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PATTERNS OF ALLUVIAL RIVERS

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INTRODUCTION

The pattern (planform) of a river can be considered at vastly different scales, depending upon both the size of the river and the part of the fluvial system that is under consideration (Figure 1). For example, in the broadest sense, river patterns comprise a drainage network (dendritic, parallel, trellis, etc; Figure 1*A*). The type of pattern is of interest to geomorphologists and geologists who interpret geologic conditions from aerial photographs.

At another scale a river reach (which in Figure 1*B* is meandering) is of interest to the geomorphologist who is interested in what that pattern reveals about river history and behavior, and to the engineer who is charged with maintaining navigation and preventing major instability. When a single meander is examined (Figure 1*C*), the hydraulics of flow, the sediment transport, and the potential for bank erosion are of concern. In addition, the sedimentologist is interested in the distribution of sediment within the bend, bed forms within the channel (Figure 1*D*), and sedimentary structures (Figure 1*E*), which also establish a component of roughness for the hydraulic engineer. Finally, the individual grains (Figure 1*F*) provide geologic information on the sediment sources, the nature of sediment loads, and the feasibility of dredging for gravel. There is an interaction of hydrology, hydraulics, geology, and geomorphology at all scales, which emphasizes the point that the fluvial system as a whole cannot be ignored, even though only a component of the system is to be studied.

In this review only the patterns or planforms of alluvial rivers are discussed, although it is apparent that the hydrologic and sediment yield characteristics of the drainage basin (Figure 1*A*), as well as its geologic history, cannot be ignored in the explanation of the pattern of any river

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reach. This article discusses the great variability and dynamic behavior of river patterns, considers the reasons for the diversity of patterns, and explains why an understanding of patterns is essential for mined-land reclamation, channel modification for flood control and navigation, the identification of areas of active tectonics, and the litigation of boundaries (Elliott 1984).

River patterns provide information on modern river characteristics and behavior. The civil engineer is involved with river patterns primarily because of the pattern changes that may occur at bridges and other sites of

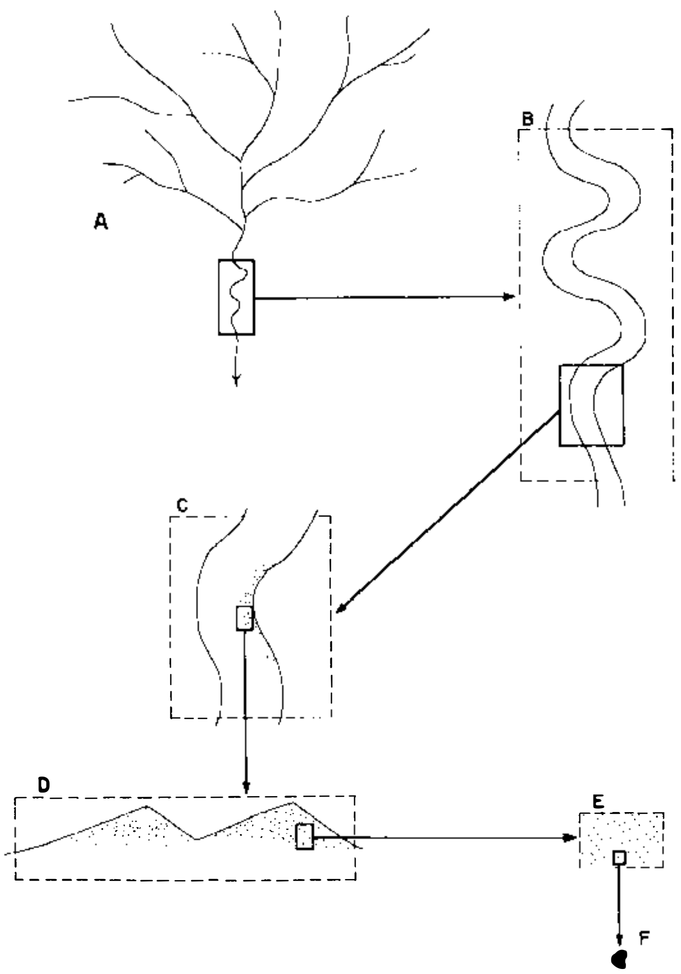

Figure 1 The fluvial system and its components.

construction (Shen et al 1981). Hence, not only the pattern and its characteristics are of interest, but also the dynamics of a particular pattern and its potential for change through time are of practical concern. In addition, an understanding of river patterns provides a basis for understanding ancient fluvial deposits and inferring environments of deposition (Galloway & Hobday 1983), and it also provides an empirical basis for determining past river morphology and paleohydrology (Schumm 1977, Gregory 1983).

