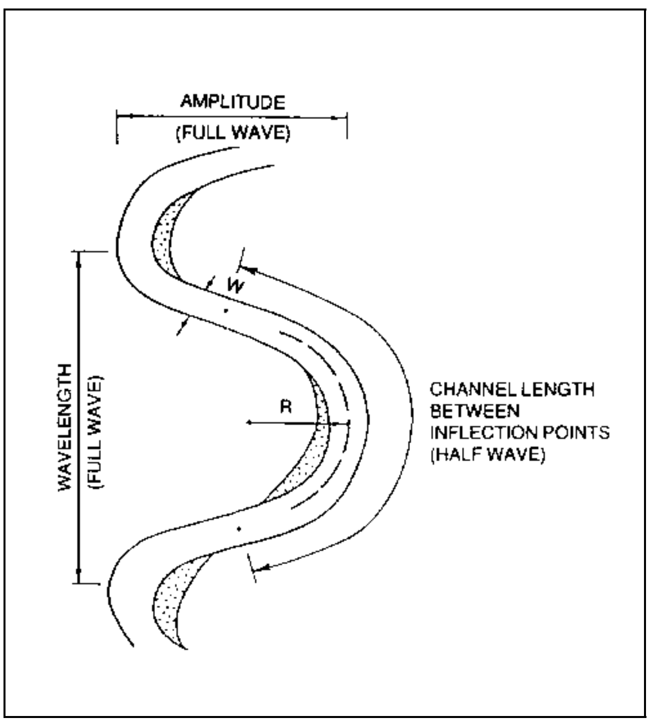


Figure 5-16. Meander geometry (after Nunnally and Shields 1985)

b. Using the information collected, an assessment is made of the system dynamics. Channels are classed as degradational, aggradational, or in equilibrium. Banks are classed as stable or unstable.

c. Hydraulic and geotechnical stability parameters are defined for reaches assessed to be stable. Generally, hydraulic parameters refer to the channel bed, for example, stable slope, boundary shear stress, or sediment transport parameters derived from modeling. Geotechnical parameters refer to the banks; they include stable bank height and angle or more complex parameters derived from detailed geotechnical analyses. For generalizing and transferring values between reaches, parameter values can be correlated with drainage area or discharge. If the watershed has subareas with different land use or geologic conditions, sets of stability parameter values may be required for each subarea.

d. Each more or less homogeneous reach of channel in the watershed is compared against the developed stability parameters and confirmed as stable, degradational, or aggradational. Additional considerations, such as the long-term effects of existing stabilization structures and anticipated changes in land use, may form part of the assessment. Anomalies within a specific reach may require further investigation.

