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CHAPTER 9. FUNDAMENTALS OF FLUVIAL GEOMORPHOLOGY AND NATURAL CHANNEL PROCESSES

9.1 FLUVIAL GEOMORPHOLOGY

Fluvial geomorphology is a study of the *form* and *structure* of the earth surface that are affected by flowing waters. Hence, a fluvial system that is to be studied is generally bounded by the limits of a watershed, as depicted below.

9.1.1 Fluvial System

Schumm [1977] provides an idealized sketch of a fluvial system (Figure 9-1a) consisting of three zones:

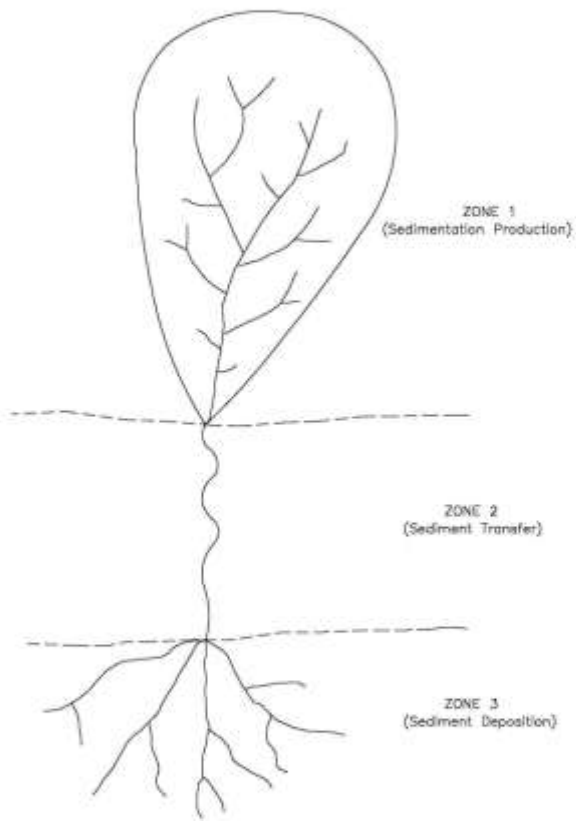


Figure 9-1a. The Fluvial System [Schumm, 1977]

Zone 1: The upper portion of the system is the watershed or drainage basin; it supplies sediment to the system.

Zone 2: The middle portion of the system is the river; it transfers sediment from Zone 1 to Zone 3.

Zone 3: The lower portion of the system may be a delta, wetland, lake, or reservoir; this portion of the system allows sediment to deposit.

These three zones are idealized because in actual conditions sediment can be deposited, eroded, and transported in all zones. However, within each zone one process is usually dominant.

For the Santa Clara Valley, Zone 1 represents the headwaters of the creeks in the California Coast Range and Diablo Mountains. Zone 2 is where the creeks run through urbanized areas of the valley, and Zone 3 is the lower valley floor immediately upstream from the San Francisco Bay. The formation of these three zones is illustrated in Figure 9-1b below. Originally prepared by the San Francisco Estuarine Institute [Wittner and McKee, 2002], this figure delineates the major watersheds in our valley except the Uvas and Llagas watersheds in the south which drain through the Santa Cruz County to the Pacific Ocean.

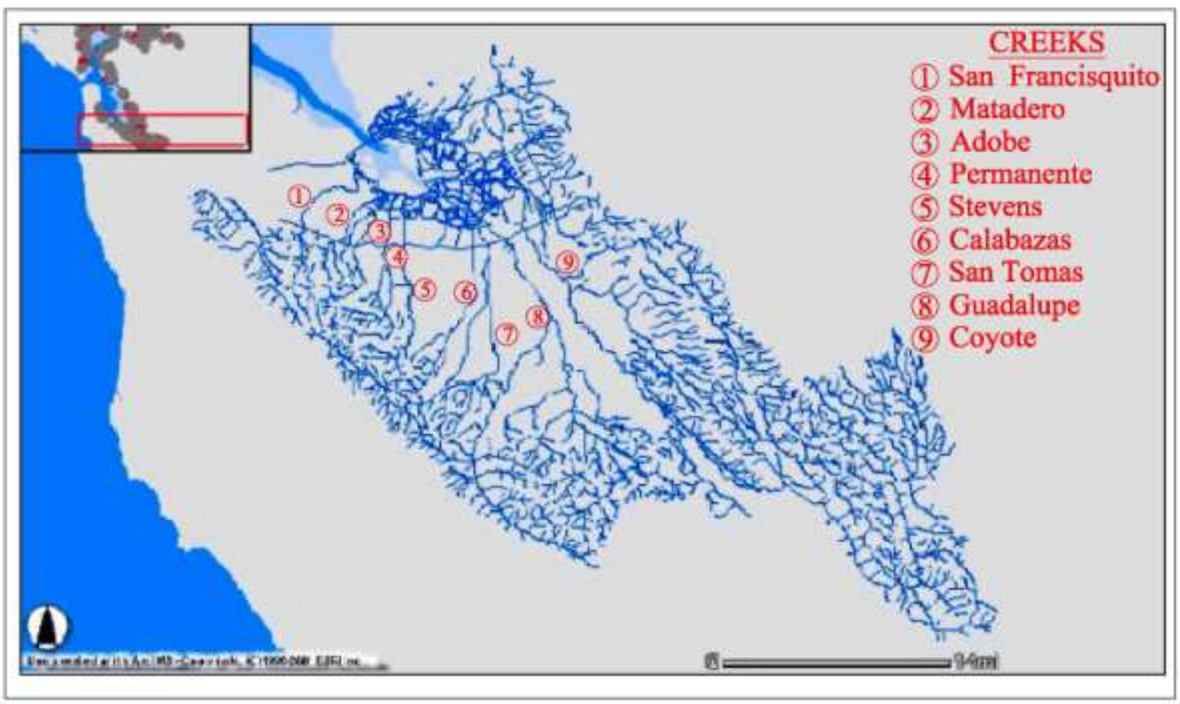


Figure 9-1b. Watershed Delineation of the Santa Clara Valley

9.1.2 Fluvial Geomorphic Concepts

Landforms often show the influence of current geomorphologic processes and may at times reflect their past history. Therefore, scrutiny of the landscape may reveal much about the past and present events and help predict future response of the system. This scrutiny may be conducted by applying geomorphic concepts to geology, hydrology, hydraulics, and urban planning.

The basic geomorphic concepts of a fluvial system include:

- The project reach is only a part of the fluvial system.

  Any reach of a river is affected by its upstream and downstream conditions. Hence, the study of channel processes should not only focus on individual channels but also the entire drainage system. This concept of considering a complete system has been most eloquently prescribed by Dr. Hans Albert Einstein [1972]: "*If we change a river we usually do some good somewhere and 'good' in quotation marks. That means we achieve some kind of a result that we are aiming at but sometimes forget that the same change which we are introducing may have widespread influences somewhere else. I think if, out of today's emphasis of the environment, anything results for us it is that it emphasizes the fact that we must look at a river or a drainage basin or whatever we are talking about as a big unit with many facets. We should not concentrate only on a little piece of that river unless we have some good reason to decide that we can do that.*"

  The effect of neglecting this concept is evident throughout the valley. The installation of the Comer debris basin on Calabazas Creek intercepted the sediments washed down from the upstream mining site and prevented them from getting to the Bay. However, it also starved the downstream reach of sediment supply and caused significant downgrading and channel incision. This example reminds us that in conducting flood protection projects, we always need to consider both flow hydraulics and sediment transport, and include the upstream, project site and downstream reaches.

- Stream channels tend toward an equilibrium state.

  Stream channels tend to evolve toward an equilibrium state in which the input of mass and energy to a specific system equals the outputs from the same system. The term "stream channel equilibrium" refers to the relative stability of the channel system and its ability to maintain its morphological characteristics over some period of time.

  Streams respond to system alterations, such as a change in runoff pattern or sediment supply due to human activities, by modifying their size, shape and profile. Streams will also make adjustments in size and profile in response to flow fluctuations in a water year. The time scale for these morphologic changes may differ, anywhere from a few months to tens and hundreds of years. Originally proposed by Chorley and Kennedy [1971], these transient conditions are described by Schumm [2006] as two states of approximate equilibrium.

  (a) Steady-state equilibrium occurs when short-term fluctuations in a given variable occur throughout the channel system, but the longer-term mean value of the variable is maintained. An example of steady-state equilibrium occurs when channels adjust to scour and deposition associated with seasonal flooding.

  (b) Dynamic equilibrium occurs when short-term fluctuations in a given variable occur around a longer-term mean value that is also changing. An example of dynamic equilibrium occurs when a stream adjusts to a reduction of sediment supply. In this instance, the stream undergoes a complex pattern of degradation, surface armor, and renewed incision as it adjusts to the new slope and geometry. A record of longitudinal profiles will show that the channel slope is continuously reduced over the years. Dynamic equilibrium is also called quasi-equilibrium in some literatures. It is a state of transition going from one set of morphologic conditions to another. Some literature, such as Hack [1960] and Rosgen [2001] equates dynamic equilibrium to a steady state in which the form or character of the river system remains unchanged. This point will further be discussed in Section 9.5.1.

Some of our creek reaches in this valley, such as the Calabazas Creek upstream of Bollinger Road, are in steady-state equilibrium because urbanization along these reaches has stayed relatively constant for some years. Other creek reaches, such as the Thompson Creek, are in dynamic equilibrium because the watershed is still being developed. A sediment transport analysis carefully executed with the aid of historical profile data should reveal the nature of the creek under this light.

- Geomorphic thresholds exist, and when exceeded, can result in abrupt changes.

  The concept of threshold implies that a gradual and progressive increase in external stress may not cause continuous responses from the system, but may eventually produce a dramatic response when the stress reaches a certain level. An example is the response of sediment to increase in flow. The sediment remains immobile until a shear stress or velocity threshold is reached.

  Geomorphic thresholds exist and geomorphic changes occur. It is important to identify the changes in progress in our projects, and develop proper measures to interrupt the cause, if appropriate, mitigate the effect, or for some instances stay away and let nature take its course.

- Geomorphic analyses must consider the proper time scale.

  Geomorphologists usually refer to three time scales in working with rivers: 1) geologic time, 2) modern time, and 3) present time. Geologic time is usually expressed in thousands or millions of years and in this time scale only major geologic activity will be significant. Formation of mountain ranges, changes in sea level, and climate change are significant in this time scale. The modern time scale describes a period of tens of years to several hundred years, and has been called the graded time scale [Schumm and Lichty, 1965]. During this period a river may adjust to a balanced condition between water and sediment discharges. The present time is considered a shorter period, perhaps one year to ten years. Within this time scale, human interventions to the natural system begin to manifest.

  A flood protection project usually requires less than ten years to plan, design and construct. However, the project life often extends into the graded time. Hence, the effect of a project needs to be considered in the proper time scale for various factors such as sediment supply, level of urbanization, runoff characteristics, etc. A computer model such as HEC-6 may be useful in studying the long-term effect of sediment supply and transport in streams.

9.2 CHANNEL MORPHOLOGY AND REGIME THEORY

Sediment and water discharges are two key independent variables that determine the size, shape, and pattern of a stream channel. Prior to extensive use of equilibrium principles by geomorphologists, hydraulic engineers used the concepts of equilibrium in regime theory. Regime theory is based on the tendency of a stream system to obtain an equilibrium state under constant environmental conditions. It consists of a set of empirical equations relating channel shape to discharge, sediment load, and bank resistance. The theory proposes that dominant channel characteristics remain stable for a period of years and that any change in the hydrologic or sediment regime leads to a quantifiable channel response such as erosion or deposition. Stream reaches that are "in regime" are able to move their sediment load through the system without net erosion or deposition and do not change their average shape and dimensions over time.

Regime theory formed the basis for a large body of works in fluvial geomorphology focusing on identifying and defining the geometric properties of equilibrium alluvial channels and their adjustments to discharge and sediment transport regimes. According to Hey [1997], the nine measurable variables used to define equilibrium channel geometry are:

- average bankfull channel width (Section 9.2.4)
- average bankfull depth (Section 9.2.4)
- maximum depth
- velocity
- height of bedforms
- wavelength of bedforms
- slope
- meander wave length (Section 9.2.3)
- sinuosity (Section 9.2.2)

These characteristics are the dependent variables for stream reaches that are *in regime*.

The six independent variables that control changes in channel dimension and shape are:

- discharge
- sediment load
- size of bed material
- bank material
- bank and floodplain vegetation (riparian and/or upland species)
- valley slope

Given enough time, changes in any of these independent variables may result in a new channel geometry that represents a stable morphology in a new equilibrium state.

There are numerous empirical relationships that have been developed to relate the dependent variables to the independent ones. Since the fundamental prerequisite for applying the regime theory is a stream *in regime*, or a stable stream, most of the relationships were established for undeveloped watersheds, where channel equilibrium has been attained through many years of operation without human intervention.

As human activities encroach into the watershed, we typically lose vegetation, surface roughness and infiltration. As a result, surface runoff increases in both volume and flow rate. This change in runoff pattern induces bank erosion and channel incision. As the channel bed elevation is degraded, soon the flow channel loses touch with the floodplain. The higher energy and larger shear stress of the floods cannot be dissipated by the floodplain, and channel incision worsens. This vicious cycle continues until a new, and milder, longitudinal profile is established where the slower velocity and lower transport capacity is in balance with the sediment load again. If urban development continues, this morphologic change will also persist. This is the reason that we need to be careful in identifying stable reaches and applying regime theory to our creeks.

The following is a sample of some of the basic trends and empirical equations developed over the years for different rivers in different areas of the United States. They may not have direct application to the creeks in the Santa Clara Valley. Instead, they are included here to show historical work in this subject.

9.2.1 Channel Dimensions

All available evidences indicate that the greater the water discharge through a channel, the larger cross section exists in that channel. Leopold and Maddock [1953] compiled a significant statistical data base using USGS gauging records, and developed the following empirical hydraulic geometry relationships between width, depth, velocity and other hydraulic characteristics for perennial streams in the United States, located mostly in the Midwest and South. The hydraulic geometry relationships are:

$$W = aQ^b \tag{9-1}$$

$$Y = cQ^d \tag{9-2}$$

where W is the water surface width, Y the depth, Q the discharge, and a, b, c, d constants dependent on the stream condition. Intuitively these empirical equations are correct in the sense that as flow increases width and depth increase. But since the only dependent variable in these equations is the water discharge, they may not adequately describe streams of varying sediment materials or sediment loads.