RIVER PATTERNS

Depending on the nature of the materials through which a river flows, there are three major categories of stream channels: bedrock, semicontrolled, and alluvial. The bedrock channel is fixed in position, and it is stable over long periods of time. If the bedrock is weak, there can be lateral shift of the channel, but in most cases bedrock control means that the channel is stable. The semicontrolled channel refers to rivers that are controlled only locally by bedrock or resistant alluvium. The pattern may change where the channel encounters more resistant materials, and the channel either can be very stable at that particular locality or can shift away from the bedrock controls. The bed and banks of alluvial channels are composed of sediment transported by the stream. Therefore, the alluvial channel is susceptible to major pattern change and to significant shifts in channel position as the alluvium is eroded, transported, and deposited, and as the sediment load and water discharge change.

Geomorphic and engineering studies have demonstrated that there is a great range of alluvial river types; thus any attempt to classify them based upon pattern characteristics alonc is a frustrating task. For example, Brice et al (1978) have illustrated the range of channel patterns (Figure 2). They recognized three basic types of channels that are characterized by degrees of sinuosity (Figures 2*A*,*B*), braiding (Figures 2*C*,*D*), and anabranching (Figures 2*E*,*F*). Sinuosity is the ratio of channel length to valley length (L_c/L_v) or valley slope to channel slope (S_v/S_c). The range of sinuosity is from 1.0 (straight) to about 3.0. Some of the most sinuous channels appear to have one meander pattern superimposed on another (two-phase patterns; see Figure 2*B*, parts 6, 7).

There are also different degrees of braiding, expressed as the percentage of channel length that is divided by islands or bars (Figure 2*C*). There are two types of braided channels: island braided and bar braided (Figure 2*D*). Islands are relatively permanent features that are vegetated, whereas bars are bare sand-and-gravel deposits. Obviously, the stability of the channel is greatly enhanced when vegetation colonizes the bars and the channel becomes island braided.

Another pattern that has been identified is the anabranch channel (Figures 2*E*,*F*). Anabranching is the division of a river by islands whose width is greater than three times water width at average discharge (Brice et al 1978). The degree of anabranching is the percentage of reach length that is occupied by large islands.

Anastomosing channels are distinct from the anabranched channels, as they are multiple channel systems (Table 1) having major secondary channels that separate and rejoin the main channel to form a network (Schumm 1977, p. 155). The individual branches of anastomosing channels can be meandering, straight, or braided; therefore, they are not considered

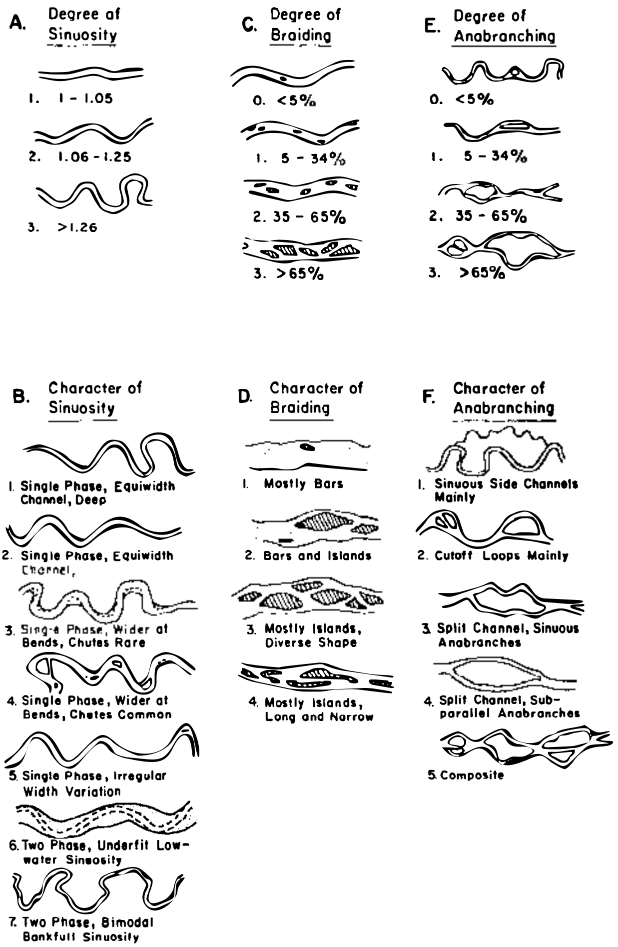

Figure 2 Types of channel patterns. (From Brice et al 1978.)

