CHAPTER 18

Engineering Geomorphology

S. A. Schumm and M. D. Harvey

18.1 INTRODUCTION

Geomorphology is the study of earth-surface forms and processes. It is "The science that treats the general configuration of the earth's surface; specifically the study of the classification, description, nature, origin and development of present landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features" (Bates and Jackson 1987, p. 272). This rather involved definition stresses the origin and evolution of landforms, and such has been the traditional concern of geomorphologists. However, it is now acknowledged that a major contribution of geomorphology can be prediction, because an understanding of past landform changes can be a great aid in the recognition of problems and the future course of landform change. If, for example, we know how a river meander has changed through time, prediction of future change can be made with more confidence (Lagasse et al. 2004). Therefore, the historical perspective of most earth scientists is an aid in prediction for current and future conditions.

Engineering geology, a field in which geologists work closely with engineers to determine how earth materials will affect engineering structures, is a well-established field (Johnson and DeGraff 1988; Legget and Hatheway 1988; Kiersch 1991). However, the application of geomorphology to engineering and environmental problems has been a more recent phenomenon (Coates 1976; Fookes and Vaughn 1986). Coates (1976, p. 6) defines engineering geomorphology simply as the combining of the "talents of the geomorphology and engineering disciplines." Sometimes this is difficult because of the disparity between engineering and geomorphic training and experience. However, Chow (1964) included a chapter on geomorphology by Strahler (1964) in his *Handbook of Applied Hydrology*, and Chang (1988) has drawn heavily on the geomorphic literature in his book on river engineering. Therefore, engineering geomorphology is the application of landform science (geomorphology) to engineering problems (Schumm and Harvey 1993; Thorne et al. 1997; Anthony et al. 2001). The major objectives of this chapter are to bring to the attention of the engineering profession (1) the importance of landform history, (2) the need to view specific problems in a broad or system context, and (3) the importance of geologic and geomorphic controls and hazards to many engineering activities for which the nominal time scale is generally 50 to 100 yrs.

Landform history involves changes through time, which can lead to conditions that threaten engineering works. For example, the slow modification of landforms by erosion, deposition, and weathering can produce abrupt changes (gullying, channel avulsion, and slope failure) that can have significant effects on engineering activities. Hence, landform or geomorphic hazards need to be identified. In addition, it is important to realize that a specific engineering site or problem is part of an integrated geomorphic system. For example, a bridge site is a small part of a fluvial system, and the character of that system both up- and downstream can significantly affect future site stability and the stability of the structure itself (Mussetter et al. 1998). Therefore, a broader perspective on the situation is desirable, and one should back away from a specific site and view it in the context of the surrounding geomorphic setting. In addition, geologic and geomorphologic controls can be far more important than is generally supposed for an engineering time scale. For example, the world's great alluvial rivers (Mississippi, Nile, Indus), although presumably dominated by hydrologic, sediment, and hydraulic controls, are, in fact, significantly influenced by geologic variables (Schumm and Winkley 1994; Schumm et al. 2000). It is important to recognize that geomorphology and engineering can be combined to provide a rational approach to many engineering and environmental problems.

In this chapter, the measurements that can be used to describe landforms quantitatively and methods that are used to date landforms will not be introduced. The reader can obtain information on specific techniques in Strahler (1964), Goudie (1981), Catt (1988), Thorne et al. (1997), and Kondolf and Piégay (2003). In addition, a discussion of the landforms and processes involved in their modification can be found in any geomorphology textbook (Ritter 1986; Bloom 1991; Scheidegger 1991; Summerfield 1991). These texts cover a wide range of topics including coastal, glacial, wind, and weathering processes, and they provide references to these topics. Fluvial geomorphology will be stressed in this chapter. Nevertheless, because engineering problems and projects are global, it is important to recognize the significance of climate and climate changes upon geomorphic processes and landforms (Bull 1991; Molnar and Ramirez 2001). Wilson (1968) has identified six morphogenetic regions where geomorphic processes differ (Table 18-1). Therefore, experience gained in one part of the world may not be directly applicable elsewhere.

The *Encyclopedia of Geomorphology* (Fairbridge 1968) and the *Glossary of Geology* (Bates and Jackson 1987) provide a ready entry to geomorphic terminology and basic literature. Because of the interdisciplinary nature of geomorphology, its literature is scattered through a variety of geologic, hydrologic, hydraulic, environmental, and geographic journals. In most of the world, with the exception of the United States, geomorphology is taught as a subject within the field of physical geography. Three journals that publish on only geomorphic topics are *Earth Surface Processes and Landforms, Geomorphology,* and *Zeitschrift für Geomorphologie*. Of considerable value is the geomorphic abstract journal *Geomorphological Abstracts*, which provides short abstracts arranged by topic of papers from the international literature.

Geomorphologists have also provided descriptions and erosional and depositional histories of identifiable regions (Thornbury 1965; Graf 1987, 1988). These provide useful background information. Goudie (1981) has provided a comprehensive review of techniques that have been used in the study of landforms and landscapes, and several volumes of collected "classic" papers deal with specific geomorphic topics (Schumm 1972; Schumm and Mosley 1973; Schumm 1977a).

Schuirman and Slosson (1992) provide examples of how geomorphic and geologic investigations can aid engineers and the courts in litigation resulting from landslides, flooding, and gravel mining. By citing examples, they indicate the type of information that is needed and the general approach that should be followed in such investigations. In a concluding chapter, they provide useful advice for engineers and geologists who become expert witnesses. It is essential to maintain objectivity and a high degree of professionalism. Similar advice to young scientists and consultants was proffered by Schumm (1988, 1991), who also stressed the need to maintain objectivity and to adhere to the standards of the profession if credibility is to be maintained and error is to be avoided.

Before the general field of engineering geomorphology is considered, especially as it pertains to the study of form, processes, and dynamics of rivers, it is necessary to consider the different types of rivers that exist and provide a brief discussion of river classification. Schumm (2005) has suggested that rivers and streams can be divided into two principal types, regime and nonregime (Table 18-2). The regime channels, defined as those that flow on and in sediments transported by the river during the present hydrologic regime, whose morphology is controlled primarily by the interactions of the flow regime and the sediment supply (Leopold et al. 1964; Schumm 1977b), can be further subdivided on the basis of patterns (straight, meandering, wandering, braided, anastomosing) and hydrology (ephemeral, intermittent, perennial, interrupted). Nonregime channels can be further subdivided into bedrock controlled or constrained, where the form of the channel is forced by nonalluvial factors such as bedrock, colluvium,

Table 18-1 Morphogenetic Regions

Region	Dominant geomorphic processes	Landscape characteristics
Glacial	Glaciation, nivation	Glacial scour and deposition, alpine topography
Periglacial	Frost action, solifluction, running water	Patterned ground, solifluction, lobes, terraces, outwash plains
Arid	Desiccation, wind action, running water	Dunes, salt pans (playas), deflation basins, angular slopes, arroyos
Semiarid (subhumid)	Running water, weathering (especially mechanical)	Pediment, fans, angular slopes with coarse debris, badlands
Humid temperate	Running water, weathering (especially chemical), creep (and other movements)	Smooth slopes, soil covered, stream deposits extensive
Selva	Chemical weathering, mass movements, running water	Steep slopes, knife-edge ridges, deep soils (laterites included)

After Wilson (1968).

glacial deposits, or extreme flood deposits (Montgomery and Buffington 1997; Tinker and Wohl 1998; O'Connor and Grant 2003) and unstable, which can include degrading (Schumm et al. 1984; Darby and Simon 1999), aggrading (Schumm 1977b), and avulsing (Schumm et al. 2000) channels.

There have been numerous attempts to classify rivers (Leopold and Wolman 1957; Schumm 1963, 1968; Mollard 1973; Kellerhals et al. 1976; Brice 1981; Mosley 1987; Rosgen 1994, 1996; Montgomery and Buffington 1997; Thorne 1997; Vandenberghe 2001), but no single classification has been developed that meets the needs of all investigators, and in fact Goodwin (1999) has even questioned the need for classification. Several factors have prevented the achievement of an ideal geomorphic stream classification, and foremost among these have been the variability and complexity of rivers and streams (Mosley 1987; Juracek and Fitzpatrick 2003). Extensive problems associated with the use of existing morphology as a basis for extrapolation (Schumm 1991) further complicate the development of a robust classification (Juracek and Fitzpatrick 2003).

However, notwithstanding the problems associated with classification in general, stream classification is widely used in the United States, with the Rosgen (1996) classification being the most commonly used. Numerous federal, state, and local agencies utilize the Rosgen (1996) classification for description of stream reaches and for guiding stream restoration or rehabilitation. Provided that the classification is used for descriptive or communicative purposes, it provides a useful tool. Unfortunately, given the widespread use of the classification, it is not appropriate in its present form for assessing stream stability, inferring geomorphic processes, predicting future geomorphic responses, or guiding stream restoration or rehabilitation activities (Miller and Ritter 1996; Wilcock 1997; Juracek and Fitzpatrick 2003). From a practical perspective, the geomorphologist's measurements of sinuosity, width-depth ratio, gradient, dimensions (width and depth), and sediment type (bed and banks), when combined with the engineer's measurements of discharge, flow velocity, shear stress, and stream power, provide the information necessary for understanding of a river and the knowledge required for prediction of future change (Schumm 2005). When quantitative information about a river is available, classifications are of less value in the design of stable stream channels and prediction of channel change.

Table 18-2 Channel Types

	Regime channels
Patterns	
	straight
	meandering (passive/active)
	wandering
	braided
	anastomosing (can be any of above patterns)
Hydrology	
	ephemeral
	intermittent
	perennial
	interrupted
	Nonregime channels
Bedrock	
	confined
	constrained
Unstable	
	aggrading (transport-limited)
	degrading (supply-limited)
	avulsing

After Schumm (2005).

18.2 HISTORY

The first objective of this chapter is to convince the reader that a combination of an understanding of present conditions (model of the present) with historical information (model of the past) is of great value for prediction of landform (drainage network, slope, river, alluvial fan, etc.) change, as a result of natural or human influences (model of the future). For the study of present conditions the collection of available topographic maps, aerial photographs, soil maps, and land-use maps, as well as hydrological and meteorological data and information on the geotechnical properties of bed and bank materials, bank vegetation, and the hydraulic character of flow, is necessary. These types of information permit description of the present situation, and this can be considered a *direct approach*, where existing information is assembled and utilized to provide present and recent historical information. However, such a short record often does not provide an adequate basis for prediction of future landform stability or change. This requires an *indirect approach*, which involves geomorphic evaluation of groups of landforms.

18.2.1 Direct Approach

A simple example of the need for recent historical information and of the direct approach is provided by a court case involving the Snake River in Jackson Hole, Wyoming (Schumm 1994). It was claimed that because the present banks of the river do not correspond with the banks as surveyed by the General Land Office (GLO) surveyors in the late 19th century, the surveys were either fraudulent or in gross error. This conclusion was supported by expert testimony that the river had not changed position for centuries. However, when the GLO surveys were compared with more recent maps and a series of aerial photographs, it became obvious that the Snake River was and is a very active river that continually erodes its banks, and therefore, the position of the banks changes through time. The historical evidence, as well as dendrochronological and pedological data, convinced a federal judge that the GLO surveys were accurate.

The direct approach uses readily available historical information. For example, information that can be used to determine the stability of a bridge crossing can be obtained in at least five ways, as follows (Shen and Schumm, 1981):

1. The history of nearby bridges should be determined. If the new bridge is to replace an older one, considerable information should be available on the past morphology and behavior of the river at that site. For example, channel width and the distance from the crown of the highway to the streambed will be available. Any change can be readily determined by comparison of the present cross-sectional characteristics with those at the time of the construction of the old bridge.
2. Conversations with long-time residents of the valley can be useful in establishing the relative stability of the river channel. Recollections are sometimes suspect, but old photographs of the river obtained from private collections, family albums, and local historical societies can be invaluable. State archives and historical societies frequently contain photographs of old bridges and fords, and hence they are a source of valuable information.
3. In the midwestern and western United States, General Land Office surveys made in the nineteenth century frequently provide information on former river widths and patterns. The earliest maps can be compared with more recent topographic maps and aerial photographs. For example, there is a series of maps, the earliest being 1765, that can be used to document Mississippi River channel pattern changes. Aerial photographs may be available from the late 1930s.
4. Records such as newspaper reports, railroad company files, church records, court transcripts, and accounts of early travelers are all possible sources for identifying channel changes.
5. Gauging station records (specific stage analysis) can be used to assess channel stability and to detect long-term hydrologic trends or the occurrence of large morphologically significant floods.

According to Brice (1974), meander shift is one of the major problems at bridge crossings. Needless to say, this hazard should be one of the easiest to recognize if maps and aerial photographs for a period of years are available to provide historical background. An example of this problem and the procedure applied to the problems at the U.S. Highway 177 crossing of the Cimarron River near Perkins, Oklahoma is abstracted from Keeley (1971).

In 1953 a new bridge was constructed over the Cimarron River downstream from an old bridge, which in 1949 was judged to be in poor condition, with erosion concentrated on the south bank about 1,500 ft (457 m) above the bridge abutment (Fig. 18-1). In 1957, there was continued erosion of the south bank immediately upstream of the south abutment during a period of large floods. Following floods, 650 ft (198 m) of riprap was emplaced on the south bank between the piles and the bridge abutment.

The second highest flood of record occurred in 1959 and all five pile-dike diversions were damaged. There was some bank erosion on the northwest bank 1,500 ft (457 m) upstream of the north abutment. During a period of high discharges between 1959 and 1962, the point of attack shifted from the south bank to the north bank. There was up to 325 ft (99 m) of erosion of the north bank between the north abutment and 2,600 ft (793 m) upstream. Five pile-dike diversion structures were constructed on the north bank, and riprap was extended upstream from thenorth abutment. In 1965, there was further scour of the north bank.

The continuing problem at this crossing, especially the shift of erosion from the south to the north bank, could have been anticipated if an evaluation of the stability of the channel had been made prior to or after construction. For example, the 1938 aerial photographs show that the channel was straight and braided at the site at the time of bridge construction, but there was a large bend about one mile upstream (Fig. 18-1).