The width of a stream of gravely beds is expected to be different from that of sandy beds. In addition to the size of the sediment bed material, relative amounts of bed load and suspended load also significantly affect channel morphology. Along the Smoky Hill-Kansas River system in Kansas, discharge increases in the downstream direction while channel width decreases from about 300 ft to less than 100 ft in central Kansas. These changes are attributed to changes in the type of sediment load introduced by major tributary streams [Schumm, 1968]. Tributaries introduce large suspended sediment loads where the width decreases, and when large bed loads are present, the width increases.

Schumm [1968] developed additional empirical equations for channel dimensions by collecting data of channel dimensions, bed and bank sediments, and water discharge at 36 cross sections of streams located in the semiarid to sub-humid regions of the Great Plains, United States and on the Riverine Plains of New South Wales, Australia. The bed material is sand, and none of them contains more than approximately 10 percent gravel [Schumm 1968, pp. 40, 45]. However, the channels show a considerable range of dimensions and hydrology: width from 27 to 800 feet, depth from 2.4 to 18 feet, width/depth ratio from 4 to 75, sinuosity from 1.05 to 2.5, and mean annual discharge from 21 to 5000 cfs. These channels are defined as stable because there has been no progressive channel adjustment during the last 10 years of record, and they are described as alluvial channels because their bed and banks are composed of sediment that is transported by the river. Data are not available for total sediment loads, but bed and bank samples were collected that are assumed to reflect the type of sediment transported. Although there were no systematic changes in the average size of the bed and bank materials, it was determined that the shape of the channels is closely related to the percentage of silt and clay in the sediments forming the perimeter of channel. Silt-clay was measured as the sediment smaller than 0.074 mm (200 mesh sieve). The width/depth ratio (W/Y) of these channels was found to be related to the percentage of silt-clay in the perimeter of the channel (M) as the following empirical equation

$$W/Y = 255 M^{-1.08} \tag{9-3}$$

"M" apparently is an index of the type of sediment being transported through the channel and is also an indication of bank stability. For five locations, where both total sediment load data are available and for which M was calculated, M was inversely related to the percentage of the total bed load (q_b), at a given discharge [Schumm 1968]:

$$M = \frac{55}{q_b} \tag{9-4}$$

Because of the great range of channel size and discharge of the channels studied, the type of sediment load is considered to be a more important control on stable channel shape than the total quantity of sediment transported through a channel. For example, in one channel a small quantity of bed load may exert the dominant control if it is the total load, whereas in another channel the same amount of bed load may exert much less influence on channel shape because it is only a small part of the total sediment load. Therefore when suspended-sediment load and water discharge are constant, an increase in the quantity of bed load will cause an increase in channel width and width/depth ratio.

In summary, for the range of channels studied, type of sediment load exerts a major control on channel shape. For a single channel with constant discharge and amount of sediment load, a change of bed load is reflected in a change of both shape and gradient.

Further analysis of the river data produced the following relations for channel width and depth (in feet):

$$W = 37 \frac{Q_m^{0.38}}{M^{0.39}} \tag{9-5}$$

$$Y = 0.6 M^{0.342} Q_m^{0.29} \tag{9-6}$$

where Q_m is the mean annual water discharge in cfs. The width (W) and the depth (Y) used in Eq. (9-5) and (9-6) are the bank full width and depth of channel in contrast to surface water width and depth used in Eq. (9-1) and (9-2).

To summarize, for alluvial rivers, when an index of the type of sediment load, M, was combined with water discharge, good correlations with width and depth were obtained. Hence, one may conclude that variations in channel dimensions among many rivers are probably attributable to differences of sediment type. Local changes of channel dimensions may, of course, be strongly affected by variations of resistance of bank sediments [Fisk 1944; Simons and Albertson, 1960; and Ackers, 1964].

We should also note that the river channels studied in Schumm's [1968] report contain only a very small amount of sediment coarser than sand. That is possibly one reason why Schumm did not find a correlation between sediment sizes and channel dimension. These alluvial rivers and sediment materials are very different from those of the Santa Clara Valley. The section presented here is to show the types of information found in the literature and caution careful use.

9.2.2 Channel Gradient

Lane [1955] indicated that channel gradient is directly related to both bed-material load and grain size and inversely related to water discharge. Based on field data, Hack [1957] and Brush [1961] concluded that downstream decreases of stream gradient depend on the resistance of the bed rocks being eroded and supplying sediment to the channels. Brush [1961] found that gradient decreased most rapidly for shale, then limestone, and least for sandstone. Bray [1973] found the following empirical equation for the channel gradient (S in feet per mile), discharge Q_2 (discharge of a 2-year recurrence interval), and sediment size D_{50} for rivers of Alberta:

$$S = 0.0965 Q_2^{-0.334} D_{50}^{0.586} \tag{9-7a}$$

Schumm [1968] indicated that the channel gradient will decrease with an increase in Qw, but will increase with an increase in Qs. This is reasonable if one thinks that the aim of the river is to balance the incoming sediment load with sediment transport through the reach. Schumm also provided the following relationships:

$$Q_w \propto \frac{WYL}{S} \tag{9-7b}$$

$$Q_s \propto \frac{WLS}{YP} \tag{9-7c}$$

where L is the meandering wavelength and P is the sinuosity. Meander wavelength, L, is defined as the distance along the valley over one wave form of the channel, as shown in Figure 9-2a. **Sinuosity** is a commonly used parameter to describe the degree of meander in a stream, defined as the ratio of the distance along the channel (channel length) to the meander wavelength. A perfectly straight channel has a sinuosity of 1.0, while a channel with a sinuosity of 3.0 or more will be characterized by tortuous meanders. This is further discussed in the next section.

9.2.3 Channel Patterns

Channel pattern describes the planform of a channel. It varies from straight to highly sinuous. In general, the primary types of channel patterns are meandering, braided, and straight. In many cases, a stream will change pattern within its length. The pattern type is dependent on slope, discharge, and sediment load.

The most common channel pattern is the meandering stream (Figure 9-2b). A meandering channel is one that is formed by a series of alternating changes in direction, or bends.

Relatively straight reaches of alluvial rivers rarely occur in nature. However, there are instances where a reach of river will maintain a nearly straight alignment for a long period of time. Even in these relatively straight reaches, the thalweg may still meander and alternate bars may be formed. Straight streams generally occur in relatively low energy environments. The **braided** pattern is characterized by a division of the river bed into multiple channels (Figure 9-3). Most braided streams are relatively high gradient and relatively coarse grained. They have to have actively and frequently transported sediment and easily eroded banks. An example in this valley is the Coyote Creek near the Coyote Creek Golf Course.

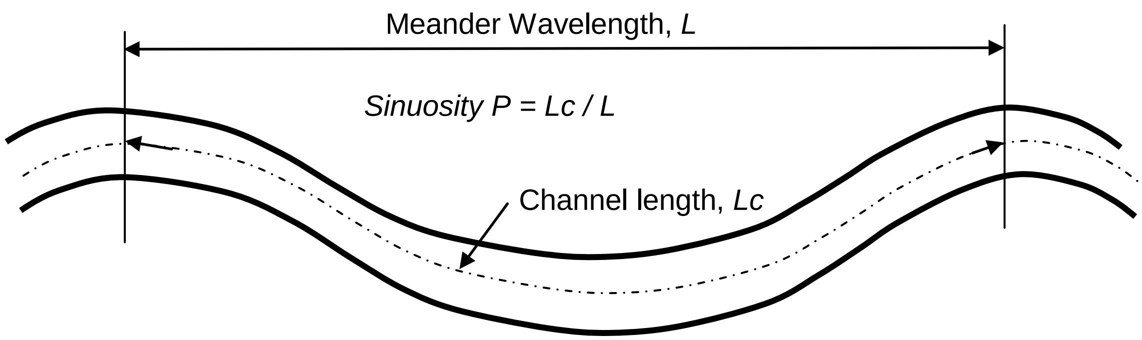


Figure 9-2a. Definition Sketch of Meander Wavelength and Sinuosity

Figure 9-2b. Typical Meandering River [Watson et. al. 1999]

Figure 9-3. Typical Braided River [Watson et. al. 1999]

Sinuosity is best measured using aerial photography. Schumm [1968] found that P is only dependent on M, the percentage of silt and clay in the sediment in the following relationship:

$$P = 1.06 M^{0.18} \qquad \text{(9-7d)}$$

Since sinuosity is affected by bedrock formations, roads, culverts, other confinement structures, and vegetation, it is not as meaningful a parameter in urbanized streams as in natural and undeveloped rivers.

9.2.4 Channel Geometry and Cross Section

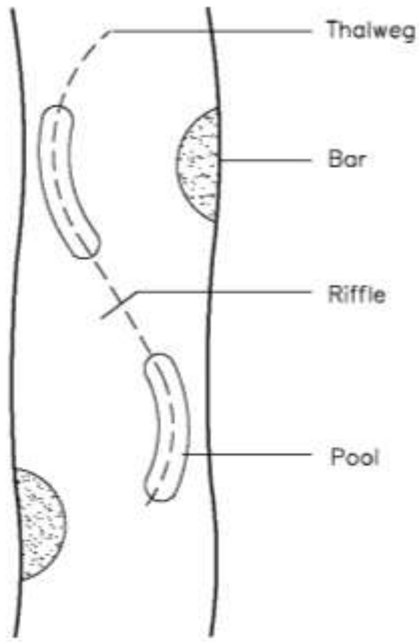
Several key features and cross sectional characteristics exist for a typical meandering natural stream. There are described in the following.

Pools and Riffles

A schematic showing features associated with channel meanders and straight sections is presented in Figure 9-4. As the **thalweg**, or trace formed by the lowest point of a cross-section, changes from side to side within a channel, the momentum of the flow shifts from side to side as well and affects the cross-sectional geometry of the stream. In bends, flow concentrates on the outer channel due to centrifugal forces. This causes the depth to increase at the outside of the bend, and this area is known as a **pool**. As the thalweg again changes sides downstream from a bend, it crosses the centerline of the channel. This area is known as the **riffle or crossing**. At the point of tangency between adjacent bends, the velocity distribution is fairly uniform across the cross section, which is approximately rectangular in shape.

Cross Section Shape

The shape of a cross section in a stream changes depending on its location along the channel with reference to the planform, the discharge, and characteristics of the sediment in the boundary and transported within the channel. The cross section in a bend is deeper at the concave (outer bank) side with a steep bank, and shallower on the convex side which typically has the formation of a **point bar**. The cross section will be more trapezoidal or rectangular in a riffle. These characteristics are illustrated in Figures 9-4 and 9-5a.



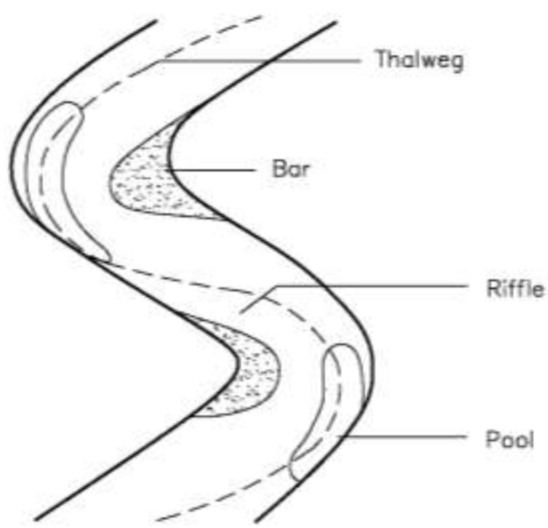


Figure 9-4. Features Associated With Straight and Meandering Rivers [Watson et. al. 1999]

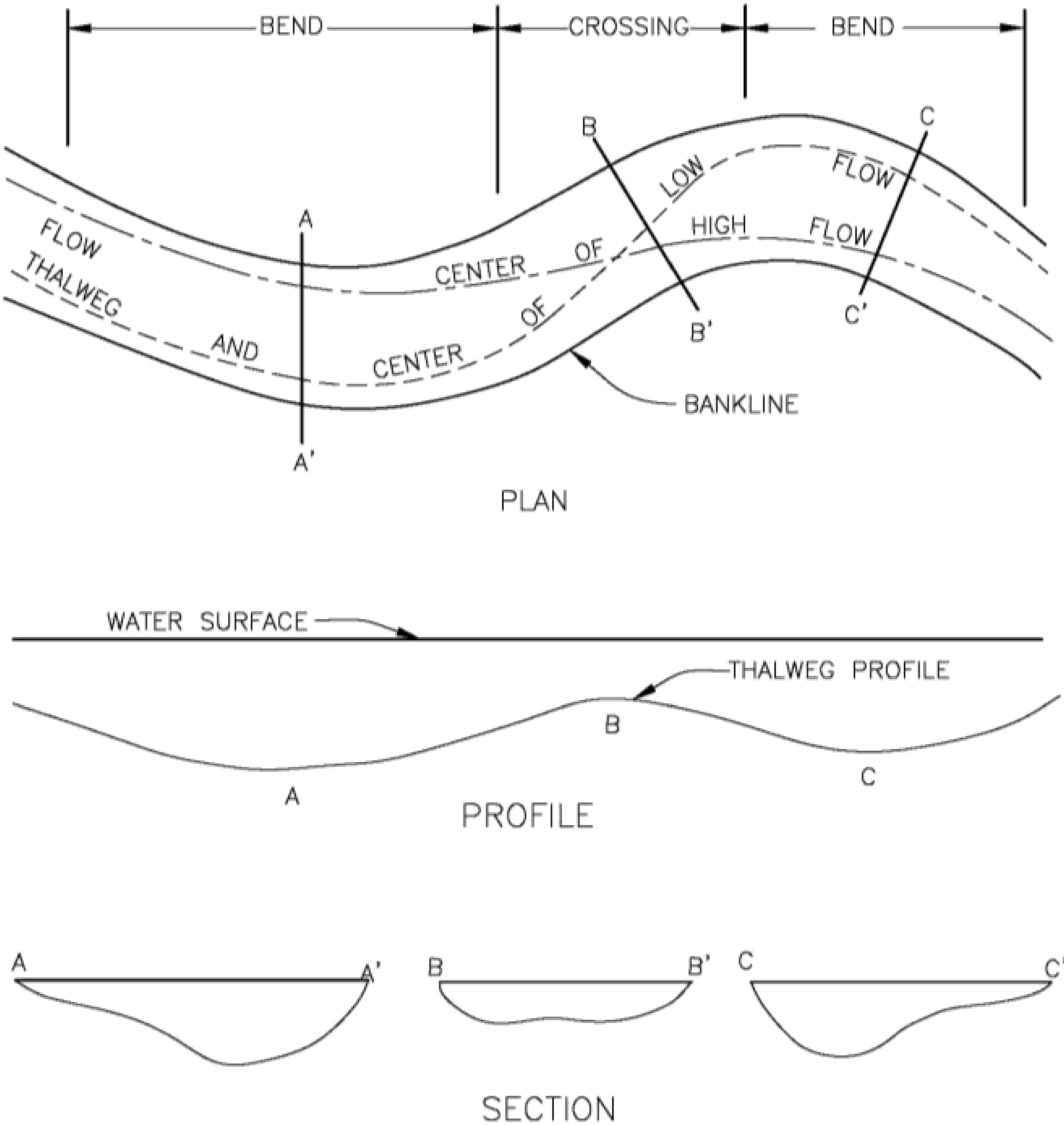


Figure 9-5a. Typical Plan and Cross Sectional View of Pools and Crossings [Watson et al. 1999].