Table 1 Classification of stable alluvial channels (after Schumm 1977)

Type of channel	Bed load (% of total load)	Type of River: Single channel	Type of River: Multiple channel
Suspended load	<3	Suspended-load channel. Width-depth ratio <10; sinuosity >2.0; gradient relatively gentle.	Anastomosing system
Mixed load	3–11	Mixed-load channel. Width-depth ratio >10, <40; sinuosity <2.0, >1.3; gradient moderate. Can be braided.	Delta distributaries Alluvial plain distributaries
Bed load	>11	Bed-load channel. Width-depth ratio >40; sinuosity, <1.3; gradient relatively steep. Can be braided.	Alluvial fan distributaries

separately from the three basic patterns (meandering, braided, and straight) identified by Leopold & Wolman (1957).

The variety of channel patterns, as illustrated by Figure 2, is a result of the great range of hydrologic conditions, sediment characteristics, and geologic histories of the rivers of the world. Therefore, river patterns provide a key to other river characteristics, both morphologic and dynamic. For example, the pattern of the alluvial channels on the Great Plains of the western United States is related to channel shape. Low width-depth ratio (i.e. relatively narrow and deep) channels are relatively sinuous, whereas wide and shallow channels are relatively straight (Schumm 1977). Therefore, an indication of the morphology and relative stability of a river can be obtained by studying its pattern or planform.

CLASSIFICATION

For simplicity and convenience of discussion, the range of common channel patterns can be grouped into five basic patterns (Figure 3). These five patterns illustrate the overall range of channel patterns to be expected in nature, but of course they do not show the details that can be seen in Mollard's (1973) 17-pattern classification or the 14 patterns described by Schumm (1981). Nevertheless, Figure 3 is more meaningful than a purely descriptive classification of channels because it is based on cause-and-effect relations and illustrates the differences to be expected when the type of sediment load, flow velocity, and stream power differ among rivers. It also explains pattern differences along the same river (Schumm 1977).

A classification of alluvial channels should be based not only on channel pattern but also on the variables that influence channel morphology. This is particularly true if the classification is to provide information on channel stability. Numerous empirical relations demonstrate that channel dimensions are largely due to water discharge, whereas channel shape and pattern are related to the type and amount of sediment load moved through the channel (Table 1). Galloway & Hobday (1983) used this classification as a basis for identifying fluvial clastic depositional systems.

As indicated by Figure 3, when the channel pattern changes from 1 to 5, other morphologic aspects of the channel also change; that is, for a given discharge, both the gradient and the width-depth ratio increase. In addition, peak discharge, sediment size, and sediment load probably increase from pattern 1 to pattern 5. With such geomorphic and hydrologic

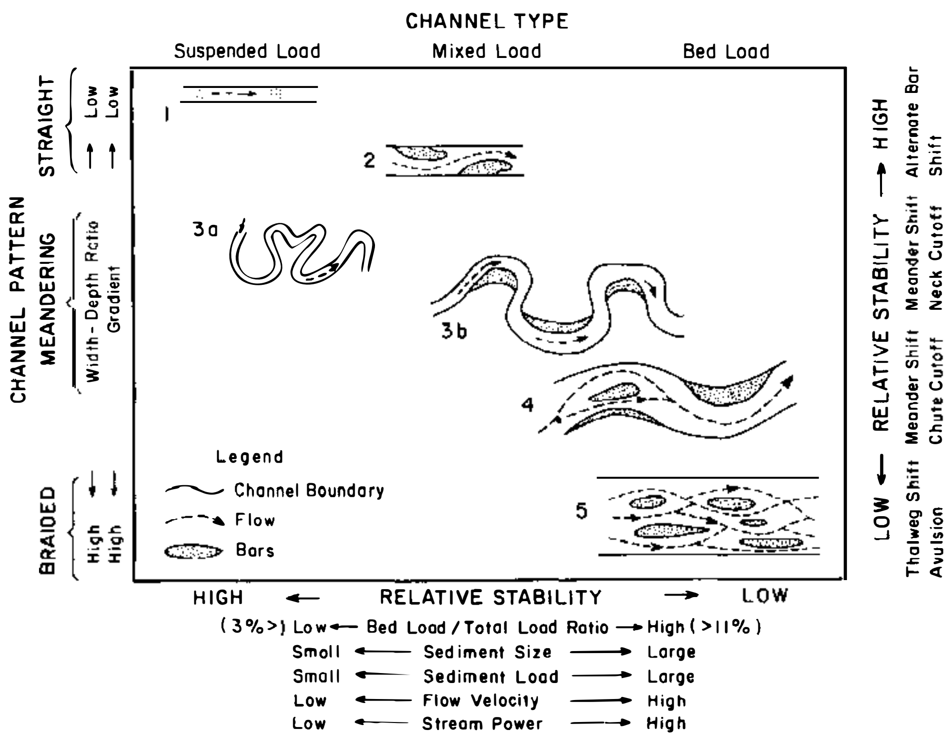

Figure 3 Channel classification based on pattern and type of sediment load, showing types of channels, their relative stability, and some associated variables. (After Schumm 1981.)