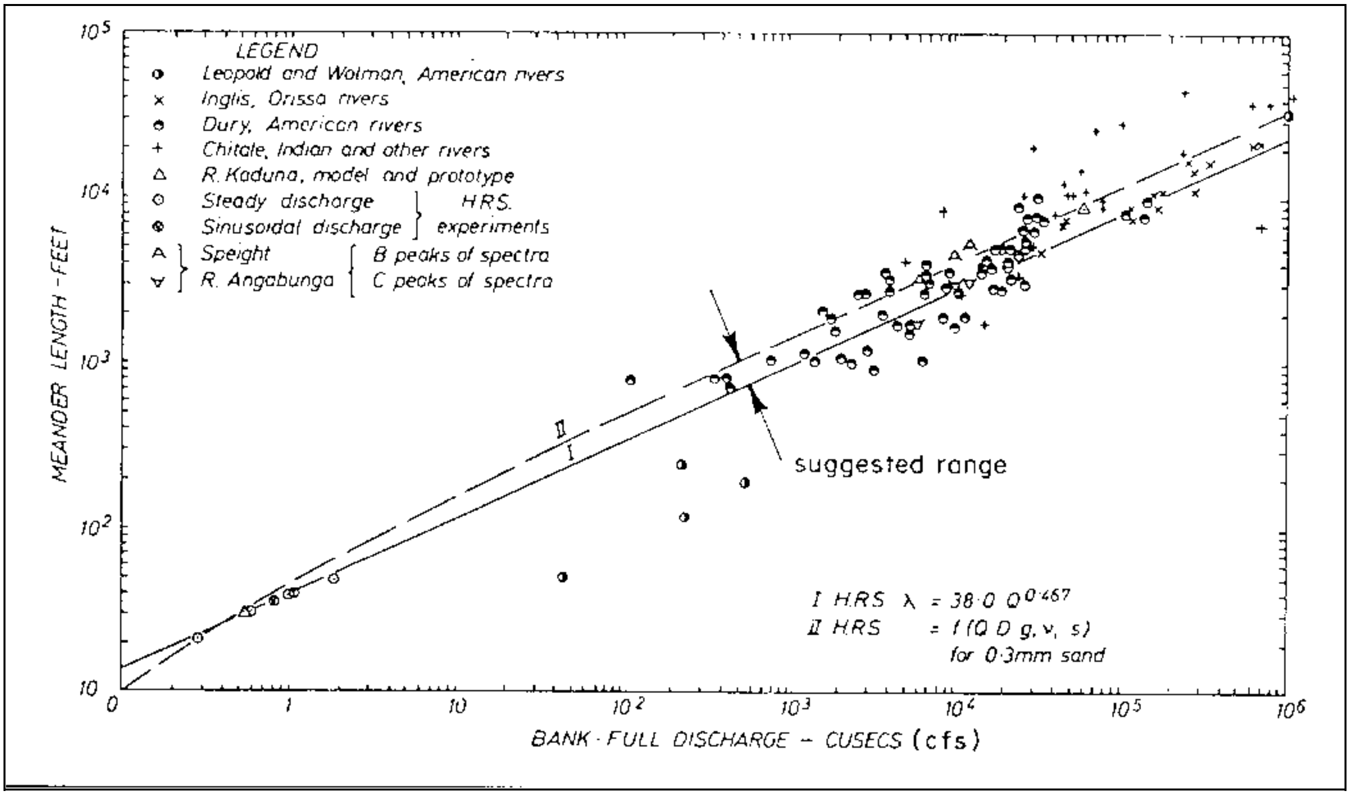


Figure 5-17. Suggested relationship between bank-full (channel-forming) discharge and meander wavelength for layout of new channel (After Ackers and Charlton 1970; courtesy of *Journal of Hydrology*)

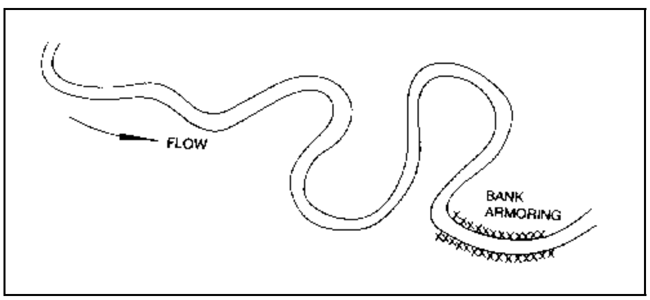


Figure 5-18. Distortion of meander pattern upstream of protected length

e. Rehabilitation measures are designed for unstable parts of the watershed and channel system. (The design of rehabilitation measures is discussed in Chapter 6.)

5-11. General Stepwise Approach

Whether or not an entire watershed needs to be evaluated, a systematic approach to evaluating and documenting the stability characteristics of the area relevant to a flood control channel project is recommended. The following sequence of steps may be found appropriate:

a. Describe characteristics of the area contributing to or affected by the project and its channel system.

b. Identify and assess existing instabilities.

c. Identify project features with stability implications.

d. Analyze stability parameters for the existing channel.

e. Evaluate and analyze potential stability problems with the completed project, and consider preventive or mitigative measures or project changes.

f. Summarize conclusions and recommendations.

5-12. Checklist of Items to Consider

The following checklist summarizes items that may be considered in a systematic stability evaluation. At each step, the investigator should consider the potentially vulnerable aspects of the system and the possibilities for prevention and mitigation, using principles and methods outlined in this manual as well as previous experience with similar projects and environments.

a. Drainage basin.

(1) Area.

(2) Shape.

(3) Physiography.

(4) Soils.

(5) Land uses and changes therein.

(6) Erosional areas.

(7) Sediment sources.

(8) Soil conservation measures.

b. Channel system.

(1) Geomorphology.

(2) Channel types and processes.

(3) Lengths and slopes.

(4) Significance of tributaries.

(5) Historical shifts and changes.