Relatively little effort would have been required to conclude that the Cimarron River was a relatively unstable channel at this site and that a major problem would be downstream bend shift. Examination of the 1938 aerial photographs with rapid field examination of the channel would have revealed the potential problem of bend shift. Hence, a minimum of historical information (the aerial photographs), combined with the perspective that a site is only a small part of a complex system, would have led to investigations of channel conditions both upstream and downstream of the bridge crossing. The major hazard was bend shift, but the accompanying shifting pattern of bank erosion and scour attracted the most attention. From the point of view of the engineer, the bridge site selected in 1958 was a reasonable one, because the channel was straight and it was near bedrock on the south side of the

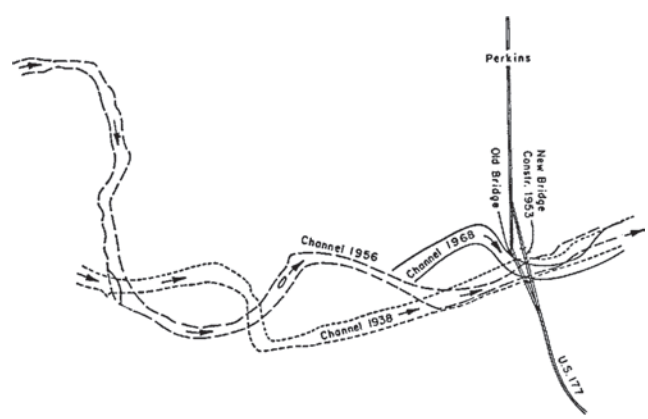

Fig. 18-1. Cimarron River meander shift as shown by 1938, 1956, and 1968 aerial photographs (from Keeley 1971).

channel. Only if the upstream changes in the channel position were recognized and the hazard identified could the engineer have anticipated the problems that developed at this site.

This example illustrates the utility of obtaining historical information as well as the need to consider a longer reach of a river rather than focusing entirely on the site of the bridge crossing. In this case, very little historical information was needed to identify the problem.

18.2.2 Indirect Approach

The indirect approach involves utilizing geomorphic information to develop a model of landform changes that in turn can be used to identify hazards and to predict change. A longer historical record can be developed using the *location for time substitution* (LTS) technique (Fig. 18-2). This has been used with great success to determine future changes of rapidly evolving landforms such as gullies, arroyos, and channelized streams, and it can be used to determine long-term evolutionary changes of landscapes (Schumm et al. 1984; Paine 1985; Schumm 1991).

If a series of cross-sections are surveyed along a channel (Fig. 18-2) that is incising as a result of natural or human-induced changes (e.g., channelization), an evolutionary model of channel adjustment can be developed (Fig. 18-3). In this way, location is substituted for time (LTS). The model presented in Fig. 18-3 was developed for incised channels in northern Mississippi using LTS, and it has both academic and practical value because it permits estimation of sediment production and agricultural land loss (Schumm et al. 1984; Darby and Simon 1999). The location-for-time substitution technique can be an effective means of developing a model of evolving landforms, which can aid the engineer in predicting change and developing a strategy for mitigation of or promotion of the change, depending upon his goals.

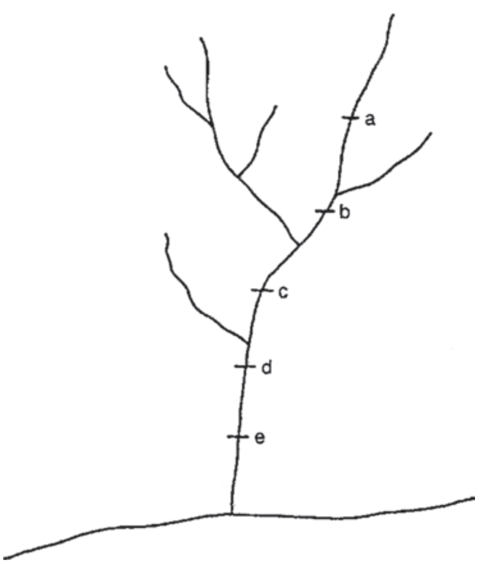

Fig. 18-2. Sketch shows method used to obtain data for location for time substitution (LTS) along an incised channel. Incision commences at mouth of channel and progresses upstream. Therefore cross sections a to e show channel evolution from original (a) to oldest (e); see Fig. 18-3.

In using LTS it is important to compare features produced by the same processes operating under the same physical conditions. For example, the evolution of an incised channel in alluvium can be determined by surveying cross-sections at several locations where the channel is in alluvium (Fig. 18-2), but one cannot combine data or compare channels in weak alluvium with channels in resistant alluvium or bedrock and expect to find meaningful results. LTS can be used to determine not only channel evolution, but also hillslope and drainage network change.

Time is an important variable in the development of an incised channel and therefore it should be an important variable in any scheme to curtail gully erosion and to reduce sediment loads. Fig. 18-4 is a conceptual diagram that shows the change in sediment yield and incised channel (gully) drainage density (length of gullies per unit area) with time. In a drainage basin that has been rejuvenated and in which gullies are developing, sediment production will increase as the length of incising channels increases (Fig. 18-4, times 1 to 4). However, at time 4 maximum headward growth of the channels has occurred, and they begin to stabilize between times 4 and 7, when there is an increase in the length of relatively stable reaches, and the length of active reaches decreases. By understanding this cycle of channel incision and gullying from initial stability (time 1) to renewed stability (time 8), it is possible to select spans of time in the cycle when land management and incised channel control practices will be most effective. For example, gullies just being initiated (time 1 or 2) and gullies almost stabilized (time 6, 7, or 8) will be the most easily controlled by structural means. Although the efforts at times 7 and 8 will have little effect, because the channels are stabilizing naturally. At time 4 control will be difficult and expensive. Obviously, consideration of such a complex evolving system for only short periods of record and short time spans can yield erroneous conclusions.

The sequence of events shown in Figs. 18-3 and 18-4 can also have wider applications. In the nineteenth century, throughout the arid and semiarid regions of the southwestern United States, channels incised to form the arroyos that were notorious suppliers of sediment to the Colorado, Green, Rio Grande, and San Juan rivers. Their incision also lowered water tables, and as a result, former grazing and farmlands were abandoned, as well as some small agricultural communities. Projections of the life of reservoirs on these rivers were based on the assumption that the high sedimentation rates generated by arroyo incision and widening (Fig. 18-3) would continue. However, if the sequence of incised-channel evolution as shown in Fig. 18-4 is generally applicable, then the arroyos will begin to stabilize, erosion will be less, and sediment will be stored in newly

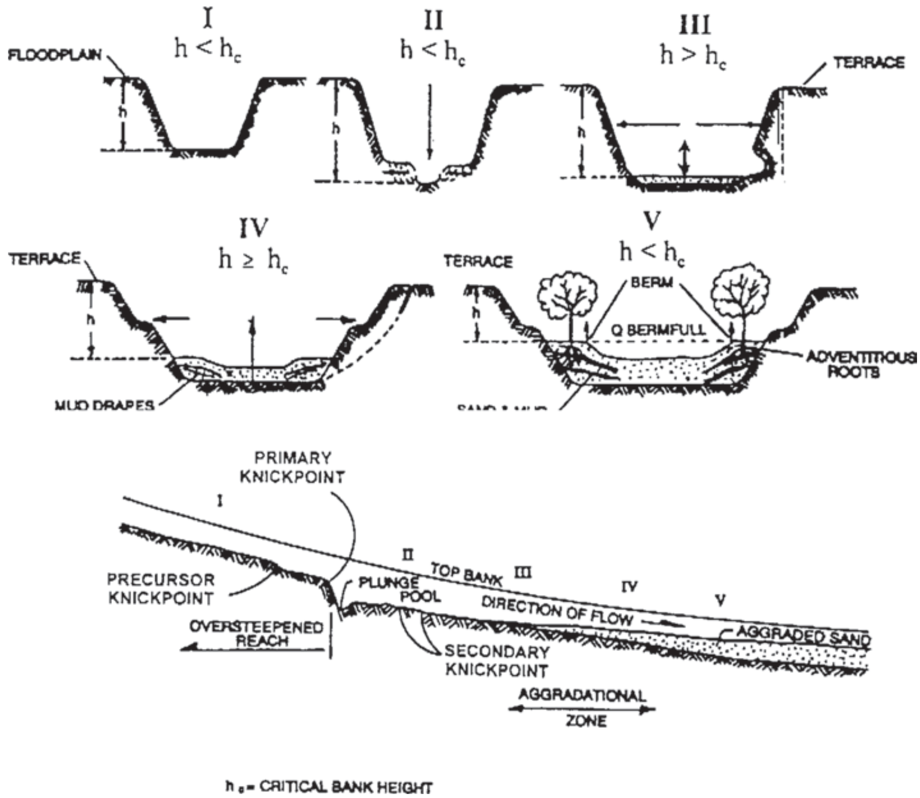

Fig. 18-3. Evolution of incised channel from original channel (I) to initial incision (II), widening (III), aggradation (IV), and eventual stability (V) (from Schumm et al. 1984).

forming floodplains. Indeed, sediment moving through the Grand Canyon of the Colorado River has decreased significantly since the later 1930s (Gellis et al. 1991), although discharge has not.

For example, based upon the average sediment delivery to Lake Powell from 1914 to 1957, it was estimated that 85,400 acre-feet (105,340,050 m^3) of sediment would be deposited in the reservoir each year. In 1963, the dam was closed, and 409 ranges were surveyed across the reservoir, which provided a means of measuring sediment accumulation in the reservoir. In 1986, the ranges were resurveyed and it was determined that only 36,946 acre-feet (45,554,420 m^3) of sediment was being deposited each year (Ferrari 1988), which is 43% of the previous calculation. During this time, flow into the reservoir was 91% of the 1914–1957 average. Hence, an understanding of the incised-channel cycle would have permitted a significant increase in the estimated reservoir life from 700 to 1,600 yrs. The same principle can be applied to other, smaller reservoirs and to sediment delivery to lakes and bays.

Location-for-time substitution is a valuable indirect tool that can be used to develop a qualitative incised channel evolution model (ICEM) that aids in understanding and prediction of landform change in both humid and semiarid regions of the United States. Harvey and Watson (1986), Watson et al. (1988, 1988b), Mussetter et al. (1994), Simon (1994), Bledsoe et al. (2002), and Watson et al. (2002) have taken this approach, and they have quantified and integrated four important facets of the ICEM process: (1) bank stability, (2) magnitude and frequency of the range of dominant

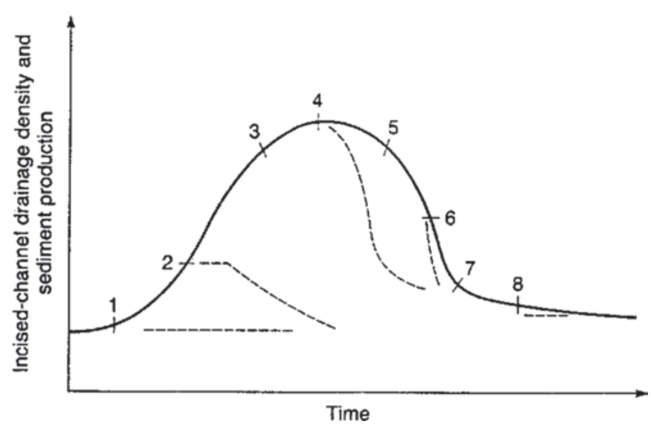

Fig. 18-4. Hypothetical change of sediment production and incised channel (gully) drainage density (ratio of channel length to drainage area) with time. Dashed lines indicate effect of gully-control structures at various times during channel evolution (from Schumm 1991).

discharges, (3) hydraulic energy of those discharges, and (4) morphological adjustments of the channel. These factors in the evolution of the incised channel can be further reduced to two dimensionless stability numbers, N_g, the geotechnical stability number, and N_h, the hydraulic stability number.

The geotechnical stability number N_g is defined as the ratio of the actual bank height (h) at a given bank angle to the critical bank height (h_c) (defined computationally or observationally):

$$N_g = \frac{h}{h_c}$$

When N_g is less than 1, the bank is geotechnically stable; when N_g is greater than 1, the bank is unstable and bank failure and channel widening are likely.

The hydraulic stability factor (N_h) is defined as the ratio of the sediment supply to the sediment transport capacity. N_h can be interpreted as a ratio of energy parameters. An example would be the ratio of shear stress or shear intensity at the effective or dominant discharge to the same parameter under conditions of equilibrium between sediment transport capacity and sediment supply. It is important to note that N_h includes sediment transport and supply. This is in contrast to most channel design procedures, which are generally based on fixed boundary approximations (Harvey and Watson 1986). N_h provides a rational basis for determining the equilibrium sediment transport–sediment supply relationship that will be required to achieve a state of dynamic equilibrium. Hydraulic stability in the channel is attained when $N_h = 1$. If $N_h > 1$, the channel will degrade, and if $N_h > 1$, the channel will aggrade.

When N_g and N_h are combined, they provide a set of design criteria that define both geotechnical and hydraulic stability in the channel. Channel stability is attained when $N_g < 1$ and $N_h = 1$. Because sediment supply to a channel fluctuates through time, it is prudent to aim for a hydraulic condition that is marginally aggradational; therefore, a more conservative approach is to allow for $N_h > 1$.

The relationship between the ICEM and the stability numbers can be seen in Fig. 18-5. The points labeled A through F can be viewed as individual locations along an incised channel (Fig. 18-3), or as a sequence of locations that are linked spatially or temporally, with point A being upstream and point F being downstream, or moving from point A counterclockwise to point F through time at a given location. These points generally correspond with the stages illustrated in Fig. 18-5. For example, if the geotechnical and hydraulic calculations place a reach of channel at point A on the diagram, the strategy should be to prevent the channel depth from increasing to the point where the critical bank height is exceeded. In contrast, if the reach is located at point E, there will be no need to treat the channel because it is in a condition of quasiequilibrium. If no action is taken when a reach is in a condition represented by point A, the sequence

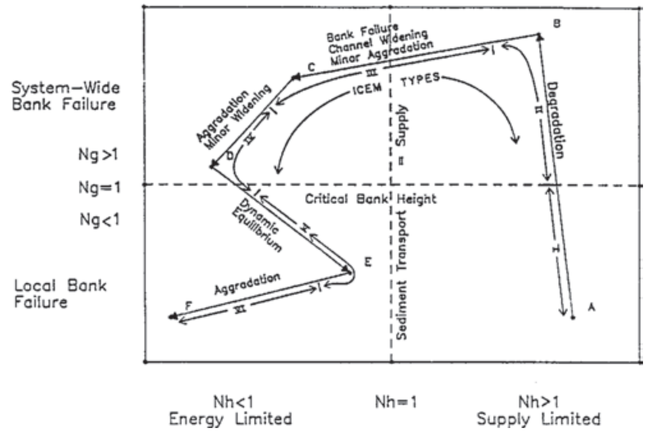

Fig. 18-5. Stability number (N_g/N_h) diagram showing the thresholds of bank stability and hydraulic stability for an incised channel. Also shown are the ICEM stages (Fig. 18-4). Note that the ICEM reach types form a continuum and the type boundaries are gradational (from Water Engineering & Technology 1989).

of channel incision and widening will move from point A to point F through time as the channel evolves.

As the channel evolves from a state of disequilibrium (A) to a state of dynamic equilibrium (E), the reach types move from the lower right to the lower left quadrant via the upper right and upper left quadrants (Fig. 18-5). Management of the channel should be aimed at keeping the channel in the lower right quadrant, or forcing it to move directly to the lower left quadrant, thereby eliminating the evolution cycle that is an inevitable consequence of bed degradation causing exceedence of the critical bank height. Forcing the channel to move directly into the lower left quadrant generally requires the use of grade-control structures and bank protection.