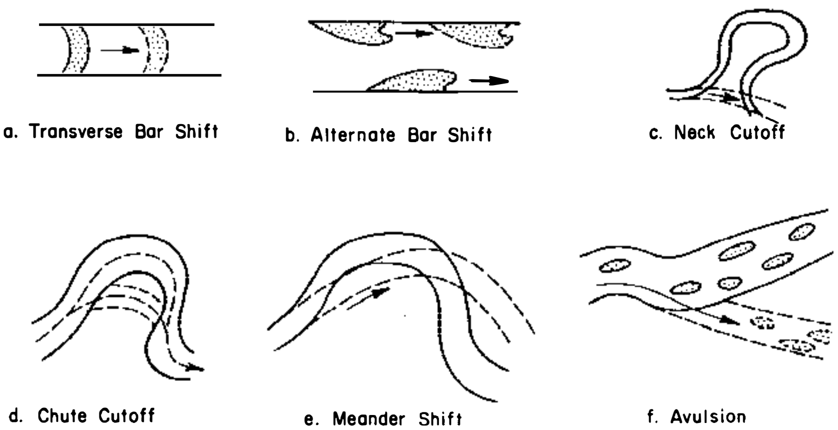

Figure 4 Some channel changes that can be expected along alluvial rivers. Dashed lines indicate future conditions.

changes, hydraulic differences can be expected, and flow velocity, tractive force, and stream power also increase from pattern 1 to 5. Therefore, the stability of a graded stream decreases from pattern 1 to pattern 5, with patterns 4 and 5 being the least stable.

A brief discussion of the five basic patterns is presented in what follows.

PATTERN 1 The suspended-load channel is straight with a relatively uniform width (Figure 3). It carries a very small load of sand and gravel. Gradients are low, and the channel is relatively narrow and deep (low width-depth ratio). The banks are relatively stable because of their high silt-clay content. Therefore, the channel is not characterized by serious bank erosion or channel shift. Bars may migrate through the channel (Figure 4*a*), but such changes should not create undue instability. Pattern 1 channels are rare, but they are stable unless the channel has been artificially straightened and therefore steepened. A naturally straight channel poses few problems, but an artificially straightened channel is subject to degradation and scour, bank erosion, and an increase of sinuosity (Schumm et al 1984).

PATTERN 2 The mixed-load straight channel has a sinuous thalweg (Figure 3). It is relatively stable and carries a small load of coarse sediment, which may move through the channel as alternate bars (Figure 4*b*). As these bars shift through the channel, banks are alternately exposed and protected by the alternate bars. Hence, at any one location the thalweg will shift with time. This means that the apparent deposition or fill at one side of the channel will be replaced by scour as an alternate bar migrates downstream.

Also, at any time, one side of the channel may be filling while the other is scouring.

PATTERN 3 This pattern is represented by two channel patterns, which are only two of a continuum of meandering patterns (Figure 2*B*). Pattern 3*a* shows a suspended-load channel that is very sinuous. It carries a small amount of coarse sediment. The channel width is roughly equal and the banks are stable, but meanders will tend to cut off at their necks (Figure 4*c*). Pattern 3*b* shows a less stable type of meandering stream. Mixed-load channels with high bed loads and banks containing low-cohesion sediment will be less stable than the suspended-load channels. The sediment load is large, and coarse sediment is a significant part of the total load. The channel is wider at bends, and point bars are large. Meander growth and shift (Figure 4*e*) and neck and chute cutoffs are also characteristic (Figure 4*c*). The channel, therefore, is relatively unstable, but the location of the cutoffs and the pattern of meander shift can be predicted. The shifting of the banks and thalweg follows a more or less regular pattern.

The shift of a meander (Figure 4*e*) creates major channel problems, as the flow alignment is drastically altered and bank erosion may become very serious. The rate of a meander shift will vary greatly depending on where in the continuum of meandering patterns the river fits.

PATTERN 4 This pattern represents a meander-braided transition (Figure 3). Sediment loads are large, and sand, gravel, and cobbles are a significant fraction of the sediment load. The channel width is variable but is relatively large compared with the depth (high width-depth ratio), and the gradient is steep. Chute cutoffs, thalweg and meander shift, and bank erosion are all typical of this pattern (Figures 4*d,e*). In addition to these problems, which are also characteristic of pattern 3, the development of bars and islands may modify flow alignments and change the location of bank erosion.

PATTERN 5 This bed-load channel is a typical bar-braided stream (Figure 3). The bars and thalweg shift within the unstable channel, and the sediment load and size are large. Braided streams are frequently located on alluvial plains and alluvial fans. Their steep gradients reflect a large bed load. Bank sediments are easily eroded, gravel bars and islands form and migrate through the channel, and avulsion (Figure 4*f*) may be common.