(6) Storage reservoirs.

(7) Grade controls.

(8) Flow diversions.

c. Hydrology.

(1) Existing flow duration.

(2) Flood frequency.

(3) Historical and recent floods.

(4) Bank-full discharge and frequency.

(5) Expected project-induced changes due to regulation, diversion, reduced floodplain storage, blockage of flood escapes, land-use changes, etc.

d. Project length of channel (divided into lengths if appropriate).

(1) Plan.

(2) Cross sections.

(3) Profile.

(4) Floodplain widths and land use.

(5) Structures and crossings.

(6) Falls and nick zones.

(7) Existing flood protection and erosion protection works.

(8) Bed and bank materials.

(9) Vegetation.

(10) Roughness.

(11) Jams of debris or ice.

(12) Boat traffic.

(13) Dredging.

(14) Gravel harvesting.

e. Existing instabilities.

(1) Erosional and depositional areas.

(2) Channel processes and meander migration.

(3) Bank erosion and failures.

(4) Degradation or aggradation.

(5) Undermined or exposed or buried structures and crossings.

(6) Nick point migration.

(7) Damage by humans or animals.

(8) Channel widening or narrowing.

f. Proposed project features.

(1) Cross sections and profiles.

(2) Levees and dikes.

(3) Flood levels and velocities.

(4) Vegetation changes.

(5) Land use changes.

(6) Recreational access.

g. Potential stability problems.

(1) Initiation or aggravation of meander migration.

(2) Crossing of planform type threshold.

(3) Changes to sediment inflows or outflows.

(4) Channel widening.

(5) Bed and bank erosion.

(6) Slope changes (degradation or aggradation).

(7) Sediment deposition.

(8) Local scour and fill (e.g., at structures and crossings).

(9) Tributary degradation or aggradation.

h. Potential mitigative measures.

(1) Bank protection.

(2) Grade controls.

(3) Vegetation.

(4) Sediment and debris basins.

(5) Upstream soil conservation.

(6) Flood bypass channels.

(7) Compound cross sections.

(8) Curved alignment.

(9) Flood detention reservoirs.

(10) Sediment dredging or harvesting.

i. Conclusions and recommendations.

(1) Significance of existing instabilities.

(2) Effect of project features on instability.

(3) Implications for operation and maintenance.

(4) Need for mitigative measures.

(5) Need for more detailed analyses.

5-13. Example of Qualitative Evaluations

A qualitative example of stability evaluation is given in this paragraph to illustrate the approaches outlined in paragraphs 5-10 through 5-12. Examples of more quantitative evaluations are given in Appendix C. The following fictional example of Flatfish River near Stony Forks summarizes a qualitative evaluation conducted in 1991 at reconnaissance level, based on a review of office information and a field inspection with interviews of residents. In practice it would be accompanied by maps and aerial and field photographs, and with references to previous reports and other sources of information. It is envisaged as a presentation of information at an early stage in project formulation.

a. Description of project-related area and channel system.

(1) Project length: 10 miles.

(2) Drainage basin.

(a) Dimensions: area 500 square miles, 40 miles long by 18 miles wide maximum.

(b) Physiography: low hills with alluvial valley.

(c) Geology: residual and alluvial soils over weak bedrock (sandstones and shales).

(d) Land use: hills wooded, valley in mixed woodland and farms, history of land clearing, recent encroachment of residential acreages.

(e) Sediment sources: surface erosion from recent logging in upper basin, high bank erosion in some tributary hill streams.

(3) Channel system.

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

(b) In project length, Flatfish River flows in broad alluvial valley through mixed farmland and residential acreages. Channel partly single and partly double with islands. Floodplain both sides except at occasional points of impingement on valley margins. Probably underlain by considerable depths of alluvium in most areas.

(c) Downstream of project length, Flatfish gradually changes to a meandering sand river, and discharges into a larger river 20 miles downstream. There are only a few minor tributaries.

(4) Flood hydrology: no hydrometric data or simulation studies are available for Flatfish River. Regional correlations suggest mean annual flood around 1,200 cfs and 50-year flood around 3,500 cfs. Largest known flood occurred in 1962 and most recent overbank flood in 1988. 1962 flood caused $10 million damage to crops and buildings, and 1988 flood $20 million mainly to residences. Extensive residential development occurred between 1962 and 1988.