Channel Bars

Channel bars are depositional features that occur within the channel. The size and location of bars are related to the sediment transport capacity and local geometry of the reach. The primary types of bars are **point bars**, **middle bars**, and **alternate bars**.

Point bars form on the inside (convex) bank of bends in a meandering stream. The development of a point bar is partially due to the secondary flows caused by centrifugal forces in the bend.

Middle bar is the term given to areas of deposition within, but not connected to the banks. Middle bars tend to form in reaches where the crossing areas between bends are excessively long and occasionally in bends due to the development of chutes.

Alternate bars are depositional features that are positioned successively down the river on opposite sides. Alternate bars generally occur in straight reaches and may be the precursor to a fully developed meander pattern.

Bankfull Channel

Bankfull channel is the channel of an alluvial river that has been shaped by the river's current hydrologic and sedimentologic regime. Given flow fluctuations, sediment loads that enter the reach, and the exchange of sediment between the channel boundary and flow stream, a natural channel evolves into a shape that best suits its purpose of conveying water and sediment efficiently. That natural channel shape typically resembles what is shown in Figure 9-5b. This channel shape includes a bankfull channel and a floodplain on each side of the channel.

As will be discussed later in Section 9.6, when one examines the amount of sediment moved by the flows in a channel, the flow rate that carries the most sediment is called the channel forming discharge. Experience tells us that this discharge is coincident to the bankfull discharge. In other words, when the flow is at the bankfull level, the bankfull discharge is proved to move the most amount of sediment, and thus shapes the channel. This is why the bankfull flow and bankfull channel dimensions are important geomorphic parameters.

Before we can examine a river channel to determine bankfull channel characteristics, we need to know if the river is in a dynamic equilibrium state, i.e., there is insignificant deposition or degradation in the reach over a period of several years. We will examine the watershed development condition, changes in impervious surface in the drainage area, land use changes, changes in sources of sediment, and the surveyed channel and invert profile changes to determine if the river is in equilibrium. Should the river not be in equilibrium, the channel shape might still be evolving and the bankfull dimensions would still change.

The bankfull discharge will vary from creek to creek, depending on sediment characteristics and flow regime, but in general it has a magnitude of 1- to 3-year return interval in the Santa Clara Valley environment. More on this subject will be discussed in Section 9.6.

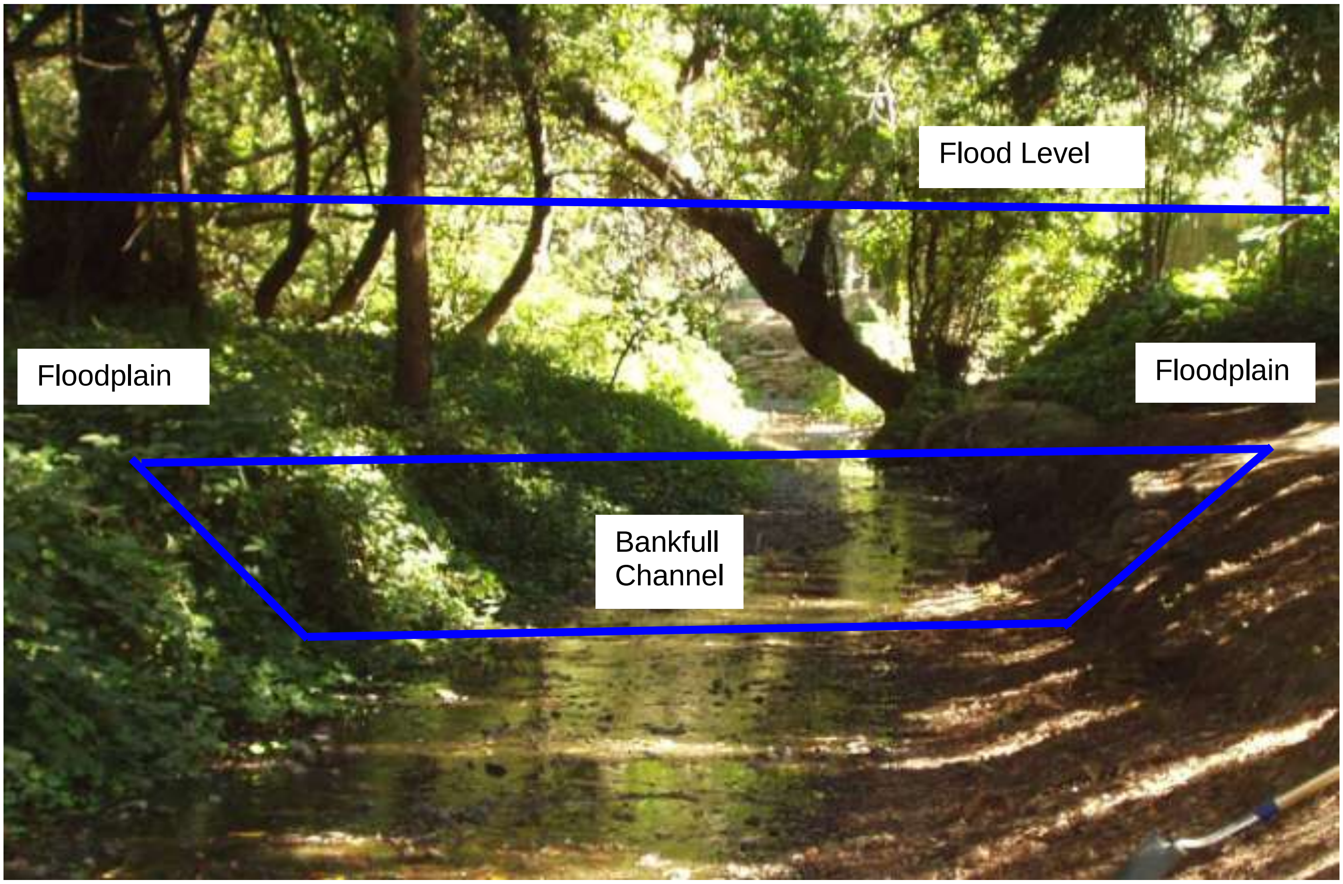


Figure 9-5b. Example of Bankfull Channel of Adobe Creek in Palo Alto

Low Flow Channel

For some rivers that carry year-round flows, they may develop a low flow channel to convey the low flows more efficiently. This low flow usually corresponds to the base flow, or the flow supplied by the groundwater table. In some literatures this base flow is referred to as the 7-day annual low flow.

For the creeks in our valley, most do not exhibit a low flow channel. This is because either the creeks are of the intermittent type and run dry for half of the year, or the year-round flow that we maintain for environmental reasons is too small to move bed sediments.

Floodplain

Floodplains are the benches sitting on either or both sides of the bankfull channel. As river flow exceeds the bankfull discharge, it overflows on the floodplain. An immediate hydraulic effect of this action is a significant increase in channel width, which reduces the hydraulic radius, and reduces the bottom shear stress Eq. (7-19). The flow regime thus attains relief from the high tractive force that is trying to mobilize the sediment, and the bankfull channel thus maintains its shape.

Typically vegetation changes from the immergent, grass or shrubs to riparian woody types going from bankfull channel to the floodplain. Sediment-carrying flows will also drop the sediment as their velocity reduces over the floodplain. Hence, the floodplain formation is dominated by suspended sediments.

Terrace

Simply put, a terrace is an abandoned floodplain. It is not formed under the current regime of the river. Instead, it represents floodplain formation at an earlier time. The older floodplain was excommunicated from the river channel through either increased flow regime which caused channel degradation and incision, or land subsidence. Both of these causes occurred in our valley and resulted in many terraces that hang above flood levels.

9.3 CHANNEL EVOLUTION

The conceptual incised channel evolution model (CEM) is of value in developing an understanding of watershed and channel dynamics, and in characterizing stable reaches. The sequence was originally used to describe the erosion evolution of Oaklimiter Creek, a tributary of Tippah River in northern Mississippi [Schumm, Harvey and Watson, 1984]. Simon and Hupp [1987] also developed a similar model of channel evolution.

A five-reach-type, incised channel evolution sequence, as generated by Schumm et al.[1984], for streams in conditions of total disequilibrium to dynamic equilibrium, is shown in Figure 9-6. Types I to V are encountered consecutively in the downstream direction, and at a given reach they occur through time. The channel evolution model describes the systematic response of a channel to base level lowering, such as one that is induced by an improperly designed storm drain outfall or increased surface runoff from a tributary. The following paragraphs characterize the conceptual types.

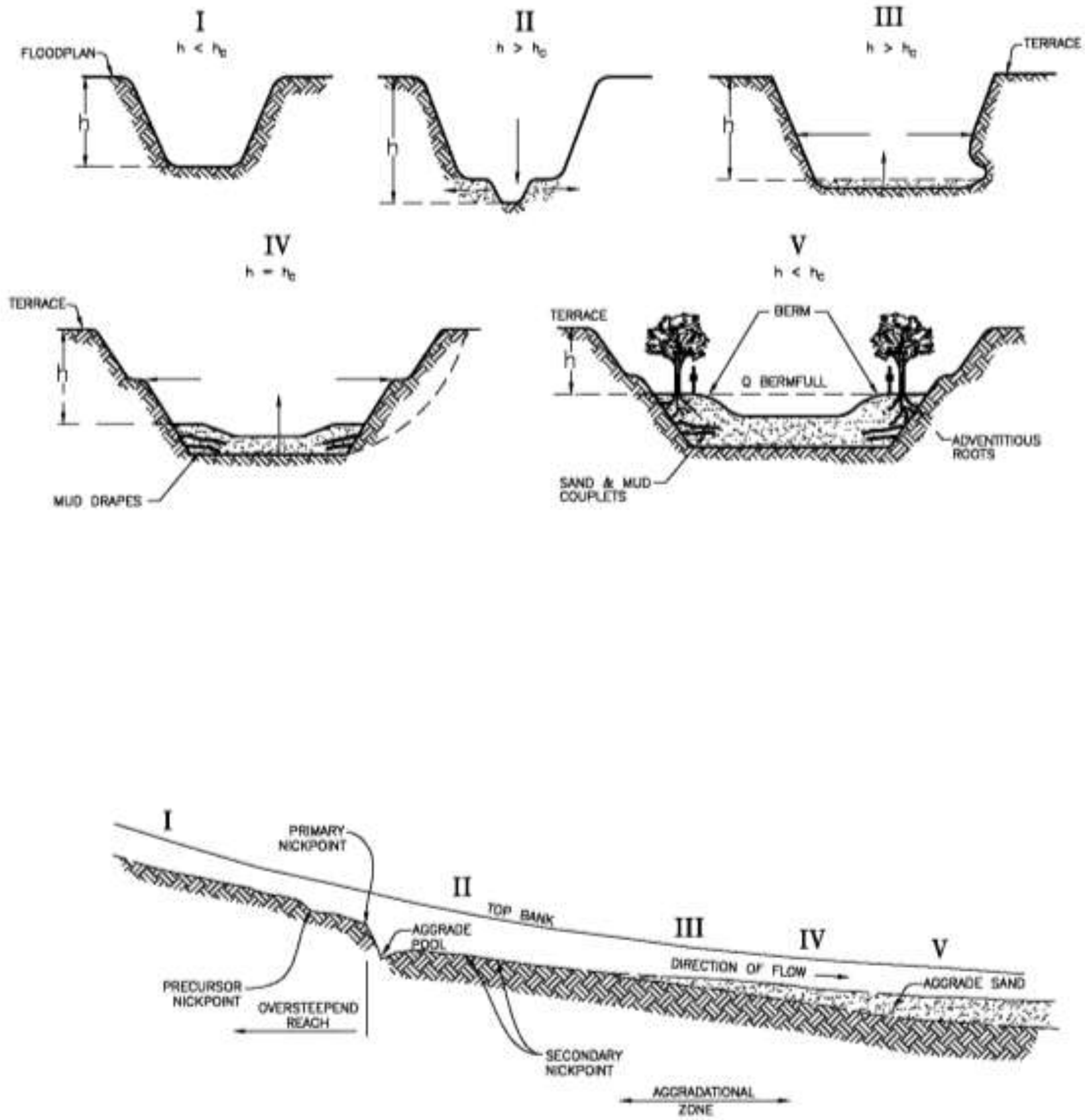


Figure 9-6. Incised Channel Evolution Sequence [Schumm et. al. 1984]

Type I reaches are typically characterized by a sediment transport capacity that exceeds sediment supply, bank height (h) that is less than the critical bank height (h_c - determined based on the bank slope angle, soil unit weight and tension-crack depth), a U-shaped cross section, small precursor knickpoints (knickpoint is the location where an abrupt change of bed elevation occurs) in the bed of the channel, and little or no bed material deposited. Width-depth ratios at bankfull stage are highly variable.

Type II reaches are located immediately downstream of the primary knickpoint and are characterized by a sediment transport capacity that exceeds sediment supply, a bank height that is greater than the critical bank height ($h>h_c$), little or no bed sediment deposits, a lower bed slope than the Type I reach, and a lower width-depth ratio value than the Type I reach because the depth has increased but the banks are not failing.