The other type of braided stream is the island-braided stream. This is a much more stable channel, and it would appear to the left of pattern 5 on Figure 3. The Mississippi River above the junction of the Missouri River is of this type. Island formation, erosion, and shift occur in these channels, but at a much slower rate than in a bar-braided channel. The anabranching or anastomosing channels may also be of this type (Figure 2*F*).

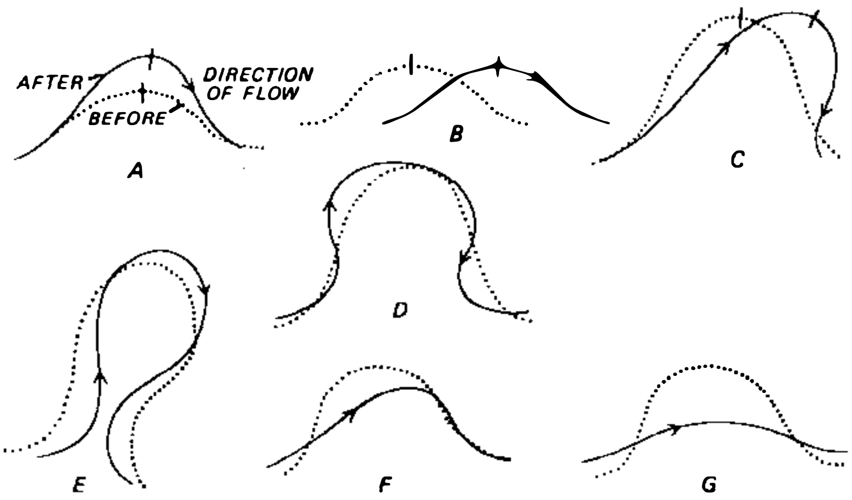

Figure 5 Patterns of meander growth and shift: (*a*) extension, (*b*) translation, (*c*) rotation, (*d*) conversion to a compound meander, (*e*) neck cutoff, (*f*, *g*) chute cutoffs. (From Brice 1974.)

PATTERN VARIABILITY

Historical studies of rivers reveal that rivers are shortened and steepened when meanders cut off, whereas rivers are lengthened and the gradient is decreased when meanders grow. Pattern change is to be expected whenever water and sediment flow through a stream channel. Figure 5 shows various modes of meander-loop behavior as observed by Brice (1974). All of these changes are associated with rivers that could be considered to be unstable. However, there are degrees of stability, and a stable river may have cutoffs and rapid meander shift and growth. From several points of view, this is an important consideration that engineers and geomorphologists should address.

Channel Stability

Because alluvial channels are composed of sediment transported by the stream, the bed and banks are erodible; therefore, no alluvial channel is actually stable in the sense that no change occurs. Rather there are degrees of stability depending upon the rate and type of channel change. For example, aggradation or degradation, caused by changes of baselevel or hydrologic conditions, will change the channel cross-section shape and dimensions. Although this is certainly an instability, the channel pattern may not be affected. On the other hand, local but dramatic changes of pattern such as cutoffs (Figures 4*c*,*d*) and meander shift (Figures 4*e*, 5) may be considered to be normal river behavior. Therefore, meander growth and shift alone is not a criterion of instability. However, a riparian landowner whose property is being destroyed by the meander change will not be convinced that such a river is relatively stable.

In straight channels, bar shift may greatly alter within-channel patterns and cause major problems with docking facilities and water intakes (Figures 4*a*,*b*), but the bank line of the channel may nevertheless be generally stable. Therefore, lateral change may be normal river behavior, but vertical change or change of channel size reflects true instability. This is an important distinction, because it is necessary to identify "stable" (graded, equilibrium, regime) channels in order to stratify river data for analysis. In order to develop relations between channel morphology, hydrology, and other characteristics, only data from stable channels should be used.

Thresholds

An important factor relating to pattern variability is the concept of geomorphic thresholds (Schumm 1977, 1979). Thresholds have been recognized in many fields, and perhaps the best known to geologists and engineers are the threshold velocities required to set in motion sediment particles of a given size. With a continuous increase in velocity, threshold velocities are encountered at which movement begins; conversely, with a progressive decrease in velocity, threshold velocities are encountered at which movement ceases. Particularly dramatic also are the changes in bed forms at threshold values of stream power.

In the examples cited, an external variable changes progressively, thereby triggering abrupt changes or failure within the affected system. The response of a system to an external influence occurs at what is referred to as the *extrinsic threshold*; that is, the threshold exists within the system, but it is not crossed and change does not occur without the influence of an external variable.

The other type of threshold is the *intrinsic threshold*, where changes occur without a change in an external variable. In dry regions, sediment storage progressively increases the slope of valley floors and alluvial fans until failure occurs by gullying. This is an intrinsic geomorphic threshold (Schumm 1979).