Utilization of ICEM and the dimensionless stability numbers N_g and N_h not only enables equilibrium reaches to be identified (i.e., $N_g < 1$: $N_h < 1$), but also permits reaches that are at risk to be identified, and provides a process-based rationale for selecting appropriate treatments. Further, this approach enables the effects of changed land use (runoff and sediment supply) to be evaluated in the context of a systems approach to watershed evaluation that is equally applicable in humid or arid regions as well as in rural or urbanizing situations (Mussetter et al. 1994; Watson et al. 2002).

18.3 SYSTEMS APPROACH

A systems approach simply means that one should not be fixated on site conditions. Rather, the site should be considered in the context of adjacent areas or landforms. Again, a court case provides a good example. Twenty-two landowners claimed that the erosion of their property along the Ohio River was caused by the raising of water levels behind navigation locks and dams. To maintain navigation on the

Ohio River during low water, a series of low dams with locks maintain a minimum navigation depth of 9 ft (2.7 m). The pool level behind the dam, therefore, never falls to the old low-water levels. It was alleged that the maintenance of the pools at a constant level caused bank erosion by wave action. Preliminary studies showed that, indeed, erosion was occurring on the litigants' lands, and their claims seemed valid. However, when the river as a whole was considered, rather than just 22 limited portions of the bank, it became clear that the river has eroding, stable, and healing banks, and the type and extent of erosion could be predicted (Schumm 1994). In fact, much of the erosion was due to the landowners' activities behind the bankline, which added water to the banks and caused slumping well above the pool level. In this case, the ability to consider a long reach of the river rather than a few specific locations permitted the development of a strong argument that the bank erosion was natural and that, in some cases, it was induced by the landowners themselves. The landowners lost the case because the judge found that the geomorphic arguments were convincing, but the landowners probably were not convinced because of their limited perspective.

18.3.1 Direct Approach

The direct approach here involves simply an evaluation of present conditions and recognition of anomalous conditions.

A major problem for the engineer is to anticipate changes of floodplain utilization and channel alterations. An excellent example is provided by the Salt River at Phoenix, Arizona, where the river and its floodplain are a convenient and abundant supply of sand and gravel. Human changes have significantly altered the Salt River in Phoenix, thereby causing changes of flow alignment, constriction of the channel, and degradation (Arizona Department of Transportation 1979).

The Interstate 10 bridge over the Salt River was constructed in 1962 (Fig. 18-6). The bridge was designed

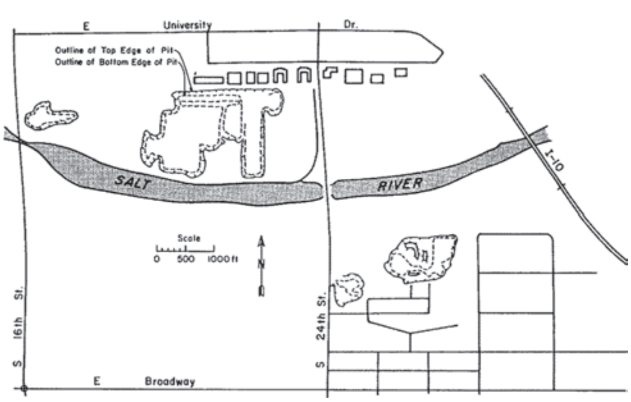

Fig. 18-6. Map showing 1-10 Bridge, Phoenix, Arizona, and downstream gravel pits (from Arizona Department of Transportation 1979).

to accommodate a 50-yr flood with a peak discharge of 175,000 cfs (4,956 m^3/s). Discharges were relatively low or nonexistent for a number of years, but a large flood (67,000 cfs [1897 m^3/s]) occurred in January 1966, and a 22,000-cfs (632 m^3/s) flood in April 1973. The river was essentially dry until in March 1978 there was a 115,000-cfs (3,257-m^3/s) flood, and it was followed by a 120,000-cfs (3,398-m^3/s) flood in December 1978. In January 1979 there was an 80,000-cfs (2267-m^3/s) flood, and finally in March 1979 there was a 48,000-cfs (1,359 m^3/s) flood. During the latter flood, scour undermined the footing of Pier No. 11 (Fig. 18-7), which caused subsidence and tilting of one of the bridge spans. The footing was 20 ft (6 m) below the channel in 1962, and a low-water channel was dredged artificially to the north between Piers 5 and 10 (Fig. 18-7). The footings of these piers were 10 ft (3 m) deeper than for Piers 11 through 19.

When the bridge was designed, it was assumed that the low-water thalweg would remain fixed in position 5 ft (1.5 m) above the deepest pier. However, as the city of Phoenix grew during the period following bridge construction, gravel mining increased and gravel pits were opened near the bridge. For example, a 30-ft-(9.1-m-) deep gravel pit was dredged on the south side of the river about 2,000 ft (609 m) downstream and 750 ft (229 m) south of the low-water channel (Fig. 18-6).

Study of aerial photographs shows that during the large 1968 flood, another thalweg developed as the existing low-water channel was filled with sediment. Floodwaters flowed into the gravel pit (Fig. 18-6), and erosion of the head wall caused development of a new channel, which was centered on Pier 11 (Fig. 18-7). Scour and undermining of Pier 11 resulted, with serious damage to that span of the bridge. The rapidly developing Phoenix area ensured that this would be the case, as gravel was excavated for construction purposes. However, a cursory look downstream would have forewarned the engineer that a grade-control structure was needed to protect the bridge, because local base level had been lowered as a result of gravel mining.

Along a 5-mile-(8-km-) long reach of the San Benito River near Hollister, California, sand and gravel mining-induced channel degradation between 1952 and 1995 has resulted in the loss of one bridge and severe damage to two others, as well as loss and damage to utility crossings (Harvey and Smith 1998). Compilation and review of historical surveys of the channel and bridges showed the progression of the channel degradation through time, and could have been used to anticipate the occurrence of the infrastructure problems. Instead, each site of damage was considered singularly and repairs were conducted without consideration of further system changes. Ongoing channel adjustments caused many of the repairs to fail and ultimately led to failure and abandonment of the structures.

Another example of a systems approach is provided by the Nile River in Egypt (Schumm and Galay 1994). It was

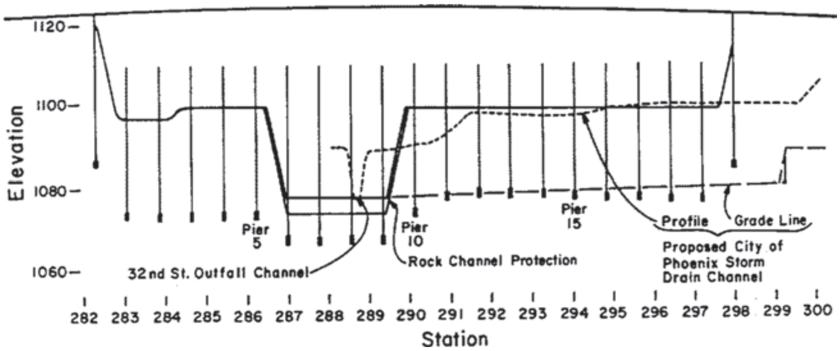

Fig. 18-7. Cross section at I-10 Bridge, Phoenix, Arizona, showing channel cross-section and location of low-water channel and bridge piers and footings (from Arizona Department of Transportation 1979).

assumed by many that following construction of the High Aswan Dam the sand-bed Nile River would be subjected to major degradation between Aswan and Cairo. However, degradation was minimal, although the bed material was mobile. Subsequent inspection of tributaries revealed that they contained coarse gravel and cobbles, which during infrequent floods and during past more humid periods were transported into the Nile valley. Available data from bores into the bed of the river reveal that gravel is encountered at shallow depths. A reasonable explanation for the lack of significant degradation is that below the sand bed of the river there is sufficient gravel to prevent degradation. Inspection of tributaries as well as of the main Nile channel would have provided information that might have led to a more complete sampling program and better estimates of potential degradation.

18.3.2 Indirect Approach

The indirect approach is similar to the location-for-time substitution, as described above, except that it is present conditions that need to be evaluated. The *location-for-condition* approach, which involves collecting data for a number of similar landforms in an area, is a means of determining the condition or relative sensitivity of a single landform or a site. A location-for-condition evaluation (LCE) has been used to identify sensitive valley floors (Fig. 18-8) that are likely to gully in Colorado and New Mexico (Patton and Schumm 1975; Begin and Schumm 1979; Wells et al. 1983a, 1983b); river reaches that are susceptible to a pattern change (Fig. 18-9) from meandering to braided (Schumm and Khan 1972; Schumm and Beathard 1976; Schumm et al. 1987); alluvial fans that are susceptible to fan-head incision (Schumm et al. 1987); and thresholds of hillslope stability (Carson 1975). Therefore, it is a means of identifying threshold conditions and the relative sensitivity of landforms (Schumm 1988).

In each of these cases data were collected at a number of locations, and a quantitative relation was developed, that could lead to the identification of threshold conditions of sensitive landforms. For example, the slope of the line in Fig. 18-8 identifies a valley floor slope in a given drainage area (a surrogate for discharge) at which erosion is likely to occur and gullies to form. The curve of Fig. 18-9, when developed for a specific river, can be used to identify river reaches that are susceptible to change from meandering to braided and vice versa. When a quantitative relation is developed between alluvial-fan slope and fan stability, alluvial fans that are susceptible to fanhead trenching can be identified (Fig. 18-10).

Both the location-for-time substitutions and the location-for-condition evaluation involve the collection of data at a number of locations and the utilization of the data

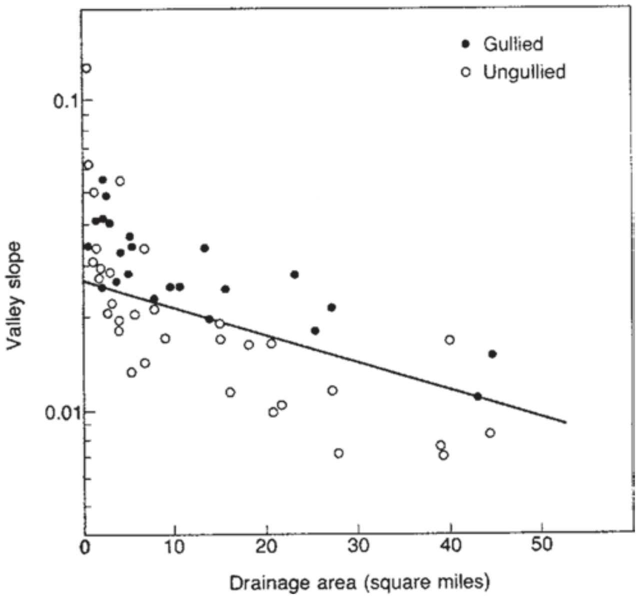

Fig. 18-8. Relation between valley slope and drainage area, Piceance Creek Basin, Colorado. The line defines the threshold slope that generally separates gullied from ungullied valley floor (from Patton and Schumm 1975).

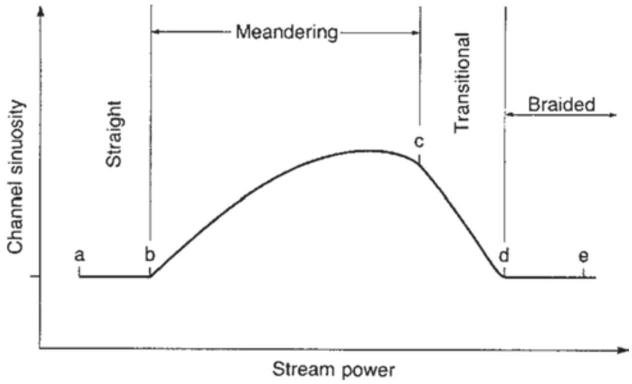

Fig. 18-9. Diagram showing how sinuosity (channel length divided by valley length) varies with stream power (tractive force times velocity of flow). With an increase of stream power or velocity, sinuosity remains constant at low values (a to b), increases with meandering (b to c), decreases through a transition from meandering to braided (c to d), and then remains braided (d to e) (from Schumm and Khan 1972).

to develop an evolutionary model (LTS) or to determine the sensitivity of a site (LCE). Both are valuable techniques that have been used primarily by geomorphologists for practical purposes of prediction, as well as for explanation of past events. Of even greater value is the fact that both techniques require that the investigator back away from a single site and look at many sites, which provides the big picture and a basis for identification of sensitive landforms.

A good example of how the system approach can put a local problem into perspective is that of Mississippi River variability. The lower river between Cairo, Illinois and Old River, Louisiana can be divided into 25 reaches based upon changes of valley slope, sinuosity, and sinuosity variability (Schumm et al. 1994). It becomes apparent immediately that this great alluvial river has significant variability, and it is not uniform for long distances. Clearly, any plan for river improvement should take these reach differences into consideration.

The number of severely eroded channelized streams in the Yazoo Basin of Mississippi precludes intensive study of all of them. Therefore, a lower-order reconnaissance-level approach to determining the status of the channel is required for planning purposes (Schumm et al. 1984; Harvey and Watson 1986). Historical and institutional data were obtained prior to the field investigation and aerial photographs and topographic maps were utilized for base maps. Aerial overflight of the watershed permitted the watershed problems to be identified in a general manner as watershed erosion, channel erosion, or flooding and sedimentation. Fieldwork involved walking (3 to 5 mi/day [5 to 8 km/day]) as much of the channel as was possible within the constraints of available time. Field mapping of ICEM reach types (Fig. 18-3) was done during the fieldwork. Thalweg slope measurements in relatively stable type reaches (Fig. 18-3) provide a minimal measurement for determining

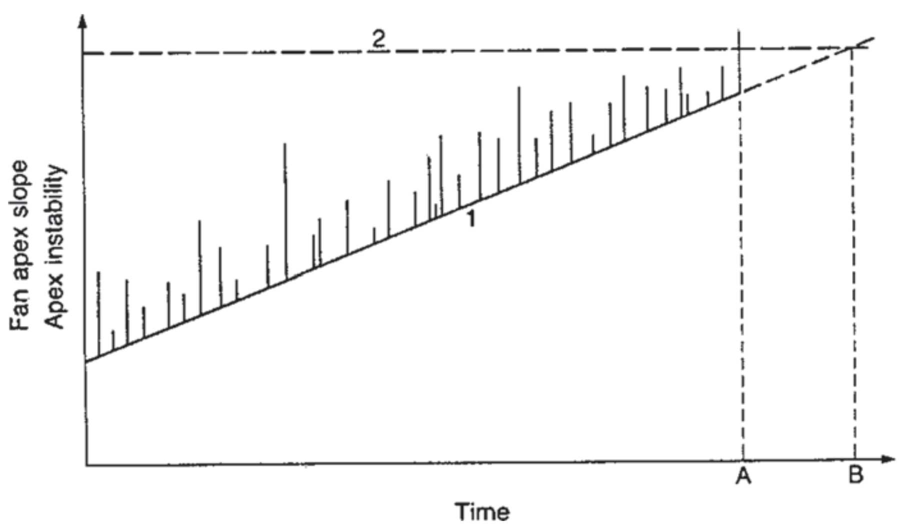

Fig. 18-10. Relation between gradient at a fanhead and alluvial fan apex instability through time. Line 1 portrays the gradually increasing slope of the fanhead. When the ascending line of fanhead slope intersects line 2, which represents the maximum slope at which the apex is stable, trenching will occur, at time B. Superimposed on line 1 are vertical lines representing changes in fanhead instability that are related to high-magnitude runoff events or longer-term climatic fluctuations. Normally, the operation of these processes has little significant morphological effect on the alluvial fan. However, when the fan slope and apex instability are high, trenching will occur sooner than expected (at time A) when a large-magnitude event exceeds the stability threshold (line 2). In reality, the event merely precipitated the eventual incision at time A rather than at time B (from Schumm and Hadley 1957).

hydraulic stability (N_h) for the channel. These values then can be compared with a regional relationship of equilibrium thalweg slope and drainage area (Fig. 18-11) that was developed from more intensive studies of other Yazoo Basin streams with similar characteristics (LCE) (Water Engineering & Technology 1989; Watson et al. 2002). For these Yazoo Basin streams, the amount of channel degradation that may occur can be estimated by plotting the hypothetical equilibrium stream slope profile of Fig. 18-11. Comparison of the existing channel profile with the hypothetical equilibrium slope profile provides information to determine possible grade control structure locations and reaches that may become geotechnically unstable (N_g>1) or hydraulically unstable (N_h>1). Within the range of drainage basin areas between about 5 and 250 square miles, equilibrium slopes range from 0.0025 to 0.0005. Bed-material samples should be obtained during the fieldwork because coarser sediments will result in higher equilibrium slopes. Most of the locations represented in Fig. 18-11 have bed material of approximately 0.15 to 0.3 mm sand.