Type III reaches are located downstream of Type II reaches and are characterized by: a sediment transport capacity that is highly variable with respect to the sediment supply, a bank height that is greater than the critical bank height ($h>h_c$), erosion that is due primarily to slab failure [Bradford and Piest 1980], bank loss rates that are at a maximum, slight bed sediment accumulation, and channel depth that is somewhat less than in Type II. The channel is widening due to bank failure.

Type IV reaches are downstream of Type III reaches and are characterized by: a sediment supply that exceeds sediment transport capacity resulting in aggradations (increase in elevation) of the channel bed, a bank height that approaches the critical bank height with a rate of bank failure lower than Type III reaches, a nearly trapezoidal cross-section shape, and a width-depth ratio higher than the Type II reaches. Type IV reaches is aggradational and has a reduced bank height. Bank failure has increased channel width, and in some reaches the beginnings of berms along the margins of an effective discharge channel can be observed. These berms are the initiation of floodplain deposits that form in aggraded reaches which were over-widened during earlier degradational (decreasing in elevation) phases.

Type V reaches are located downstream of Type IV reaches and are characterized by: a dynamic balance between sediment transport capacity and sediment supply for the effective discharge channel, a bank height that is less than the critical bank height for the existing bank angle, colonization by riparian vegetation, an accumulated bed sediment depth, a width-depth ratio that exceeds the Type IV reach, and generally a compound channel formed within a newly formed floodplain. The channel is in dynamic equilibrium. Bank angles have been reduced by accumulation of failed bank materials at the toe of the slope and by accumulation of berm materials which may be alternating point bars.

The sequence of channel evolution is based on observed changes in channel morphology due to a single base level lowering without changes in the upstream land use and sediment supply. The sequence is applicable only in a system context, and local erosion such as in bends or caused by deflection of flow by debris may cause difficulty and complications.

The primary value of the sequence is to determine the evolutionary state of the channel from field reconnaissance. The morphometric characteristics of the channel reach types can also be correlated with hydraulics, geotechnical, and sediment transport parameters [Harvey and Watson, 1986; Watson et al., 1988]. The evolution sequence provides an understanding that reaches of a stream may differ in appearance, but channel form in one reach is associated with other reaches by an evolving process.

The U.S. Army Corps of Engineers [1990] used the channel evolution sequence in developing regional stability curves relating the bed slope of Type V channels as a function of the measured drainage area. Quasi-equilibrium, Type V reaches were determined by field reconnaissance of knowledgeable personnel. Figure 9-7 is an example of the empirical bed slope and drainage area relationship for Hickahala Creek, in northern Mississippi. The 95% confidence intervals of the regression line are shown. The slope-area curve is an example of an empirical relationship that does not explicitly include the primary factors of water and sediment discharge, sediment load, hydraulic roughness, and channel morphology.

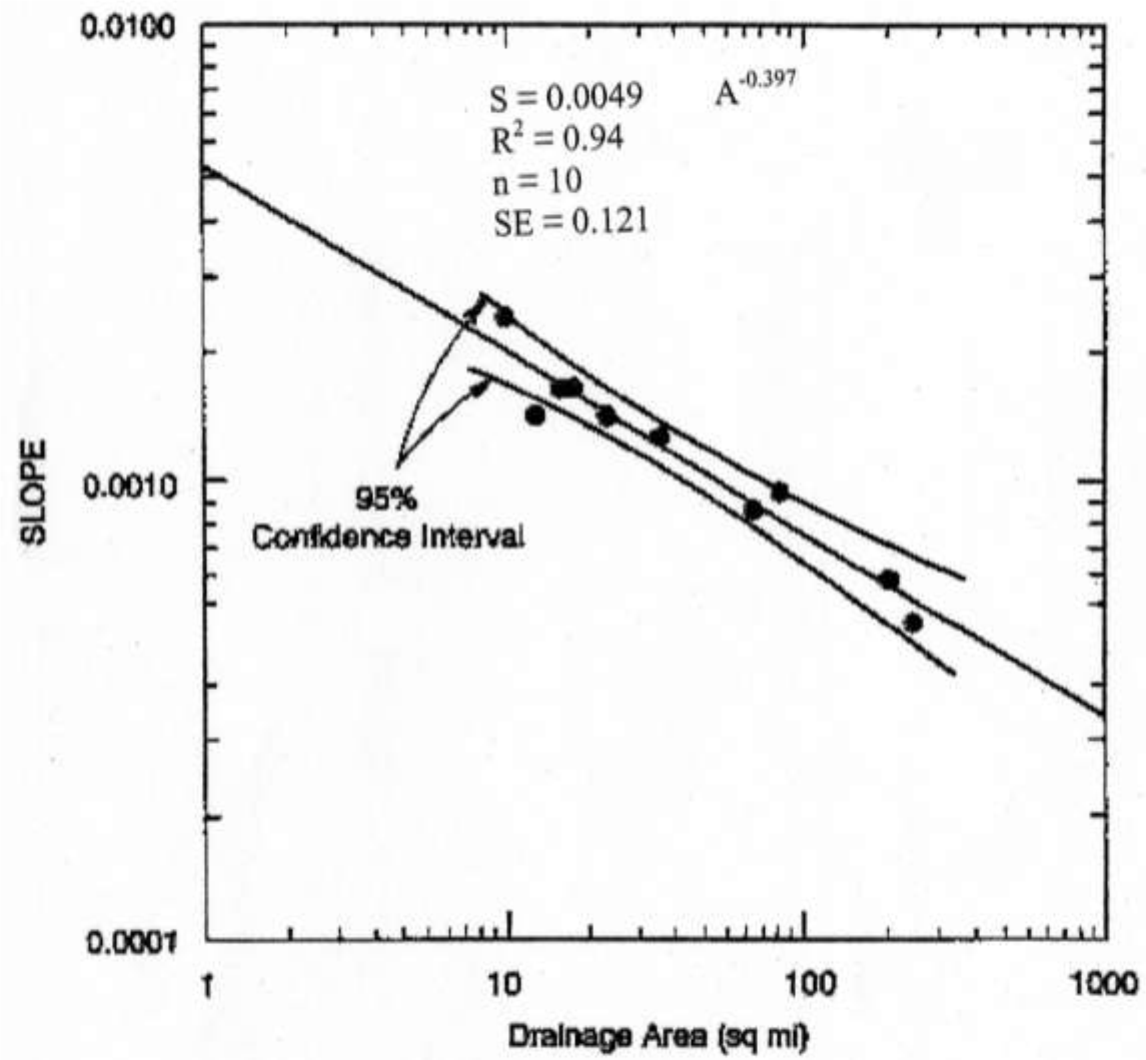


Figure 9-7. Hickahala Creek Watershed, Slope-Drainage Area Relationship [Watson et al., 1999]

Watson et al. [1995b] stated that stream classification is an essential element in transferring knowledge and experience pertaining to channel design from location to location. A computer program was developed to record a comprehensive data set for a watershed and for channel sites, and to present alternative classification of each based on three classification systems: Schumm [1977], Rosgen [1994], or Montgomery and Buffington [1993]. Watson et al. [1995a] found that improvement in stability of the incised reaches has resulted in lower channel slope and sediment yield. Hence, the slope-area curve must be constantly updated, or a design method that specifically includes sediment yield should be used.

Washington State [WSAHGP 2003] also noted that "most classification systems are based on the existing channel morphology of a stream in dynamic equilibrium, a rare occurrence especially in disturbed or urban watersheds. Therefore, a classification system must be used with the understanding that fluvial systems are constantly adjusting and evolving in response to changes in slope, hydrology, land use and sediment supply. Furthermore, classification systems are rarely appropriate as the basis for a channel or streambank design."

9.4 QUANTIFICATION OF THE EVOLUTIONARY SEQUENCE

The parameters of the Channel Evolution Model (Section 9.3) are difficult to quantify and to incorporate in design guidance. The parameters can be compressed into two dimensionless stability numbers: N_g is a measure of bank stability and N_h is a measure of sediment continuity. For a channel to be stable, bank stability and sediment continuity are essential.

The bank stability number, N_g, is defined as

$$N_g = \frac{\text{existing bank height (h) under the existing angle}}{\text{critical bank height (}h_c\text{) under the existing angle}} \tag{9-8}$$

Bank stability is attained when N_g is less than unity ($N_g < 1$). Therefore, N_g provides a rational basis for evaluating the requirements for bank stabilization and for evaluating the consequences of further bed degradation.

The hydraulic stability number, N_h, is defined as

$$N_h = \frac{\text{actual existing sediment transport capacity}}{\text{desired sediment transport capacity}} \tag{9-9}$$

Sediment continuity yields $N_h = 1.0$. It is important to note that the definition of N_h includes sediment transport and supply. Hydraulic stability in the channel is attained when N_h equals to 1. If N_h is less than 1, then the channel will be aggraded; and if N_h is greater than 1, then the channel will be degraded. Since sediment supply to a channel can change through time, it is prudent to design rehabilitation measures that will allow for the fluctuations in sediment supply.

In combination, N_g and N_h provide a set of design criteria that define both bank and hydraulic stability in the channel. Grade-control structures constructed in the channel should induce upstream deposition of sediment in the bed of the channel. Reduction in the sediment transport capacity as a result of slope reduction permits deposition of sediment. This reduces the bank height of the channel. Continued bank erosion will occur only if the failed bank materials are removed by fluvial processes. The aggradation upstream of the grade-control structure eventually will result in increased bank stability. In reality, cohesive materials and vegetation may make an estimate of critical bank height difficult analytically. Observation in the immediate vicinity for stable banks under similar vegetative growth and soil materials may be the only indication. Geotechnical soil boring and analysis may help to provide baseline information.

The dimensionless stability numbers, N_g and N_h, can be related to the channel evolution modes, as shown in Figure 9-8. As the channel evolves from a state of disequilibrium to a state of dynamic equilibrium through the five reach-types of the Oaklimiter Sequence, the channel condition will progress through the four stability diagram quadrants in a counter-clockwise direction. Rehabilitation of the channel should attempt to omit as many of the quadrants as possible to reduce the amount of channel deepening and widening.

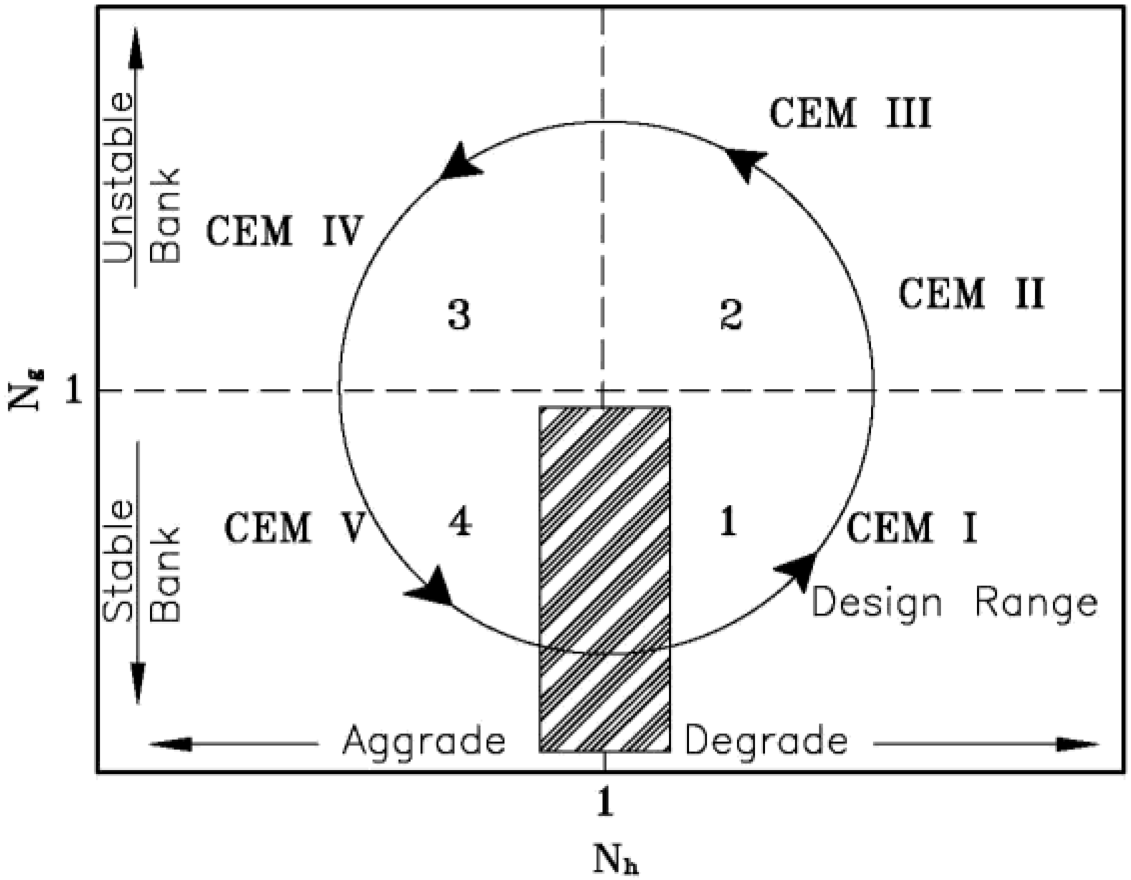


Figure 9-8. Comparison of the Channel Evolution Sequence and the Channel Stability Diagram [After Watson et. al., 1999]

Each quadrant of the stability diagram is characterized by a pair of geotechnical and hydraulic stability numbers. Stream reaches that plot in each quadrant have common characteristics with respect to stability, flood control, and measures that may be implemented to achieve a project goal.

Quadrant 2 ($N_g > 1$, $N_h > 1$) streams are severely unstable; the channel bed is degrading and channel banks are geotechnical unstable. Grade control must be used to reduce bed slope, transport capacity, and the value of N_h. Both flood control and bank stability must be considered when determining the height to which grade control should be constructed. A series of grade control structures can reduce bank height enough to stabilize the banks, but a combination of grade control and bank sloping may better resolve flood control while meeting stability objectives.

Quadrant 1 ($N_g < 1$, $N_h > 1$) is not as severe as Quadrant 2; the channel bed may be degrading or may be incipiently degradational, but the channel bank is not yet geotechnically unstable. Bank erosion is occurring only locally and bank stabilization measures such as riprap or tree log toe protection and/or bank vegetation may be applied. However, local stabilization will not be successful if bed degradation continues, moving to Quadrant 2, and destabilizing the channel stabilization measures. When flood control is a project goal, almost any channelization measure or construction of levees will increase the N_h instability, shifting the value to the right and increasing the opportunity to make $N_g > 1$. Flow control using a reservoir or detention basin can address flood control and improve stability if the new flow duration curve reduces cumulative sediment transport; however, changing the flow duration curve and reducing the available sediment supply are potentially destabilizing factors. All of these factors should be considered in projects. Bed stabilization through the use of a grade control structure may be desirable.