The variability of sinuosity and the range of pattern changes from meandering to braided provide excellent examples of the effects of both intrinsic and extrinsic threshold conditions. Fisk (1944) and Winkley (1970) showed that the sinuosity and length of the Mississippi River have varied dramatically through time. Its sinuosity decreased to a minimum when an avulsion or a series of cutoffs straightened its channel. Such changes may be related to major changes of sediment load or to an increase of peak discharge, but they may also be due to a progressive increase of sinuosity (with an accompanying reduction of channel gradient) to the point that aggradation and cutoffs or avulsion results. Such a situation appears to exist along the sinuous parts of the Rio Puerco arroyo, New Mexico, where the meander amplitude has increased in some reaches to the point that sediment is being deposited in the upstream limb of each meander and the bends are being cut off (Figure 9-3 of Schumm 1977). These changes reflect an intrinsic control by the channel pattern itself.

The work of Lane (1957) and Leopold & Wolman (1957) indicates that there is a gradient or discharge threshold above which rivers tend to be braided (Figures 6, 7). The experimental work reported by Schumm & Khan (1972) shows that for a given discharge, as valley-floor slope is progressively increased, a straight river becomes sinuous and then eventually braided at high values of stream power and sediment transport (Figure 8). Rivers that are situated close to the meandering-braided threshold should have a history characterized by transitions in morphology from braided to meandering and vice versa.

The suggestion made here is that if one can identify the natural range of patterns along a river, then within that range the most appropriate channel

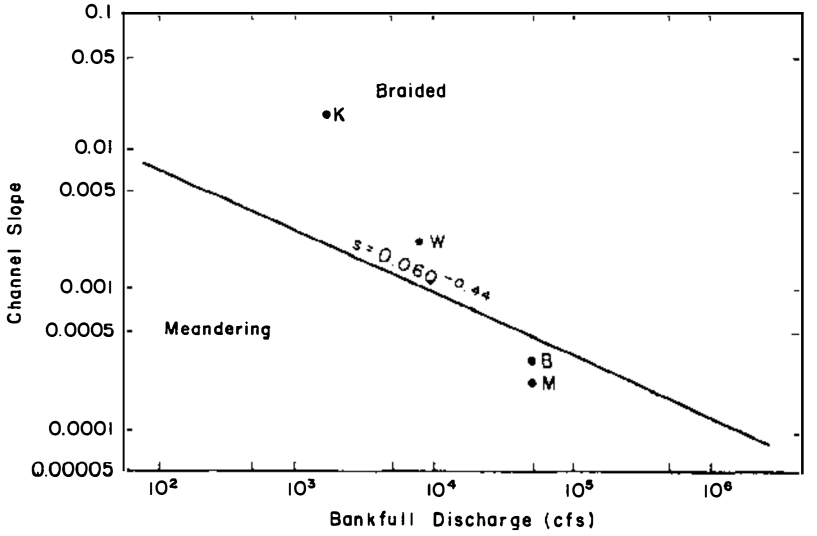

Figure 6 Leopold & Wolman's (1957) relation between channel patterns, channel gradient, and bankfull discharge. The letters B and M identify braided and meandering reaches of the Chippewa River, while the letters K and W refer to the Kowhai and Wairau rivers. (From Schumm & Beathard 1976.)

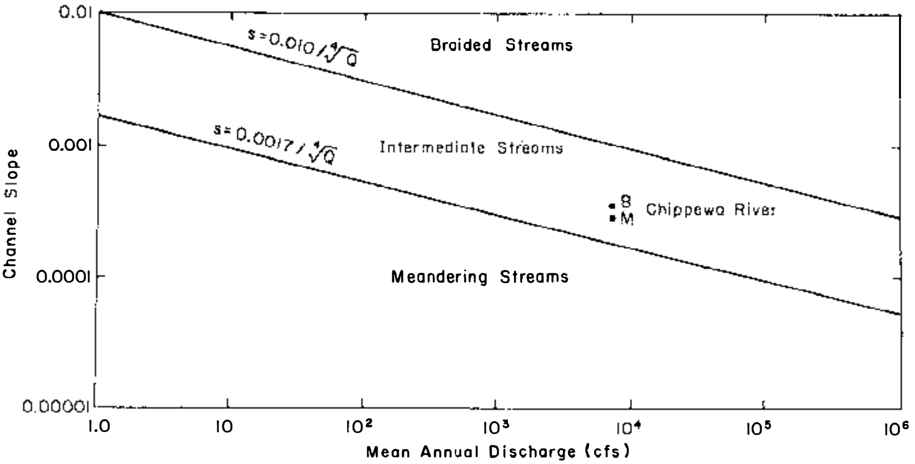

Figure 7 Lane's (1957) relation between channel patterns, channel gradient, and mean discharge. The letters B and M identify the positions of the braided and meandering reaches of the Chippewa River. (From Schumm & Beathard 1976.)