The extent of channel erosion can also be mapped during the fieldwork. This mapping will include both bed and bank erosion, and a preliminary determination of the causes of the erosion can be made. The use of either generalized or channel-specific bank stability relations will provide an estimate of N_g.

Field mapping will provide an estimate of the number of small tributaries, field drains, and top-bank gullies that may have to be treated to prevent further erosion of these features. Further, the extent of threatened infrastructure features (bridges, culverts, and pipeline crossings) can be identified during the fieldwork. Measures previously installed to prevent erosion of the channel also can be mapped and an evaluation of their success or failure can be made. The

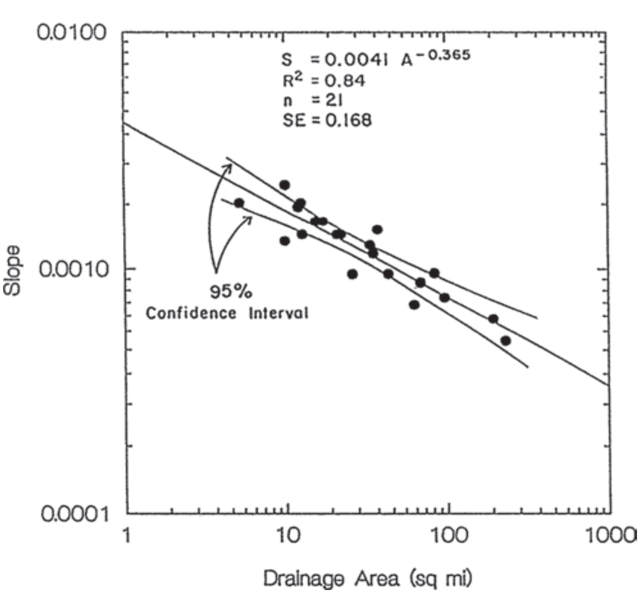

Fig. 18-11. Equilibrium channel slope plotted again drainage area for Hickahala, Batupan Bogue, and Hotopha Creeks, Mississippi (from Water Engineering & Technology 1989).

information derived from the reconnaissance geomorphic study can be used to provide a preliminary estimate of the requirements for watershed and channel rehabilitation.

In summary, the geomorphic investigation will permit the watershed problems to be quantified on a preliminary basis. The ability to define the ICEM types permits the equilibrium reaches to be identified. The equilibrium thalweg slope values (Fig. 18-11) provide a target slope for rehabilitation of reaches that are in a state of disequilibrium. A critical bank height can be estimated from a generalized relationship, or from a relationship that is specific to the channel under investigation. These data can then be used to develop a preliminary integrated watershed rehabilitation plan.

An example of how purely geomorphic observations can be of value to engineers concerned with highway and pipeline crossings of landforms and the identification of hazardous sites on landforms is provided by detailed geomorphic mapping of alluvial fans.

An alluvial fan is “a sedimentary deposit located at a topographic break, such as the base of a mountain front, escarpment, or valley side, that is composed of fluvial and/or debris flow sediments and which has the shape of a fan either fully or partly extended” (National Research Council 1996). Because fans can grow both vertically and longitudinally, highways and bridges on fans can be buried and culverts blocked either by vertical deposition on the fan or by fan enlargement (Fig. 18-12a). In addition, lateral channel shifting, avulsion, and bifurcation can direct flood flows against unprotected areas. Channel incision can lead to breaching of highways and bridge failure, and the instability of channels on fans can lead to abandonment of bridges as new channels form and as old channels fill. In addition, highways can redirect flow paths, causing property damage and even loss of life. Therefore, “an alluvial fan is an environment where the combination of sediment availability, slope and topography creates hazardous conditions . . .” (National Research Council 1996). In addition, urban development on fans requires a careful evaluation of alluvial fan topography to avoid construction in flood-prone areas.

Flood paths and the morphology of alluvial fans can differ greatly in space and time. For example, the sketches of Fig. 18-12 show examples from a continuum of alluvial fan types. Figure 18-12a shows a fan that has been trenched, and flow that is confined to a single deep channel from the topographic apex (T) to the hydrographic apex (H), where the flow expands. On this type of fan, a highway crossing the toe of the fan is subject to alluvial-fan flooding, whereas a highway crossing the middle or upper part of the fan is affected only by changes of the incised channel. The greater part of this fan lies above the effects of flooding. Figure 18-12b shows a fan with a fanhead trench. The hydrographic apex is closer to the topographic apex at the fanhead. Most of this fan below the hydrographic apex is subject to flooding. Figure 18-12c shows a fan that does not have a well-defined incised channel. The topographic and

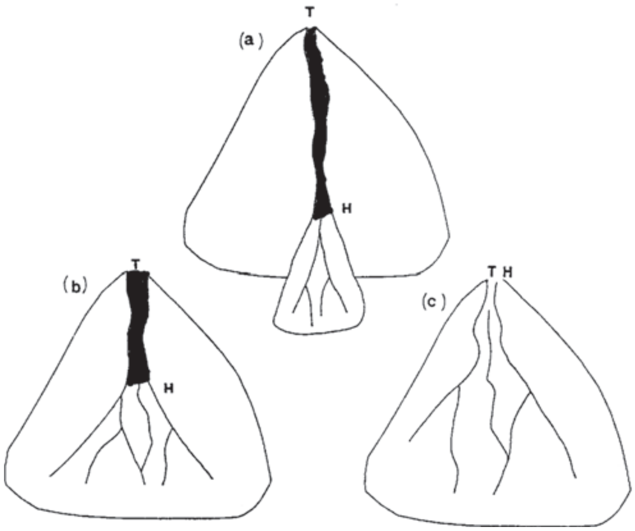

Fig. 18-12. Three examples of alluvial-fan morphology. The letter T identifies the topographic apex, which is the location where sediment and water from the upstream drainage basin enter the fan. The letter H identifies the location of the hydrographic apex, where channel flow becomes unconfined and produces alluvial-fan flooding. The shaded portions of the main channels of fans a and b are incised (from Schumm 2005).

hydrographic apex occupies the same location, and most of the fan surface is subject to flooding.

This range of fan types has been described by Hunt and Mabey (1966) in Death Valley and observed through time in experimental studies (Schumm et al. 1987). Therefore, within one area a range of fan types can occur, and during floods, fan morphology can change significantly.

A report prepared by the Committee of Alluvial Fan Flooding and published by the National Research Council (NRC) (1996) may provide engineers with useful information about these dynamic landforms. The purpose of the committee was to aid floodplain managers in determining the potential extent of flooding on alluvial fans.

Flooding on alluvial fans differs greatly from riverine flooding because it is characterized by (a) flow path uncertainty below the hydrographic apex, (b) abrupt deposition of sediment as a stream or debris flow loses its competence to carry material eroded from a steeper, upstream source area, and (c) channel incision, which reworks previously deposited sediment and shifts it down-fan (Fig. 18-12a). The potential for avulsion, deposition, and channel blockage and incision is important and some aspects of a three-stage procedure developed by the NRC committee can be of value to any engineer involved with alluvial fans.

The committee's procedure consisted of (1) identifying the fan and its extent, (2) identifying active areas on the fan, and (3) identifying areas subject to 100-yr flooding. Stages 1 and 2 involve the identification of active portions of a fan, where there is a probability of channel change, channel abandonment, and channel incision. For example, debris flows are effective in blocking existing channels. A drainage basin may produce stream flows for a very long time as sediment is stored in the valleys of the drainage basin above the topographic apex, but during major storms, flushing of the stored sediments may block channels on the fan and convert fan (a) of Fig. 18-12 to fan (b) or (c).

Surprisingly, identification of relatively recent debris flow deposits, which suggests very high sediment delivery from the drainage basin, may, in fact, be an indication of future stability. That is, stored sediment has been flushed from the drainage basin, and it may be a very long time before sufficient sediment accumulates again to produce debris flows, even under extreme rainfall.

Local aggradation in a channel can lead to avulsion because avulsion is likely to occur in places where deposition has raised the floor of the channel to a level that is nearly as high as the surrounding fan surface. This condition can be identified in the field by observation or by surveying cross-fan profiles.

To evaluate the relative stability of an alluvial fan or an alluvial-fan complex, the investigations should consist of three parts. The first part is an office study of aerial photographs and maps, which should identify the active zones of the fan that are subject to alluvial-fan flooding (Fig. 18-12) and the sites of potential channel change. If it is determined that the fan is deeply incised (Fig. 18-12a), then the hazards are restricted to incised-channel change (Fig. 18-3). Initial office procedures include the review of topographic maps and aerial photographs to determine the location and the morphology of the fan and its channels. Other data that can be gathered include historical maps and old photographs to document previous channel changes, changes in channel morphology, and the areas of the fan that may be classified as either active or inactive. Soil and geologic maps can be examined to confirm the relative geologic age of fan deposits. Climatologic data and appropriate hydrologic analyses will be needed to determine the magnitude and frequency of flooding to be expected.

The second part of the investigation consists of a field evaluation of sediment storage in the drainage basin above the topographic apex and the specific morphologic characteristics of the fan. Field investigations by a trained observer should include gathering information on elevation differences across the fan, if detailed topographic maps are not available. Vegetation types, soil characteristics, and other evidence of age (desert varnish, desert pavement) should be noted to confirm the location of active or inactive portions of the fan. Observations and measurements of channel conditions must be made. The results of the office and field investigations should provide sufficient information for the identification of potential problems. This is the third part of the investigation, which utilizes the results of Parts 1 and 2 of the investigation to provide sufficient information for an evaluation of the potential for debris flows and to identify locations of potential channel deposition, incision, and avulsion on the fan. For example, on a fan like that of Fig. 18-12b, if two of the three unincised channels below the hydrographic index were to join, any bridge that was designed for present conditions would be inadequate, and it would probably fail. However, the field investigation should have determined if one of the channels would become dominant and capture the flow of other channels. If this would threaten the stability of the highway crossing, appropriate countermeasures could be undertaken.

The ideal result of any study of an alluvial fan is a geomorphic map delineating active and inactive portions of the fan and the identification of problem sites within the active portions of the fan. Figure 18-13 shows a hypothetical alluvial fan that has a variety of features of different ages. Careful investigation of the characteristics of the fan reveals areas that have not changed in perhaps thousands of years, whereas others are hazardous sites for construction. For example, the area designated as A is an old fan surface that has been entrenched and does not receive runoff or debris flows from the mountain source area. B is a surface that is entrenched (but stands at an elevation below that of A) and will not be flooded or eroded by the channel, but it can become subject to these hazards if the current channel becomes blocked by a debris-flow deposit. C and D are, respectively, bouldery lobes and levees indicating former deposition by debris flows within and along the channel. E denotes distributary channels that show no evidence of major scour, fill, migration, or avulsion during recent large floods and can convey all or most of a 1% (100-yr) flood. Areas indicated with F are subject to sheet flooding. G is a channel with signs of recent migration and for which future behavior is highly uncertain. H is a surface that is subject to overbank flooding, channel shifting, or invasion from a distributary channel that might avulse from G, and hence it is subject to alluvial fan flooding. A map such as Fig. 18-13 will be of great value to anyone concerned with the safety of structures on alluvial fans (highways, bridges, and urban development).

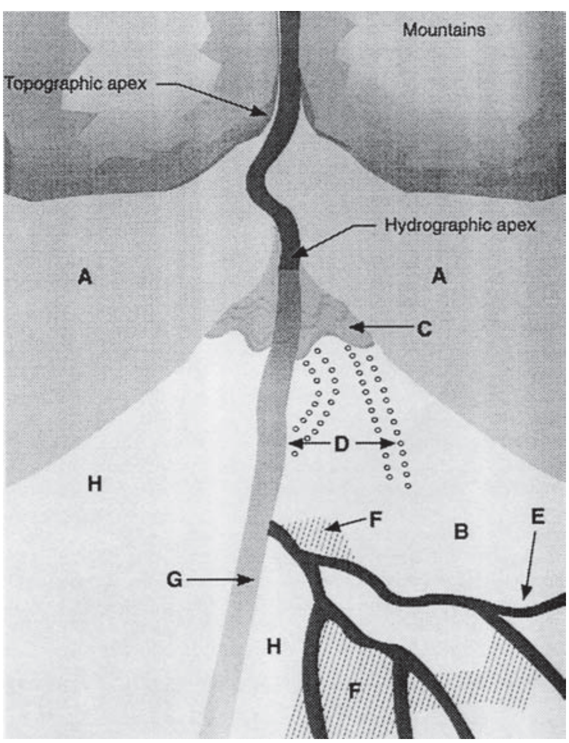

Fig. 18-13. Example of idealized geomorphic map of an alluvial fan. The areas with solid shading are recognizable channels; the darker ones have stable forms and positions; and the lighter ones have the capacity to change form or position. See text for discussion (from National Research Council 1996).

There are numerous ways that the landscape and individual landforms can change. An important issue in this regard is landform sensitivity. This involves the development of a condition at which a major change can be precipitated by a relatively minor perturbation. Examples are gullying in alluvial valleys or at the heads of alluvial fans as deposition progressively steepens these surfaces until incision occurs (Figs. 18-8, 18-9, 18-10). A further example is the growth of meander amplitude until a cutoff is inevitable as the gradient around a bend progressively decreases.