(5) Project length of river.

(a) Planform. Irregular meanders with splitting around islands. Meanders typically about 1,000-ft wavelength by about 500-ft full-wave amplitude. Comparison of 1984 and 1950 aerial photos indicates substantial channel migration, and trend to wider channel with more exposed bars.

(b) Profile. Average slope 8 ft per mile. Sequence of pools and riffles at low flow. No visible rock rapids or nick zones. Narrow bridge at lower end may cause backwater effect at high flows.

(c) Cross sections. Typical bank-full section (in single-channel reach) about 70 by 4 ft, but considerable variability. Summed width of double reaches about 100 ft. Summed floodplain width (both sides) 500 to 1,500 ft. Floodplain cover about 40% grass, 30% crops, 30% trees. Overbank flow about once every 2 years, allegedly more frequent than in past. No existing flood protection dikes.

(d) Boundary materials. Bed: sand and gravel up to 50 mm. Channel bars variable in form and in surface grain sizes. Banks stratified: 1 to 2 ft overbank silt and fine sand overlying medium sand and gravel. Banks mostly cleared of vegetation except through wooded floodplain areas. Some local bank protection of limited effectiveness using timber piles and car bodies. Some complaints of accelerated erosion due to protection of neighboring properties.

(e) Miscellaneous observations. Water is clear in low flow, turbid in floods. Gravel moves actively on bars under moderate flows. Log debris on some bars and islands. Alleged adverse effects from logging in upper basin. Some winter ice but no effects on channel stability. No significant boat traffic. No local flood control on similar streams.

b. Existing instabilities.

(1) Drainage basin. Basin land use changes may have somewhat increased flood peaks, sediment loads, and debris. An apparent trend of increasing channel instability may continue. There are no plans for controlling basin erosion, which is not considered a major problem.

(2) Channel system. Outside the project area, it has not been examined in detail. Superficially there appear to be no major upstream instabilities. Any change in sediment deliveries to downstream reaches would be of concern to fishery authorities.

(3) Project channel. Substantial lateral instability: eroding banks, loss of land, mobile channel bars. Aerial photos suggest bank recession rates up to 5 ft per year, residents allege even higher local rates. A supply of coarse sediment enters the length from upstream. No evidence of profile instability: bridge foundations near either end show no indication of degradation or aggradation. Some apparent increase in average width since 1950 aerial photos. Only isolated local attempts to control bank erosion.

c. Analysis of stability parameters. This step is omitted in this qualitative evaluation. See quantitative examples in Appendix C.

d. Stability implications of project features. The proposal is to construct levees on both sides of the channel, to contain floods up to the 50-year level. Riparian owners would like the levees to be close to the riverbanks and assume that there would also be bank protection. Project details have not been determined.

e. Assessment of potential stability problems with proposed project.

(1) Altered flood hydrology. Levees close to the river would probably increase flood peaks to some degree because of the deregulating effect of eliminating floodplain storage. This effect can be reduced if the levees are set back. Surveys and hydrologic/hydraulic analyses would be required to examine these effects.

(2) Lateral instability. Existing lateral instability poses problems for close-set levees. Substantial setback is indicated to avoid excessive bank protection costs. Increased in-channel flow peaks may tend to increase lateral instability and sediment supply to downstream. Erosion protection of river banks or levee faces may be required at least locally.

(3) Profile instability. Some flattening of slope may be expected because of increased in-channel flood peaks, but process is likely to be slow and controlled by armoring of bed material. Grade controls could be installed at a later stage if a problem develops.

(4) Cross-sectional instability. There may be a tendency for cross sections to widen and possibly deepen eventually, because of increased in-channel flood peaks. This is unlikely to be of serious concern under present development.

f. Summary.

(1) A workable scheme for 50-year flood protection can be developed. The existing channel is laterally unstable and is liable to encroach on levees located near the channel. Because it eliminates much floodplain storage and increases in-channel flood peaks, the project may aggravate meander shifting and alter channel properties somewhat. Potential maintenance problems include bank protection to secure the levees and increased delivery of sediment to downstream reaches.

(2) Further studies should consider a range of solutions to the flooding problem. Any solution involving levees should recognize the effects of existing and possibly enhanced instability on the security of the levee system, and should provide for adequate protection against erosion or undermining.