Quadrant 3 ($N_g > 1$, $N_h < 1$) has a severe and dynamic problem with gravity driven bank failure, but without continued bed degradation. Bank sloping could be effective without grade control emplacement. Local bank stabilization measures in either Quadrant 2 or 3 are unlikely to be successful. Flow control in these two quadrants could be beneficial, but must be considered in the context of extreme reach instability and grade control is likely to be required.

Quadrant 4 ($N_g < 1$, $N_h < 1$) is characterized by general aggradation. Local bank stabilization measures will be effective. As N_h decreases in this quadrant, the potential for channel aggradation-related flood control problems increases.

The desirable range for long-term channel stability is for N_g to be less than one, and for N_h to be approximately one ($N_g < 1$, $N_h \approx 1$). If flood capacity is not sufficient as N_g approaches 1, levees or a compound channel should be considered.

The U.S. Army Corps of Engineers [1990] used the channel stability diagram to review stability of Nelson, Beards, Catheys, and James Wolf Creeks, as shown in Figure 9-9. Figure 9-10 depicts the change resulting from channel stabilization measures that move two streams from degradation to aggradation (Stream A), and from degradation and unstable banks to aggradation and stable banks (Stream B). The proper characteristics for long-term stability are neither aggrading nor degrading, with stable banks.

To summarize this discussion, it is imperative to achieve a stable channel design before considering bank protection. Stable channels may be designed by balancing the upstream sediment supply with sediment transport in the project reach. A practical and effective method to estimate critical bank height is to observe the reaches in the immediate vicinity to look for stable bank heights under similar soil and vegetative conditions. Geotechnical investigation and analysis may be necessary, but may not reveal the true stable condition under vegetative protection.

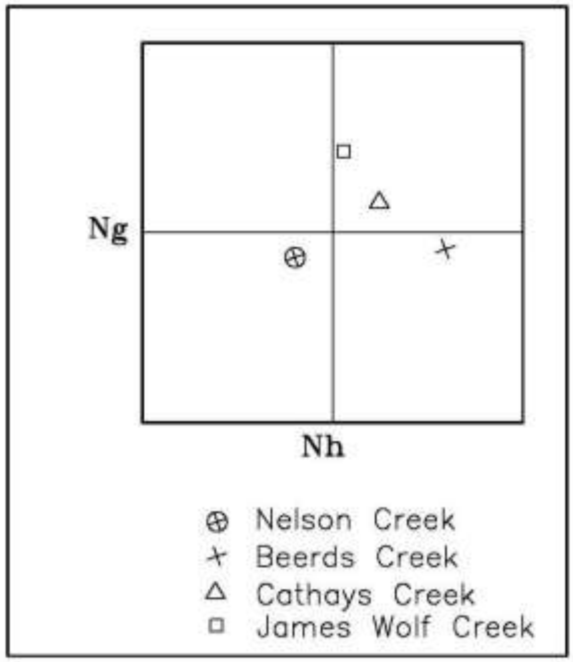


Figure 9-9. Creek Channels of Hickahala Watershed Plotted on N_g-N_h Diagram [USACE, 1990]

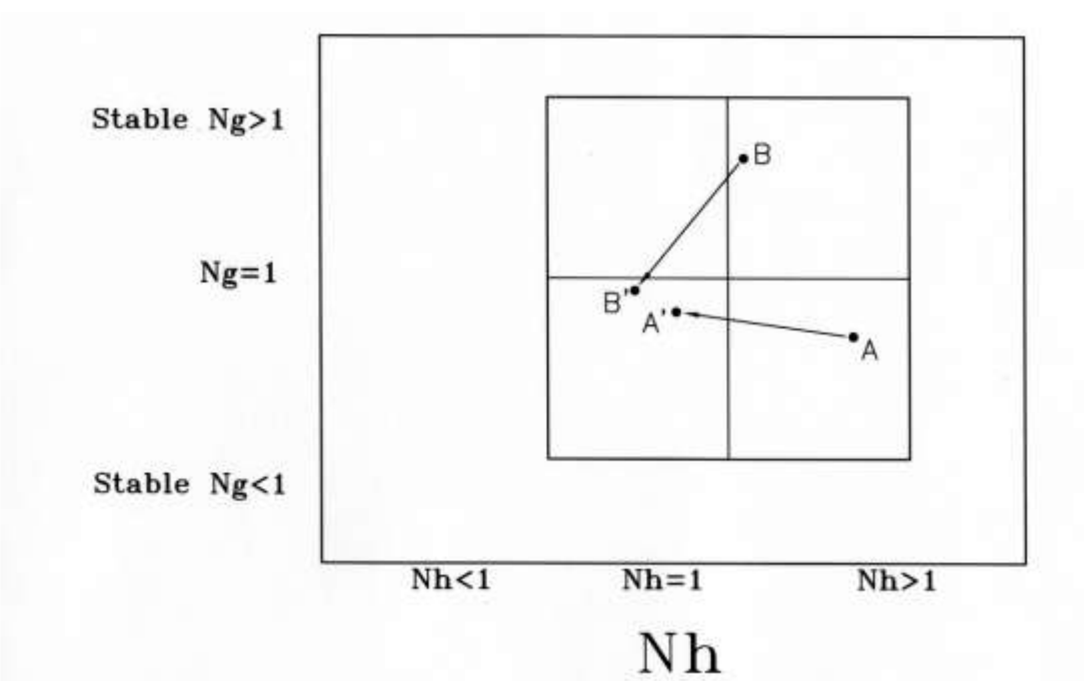


Figure 9-10. Dimensionless Stability Diagram Showing Effect of Stabilization Measures Applied on Two Hypothetical Streams [Watson et. al. 1999]

9.5 CHANNEL STABILITY CONCEPTS

Stream bank protection measures often fail, not as the result of inadequate structural design, but because of failure of the designer to incorporate existing and future channel morphologic characteristics into the design. For this reason, it is important for us to have a general understanding of stream processes to insure that the selected stabilization measures will work in harmony with the existing and future river conditions. This section describes the basic concepts of channel stability. The goal is to allow us to assess whether the erosion at a particular site is due to local instability causes or is the result of some system-wide instability problems that may be affecting a more extensive river reach.

9.5.1 Stable Channel

The concept of a stable channel has been described in many different terms by various people working on the subject. Channel stability, dynamic equilibrium, quasi equilibrium, graded, and in regime were all used to describe a channel that has attained a balance between sediment load coming into the reach and sediment transport out of the reach to result in no net change to the channel slope or cross-sectional dimensions over some time period. Among these terms, the stable channel and channel in regime have the least ambiguity. They mean a channel without net degradation or aggradation or bank erosion problems. Dynamic equilibrium, on the other hand, as defined by Chorley and Kennedy [1971] and Schumm [2006] and shown in Figure 9-11a, represents that, on top of the short-term fluctuations around the mean, there is still a gradual net change in the morphologic characteristic of the channel over a longer time scale. In a strict sense, the dynamic equilibrium is not a stable condition and it represents a transition between 2 stable conditions. However, it has been interpreted by many researchers, i.e., Rosgen [2001], to have the same meaning as a stable channel.

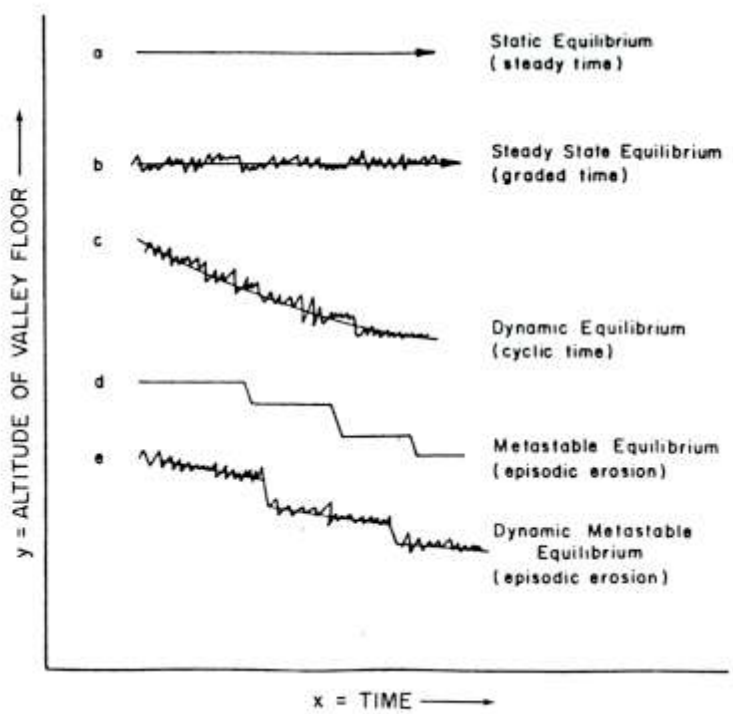


Figure 9-11a. Types of Channel Equilibrium Defined by Chorley and Kennedy [1971]

Many researchers interpret dynamic equilibrium as an equilibrium condition with continuous (dynamic) sediment movements in the channel, but without net sediment aggradation or degradation. Under this dynamic equilibrium condition, there may be ongoing changes in the stream bank, erosion may result, and bank stabilization may be necessary, but sediment transport is generally in balance. For the rest of the manual, we will adopt this representation, and treat channel stability and dynamic equilibrium as equals.

A channel that has adjusted its dependent variables, as described in Section 9.2, to accommodate the basin inputs (independent variables) is said to be stable. Mackin [1948] gave the following definition of a graded stream:

> "A 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 the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium."

The equilibrium concept of streams discussed above can also be described by various qualitative relationships. One of the most widely used relationships is the one proposed by Lane [1955] which states that

$$q_{bmT} D_{50} \propto QS \qquad (9\text{-}10)$$

where q_{bmT} is the total bed material load (Eq. (9-12), D_{50} is the median size of the bed material, Q is the water discharge, and S is the slope,. This relationship (commonly referred to as Lane's Balance) is illustrated in Figure 9-11b. Mackin's concept of adjustment to changes in the controlling variables is easily illustrated by Lane's balance which shows that a change in any of the four variables will cause a change in the others such that equilibrium is restored. When a channel is in equilibrium, it will have adjusted these four variables such that the sediment being transported into the reach is transported out, without significant deposition in the bed (aggradation), or excessive scour (degradation). It should be noted that most people recognize stability as a condition in which a channel is free to migrate laterally by eroding one bank and accreting the other at a similar rate.

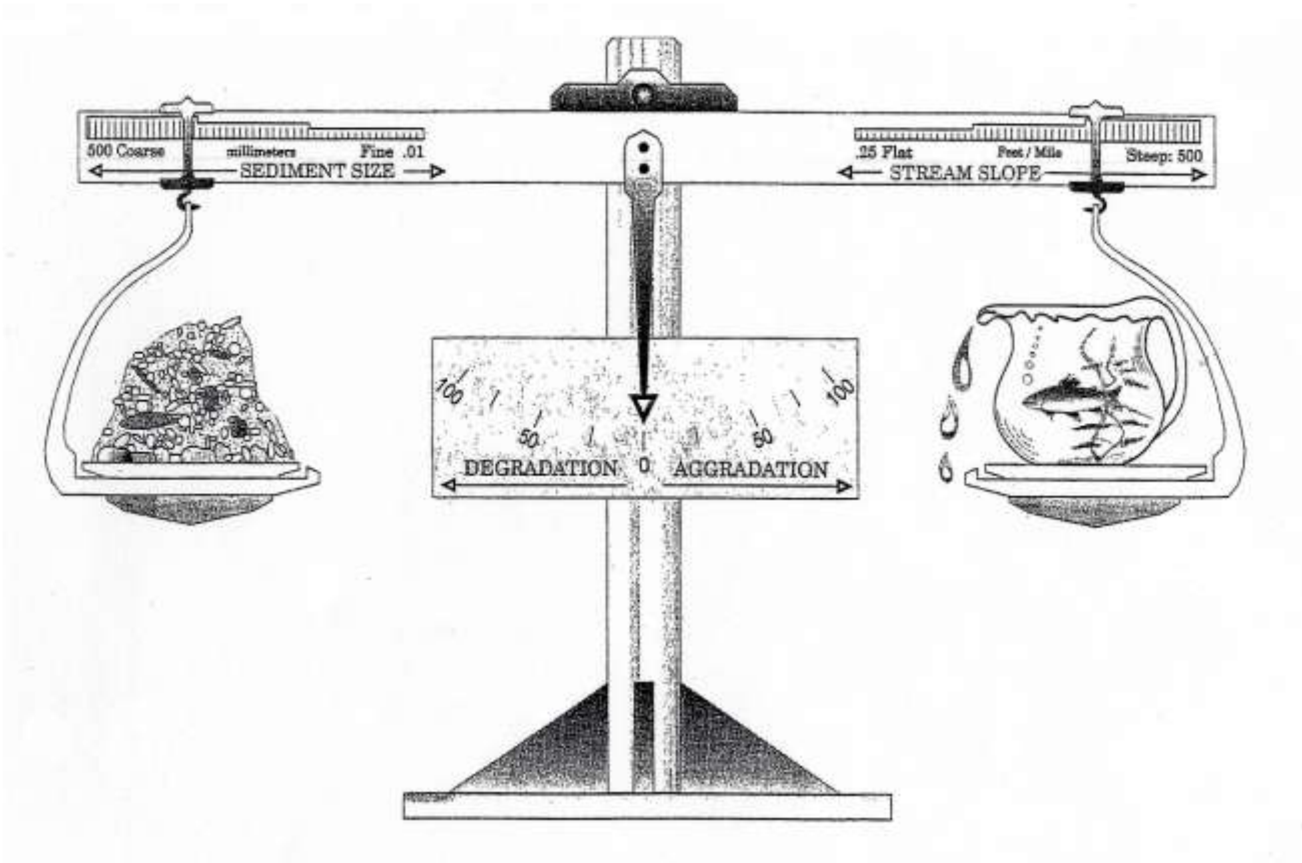


Figure 9-11b. Schematic of the Lane Relationship for Qualitative Analysis [After Lane, 1955, from Rosgen, 1996].