Point-bar development and concave bank erosion have been a principal concern of those studying the dynamics of meandering rivers. Figure 18-14 is a schematic diagram of a reach of a meandering river that defines the terms that are used in this discussion of the dynamics of the Sacramento River. Erosion along the concave bank occurs because of convective acceleration in downstream flow (Henderson 1966) and because of intensification of cross-stream flow. Both are caused by flow convergence, which implies that the shape of a meander bend significantly affects bank erosion (Nanson and Hickin 1986). As the radius of curvature of the bend decreases, the channel cross-section in the pool zone is constricted laterally because of vertical growth of the

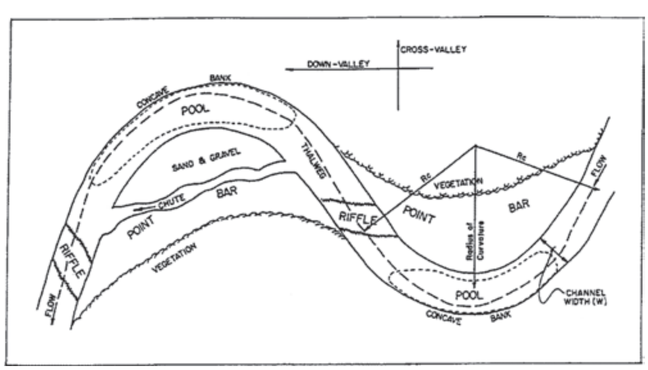

Fig. 18-14. Schematic diagram showing in planform the geomorphic surfaces and features that are associated with meander bends (from Harvey 1989).

point bar (Carson 1986). Therefore, lateral migration of the channel and concave bank erosion are dependent on the flow characteristics and the shape of the bend.

The rate of bank retreat is dependent on the resistance to erosion of the concave bank materials (Nanson and Hickin 1986), the duration and magnitude of the flows (Odgaard 1987), the radius of curvature of the bend (Nanson and Hickin 1986; Odgaard 1987), and the capacity of the flows to transport bed-material sediment (Neill 1984; Nanson and Hickin 1986). Channel migration is a discontinuous process because it is dependent on the occurrence of flood flows (Brice 1977). Initially bends migrate in a cross-valley direction (extension), but eventually bends advance in the down-valley direction (translation) (Leeder and Bridge 1975; Brice 1977; Nanson and Hickin 1986).

Meander bends eventually cut off when the radius of curvature decreases below a certain value, which is specific to each stream. Reduction of the radius of curvature of a bend causes backwater upstream of the bend, and this is expressed physically as a reduction in the slope of the water surface. Because the sediment transport capacity of the flows is proportional to the slope of the water surface squared, a reduction in slope reduces the sediment transport capacity of the flows. This causes deposition of sediment in the upstream limb of the bend between the pool and riffle (Fig. 18-14). Deposition of sediment reduces the flow capacity of the channel and this causes flows to be diverted over the point bar. These flows erode the point bar surface and form chutes (Carson 1986; Lisle 1986). However, cutoffs can occur as a result of either chute development (Brice 1977; Lewis and Lewin 1983) or neck closure (Fisk 1947).

Bagnold (1960), Leeder and Bridge (1975), and Nanson and Hickin (1986) have demonstrated that lateral migration rates of meandering rivers can be correlated with the radius of curvature (R_c) of bends. Migration rates are highest when the ratio of radius of curvature to channel width (W), R_c/W, is about 2.5. Radii of curvature and 1981–1986 migration rates (MR) for 11 Sacramento River bends were measured to obtain short-term data on river behavior (Harvey 1989). Radii of curvature ranged from 381 to 838 m and migration rates varied from 37 to 10 m/yr. A least-squares regression of the data is

$$\mathrm{MR} = 53.57 - 0.049R_c \quad (R^2 = 0.69) \qquad (18\text{-}1)$$

To determine long-term behavior of the river, radii of curvature and migration rates of the Sacramento River for the period of record (1896–1986) were utilized. The radii of curvature were assigned to nine class intervals that varied by 76-m increments from 229 to 838 m. The average channel width in each bend was determined, and both the migration rate and radius of curvature were divided by the channel width. The average width of the river in the study reach was 150 m. The relationship between the ratio of radius of curvature to width (R_c/W) and the ratio of migration rate to width (MR/W) is shown in Fig. 18-15.

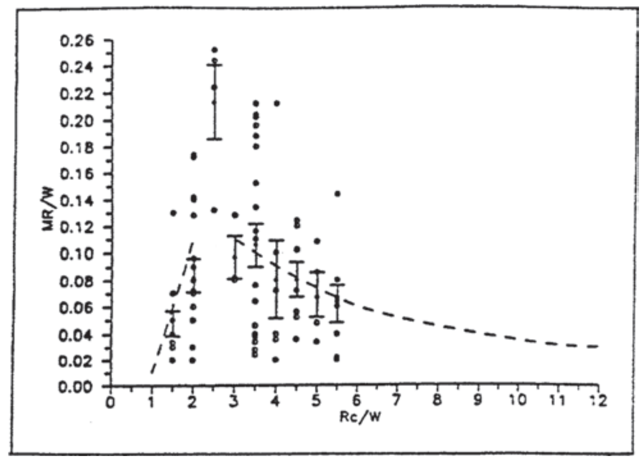

Fig. 18-15. The ratio of migration rate (MR) to channel width (W) plotted against the ratio of radius of curvature (R_c) to width. The asterisks and bars represent the means and standard errors, respectively. The curves are from Nanson and Hickin (1986) (from Harvey 1989).

For radii of curvature greater than 381 m ($R_c/W > 2.5$) the least-squares regression is

$$\mathrm{MR} = 6.98 \times 10^4 R_c^{-1.333} \quad (R^2 = 0.83) \qquad (18\text{-}2)$$

and for radii of curvature less than 381 m ($R_c/W \geqslant 2.5$) the least-squares regression is

$$\mathrm{MR} = 2.2 \times 10^{-6} R_c^{2.875} \quad (R^2 = 0.94) \qquad (18\text{-}3)$$

The reason for subdividing the data is provided by Fig. 18-15. Nanson and Hickin's (1986) curves show that for R_c/W values between 1 and 2.5 there is a direct relationship between MR/W and R_c/W. Conversely, for R_c/W values greater than 2.5 there is an inverse relationship between MR/W and R_c/W.

Brice (1977) assumed that most bends on the Sacramento River would cut off by the time the radius of curvature had decreased to 381 m. However, a number of low-radius-of-curvature bends (less than 381 m) are located in the lower part of the study reach near Colusa. This may be due to the fact that the sediments are finer, more cohesive, and therefore more resistant to erosion. The median radius of curvature for a cutoff is 380 m, but the range is from 305 to 610 m. Ninety percent of all cutoffs occur when the radius of curvature is less than 533 m. The radii of curvature of bends that had cut off since 1908 (10) and pre-1908 meander scars on the floodplain (22) were measured. The radii of curvature of four bends that had cut off following revetment were also measured.

A dimensionless cutoff index, defined as the ratio of the radius of curvature to the migration distance (R_c/MD), was developed to predict cutoff occurrence (Harvey 1989).

Equation (18.1) was used to determine the MD values for the cutoff index for both the recent (10) and floodplain (22) cutoffs. With the exception of two floodplain cutoffs, the R_c/MD values were less than 4. The mean and standard deviation for the recent cutoffs were 2.7 and 1.0, respectively, and the values for the floodplain cutoffs were 2.6 and 0.9, respectively. Therefore, cutoffs can be expected to occur when the value of the cutoff index (R_c/MD) lies between 1.7 and 3.7.

The cutoff indices for 14 bends between Glenn and Chico Landing were calculated using measured values of MD between 1981 and 1986. The data indicate that seven of the bends have R_c/MD values that lie within the range of values that were identified for cutoffs ($1.7 < R_c/\mathrm{MD} < 3.7$). Associated with these R_c/MD values for these seven bends are two other characteristics that were identified on 1986 aerial photographs: (1) the presence of a midchannel bar in the upstream limb of the bend, and (2) the presence of chutes across the point bar. Therefore, it appears that cutoffs can be predicted on the basis of the value of the cutoff index and the presence of the two ancillary features. This was tested on the bend at river distance 278.4 km, which had cut off in 1986. This bend was revetted prior to 1981 and, therefore, no migration of the bend took place between 1981 and 1986. However, the radius of curvature of the bend decreased from 572 m in 1981 to 343 m in 1986. The MD value for a radius of curvature of 343 m (Eq. (18.1)) is 181 m and, therefore, the cutoff index (R_c/MD) is 1.9. The aerial photographs confirm the presence of both a midchannel bar in the upstream limb of the bend and chutes on the point bar.

The ability to predict changes in river planform is important for managing rivers for erosion and flood control. Prediction of future changes is dependent on understanding the past behavior of the river, but uncertainty in prediction is introduced because of the stochastic nature of flood events, which cause the change, and variability of floodplain sediments, which can either accelerate or retard erosion.

18.4 GEOMORPHIC HAZARDS

Objective 3 of this chapter is to consider the geomorphologic factors that influence landforms (engineering sites) and the hazards associated with them. This should aid the engineer in anticipating problems and avoiding hazardous situations, or at least, being aware of potential hazards.

Landform change can be considered to be a geomorphic hazard if it impacts on engineering plans or works. The word *hazard* refers to a potential danger or risk. The hazard may pose a relatively minor risk that will have a minimal impact, or it may be a potential catastrophe or disaster that involves great damage and loss of life. Most books on natural hazards concentrate on the spectacular events such as coastal erosion during hurricanes, volcanic eruptions, earthquakes, avalanches, landslides, and subsidence (White 1974; Bolt et al. 1975; Hewitt and Burton 1975; Asimov 1979; Blong and Johnson 1986).

There are at least three types of geomorphic hazards that involve different spans of time, different degrees of damage, and different energy expenditures: (1) an abrupt change that is a catastrophic event, e.g., a landslide that occurs rapidly as a result of an equally catastrophic meteorological event, earthquake, or human activity (removal of toe support); (2) a progressive change that leads to an abrupt change, e.g., weathering that leads to slope failure, gullying of a steepening alluvial fan, meander growth to cutoff, and channel avulsion; and (3) a progressive change that has slow but progressive results, e.g., bank erosion, hillslope erosion, channel incision, and channel enlargement. The difference between geomorphic hazards and others is that geomorphic hazards may involve a slow progressive change that, although in no sense catastrophic, can eventually involve costly preventive and corrective measures. Therefore, geomorphic hazards can be defined as any landform change, natural or otherwise, that adversely affects the geomorphic stability of a place.

As noted earlier (Figs. 18-8, 18-9, and 18-10), a major concern of the geomorphologist, which will be of value to the engineer, is the identification of sensitive landforms and the threshold conditions under which either failure or stability occurs. A failure threshold can be a meander cutoff, channel avulsion, channel incision, gullying, or slope failure. A stability threshold is the condition under which an unstable landform achieves a new condition of relative stability. Both conditions are important because the engineer would like to anticipate and plan for the first, and recognition of the second could result in less drastic reclamation or stabilization efforts (Fig. 18-4).

18.4.1 Hazard Identification

For purposes of discussion, the fluvial system can be divided into four landform types: (1) drainage networks, which consist of the stream channels and valleys that compose the sediment source area; (2) hillslopes, which fill the area between the channels of the drainage network; (3) main channels, which convey water and sediment from the drainage networks; and (4) piedmont and plain areas that include alluvial fans and deltas, the areas of sediment accumulation.

A list of 28 geomorphic hazards and the four major variables that influence them is summarized in Table 18-3, which can serve as a check list during site selection or evaluation, particularly if it is anticipated that human activity will alter hydrologic conditions or base level. Base level here is defined as the level to which a stream is graded, and a change, as a result of reservoir or lake draining or filling or any activity that causes a lowering of a stream channel such as channelization or gravel mining, will affect the stream. Time is included with the variables discharge (increase or decrease,) sediment load (increase or decrease), and base-level change (up or down), because landforms change naturally through time, and time is an index of energy expended or work done. The hazards are grouped according to the landforms affected

Table 18-3 Variables Affecting Geomorphic Hazards

	Variables						
		Discharge		Sediment load		Base level	
Geomorphic hazards	Time	+	−	+	−	Up	Down
A. Drainage networks							
(a) Erosion							
(1) rejuvenation		X			X		X
(2) extension		X			X		X
(b) Deposition							
(1) valley filling				X		X	
(c) Pattern change							
(1) capture	X	X		X		X	X
B. Slopes							
(a) Erosion							
(1) denudation-retreat	X	X			X		X
(2) dissection		X			X		X
(3) mass failure	X	X			X		X
C. Rivers							
(a) Erosion							
(1) degradation (incision)		X			X		X
(2) knickpoint formation and migration	X	X			X		X
(3) bank erosion	X	X		X	X	X	X
(b) Deposition							
(1) aggradation			X	X		X	
(2) back and downfilling			X	X		X	
(3) berming			X	X			
(c) Pattern change							
(1) meander growth and shift	X	X		X	X		X
(2) island and bar formation and shift	X			X		X	
(3) cutoffs	X	X		X		X	X
(4) avulsion	X	X		X		X	
(d) Metamorphosis							
(1) straight to meandering				X			X
(2) straight to braided		X	X	X		X	X
(3) braided to meandering					X		X
(4) braided to straight		X	X		X		X
(5) meandering to straight				X		X	X
(6) meandering to braided		X	X	X		X	

(Continued)

Table 18-3 Variables Affecting Geomorphic Hazards *(Continued)*

		Variables					
		Discharge		Sediment load		Base level	
Geomorphic hazards	Time	+	−	+	−	Up	Down
D. Piedmont and coastal plains							
(a) Erosion							
(1) dissection							
(b) Deposition							
(1) aggradation	X		X	X		X	
(2) progradation	X						X
(c) Pattern change							
(1) pattern development		X			X		X
(2) avulsion	X	X		X		X	

After Schumm (1988).

(drainage networks, slopes, channels, piedmont, and plains) and the results of the hazard (erosion, deposition, pattern change, metamorphosis). In Table 18-2, the hazards that will be affected by the passage of time or by a change of discharge, sediment load, or base level are indicated by an X. This provides a ready means of identifying potential geomorphic hazards that should be of concern at any site, and they are described in sequence below.

18.4.2 Drainage Network Hazards

Rejuvenation (Aa1) involves the deepening or incision of a drainage network. The deepening will also cause headward growth of tributaries and perhaps the addition of tributaries in formerly undissected areas. The depth of incision may only be minor if discharge is increased slightly or if sediment loads are decreased, but it can be major and deep with a major lowering of base level. In the latter situation any site may be in jeopardy, but in the former, only sites on floodplains or terraces will be affected. Rejuvenation of a drainage system and its headward extension can be halted by emplacement of grade-control structures (Schumm et al. 1984). If left unchecked, the impact can be very great over large areas, especially on fragile lands of the semiarid western United States (Cooke and Reeves 1976).