pattern and sinuosity probably can be identified. If so, the engineer can work with the river to produce its most efficient or most stable channel. Obviously a river can be forced into a straight configuration, just as it can also be made more sinuous, but there is a limit to the changes that can be induced; beyond this limit, the channel cannot function without a radical morphologic adjustment, as suggested by Figures 6, 7, and 8. The

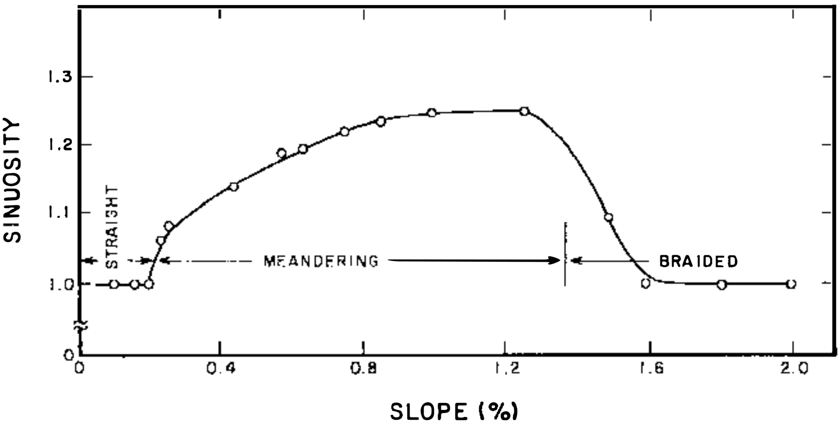

Figure 8 Relation between flume slope and sinuosity during experiments at constant water discharge. Sediment load, stream power, and velocity increase with flume slope, and a similar relation can be developed with these variables. (From Schumm & Khan 1972.)

identification of rivers that are near the pattern threshold would be useful, because a braided river near the threshold might be converted to a more stable single-thalweg stream. On the other hand, a meandering stream near the threshold should be identified in order that steps might be taken to prevent braiding due perhaps to sediment load changes as a result of changes of land use.

In most cases it is difficult to determine if a river is susceptible to the type of treatment discussed in the preceding sections. Perhaps the best qualitative technique for gauging river stability is to compare the morphology of numerous reaches and then determine whether or not therc has been a change in the position and morphology of the channel during the last few centuries. Another approach might be to identify the position of the river on the Leopold & Wolman (1957) or Lane (1957) gradient-discharge graphs (Figures 6 and 7). If a braided river plots among the meandering channels, or vice versa, it is unstable and a likely candidate for change.

An example is provided by the Chippewa River of Wisconsin (Schumm & Beathard 1976), a major tributary of the Mississippi River. Thc Chippewa rises in northern Wisconsin and flows 320 km to the Mississippi, entering it 120 km below Saint Paul. It is the second largest river in Wisconsin, with a drainage basin area of 24,600 km^2.

From its confluence with the Mississippi to the town of Durand, 26.5 km up the valley, the Chippewa is braided. The main channel is characteristically broad and shallow, and it contains shifting sand bars. The bankfull width, as measured from US Geological Survey topographic maps, is 333 m. The sinuosity of this reach is very low (1.06). However, in the 68-km reach upstream from Durand to Eau Claire, the Chippewa River abruptly changes to a meandering configuration, with a bankfull width of 194 m and a sinuosity of 1.49. The braided reach has a channel gradient of 0.00033, whereas the meandering reach has a gradient of 0.00028.

The relations described by Leopold & Wolman (1957) and Lane (1957) provide a means of evaluating the relative stability of the modern channel patterns of the Chippewa River. The bankfull discharge was plotted against channel slope in Figure 6 for both the braided and the meandering reaches of the Chippewa. The value used for the bankfull discharge is 1503 $m^3 s^{-1}$ (53,082 cfs), which is thc flood dischargc having a return period of 2.33 years. The braided reach plots higher than the meandering reach, but both are well within the meandering zone, as defined by Leopold & Wolman. This suggests that the braided reach is anomalous; that is, according to this relation the lower Chippewa would be expected to display a meandering pattern rather than a braided one. Even when the 25-year flood of 98,416 cfs is used, the braided reach still plots within the meandering region of Figure 6.

When the Chippewa data are plotted on Lane's graph (Figure 7), the same relation exists. The Chippewa falls in the intermediate region, but within the range of scatter about the regression line for meandering streams. Again the braided reach is seen to be anomalous because it should plot much closer to or above the braided-stream regression line. The position of the braided reach, as plotted in both figures, indicates that this reach should be meandering, and historical studies reveal that it had a sinuosity of about 1.3 in the late eighteenth century, before an avulsion changed the position and pattern of the channel.