Meandering can be thought of as nature's way of adjusting its energy (slope) to the variable inputs of water and sediment. Cutoffs (oxbow lakes) and abandoned courses in the floodplain attest to be dynamic behavior of rivers. Oftentimes one draws the erroneous conclusion that a disequilibrium condition exists because natural cutoffs are occurring. However, this type of dynamic behavior is common in rivers that are in a state of dynamic equilibrium. In this situation, as natural cutoffs occur, the river may be obtaining additional length elsewhere through meandering, with a net overall reach length and slope remaining unchanged.

In summary, a stable river, from a geomorphic perspective, is one that has adjusted its width, depth, and slope such that there is no significant aggradation or degradation of the stream bed or significant planform changes (meandering to braided, etc.) within the engineering time frame (generally less than 50 years). By this definition, a stable river is not in a static condition, but rather in a state of dynamic equilibrium where it is free to adjust laterally through bank erosion and bar building. This definition of geomorphic stability here is to establish a reference point for the discussion of system and local instability in the following sections.

9.5.2 System Instability

The equilibrium of a river system can be disrupted by various factors. Once this occurs the channel will attempt to re-gain equilibrium by making adjustments in the dependent variables. These adjustments are generally reflected in channel aggradation, degradation, or changes in planform characteristics (meander wavelength, sinuosity, etc.). Depending upon the magnitude of the change and the basin characteristics (bed and bank materials, hydrology, geologic or man-made controls, sediment sources, etc.) these adjustments can propagate throughout the entire watershed and even into neighboring systems. For this reason, the disruption of an equilibrium condition will be considered as system instability.

More complete discussions of channel morphologic responses to system instability may be found in Simons and Senturk [1992], Schumm [1972], Richards [1982], Knighton [1984], and Thorne et al. [1997].

9.5.3 Causes of System Instability

The stability of a channel system can be affected by a number of natural or human-induced factors. Natural processes such as climatic changes and tectonic plate movement obviously can cause changes but these changes generally occur over thousands or perhaps millions of years and, therefore, are not often a direct concern to an individual trying to stabilize a streambank. On the other hand, natural factors such as earthquakes and volcanic eruptions can cause significant impacts within the engineering time span. However, the most commonly encountered system instability problems are generally attributed, at least in part, to human activities.

Any time one or more of the independent variables (runoff, sediment loads, sediment size, valley slope, etc.) in a watershed are altered there is a potential for system instability. The particular system response will depend on the magnitude of change and the existing morphological sensitivity of the system. Therefore, each system is unique and there is no standard response that applies to all situations. With this in mind, it is not practical to attempt to discuss all the possible scenarios of channel response. Rather, the aim of this discussion is to present some of the more common factors causing system instability, and to illustrate how a particular channel response might be anticipated using the stability concepts discussed earlier.

A list and brief discussion of some of the more common causes of system instability are presented in the following sections. For this discussion the causes have been grouped into three categories: (1) downstream factors, (2) upstream factors, and (3) basin-wide factors. Following this, a brief discussion is presented concerning complex response and the complications involved when a system is subject to multiple factors.

Downstream Factors

The stability of a channel system can be significantly affected by a downstream **base level lowering**. Base level refers to the downstream controlling water surface or bed elevation for a stream. One of the most common causes of base level lowering is the implementation of cutoffs or channelization as part of channel improvement projects. As indicated by Lane's relation (Eq. (9-10) and Figure 9-11b), the increased slope must be offset by one of the other variables. If the discharge and bed material are assumed to remain constant, then the channel must adjust to the increased slope by increasing its bed material load. This increased sediment load will be derived from the bed and banks of the channel in the form of channel degradation and bank erosion. As the bed continues to degrade, the zone of increased slope will migrate upstream and the increased bed material load is transmitted downstream to drive aggradational instability.

The manner in which degradation migrates through a channel system is a very complex process. Before this process is discussed some of the relevant terminology must first be addressed. The following definition of terms is based on the terminology used by Schumm et al.

[1984]. **Channel degradation** simply refers to the lowering of the channel bed. Field indicators of degradation occur in the form of knickpoints or nickzones (in literatures nick and knick are the same). **Knickpoint** is a location of an abrupt change of bed elevation and slope. It may be visualized as a waterfall or vertical discontinuity in the stream bed. A **knickzone** is often composed of a series of small knickpoints. Knickpoints and nickzones are often referred to as headcuts. While headcut is a commonly used term, it does generate some confusion because it is also used as a description of the headward migration process of degradation. To avoid this confusion, the field indicators of degradation (knickpoints and nickzones) will not be referred to as headcuts. Rather, a headcut (or headcutting) is defined as a headward migrating zone of degradation. This headcutting may occur with or without the formation of knickpoints or nickzones which are purely, a function of the materials encountered.

Once headcutting is initiated, it may proceed rapidly through the system. The rate of headward advance is a direct function of the materials encountered in the bed and also the basin hydrology. If the channel bed is composed primarily of non-cohesive sands and silts, then no knickpoints or nickzones will form and headcutting will work upstream by parallel lowering of the bed. However, if consolidated materials such as clays, sandstones, or other resistant materials occur in the channel bed, then knickpoints or nickzones will form as degradation encounters these resistant layers. When this occurs the headward migration rate may slow considerably. Therefore, the dominant factor affecting the headward migration rate is the relative resistance to erosion of the bed materials, and to a lesser degree the discharge in the stream.

As degradation migrates upstream it is not restricted to the main stem channel. When headcutting passes through tributary junctions it lowers the base level of these streams. This initiates the degradation process for the tributary. The localized increased slope at the confluence produces an increased sediment transport capacity that results in degradation of the tributary stream bed. This process can continue upstream rejuvenating other tributaries until the entire basin has been affected by the downstream base level lowering.

Upstream Factors

System instability may be initiated by upstream alterations in the basin. This alteration may most commonly result from a change in the incoming discharges of water and/or sediment. Looking at Lane’s balance I (Figure 9-11b), it can be seen that either an increase in the water discharge or a decrease in the sediment load will initiate channel degradation, i.e., reduction in slope. These changes may be caused by watershed development which results in increased surface runoff or by the construction of a debris dam to intercept sediment. A discussion of the effects of these changes on channel stability follows.

Construction of a dam has a direct impact on the downstream flow and sediment regime. Since both flow and sediment load will decrease downstream from the dam, Lane’s equation shows that these 2 changes have counteracting effects on channel slope. Most likely in the immediate reach downstream from the dam, the effect of reduced sediment load outweighs that of reduced flow, and degradation will result. Further downstream, the increased sediment discharge from the degradation upstream may cause aggradation. This scenario was reflected in the Calabazas Creek following construction of the Comer debris basin.

Channel adjusts to the increased flow rate and duration due to urbanization by degrading to reduce channel slope. Degradation may migrate downstream with time, but generally it is most significant during the first few years following watershed development. An increase in discharge can have a significant impact on channel planform as well as vertical stability. Schumm [1977] proposed a qualitative relation similar to Lane's that included meander wavelength and was discussed in Section 9.2.2:

$$Q_w \propto \frac{WYL}{S} \tag{9-7b}$$

where Q is the discharge, W is the width, Y is the depth, L is the meander wavelength, and S is the slope. It indicates that an increase in discharge may result in an increase in meander wave length which will be accomplished through erosion of the streambanks. Therefore, whenever urbanization or flow diversion is proposed the potential for increased meander activity should be considered. If a stream is in the process of increasing meander wavelength, then stabilization of the bends along the existing alignment is likely to be unsuccessful and is not recommended.

Basin-Wide Factors

Sometimes changes in the independent variables cannot be attributed to a specific upstream or downstream factor, but rather are occurring on a basin-wide basis. This often results from a major land use change. These changes can significantly modify the incoming discharge and sediment loads to a channel system. For example, land use change from agricultural to residential can increase peak flows and reduce sediment delivery, both of which will tend to cause channel degradation. A land use change from forest to row crop on the other hand might cause significant increase in sediment load to result in aggradation of the channel system. Unfortunately, it is difficult, if not impossible, to predict when basin-wide changes such as these will occur. Therefore, the best a designer can do is to design bank protection measures to accommodate the most likely future changes in the watershed. For instance, if there is a possibility of future urbanization in the upper watershed, then additional riprap may be needed to protect the bank from the destabilizing impact of future bed lowering.

9.5.4 Complexities and Multiple Factors

Lane's balance and other geomorphic analyses of initial morphological response to system disturbance provide a simple qualitative method for predicting the channel response to an altered condition. However, it does not take into account the magnitude of the change nor the existing condition of the stream. For instance, according to Lane's diagram of Fig. 9-11b a meander cutoff, i.e., increased channel slope, should induce degradation. While this is often the case, there are many examples where there may be no observable change in the channel morphology following construction of meander cutoffs. Brice [1981] documented the stability of streams at 103 sites in different regions of the United States where channels had been relocated. He found that following cutoffs, 52% of the channels showed no change, 32% showed improvement, and 16% exhibited channel degradation. This study indicates that predicting channel response to cutoffs is not nearly as simple as may be inferred from Lane's balance. Different site conditions may produce significantly varied responses to a common alteration. For instance, a rock outcrop or concrete culvert in the channel may serve to control grade and prevent degradation. Therefore, one should always consider specific site conditions when attempting to predict, even in qualitative terms, the behavior of river systems.

Previous discussions have focused primarily on the initial response of a channel to various alterations in the watershed. However, it must be remembered that the entire watershed is connected and that changes in one location can, and often do, affect the channel stability at other locations, which in turn provides a feedback mechanism whereby the original channel response may be altered. For example, the initial response to a base level lowering due to channelization may be channel degradation. However, as this degradation migrates upstream the sediment supply to the downstream reach may be significantly increased due to the upstream bed and bank erosion. This increased sediment load coupled with the slope flattening due to the past degradation may convert the channel from a degradational to an aggradational phase. Multiple responses to a single alternation have been referred to as complex response by Schumm [1977].

Another complicating factor in assessing the cause and effect of system instability is that very rarely is the instability a result of a single factor. In a watershed where numerous alterations (dams, levees, channelization, land use changes, etc.) have occurred at different times, the channel morphology will reflect the integration of all these factors. Unfortunately, it is extremely difficult and often impossible to sort out the precise contributions of each of these components to the system instability. The interaction of these individual factors coupled with the potential for complex response makes assessing the channel stability and recommending channel improvement features, such as bank protection, extremely difficult. There are numerous qualitative and quantitative procedures that are available. Regardless of the procedure used, one should always recognize the limitations of the procedure, and the inherent uncertainties with respect to predicting the behavior of complex river system.

9.5.5 Local Instability

In this section, local instability refers to bank erosion that is not symptomatic of a disequilibrium condition in the watershed (i.e., system instability) but results from site-specific factors and processes. A most common form of local instability is bank erosion along the concave bank in a meander bend which is occurring as part of the natural meander process. Local instability does not imply that bank erosion in a channel system is occurring at only one location or that the consequences of this erosion are minimal. As discussed earlier, erosion can occur along the banks of a river in dynamic equilibrium. In these instances the local erosion problems are amenable to local protection works such as bank stabilization measures. However, local instability can also exist in channels where severe system instability exists. In these situations the local erosion problems will probably be accelerated due to the system instability, and a more comprehensive treatment plan will be necessary. This will be our approach to the treatment of erosion repair and bank protection designs of Chapter 4.

Overview of Meander Bend Erosion

As noted above, erosion in meander bends is probably the most common process responsible for local bank retreat and, consequently, is the most frequent reason for initiating a bank stabilization program. A key element in stabilization of an eroding meander bend is an understanding of the location and severity of erosion in the bend, both of which will vary with stage and planform geometry.

As streamflow moves through a bend, the velocity and tractive force concentrate along the outer bank. Consequently, erosion in bends is generally much greater than in straight reaches. In some cases, the tractive force may be twice that in a straight reach just upstream and downstream of the bend. The tractive force is also greater in tight bends than in longer-radius bends (see Figure 8-10 originally produced by Soil Conservation Services [SCS 1977]). This was confirmed by Nanson and Hickin [1986] who studied the migration rates in a variety of streams, and found that the erosion rate of meanders increases as the radius of curvature to width ratio (r/w) decreased below a value of about 6, and reached a maximum in the r/w range of 2 to 3. Biedenharn et al. [1989] studied the effects of r/w and bank material on the erosion rates of 160 bends along the Red River in Louisiana and also found that the maximum erosion rates were observed in the r/w range of 2 to 3. However, the considerable scatter in their data indicates that other factors, particularly bank material composition, were also modifying the meander process.

The severity and location of bank erosion also changes with stage. At low flows, the main thread of current tends to follow the concave (outside) bank alignment. However, as flow increases, the flow tends to cut across the convex bar to be concentrated against the concave bank below the apex of the bend. Friedkin [1945] documented this process in a series of laboratory tests on meandering in alluvial rivers. Because of this process, meanders tend to move in the down-valley direction, and the zone of maximum erosion is usually in the downstream portion of the bend due to the flow impingement at the higher flows. This explains why the protection of the downstream portion of the bend is so important in any bank stabilization scheme. The material eroded from the outer bank is transported downstream and is generally deposited in the next crossing or point bar. This process also results in the deposition of sediment along the upper portion of the concave bank. This depositional feature is often a good indicator of the upstream location to start a bank protection measure.

Streambank Erosion and Failure Processes

The terms streambank erosion and streambank failure are often used to describe the removal of bank material. Streambank erosion generally refers to the hydraulic process where individual soil particles at the bank's surface are carried away by the tractive force of the flowing water. The tractive force increases as the water velocity and depth of flow increase. Therefore, the erosive forces are generally greater at higher flows. Streambank failure differs from erosion in that a relatively large section of bank fails and slides into the channel. Streambank failure is often considered to be a geotechnical process. A detailed discussion of the erosion and failure processes discussed below is provided by Thorne [1993].

Identifying the processes responsible for bank erosion is not an easy task and often requires some training beyond the purpose of this manual. The primary erosion processes are parallel flow, impinging flow, piping, freeze/thaw, sheet erosion, rilling/gullying, wind waves, and vessel forces.

Serious bank retreat often involves geotechnical bank failures as well as direct erosion by the flow. Such failures are often referred to as "bank sloughing" or "caving", but these terms are poorly defined and their use is to be discouraged. Examples of different modes of geotechnical stream bank failure include soil fall, rotational slip, slab failure, cantilever failure, pop-out failure, piping, dry granular flow, wet earth flow, and other failure modes such as cattle trampling.