Extension (Aa2) is the headward growth of tributaries, and it involves the addition of tributaries in formerly undissected areas. It causes erosion closer to drainage divides, and surface sites can be significantly affected by gullying and the headward growth of channels (Schumm et al. 1984).

Valley filling (Ab1) involves major sediment deposition in channels and on floodplains. This is caused by a great influx of sediment or by base-level rise. Deposition may bury a site, or it may be inundated by floods, as flood levels increase. This type of major deposition can follow channel incision and rejuvenation (Aa) when large quantities of sediment are set in motion and eventually deposited on flatter slopes and wider reaches of valleys. Deforestation, urbanization, and agricultural and mining activities can have the same impact (Toy and Hadley 1987).

Capture (Ac1) is the change of a stream course by the natural diversion of water into a stream at a lower elevation. The diversion causes steepening of the stream gradient and rejuvenation and probably extension (Aa1, Aa2) of the captured drainage network. The progress can be induced by base-level lowering, which increases the energy of the lowland stream, or by base-level rise, which as a cause of deposition may induce a channel to shift to a steeper straighter route. It can occur naturally through time, and the process can be accelerated by an increase of discharge and sediment load. Capture is a type of channel avulsion (Cc4), but although evidence for it is common in the landscape, it will be a slow process and an unlikely event unless promoted by human activities that cause major flow diversions.

18.4.3 Slope Hazards

Denudation and retreat (Ba1) of both hillslopes and escarpments in a watershed can be accelerated by increased water flow over the slope, by reduced vegetation cover, and by increased flow in adjacent streams or decreased sediment loads that lead to channel degradation and undercutting of slopes (Ca1) or to drainage network rejuvenation (Aa1) by base-level lowering. However, slope erosion will occur inevitably, during the passage of time, which will threaten a site near the top, or near the edge of a slope (Carson and Kirkby 1972; Selby 1982; Brunsden and Prior 1984; Toy and Hadley 1987; Parsons and Abrahams 1992).

Slope dissection (Ba2) by channels will occur if there is network extension (Aa2) as a result of adjacent channel incision or headward growth caused by discharge, sediment load, or base-level change.

Mass failure (Ba3) may occur (slumping, debris flow) owing to increased water content of the slope material or by an increase of slope height by channel incision or undercutting of the slope by fluvial or human action (Schuster and Krizek 1978).

18.4.4 River Hazards

Stream channels, wherever they are located in the fluvial system, change morphology and behavior with time, they respond to discharge, sediment load, and base-level changes, and they potentially pose a great hazard to the works of humans (Gregory 1977; Richards 1987; Brookes 1988; Petts et al. 1989).

Degradation (Ca1) is the lowering of a streambed by erosion. Degradation is a major adjustment of a river to external controls. The adjustment takes place over long reaches of channel. The deepening of the channel may also cause the undermining of banks and widening of the channel (Ca3).

Knickpoint migration (Ca2) is the upstream shift of an inflection in the longitudinal profile of the stream. This break in the smooth curve of the stream gradient results from rejuvenation of the stream or from the outcropping of more resistant materials in the bed. It is the former that is of concern here. A knickpoint in alluvium moves upstream, especially during floods. Above the profile break the river is stable; below the break there is erosion. As the knickpoint migrates past a point, a dramatic change in channel morphology and stability occurs (Schumm et al. 1987). Knickpoints are of two types: first is a sharp break in profile that forms an in-channel scarp called a headcut (Fig. 18-16a), and second is a steeper reach of the channel or knickzone over which elevation change is distributed (Fig. 18-16b). It is important to recognize that through time a stable reach of river may suddenly become very unstable as a result of passage of a knickpoint.

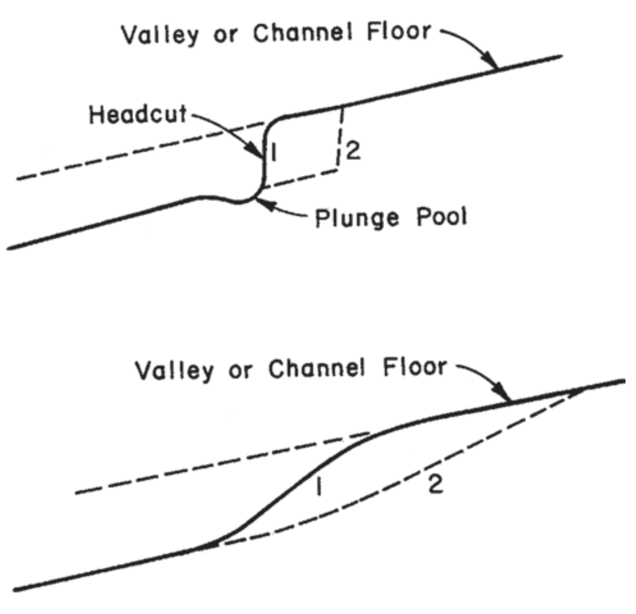

Fig. 18-16. Types of knickpoints. Dashed lines show former and future position of channel floor and knickpoint.

Bank erosion (Ca3) is the removal of bank materials either grain by grain or by mass failure. Erosion can occur by river action that undercuts a bank or by simple erosion of the bank sediments. In addition, bank erosion can occur by mass failure, as a result of surcharging the bank by construction or dumping, or by seepage forces and pore-water pressures that are related to increased water movement through bank sediment. In the latter case, the river is the transporting agent that removes the slumped bank materials rather than the primary erosive agent. The effect of bank erosion is a shift in the bankline of the river and the introduction of additional sediment into the channel. Erosion of both banks widens the channel, and may lead to aggradation (Cb1). Bank erosion is a major component of other hazards such as degradation and scour, meander shift, cutoffs, and various types of river metamorphosis.

Bank erosion is a natural consequence of normal river behavior through time, but it can be accelerated by changes of discharge, sediment load, and base level. Either an increase or decrease of sediment load or a rise or fall of base level can cause bank erosion. Channel incision increases bank height and the likelihood of bank failure.

Aggradation (Cb1) is defined simply as the raising of a streambed by deposition. Aggradation is not local; it is rather a major adjustment of a river to external controls. The main effect of aggradation is to raise the streambed. However, aggradation may continue to the extent that new hazards are generated. For example, it may cause avulsion, cut off meanders, and change channel pattern. In addition, aggradation may lead to bank erosion (Ca3) as flow paths are changed by bar formation, and decreased channel capacity will increase flooding.

Backfilling and downfilling (Cb2) are deposition or channel filling from downstream to upstream or vice versa. With backfilling, the channel is partly or entirely blocked and deposition begins at this point and then proceeds upstream (Schumm 1977, p. 150). Backfilling differs from aggradation as defined earlier because it starts at one location in the channel and then is propagated upstream. In contrast, downfilling (Cb2) occurs when deposition progresses in a downstream direction, and it is the reverse of backfilling. Both backfilling and downfilling are types of aggradation that influence long reaches of a channel, and they can affect a reach of river from either the upstream or downstream direction after it has been stable for a long time. Consequences of backfilling and downfilling are similar to those of aggradation (Cb1). The channel bed will rise as the wave of sediment passes. Increased flooding will result as the channel fills.

Berming (Cb3) refers to the deposition of primarily fine-grained sediments on the sides of the channel, and it is the opposite of bank erosion. Berming will reduce the area of the channel and cause increased flood stages. Berming reduces channel capacity, but the narrowing of the channel may cause degradation and scour. This hazard is less serious than the other depositional hazards.

Pattern change (Cc) refers to the change of channel pattern and position that occurs naturally through time. The four types of pattern-change hazards occur in different ways. Meander growth and shift (Cc1) and bar and island formation and shift (Cc2) usually occur relatively slowly and at variable rates, but the change can be viewed as progressive, whereas cutoffs (Cc3) and avulsion (Cc4) occur relatively rapidly and episodically. Nevertheless, the conditions leading to cutoffs and avulsion can be observed, and these hazards should be predictable.

Meander growth and shift (Cc1) involve a change in the dimensions and position of a meander. Meander amplitude and width increase as a meander enlarges (Fig. 18-17). Meander shift involves the displacement of the meander in a downstream direction (Fig. 18-17). Usually the meander both grows and shifts downstream, although some parts of the bend can actually shift upstream. There is probably more information available on this hazard than on any other, with the exception of cutoffs. Meander growth and shift not only cause bank erosion at the crest and on the downstream side of the limbs of a meander, but also change the flow alignment. Further, increased meander amplitude results in local reduction of gradient, with possible aggradation in the bend. Meander growth and shift will be of greatest significance where discharge is great, bank sediments are weak, and bank vegetation is negligible due to aridity or to agricultural practices.

Island and bar formation and shift (Cc2) are within-channel phenomena. Unlike meander shift or meander cutoffs, which involve the entire channel pattern, bars and islands can evolve within the channel, and the bankline pattern itself may remain unchanged. Therefore, this hazard involves the development and migration of sediment accumulations (bars and islands) in alluvial channels, which can lead to increased bank erosion, local flooding, and threats to structures.

Popov (1964) has classified the types of island changes that he observed occurring in the River Ob in the Soviet Union. He found that there were five ways islands changed (Fig. 18-18). A sixth and seventh could be added, the formation of an island and the complete destruction of an island, but Fig. 18-18 does convey the important concept that bars and islands may be ephemeral as well as dynamic features of a channel (Osterkamp 1998; Osterkamp et al. 2001; Harvey et al. 2003). The result of bar and island formation in a channel is to deflect the flow and perhaps to increase erosion of the banks of the channel. This erosion will enlarge the channel and islands may form as a result of reduced water stage and increased channel width.

Cutoff (Cc3) produces a new and relatively short channel across the neck of a meander bend. This drastically reduces the length of the stream in that reach and significantly steepens its gradient. The neck cutoff has the greatest effect (Fig. 18-17e) on the channel. Another type of cutoff is the chute cutoff (Figs. 18-17f and 18-17g), which forms by cutting across a portion of the point bar. The chute cutoff generally forms in recently deposited alluvium, whereas the neck cutoff forms in recent alluvium as well as in older consolidated alluvium or even in weak bedrock.

The consequence of cutoffs of both types is that the river is steepened abruptly at the point of the cutoff. This can lead to scour at that location and propagation of the scour in an upstream direction. The results are similar to those described for degradation and knickpoint migration (hazards Ca1, Ca2).

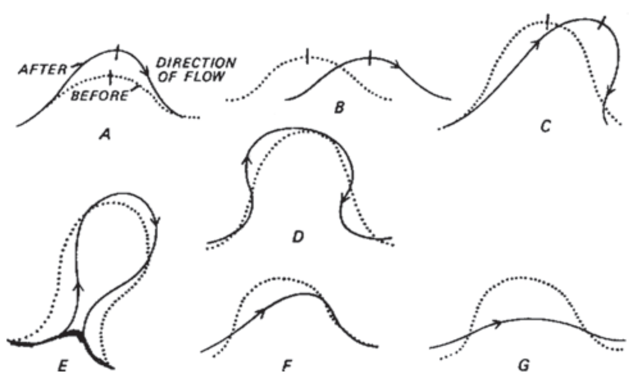

Fig. 18-17. Patterns of meander growth and shift: (a) extension, (b) translation, (c) rotation, (d) conversion to a compound meander, (e) neck cutoff, (f, g) chute cutoffs (from Brice 1974).

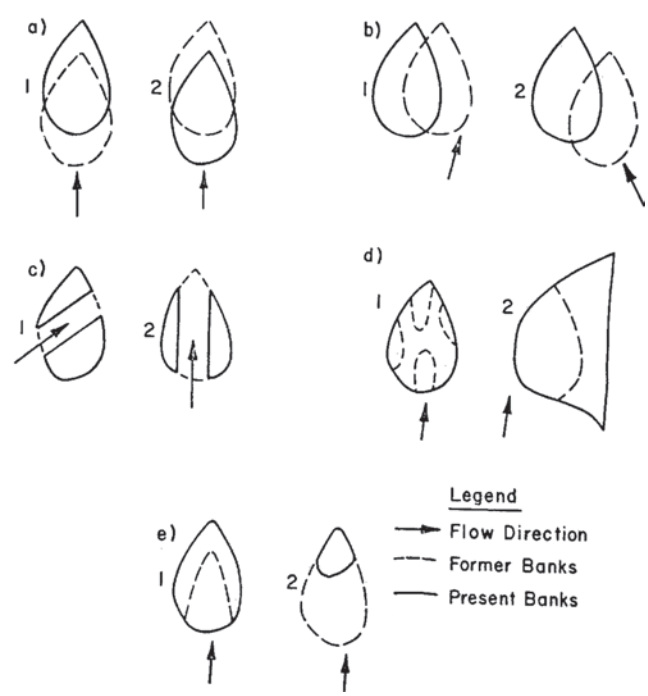

Fig. 18-18. Island change according to Popov (1964). Arrows show direction of flow. Solid lines are original locations of islands; dashed lines show changes. (a) Island shifts up or downstream. (b) Island shifts laterally. (c) Island divided by channel. (d) Small islands coalesce and island joins floodplain. (e) Islands increase or diminish in size.

In the downstream direction, the gradient of the channel is not changed below the site of the cutoff, and therefore, the increased sediment load caused by upstream scour will usually be deposited below the cutoff, forming a large bar, or it may trigger additional downstream cutoffs.

Avulsion (Cc4) is the abrupt change of the course of a river. A channel is abandoned and a new one formed as the water and sediment take a new course across the floodplain, alluvial fan, or alluvial plain (Figs. 18-12 and 18-13). A meander cutoff (Cc3) is a type of avulsion because it is a relatively rapid change in the course of the river during a short period of time, but avulsion, as defined here, involves a major change of channel position below the point of avulsion. If, through avulsion, the river takes a shorter course to the sea, it will have a steeper gradient, and erosion above the point of avulsion is likely unless a bedrock control prevents upstream degradation.

River metamorphosis (Cd) is a complete change of river morphology (Schumm 1977, p. 159). As the word indicates, this consists of significant changes not only in the dimensions of the river, but in its pattern and shape. Considering the types of channels identified, it is possible to consider six types of river metamorphosis as follows: a straight channel changes to (1) meandering or (2) braided, a braided channel changes to (3) meandering or (4) straight, and a meandering channel changes to (5) straight or (6) braided. It is not necessary to define each type of metamorphosis, because the change is obvious based on pattern alone. There is some similarity in the hazards posed by some types of metamorphosis, and they can be discussed as three pairs.

Straight and braided to meandering (Cd1 and Cd3). A straight channel may develop alternate bars and a sinuous thalweg if there is an increase of discharge and sediment load. If the straight channel begins to meander, meander growth, shift, cutoff, and avulsion (Hazards Cc1, Cc3, and Cc4) will also occur when the metamorphosis takes place.

In the case of a metamorphosis from braided to meandering, the change may actually result from a decrease of sediment load that produces increased channel stability. The decreased gradient will reduce the erosional forces acting on the channel, and although the development of meanders is a hazard itself (Hazard Cc1), they will probably form in the space occupied by the old braided channel. In both cases, the channel may degrade.