9.6 BANKFULL CHANNEL AND GEOMORPHOLOGY

Bankfull channel is the most important concept of geomorphology that affects our work in flood protection, river rehabilitation or restoration. The understanding of this concept, determination of bankfull channel dimensions, and utilization of this information in design is critically important. This section intends to introduce a few more bankfull-related terms frequently encountered in the literatures, and sets the stage for design procedures that will be discussed in Chapter 1.

9.6.1 Bankfull Discharge

Bankfull discharge is the maximum discharge that the channel can convey without overflowing onto the floodplain. This discharge is considered to have morphological significance because it represents the breakpoint between the process of channel formation and floodplain formation.

The bankfull discharge is determined first by identifying bankfull stage and then determining the discharge associated with that stage. Many field indicators exist of the bankfull stage. The most common definition of bankfull stage is the elevation of the active floodplain [Wolman and Leopold, 1957]. If an active floodplain does not exist, as in some reaches of an incised channel, look upstream or downstream in the immediate vicinity.

Another common definition of bankfull stage is the elevation where the width to depth ratio is a minimum [Wolman 1955, Pickup and Warner 1976]. This definition, diagramed in Figure 9-12a, is systematic and only relies on accurate field survey.

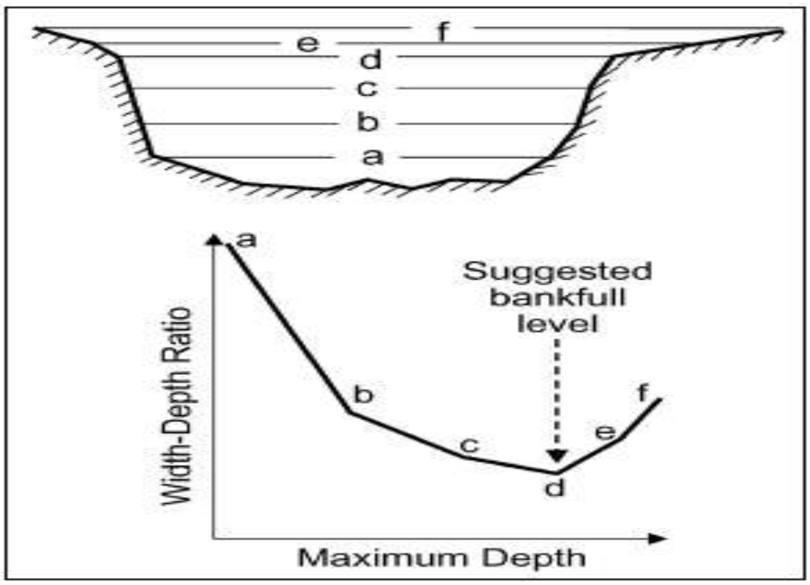


Figure 9-12a. Bankfull Stage Using Width-Depth Ratio, After [Knighton 1984]

Wolman [1955] also combines the width to depth ratio criterion with identifying a discontinuity in the channel boundary such as a change in its sedimentary or vegetation characteristics. Schumm [1960] defined bankfull stage as the height of the lower limit of perennial vegetation, primarily trees. Similarly, Leopold [1994] states that a change in vegetation, from herbs, grasses, and shrubs to woody trees indicates the bankfull stage.

It is worthwhile to note again that the bankfull stage is geomorphologically significant only in stable channels. If the reach under study is not stable, the bankfull characteristics will change as the channel evolves. In that case, search for bankfull indications in an immediate upstream or downstream reach that is stable.

Another characteristic of the bankfull channel is that the shear stress on the channel bottom will peak near the bankfull flow when wide floodplains are present, and further increase in flow will result in a reduction in energy slope and shear stress. This characteristic is illustrated in Figure 9-12b.

Figure 9-12b(1) shows the cross-section with definitions of the bankfull width, floodplain width and entrenchment ratio. The entrenchment ratio, defined as the ratio of channel width at 2 times the bankfull depth to the bankfull width, is used here to represent the effect of floodplain width. The wider is the floodplain, the larger becomes the entrenchment ratio (ER). Figure 9-12b(2) shows the change in energy slope with increasing ER. Without floodplains, when ER=1.6, increasing the flow beyond bankfull will see the energy slope continue to rise. With increasing floodplains the energy slope will drop below the bankfull level ($S/S_{bf} < 1$) when flow spreads onto the floodplains. Further increase in floodplain width beyond ER=7 will have diminishing benefit.

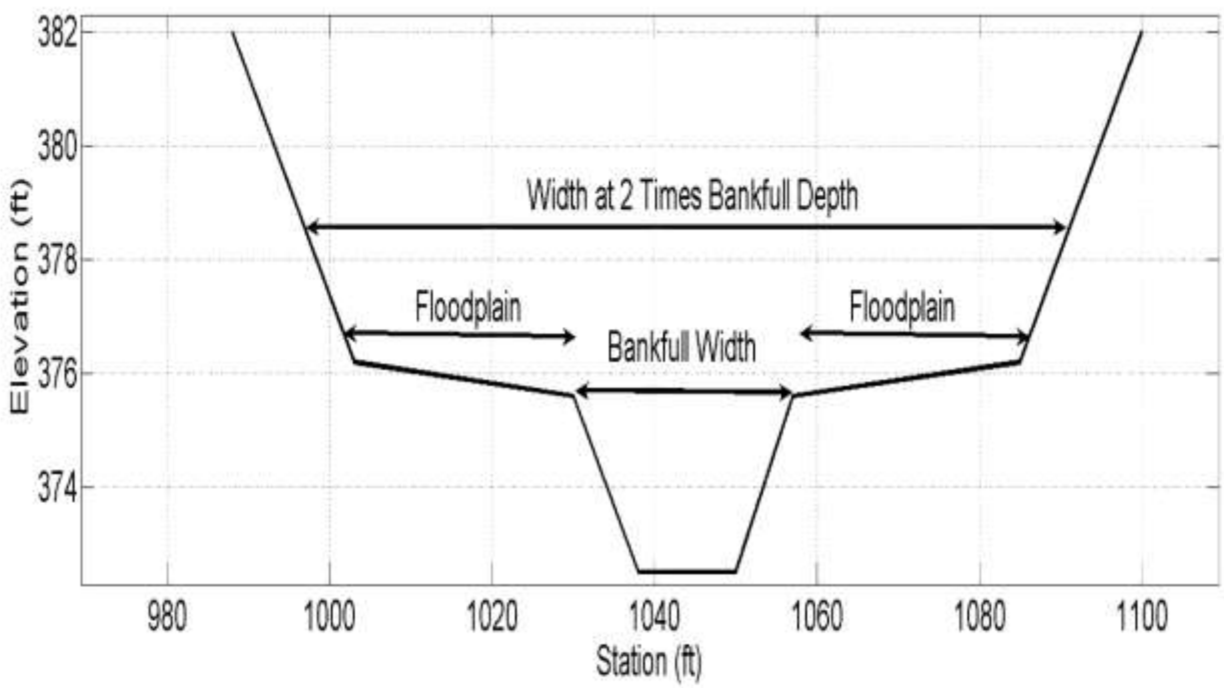


Figure 9-12b(1). Definition Sketch of Channel Cross-Section

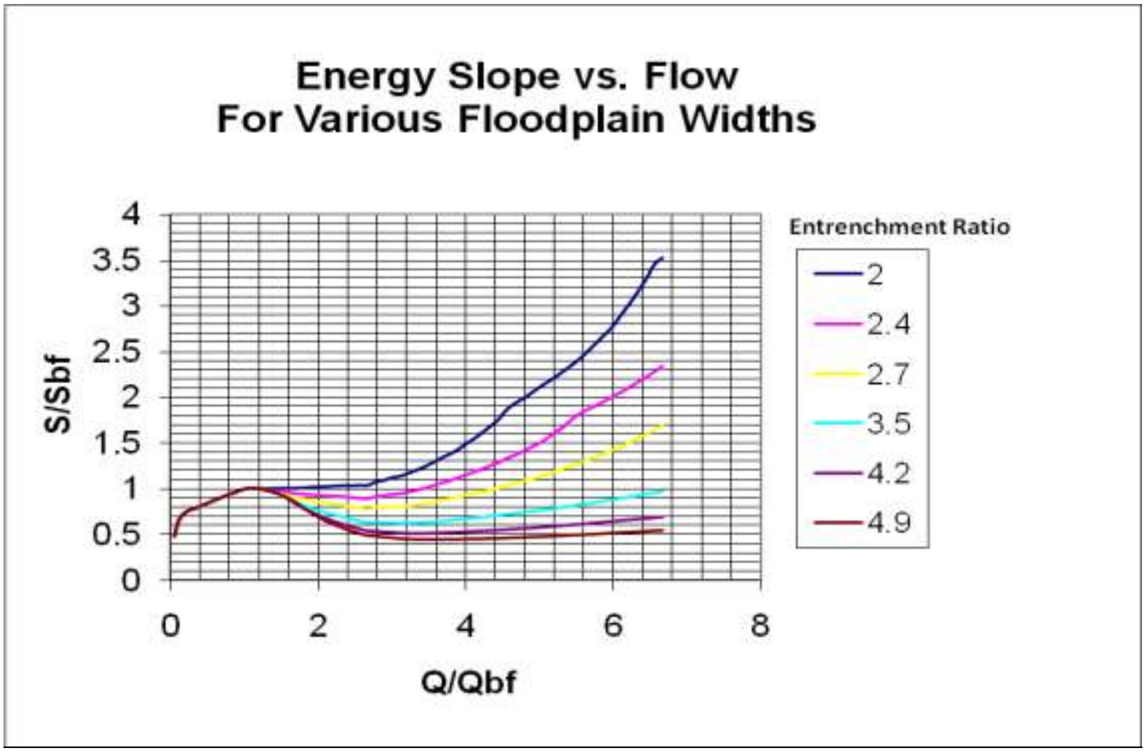


Figure 9-12b(2). Variation of Energy Slope With Floodplain Width

Figure 9-12b(3) shows how the dimensionless bottom shear stress (τ/τ_{bf}) changes with flow and floodplain width. Given a floodplain as wide as the bankfull width, e.g., $W_{fp}/W = 1$, the bottom shear stress will remain at about the bankfull level until the flow triples the bankfull flow, and further increasing in flow will see an increase in shear to beyond the bankfull level. When the floodplain is wider than 2 times the bankfull width, the bottom shear will remain fairly constant at 70% of the bankfull level through the flow regime.

This information is useful in 2 aspects. First, if there are wide floodplains, shear stress in the channel may be limited to a maximum of 1.2 times the bankfull shear and channel protection may be designed using a flow about 1.5 times the bankfull flow. An analysis similar to that depicted in Figure 9-12b(3) has to be performed to quantify the shear-stress requirements. Secondly, when a floodplain is not available, the bottom shear will increase with flow, and the design flow for channel protection should then be determined based on a risk analysis of cost and benefit. Caltran [2000] requires an analysis of risks to human life and property damage against cost of building or replacement, and finds 10% to 1% flow appropriate in different cases. We will define our design-flow requirements later in Chapter 4 and 3 based on different channel conditions.

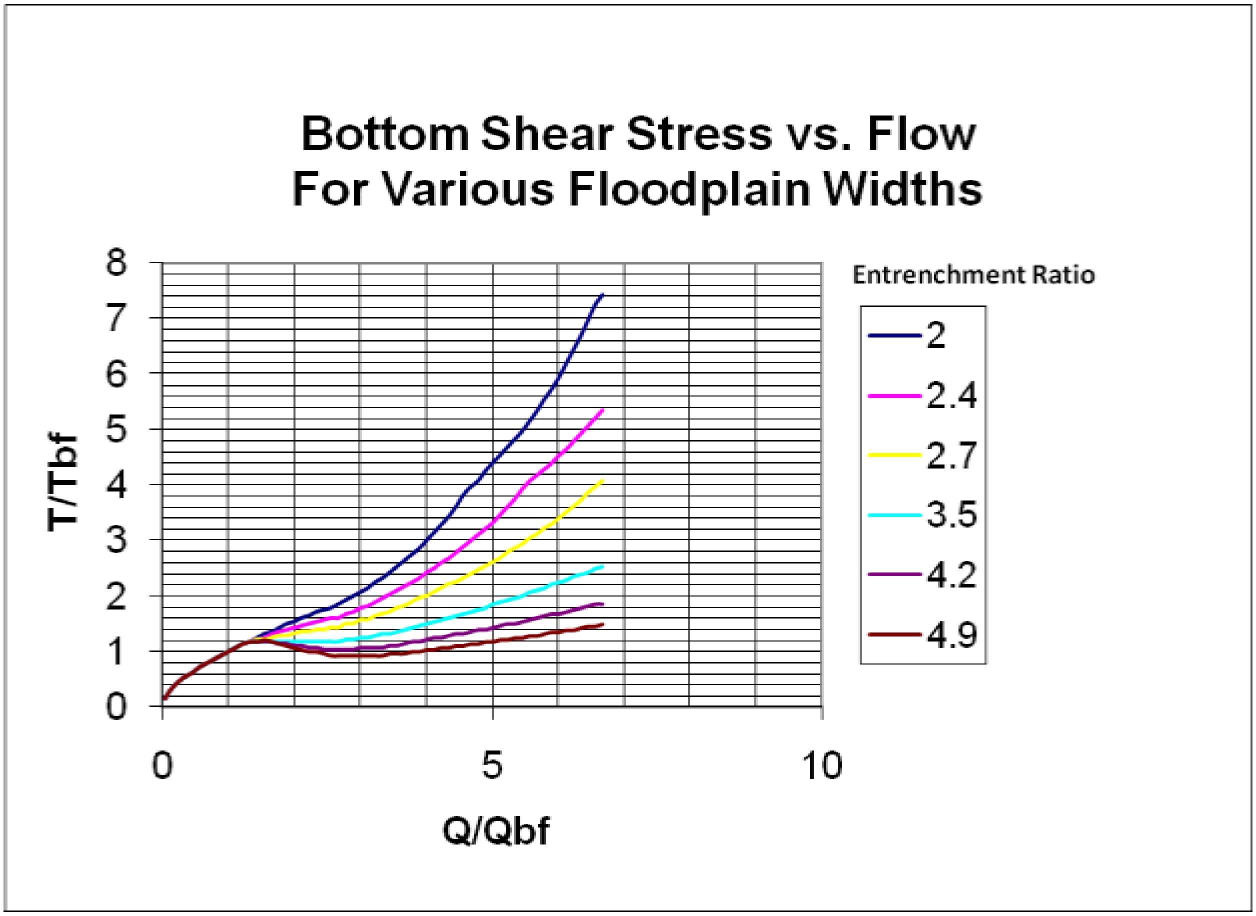


Figure 9-12b(3). Variation of Bottom Shear Stress With Floodplain Width

Some literatures show data associating bankfull discharge to watershed area, such as Emmett [1975] for the Salmon River in Idaho, as duplicated in Figure 9-13.

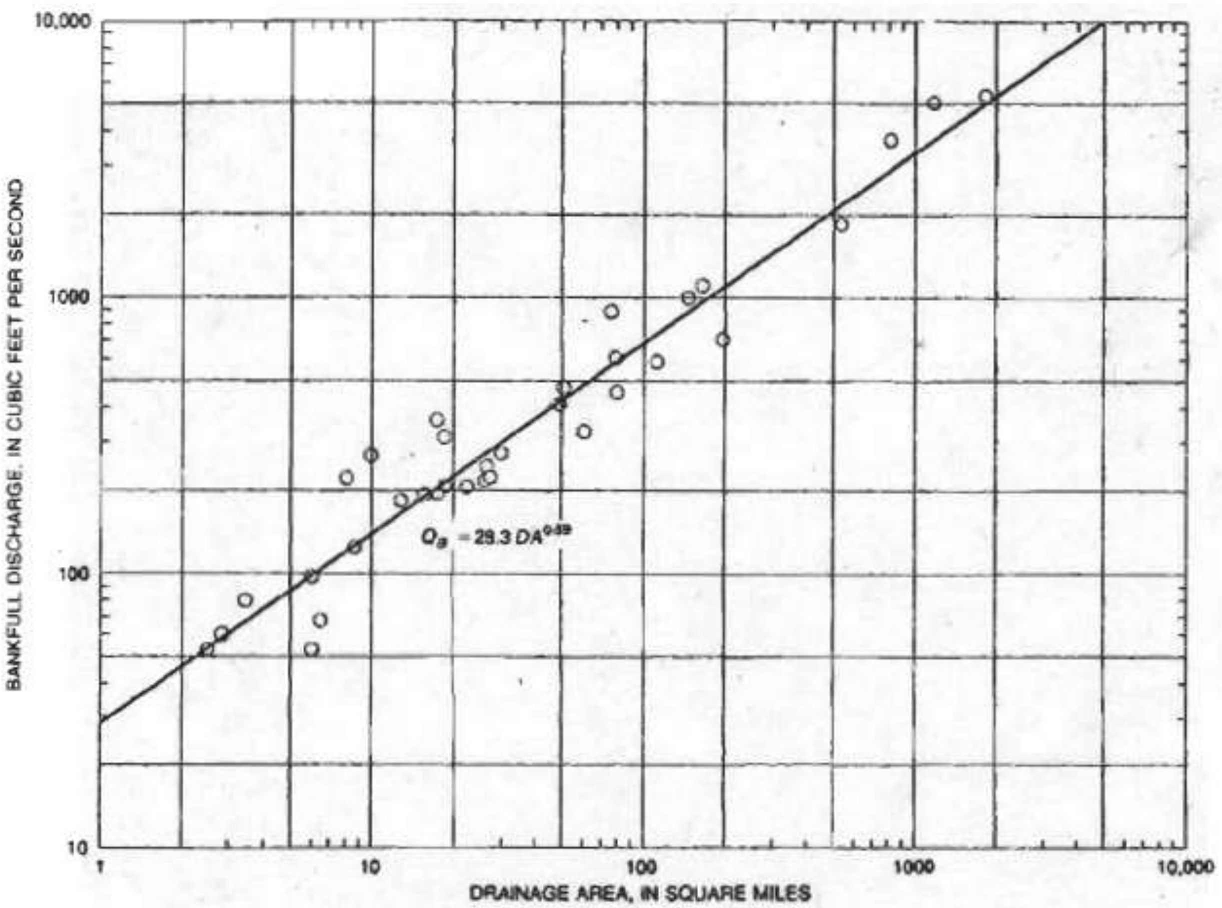


Figure 9-13. Bankfull Discharge as a Function of Drainage Area, Emmett [1975]

Although the regression line fits the data in a visually satisfactory fashion, it should be noted that for a drainage area of 70 mi2, the bankfull discharge varied between 900 and 900 cfs. This large range should not be attributed to errors in field measurements, but rather to the natural variation in bankfull discharge with drainage area. As commented by Copeland [2000], this approach is not recommended because drainage area is only one of many parameters affecting runoff. The watershed development, slope, rainfall patterns, and soil characteristics all play a role. In the urbanized Santa Clara Valley, we should especially be careful to consider watersheds of similar physiographical and urbanization characteristics when examining data in this fashion, or in the form of Eq. 9-1 and Eq. 9-2.

It is of interest to note that in the literatures, the recurrence interval for most of the reported bankfull discharges range from 1 to 2 years.

9.6.2 Channel-Forming or Effective Discharge

Channel forming discharge is defined as the mean of the discharge that transports the largest fraction of the annual sediment load over a period of years [Andrew, 1980]. It is also called the effective discharge. It incorporates the principle prescribed by Wolman and Miller [1960] that the channel-forming discharge is a function of both the magnitude of the event and its frequency of occurrence. It is calculated by integrating the flow-duration curve and a bed-material sediment rating curve. A graphical representation of the relationship between sediment transport, frequency of the transport, and the effective discharge is shown in Figure 9-14. The peak of curve III in Figure 9-14 marks the discharge that is most effective in transporting sediment, and therefore it is hypothesized that it does the most work in forming the channel.

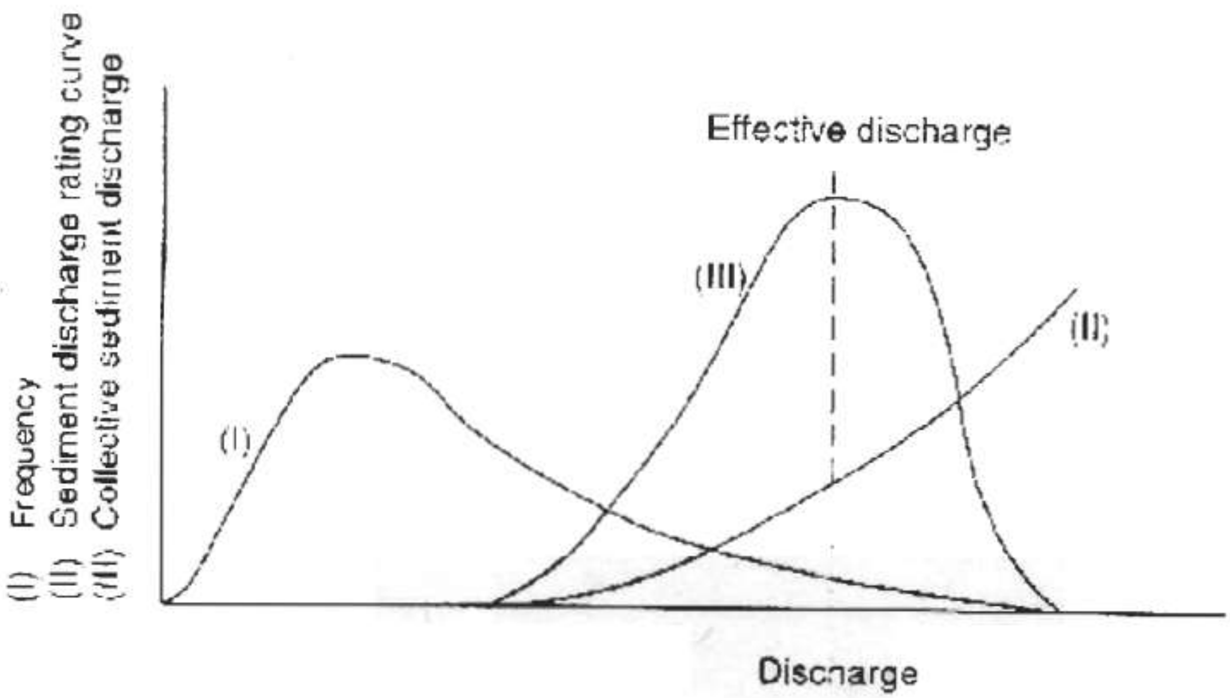
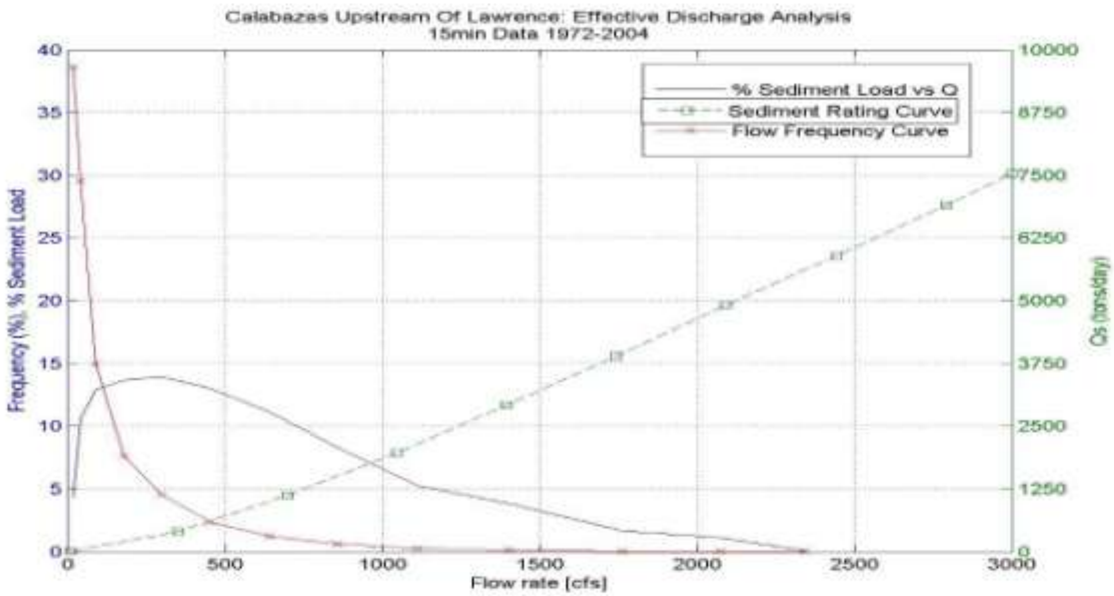


Figure 9-14. Derivation of Effective (Channel-Forming) Discharge

Using this approach, 33 years of flow data measured at the Wilcox High School station, and sediment data collected in the river, the effective discharge for Calabazas Creek Upstream of Lawrence Expressway was computed and shown in Figure 9-15. The detailed calculation procedure will be discussed in Section 1.2. The channel-forming or effective discharge for this Calabazas Creek reach, approximately 300 cfs, corresponds to a flow of 1.05 year recurrence interval. The bankfull flow, on the other hand, as estimated from bankfull dimensions and hydraulic characteristics, is 250 cfs, corresponding to a 1.03 year recurrence interval. Although for this example the bankfull and effective flows are very closely related, there are other examples in the literature [for instance Crowder and Knapp, 2002 and Biedenharn and Copeland, 2000] that show both varying from 1 to 3 year recurrence intervals, and there are other reports [Pickup and Warner, 1976] that determined bankfull recurrence intervals ranged from 4 to 10 years. It is evident that recurrence interval relationships are intrinsically different for channels with flashy hydrology, ephemeral flow regime and in arid environment. So far our data show that our environment applies to the 1-3 year bankfull recurrence interval, but this should always be verified in the field. As more data become available from our creeks, we will gain more insight into this creek characteristic.



9.6.3 Dominant Discharge

The dominant discharge is defined as a flow rate that, given near steady state conditions and over moderate time scales, will shape the bankfull channel the same way as the natural hydrologic regime does. Hence, it is a hypothetical term, but is one that has been used interchangeably with the bankfull discharge, channel-forming discharge and effective discharge in the literatures.

9.6.4 Channel Design Considerations

This section will summarize the basic concepts of hydraulics, sediment transport and geomorphology involved in designing a river channel in the Santa Clara County. These concepts are integrated and presented as design considerations that engineers should follow in the design process. The underlying assumptions are that in our highly developed urban setting, our projects usually involve limited flexibility in channel alignment, and that out goal is to develop a stable channel reach that is in harmony with the environment. The channel design considerations include:

(1) Determine appropriate cross-sectional dimensions. These may include the low-flow, bankfull-flow and floodplain channels. They need to correspond to the flow and sediment characteristics of the channel. The considerations are listed below:

- Determine low flow channel dimension. If the existing project reach, the upstream and downstream show evidence of a low flow channel, identify the dimensions, and verify with the HEC-RAS model that it corresponds to the normal base flow or the 7-day annual low flow. If there is no evidence of a low flow channel in the vicinity, design without a low flow channel.

- Determine bankfull channel dimension. Determine the bankfull channel dimensions by conducting field observations and effective-flow analysis, and verify with HEC-RAS model that the bankfull stage corresponds to the effective flow approximately.

- Determine floodplain dimension. Based on the real-estate constraints of the project reach, the floodplain channel may include wide top-of-bank areas, which is preferred, deep and incised natural channel, or deep channel formed by artificial floodwalls or levees. Verify by using HEC-RAS that the channel contains the design flood.

(2) Determine appropriate planform, if necessary, by simulating the sinuosity of the immediate upstream and downstream reaches.

(3) Determine incoming sediment load. Through a combination of field measurements and sediment transport calculations using SAM determine the sediment rating curve for the river upstream of the project reach.

(4) Determine stable channel slope of the project reach. Conduct a sediment transport analysis using SAM or HEC-6 to determine a stable channel slope that balances the incoming sediment load with in-reach sediment transport. If necessary incorporate grade control structures to achieve stable channel.

(5) Determine surface protection. Duplicate the surface armor material in the upstream and downstream reaches. Verify adequacy of this material by checking the bottom shear stress of the bankfull flow and the ability of this material, plus vegetation, to resist initiation of motion.

(6) Determine planting requirements that are consistent with the design hydraulic roughness and enhance the natural environment.

More details of these design considerations and procedures will be discussed in Chapters 2 through 3.

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