Meandering and braided to straight (Cd5 and Cd4). A bar-braided channel can become island-braided when the bars are colonized by vegetation, and then these islands are incorporated into a new floodplain to form a straight channel. The narrowed straight channel should degrade, but not appreciably. The narrower channel will probably represent a more stable condition, although the increased presence of vegetation may raise the stage of large floods.

The conversion of a meandering channel to a straight channel will be the result of a series of natural cutoffs. The steepened gradient will cause bank erosion and perhaps degradation. Unless there have been hydraulic changes, the channel will attempt to meander, and the channel will be very unstable. This is especially true when the channel has been straightened artificially.

Straight and meandering to braided (Cd2 and Cd6). A straight channel can braid if significant bank erosion occurs with aggradation (Cb1), a result of a major increase of sediment load. A meandering channel will braid for the same reasons. The result will be bank erosion and channel widening (Ca3) with bar and island formation (Cc2). Obviously the change from meandering to braided will be very dramatic.

18.4.5 Piedmont and Coastal Plain Hazards

On a coastal plain, piedmont plain, alluvial fan (Rachocki and Church 1990), or delta, the major hazards are associated with the channel changes discussed above. For example, an increase of discharge, a decrease of sediment load, or a fall of base level will cause channels to incise, dissecting (Da1) the alluvial or bedrock surface. Similar change may cause rejuvenation and extension of drainage networks (Aa1, Aa2) or the *development of a new drainage network* (Dc1). General *aggradation* (Db1) will eventually bury a site, but before the burial is complete, it will be subjected to increased flooding and potential erosion.

Progradation (Db2) is the growth of a delta or fan. It is characteristic of a dynamic landform that will be subjected to periods of erosion as it grows. *Avulsion* (4c2) will be common on an unconfined surface such as an alluvial plain, delta, or alluvial fan, especially if progradation or aggradation is occurring. This channel shifting will render any surface site hazardous. The avulsion can also occur on piedmont or alluvial plains by capture (1c1).

The identification of 28 geomorphic hazards provides a check list (Table 18-2) that can be used to review the potential geomorphic hazards that may exist at a site. For most sites, only a few hazards will be of concern. Although Table 18-2 provides a means of determining what hazards may occur in a landscape through time or with a change of discharge, sediment load, or base level, the most important aspect of hazard research is to determine where and when the hazard will occur.

18.5 THE ENGINEERING GEOMORPHIC APPROACH

An understanding of landform history, taking a broader view of the problem, and a recognition that geologic and geomorphic controls can exert a dominant influence on a river reach or construction site should provide the engineer with a valuable basis upon which to develop plans and to select sites that will not be exposed to geomorphic hazards, or at least to plan for the occurrence of particular hazards (Table 18-2).

Numerous problems must be considered in dealing with the complex surface of the planet. In particular, one should not extrapolate beyond the limits of available data. In fact, well-established relations developed in other areas may not always pertain, and therefore, field investigations are usually necessary. A good example of the need to understand the geomorphic setting is provided by litigation between the U.S. Forest Service and the State of Colorado regarding the need for channel maintenance flows. The Forest Service claimed that any diversion of streams in the National Forests would cause the streams to decrease in size, which was considered to be an unfavorable condition. This assumption was based upon hydraulic geometry relations that show close positive relations between channel width, depth, and discharge, which were developed for low-gradient alluvial streams (Leopold and Maddock 1953). However, these relations were not valid for mountain streams draining areas of less than 15 square miles with slopes greater than about 4% because other factors such as log jams, beaver dams, glacial deposits, colluvium, and bedrock become the dominant controls on channel morphology and adjustability (Montgomery and Buffington 1993, 1997; Schmidt and Potyondy 2004). Obviously, careful field study was necessary to determine the major influences on these streams. Additionally, even in locations where the form of the channel is not forced by nonfluvial factors, caution must be used with generalized hydraulic geometry relationships for design purposes (Rinaldi and Johnson 1997; Doll et al. 2002)

Examples have been provided of how a combined geomorphic engineering approach can result in better and cost-effective planning. The incised-channel model for channelized streams (Fig. 18-3), the evaluation of bridge sites (Figs. 18-1 and 18-6), and meander growth and shift (Fig. 18-17) are all examples of how consideration of change through time, taking a broader perspective, and recognition of geologic and geomorphic controls can aid the engineer. Thorne and Baghirathan (1994) have developed a scheme for morphological studies of large rivers using this approach.

The geomorphic-engineering approach to a problem or site evaluation should ideally consist of three phases or levels of sophistication, as follows: reconnaissance level, survey level, and design level. At the preliminary stage of a project the reconnaissance level would involve a system approach that brings together geologic and geomorphic data and observations, as well as available climatic and hydrologic data as needed. The survey level involves surveying, mapping, and perhaps geomorphic mapping (Fig. 18-13), to quantify the qualitative relations developed during the reconnaissance-level study. Both of these levels involve both geomorphologists and engineers. The final design-level work is carried out by the engineer, relying on the relations and data obtained during the previous two levels of study. This approach is described in some detail, with examples, in Schumm et al. (1984).

A final example reveals the problem of ignoring the cooperative approach (Keaton et al. 1988; Keaton 1995). In May and June 1983, significant damage occurred along the Wasatch Front, Utah, due to snowmelt-induced debris flows. The worst damage occurred in Farmington due to a debris slide, which mobilized into a debris flow, incorporating over 90% of its mass from the channel of Rudd Creek.

The 1983 debris flows were triggered by landslides caused by a heavy snow pack, an abnormally late rapid snowmelt, and an undrained bedrock aquifer. Geologic studies of the structural fabric and hydrogeology of the landslide source areas indicate that these landslide-induced debris flows were a rare geologic event, perhaps the first such event during the last few thousand years. Most of the earlier historical debris flows were generated by erosion during cloudburst storms that fell on watersheds depleted of vegetative cover by overgrazing and burning. Geologic studies of alluvial fans at the mouths of central Davis County canyons indicate that (1) the majority of alluvial-fan building occurred during the early Holocene (about 10,000 yrs ago) when much ice-age sediment was available for transport, (2) few if any debris flows occurred between the early Holocene and the 1920s, and (3) if historical debris-flow events were representative of the long-term rate of sediment deposition on alluvial fans, the fans would be major landforms instead of the minor features they actually are. The majority of sediment incorporated into debris flows triggered by either landslides or cloudburst storms was derived from the stream channel. Geologic studies of central Davis County stream channels indicate that (1) debris production and accumulation in channels is a slow, intermittent process, (2) stream channels that have produced debris-flow events during historical time have not yet been recharged with sediment, (3) future debris flows from drainages cleaned of sediment will likely be of less volume than initial historical events, until the drainages have been recharged with sediment, and (4) the most likely channels to produce large debris flows in the near future are those that have not produced historical debris flows.

Approximately $12 million was spent in Davis County to build or refurbish debris basins following the 1983 debris-flow events; less than $30,000 was spent on geologic research to understand the debris-flow processes. Had geologic studies been conducted prior to construction of the debris basins, more emphasis could have been placed on building debris basins at the mouths of canyons that have not produced historical debris flows, instead of canyons that had produced debris flows during historical time.

The results of the geologic investigation appear to be contrary to common sense, but the evidence is clear. The changing situation through time along the Wasatch Mountains front is expectable from a geomorphic point of view, and it is analogous to the declining sediment loads in the Colorado River as a result of decreased erosion in the incised arroyos of the Southwest (Fig. 18-4).

18.6 CONCLUSIONS

Geomorphology is the study of landforms, which involves their classification, description, origin, and evolutionary development. The traditional concern of geomorphologists has been the origin and evolution of landforms, but a more recent development is the prediction, based upon understanding of system dynamics, of landform response to natural and human influences.

The major objectives of this chapter were to bring to the attention of the engineering profession (1) the importance of system history, (2) the need to view a specific problem in a system context, and (3) the importance of geologic and geomorphic variables in engineering activities. For example, if a river meander has changed through time, prediction of future change can be made with more confidence. Therefore, the historical perspective can be a valuable aid in prediction. In addition, it is important to realize that a specific engineering project site is part of a larger geomorphic system. For example, a bridge site is a small part of a fluvial system and the character of that system both up- and downstream can significantly affect future site stability. Finally, geology and geomorphology can be far more important than is generally supposed within an engineering time scale. For example, the world's great alluvial rivers (Mississippi, Nile, Indus), although presumably dominated by hydrological, sediment, and hydraulic controls, are, in fact, significantly influenced by geologic variables. These principles were illustrated in the chapter by examples that were selected to demonstrate how geomorphology and engineering can be combined to provide a rational approach to engineering and environmental problems.

REFERENCES

Anthony, D. J., Harvey, M. D., Laronne, J. B., and Mosley, M. P., eds. (2001). *Applying geomorphology to environmental management.* Water Resources Pub., Highlands Ranch, Colo.

Arizona Department of Transportation. (1979). "Salt River Bed study report (Photogrammetry and mapping services)." Arizona Department of Transportation, Phoenix.

Asimov, I. (1979). *A choice of catastrophes.* Simon & Schuster, New York.

Bagnold, R. A. (1960). "Some aspects of the shape of river meanders." *Professional Paper 181E*, U.S. Geological Survey, Washington, D.C., 135–144.

Bates, R. L., and Jackson, J. A., eds. (1987). *Glossary of geology*. American Geological Institute, Alexandria, Va.

Begin, Z. B., and Schumm, S. A. (1979). "Instability of alluvial valley floors: A method for its assessment." *American Society of Agricultural Engineering* 22, 347–350.

Bledsoe, P. B., Watson, C. C., and Biedenharn, D. S. (2002). "Quantification of incised channel evolution and equilibrium." *American Water Resources Association Journal* 38, 861–870.

Blong, R. J., and Johnson, R. W. (1986). "Geological hazards in the Southwest Pacific and Southeast Asian regions: Identification, assessment and impact." *Australian Geology and Geophysics Journal* 10, 1–15.

Bloom, A. L. (1991). *Geomorphology*. Prentice Hall, Englewood Cliffs, N.J.

Bolt, B. A., Horn, W. L., MacDonald, G. A., and Scott, R. F. (1975). *Geological hazards.* Springer-Verlag, New York.

Brice, J. (1977). "Lateral migration of the middle Sacramento River, California." *Water Resources Investigation 77–43*, U.S. Geological Survey, Washington, D.C.

Brice, J. C. (1974). "Evolution of meander loop." *Geological Society of America Bulletin* 85, 581–586.

Brice, J. C. (1981). "Stability of relocated stream channels." *Report FHWA/RD-80/158*, Federal Highway Commission, Washington, D.C.

Brookes, A. (1988). *Channelized rivers, perspectives for environmental management.* Wiley, Chichester, U.K.

Brunsden, D., and Prior, D. B., eds. (1984). *Slope instability*. Wiley, Chichester, U.K.

Bull, W. B. (1991). *Geomorphic responses to climate change*. Oxford Univ. Press, Oxford, U.K.

Carson, M. A. (1975). "Threshold and characteristic angles of straight slopes." *Fourth Guelph Symposium on Geomorphology*, Geobooks, Norwich, U.K., 19–34.

Carson, M. A. (1986). "Characteristics of high-energy meandering rivers: The Canterbury Plains, New Zealand." *Bulletin Geological Society of America* 97, 886–895.

Carson, M. A., and Kirkby, M. J. (1972). *Hillslope form and process*. Cambridge Univ. Press, Cambridge, U.K.

Catt, J. A. (1988). *Quaternary geology for scientists and engineers*. George Allen & Unwin, London.

Chang, H. H. (1988). *Fluvial processes in river engineering*. Wiley, New York.

Chow, V. T., ed. (1964). *Handbook of applied hydrology.* McGraw-Hill, New York.

Coates, D. R. (1976). *Geomorphology and engineering*. Dowden, Hutchinson & Ross, Stroudsburg, Pa.

Cooke, R. V. and Reeves, R. W. (1976). *Arroyos and environmental change in the American Southwest*. Clarendon, Oxford, U.K.

Darby, S. E. and Simon, A., eds. (1999). *Incised river channels*. Wiley, Chichester, U.K.

Doll, B. A., Wise-Frederick, D. E., Buckner, C. M., Wilkerson, S. D., Harman, W. A., Smith, R. E., and Spooner, J. (2002). "Hydraulic geometry relationships for urban streams throughout the Piedmont of North Carolina." *Journal of American Water Resources Association* 38(3), 641–651.

Fairbridge, R. W., ed. (1968). *The encyclopedia of geomorphology*. Reinhold, N.Y.

Ferrari, R. L. (1988). "1986 Lake Powell survey." Bureau of Reclamation, Denver, Colo.

Fisk, H. N. (1947). "Fine-grained alluvial deposits and their effect on Mississippi River activity." *Waterways Experiment Station Report 2*, U.S. Army Corps of Engineers, Vicksburg, Miss.

Fookes, P. G., and Vaughn, P. R. (1986). *A handbook of engineering geomorphology*. Chapman & Hall, New York.

Gellis, A., Hereford, R., Schumm, S. A., and Hayes, B. R. (1991). "Channel evolution and hydrologic variations in the Colorado River basins." *Journal of Hydrology* 124, 318–344.

Goodwin, C. N. (1999). "Fluvial classification: Neanderthal necessity or needless normalcy." *Wildland Hydrology* 25, 229–236.

Graf, W. L., ed. (1987). *Geomorphic systems of North America*. Centennial Special Volume 2, Geological Society of America.

Graf, W. L. (1988). *Fluvial processes in dryland rivers*. Blackburn Press, Caldwell, N.J.

Gregory, K. J., ed. (1977). *River channel changes.* Wiley, Chichester, U.K.

Goudie, A. (1981). *Geomorphological techniques*. Allen & Unwin, London.

Harvey, M. D. (1989). "Meanderbelt dynamics of the Sacramento River, California." D. L. Abell, (ed), *Proceedings California Riparian Systems Conference*, D. L. Abell, ed., *General Technical Report PSW-110*, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif., 54–61.

Harvey, M. D., Mussetter, R. A., and Anthony, D. J. (2003). "Abstract: Island aging and dynamics in the Snake River, Western Idaho, USA." *Proceedings of Hydrology Days 2003*, American Geophysical Union, Fort Collins, Colo.

Harvey, M. D., and Smith, T. W. (1998). *Gravel mining impacts on San Benito River, California*. "Proceedings of the 1998 International Water Resources Engineering Conference, Hydraulics Division," ASCE, New York.

Harvey, M. D. and Watson, C. C. (1986). "Fluvial processes and morphological thresholds in incised channel restoration." *Water Resources Bulletin* 3(3), 359–368.

Henderson, F. M. (1966). *Open channel flow*. Macmillan, New York.

Hewitt, K., and Burton, I. (1975). *The hazardousness of a place*. University of Toronto Press, Toronto.

Hunt, C. B., and Mabey, D. R. (1966). "The stratigraphy and structure, Death Valley, California." *Professional Paper 494-A*, U.S. Geological Survey, Washington, D.C.

Johnson, R. B., and DeGraff, J. V. (1988). *Principles of engineering geology*. Wiley, New York.

Juracek, K. E., and Fitzpatrick, F. A. (2003). "Limitation and implications of stream classification." *Journal of American Water Resources Association* 83(3), 659–670.

Keaton, J. R. (1995). "Dilemmas in regulating debris-flow hazards in Davis County, Utah." *Environmental and engineering geology of the Wasatch Front region*, W. R. Lund, ed., *Publication 24*, Utah Geological Association, Salt Lake City, 185–192.

Keaton, J. R., Anderson, L. R., and Mathewson, C. C. (1988). "Assessing debris flow hazards on alluvial fans in Davis County, Utah." *24th Symposium Engineering Geology and Soils Engineering, Proceedings*, Washington State University, Pullman, 89–108.

Keeley, J. W. (1971). *Bank protection and river control in Oklahoma*. Federal Highway Administration, Oklahoma Division, Oklahoma City.

Kellerhals, R., Church, M., and Bray, D. I. (1976). "Classification and analysis of river processes." *Journal of Hydraulic Division Proceedings* 102, 813–829.

Kiersch, G. A. (1991). "The heritage of engineering geology. The first hundred years." Centennial Special 3, Geological Society of America, Boulder, Colo.

Kondolf, G. M., and Piégay, H., eds. (2003). *Tools in fluvial geomorphology*. Wiley, Chichester, U.K.

Lagasse, P. F., Spitz, W. J., Zevenbergen, L. W., and Zachmann, D. W. (2004). "Handbook for predicting stream meander migration." *NCHRP Report 533*, Transportation Research Board, Washington, D.C.

Leeder, M. R., and Bridge, P. H. (1975). "Flow separation in meander bends." *Nature* 235, 338–339.

Legget, R. F., and Hatheway, A. W. (1988). *Geology and engineering*. McGraw-Hill, New York.

Leopold, L. B., and Maddock, T., Jr. (1953). "Hydraulic geometry of stream channel and some physiographic implications." *Professional Paper 252*, U.S. Geological Survey, Washington, D.C.

Leopold, L. B., and Wolman, M. G. (1957). "River channel patterns: Braided meandering and straight." *Professional Paper 282-B*, U.S. Geological Survey, Washington, D.C.

Leopold, L. B., Wolman, M. G., and Miller, J. P. (1964). *Fluvial processes in geomorphology*. Freeman, San Francisco.

Lewis, G. W., and Lewin, J. (1983). "Alluvial cutoffs in Wales and the Borderlands." *Special Publication No. 6*, International Association of Sedimentologists, Oxford, U.K., 145–154.

Lisle, T. E. (1986). "Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California." *Bulletin Geological Society of America* 97, 999–1011.

Miller, J. R., and Ritter, J. B. (1996). "An examination of the Rosgen classification of natural rivers." *Catena* 27, 295–299.

Mollard, J. D. (1973). "Airphoto interpretation of fluvial features: Fluvial processes and sedimentation." *Proceedings of Hydrology Symposium, University of Alberta*, Information Canada, Ottawa, Ont., 341–380.

Molnar, P., and Ramirez, J. A. (2001). "Recent trends in precipitation and streamflow in the Rio Puerco Basin." *Journal of Climate* 14, 2317–2328.

Montgomery, D. R., and Buffington, J. M. (1993). "Channel classification: Prediction of channel response and assessment of channel condition." *TFW-SH10-93-002*, Washington Department of Environmental Resources, Timber Fish & Wildlife, Seattle.

Montgomery, D. R., and Buffington, J. M. (1997). "Channel-reach morphology in mountain drainage basins." *Geological Survey of America Bulletin* 109, 596–611.

Mosley, M. P. (1987). "The classification and characterization of rivers." *River channels*, K. Richards, ed., Blackwell, Oxford, U.K., 295–320.

Mussetter, R. A., Harvey, M. D., Wolff, C. G., Peters, M. R., and Trabant, S. C. (1998). "Channel migration effects on bridge failure in South Fork Snake River, Idaho." *Proceedings of the ASCE 1998 Water Resources Engineering Conference,* ASCE, New York.

Mussetter, R. A., Lagasse, P. F., and Harvey, M. D. (1994). *Erosion and sediment design guide*. Prepared for Albuquerque Metropolitan Arroyo and Flood Control Authority.

Nanson, G. C. and Hickin, E. J. (1986). "A statistical analysis of bank erosion and channel migration in Western Canada." *Bulletin Geological Society of America* 97, 497–504.

National Research Council. (1996). *Alluvial fan flooding*. National Academy Press, Washington, D.C.

Neill, C. R. (1984). "Bank erosion versus bedload transport in a gravel river." *Proceedings of the River Meandering Conference*, ASCE, New York, 204–211.

O'Connor, J. E., and Grant, G. E., eds. (2003). "A peculiar river: Geology, geomorphology, and hydrology of the Deschutes

River, Oregon." *Water Science and Application 7,* American Geophysical Union, Washington, D.C.

Odgaard, A. J. (1987). "Stream bank erosion along two rivers in Iowa." *Water Resources Research* 23, 1225–1236.

Osterkamp, W. R. (1998). "Processes of fluvial island formation, with examples from Plum Creek, Colorado, and Snake River, Idaho." *Wetlands* (4), 530–545.

Osterkamp, W. R., Johnson, W. C., and Dixon, M. D. (2001). "Biophysical gradients related to channel islands, middle Snake River, Idaho." *Geomorphic processes and riverine habitat,* J. M. Dorava, D. R. Montgomery, B. B. Palcsak, and F. A. Fitzpatrick, eds., *Water Science and Application No. 4*, American Geophysical Union, Washington, D.C., 73–83.

Paine, A. D. M. (1985). "Ergodic reasoning in geomorphology: Time for a review of the term?" *Progress in Physical Geography* 9, 1–15.

Parsons, A. J., and Abrahams, A. D., eds. (1992). *Overland flow, hydraulics and erosion mechanisms*. Chapman & Hall, New York.

Patton, P. C., and Schumm, S. A. (1975). "Gully erosion, northern Colorado: A threshold phenomenon." *Geology* 3, 88–90.

Petts, G. E., Moller, H., and Roux, A. L., eds. (1989). *Historical change of large alluvial rivers: Western Europe*. Wiley, Chichester, U.K.

Popov, I. V. (1964). "Hydromorphological principles of the theory of channel processes and their use in hydrotechnical planning." *Soviet Hydrology*, 158–195.

Rachocki, A. H., and Church, M., eds. (1990). *Alluvial fans, a field approach*. Wiley, Chichester, U.K.

Richards, K., ed. (1987). *River channels*. Blackwell, Oxford, U.K.

Rinaldi, M., and Johnson, P. A. (1997). "Characterization of stream meanders for stream restoration." *ASCE, Journal of Hydraulic Engineering* 123, 567–570.

Ritter, D. F. (1986). *Process geomorphology*. Brown, Dubuque, Iowa.

Rosgen, D. L. (1994). "A classification of natural rivers." *Catena* 22, 169–199.

Rosgen, D. L. (1996). *Applied river morphology*. Wildland Hydrology, Pagosa Springs, Colo.

Scheidegger, A. E. (1991). *Theoretical geomorphology*, 3rd Ed., Springer-Verlag, New York.

Schmidt, L. J., and Potyondy, J. P. (2004). "Quantifying channel maintenance instream flows: An approach for gravel-bed streams in the western United States." *General Technical Report RMRS-GTR-128*, USDA, Forest Service, Rocky Mountain Research Station.

Schuirman, G., and Slosson, J. E. (1992). *Forensic engineering*. Academic Press, New York.

Schumm, S. A. (1963). "A tentative classification of alluvial river channels." *Circular 477*, U.S. Geological Survey, Washington, D.C.

Schumm, S. A. (1968). "River adjustment to altered hydrologic regimen, Murrumbidgee River and paleochannels, Australia." *Professional Paper 598*, U.S. Geological Survey, Washington, D.C.

Schumm, S. A., ed. (1972). *River morphology*. Dowden, Hutchinson & Ross, Stroudsburg, Pa.

Schumm, S. A., ed. (1977a). *Drainage basin morphology.* Dowden, Hutchinson & Ross, Stroudsburg, Pa.

Schumm, S. A. (1977b). *The fluvial system*. Wiley, New York.

Schumm, S. A. (1988). "Geomorphic hazards—Problems of predictions." *Zeit. Geomorph. Suppl.* 67, 17–24.

Schumm, S. A. (1991). *To interpret the Earth*. Cambridge University Press, Cambridge, U.K.

Schumm, S. A. (1993). "River response to baselevel change: Implications for sequence stratigraphy." *Journal of Geology* 101, 279–294.

Schumm, S. A. (1994). "Erroneous perceptions of fluvial hazards." *Geomorphology* 10, 129–138.

Schumm, S. A. (2005). *River variability and complexity*. Cambridge University Press, Cambridge, U.K.

Schumm, S. A., and Beathard, R. M. (1976). "Geomorphic thresholds: An approach to river management." *Rivers 76*, ASCE, New York, 1, 707–724.

Schumm, S. A., Dumont, J. F., and Holbrook, J. M. (2000). *Active tectonics and alluvial rivers.* Cambridge University Press, Cambridge, U.K.

Schumm, S. A., and Galay, V. J. (1994). "The River Nile in Egypt." *The variability of large alluvial rivers*, S. A. Schumm and B. R. Winkley, eds., ASCE, New York, 75–100.

Schumm, S. A., and Hadley, R. J. (1957). "Arroyos and the semiarid cycle of erosion." *American Journal of Science* 225, 161–174.

Schumm, S. A., Harvey, M. D., and Watson, C. C. (1984). *Incised channels. Initiation, evolution, dynamics, and control*. Water Resources, Littleton, Colo.

Schumm, S. A., and Khan, H. R. (1972). "Experimental study of channel patterns." *Geological Society of America Bulletin* 83, 1755–1770.

Schumm, S. A., and Mosley, M. P., eds. (1973). *Slope morphology*. Dowden, Hutchinson & Ross, Stroudsburg, Pa.

Schumm, S. A., Mosley, M. P., and Weaver, W. E. (1987). *Experimental fluvial geomorphology*. Wiley, New York.

Schumm, S. A., Rutherfurd, I., and Brooks, J. (1994). "Pre-cutoff morphology of the lower Mississippi River." *The variability of large alluvial rivers,* S. A. Schumm and B. R. Winkley, eds., ASCE, New York, 13–44.

Schumm, S. A., and Winkley, B. R. (1994). *The variability of large alluvial rivers.* ASCE, New York.

Schuster, R. L., and Krizek, R. J., eds. (1978). Landslides, analysis and control. *Transportation Research Board Special Report 176*, National Academy Sciences, Washington, D.C.

Selby, M. J. (1982). *Hillslope materials and processes.* Oxford University Press, Oxford, U.K.

Shen, H. W. and Schumm, S. A. (1981). "Methods for assessment of stream-related hazards to highways and bridges." *Report FHWA/RD-80/160*, Federal Highway Administration.

Simon, A. (1994). "Gradation processes and channel evolution in modified West Tennessee streams: Process, response and form." *Professional Paper 1470*, U.S. Geological Survey.

Strahler, A. N. (1964). "Quantitative geomorphology of drainage basins and channel networks." *Handbook of applied hydrology*, V. T. Chow, ed., McGraw-Hill, New York, 4-39–4-76.

Summerfield, M. A. (1991). *Global geomorphology*. Longmans, Harlow, U.K.

Thornbury, W. D. (1965). *Regional geomorphology of the United States*. Wiley, New York.

Thorne, C. R. (1997). "Channel types and morphological classification." *Applied fluvial geomorphology for river engineering and* *management,* C. R. Thorne, R. D., Hey, and M. D. Newson, eds., Wiley, Chichester, U.K., 175–222.

Thorne, C. R., and Baghirathan, V. R. (1994). "Blueprint for morphologic studies." *The variability of large alluvial rivers*, S. A. Schumm and B. R. Winkley, eds., ASCE, New York, 441–453.

Thorne, C. R., Hey, R. D., and Newson, M. D., eds. (1997). *Applied fluvial geomorphology for river engineering and management*. Wiley, New York.

Tinker, K. J., and Wohl, E. E., eds. (1998). *Rivers over rock: fluvial processes in bedrock channels*. *Geophysical Monograph 17*, American Geophysical Union, Washington, D.C.

Toy, T. J., and Hadley, R. F. (1987). *Geomorphology and reclamation of disturbed lands*. Academic Press, New York.

Vandenberghe, J. (2001). "A typology of Pleistocene cold-based rivers." *Quaternary International* 79, 111–121.

Water Engineering & Technology, Inc. (1989). "Systems approach to watershed analysis." Prepared for U.S. Army Corps of Engineers, Vicksburg District, Contract No. DACW38-99-D-0099, Delivery Order 0004.

Watson, C. C., Biedenharn, D. S., and Bledsoe, B. P. (2002). "Use of incised channel evolution models in understanding rehabilitation alternatives." *American Water Resources Association Journal* 38, 151–160.

Watson, C. C., Harvey, M. D., Biedenharn, D. S., and Combs, P. G. (1988a). "Geotechnical and hydraulic stability numbers for channel rehabilitation. I: The approach." *ASCE Hydraulics Division 1988 National Conference Proceedings*, S. R. Abt and J. Gessler, eds., ASCE, New York, 120–125.

Watson, C. C., Harvey, M. D., Biedenharn, D. S., and Combs, P. G. (1988b). "Geotechnical and hydraulic stability numbers for channel rehabilitation. II: Application." *ASCE Hydraulics Division 1988 National Conference Proceedings*, S. R. Abt and J. Gessler, eds., ASCE, New York, 126–131.

Wells, S. G., Bullard, T. F., Smith, L. N., and Gardner, T. W. (1983a). "Chronology, rates, and magnitudes of late Quaternary landscape changes in the southeastern Colorado Plateau." *Chaco Canyon country, American Geomorphological Field Group, Guidebook*, S. G. Wells, D. W. Love, and T. W. Gardner, eds., Albuquerque, N.M., 177–185.

Wells, S. G., Bullard, T. F., Miller, J., and Gardner, T. W. (1983b). "Applications of geomorphology to uranium tailings siting and groundwater management." *Chaco Canyon country*, *American Geomorphological Field Group, Guidebook*, S. G. Wells, D. W. Love, and T. W. Gardner, eds., Albuquerque, N.M., 51–56.

White, G. F. (1974). *Natural hazards.* Oxford University Press, New York.

Wilcock, P. (1997). "Friction between science and practice: The case of river restoration." *EOS Forum* 78, October 14.

Wilson, L. (1968). "Morphogenetic classification." *The encyclopedia of geomorphology*, R. W. Fairbridge, ed., Reinhold, New York, 717–729.

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