It appears that the lower Chippewa has not been able to adjust as yet to its new position and steeper gradient, and the resulting bed and bank erosion has supplied large amounts of sediment to the Mississippi. The normal configuration of the lower Chippewa is sinuous, and if it could be induced to assume such a pattern, the high sediment delivery from the Chippewa could be controlled. An appropriate means of channel stabilization and sediment load reduction in this case is the development of a sinuous channel.

More detailed studies of the Chippewa River basin since the above suggestions were made (Schumm & Beathard 1976) indicate that upstream sediment production must be controlled, especially where the upper Chippewa River is cutting into the Pleistocene outwash terraces. If the contribution of sediment from these sources were reduced, the lower Chippewa could resume its sinuous course.

An indication that the pattern conversion of the Chippewa could be successful if the upstream sediment sources were controlled is provided by the Rangitata River of New Zealand (Schumm 1979). The Rangitata is the southernmost of the major rivers that traverse the Canterbury Plain of the South Island. It leaves the mountains through a bedrock gorge. Above the gorge, the valley of the Rangitata is braided, and it appears that the Rangitata should be a braided stream below the gorge, as are all the other rivers crossing the Canterbury Plain. However, below the gorge, the Rangitata is meandering. A few miles farther downstream, the river cuts into high Pleistocene outwash terraces, and it abruptly converts from a meandering to a braided stream. The braided pattern then persists to the sea. If the Rangitata could be isolated from the gravel terraces, it probably could be converted to a single-thalweg sinuous channel, because the Rangitata is a river near the pattern threshold.

Other New Zealand rivers are also near the pattern threshold, and therefore they are susceptible to pattern change. In fact, New Zealand engineers are attempting to accomplish this pattern change on these rivers in order to produce "single-thread" channels that will reduce flood damage and be less likely to acquire large sediment loads from their banks and terraces. For example, the Wairau River, a major braided stream, has been converted from its uncontrolled braided mode to that of a slightly sinuous, single-thalweg channel that is relatively more stable (Pascoe 1976). The increase in sinuosity is only from 1.0 to 1.05, and this was accomplished by the construction of curved training banks. In Figure 6 the Wairau River plots close to the threshold line, and with the reduction of sediment load produced by bank stabilization it appears that the pattern threshold can be crossed successfully.

The Kowhai River of New Zealand is being modified in the same manner as the Wairau (Thomson & MacArthur 1969). Whereas much of the sediment load in the Wairau River is derived from bank and terrace erosion, which can be controlled, high sediment loads are delivered to the Kowhai River directly from steep and unstable mountain slopes. In Figure 6 the Kowhai River plots well above the threshold line, and without a major reduction in upstream sediment, it may be difficult to maintain a single-thalweg channel at this location.

The variability of the Rangitata River pattern indicates that conversions from braided to single-thalweg channels should be possible for the Chippewa and Wairau rivers. However, not all braided rivers can be so readily modified, as such a change depends on their position with regard to the pattern thresholds in Figures 6, 7, and 8.

RIVER METAMORPHOSIS

In addition to the expectable alterations of channel patterns that have been already discussed, major changes of discharge, sediment type, and sediment load can also occur as a result of either man's activities or past climatic changes, and these changes may drastically and totally alter river morphology (Hickin 1983). This transformation has been referred to as river metamorphosis (Schumm 1969, 1977, pp. 159–71). There are six possibilities of metamorphosis as each of the three channel types change to the other two types (that is, a straight channel may become sinuous or braided, a meandering channel may become straight or braided, and a braided channel may become straight or meandering). In each case, the change in the controlling variables differs and the river response is dramatically different.

The South Platte and Arkansas rivers in eastern Colorado are excellent examples of rivers that have undergone dramatic historic changes so extensive that they can be termed a metamorphosis (Schumm 1969, Nadler & Schumm 1981). Measurements and reports by explorers in the early part of the nineteenth century show that both rivers were wide (up to 1.5 km), shallow braided streams. The rivers today exhibit very different channel characteristics (Figure 9).

A

B

Figure 9 *A* Aerial photograph of the South Platte River near Julesburg, Colorado, in July 1977. The channel in the nineteenth century occupied the area now supporting cottonwood treegrowth. *B* Aerial photograph of the Arkansas River near Bent's Old Fort (east of La Junta, Colorado) in June 1977. The channel in the nineteenth century was braided.

The South Platte and Arkansas rivers originate in the mountains of central Colorado and flow eastward on valley alluvium of Pleistocene and Holocene age. Both rivers experienced large seasonal fluctuations in discharge due to snow melt, and they decreased in volume as they crossed the semiarid plain, owing to seepage and evaporation losses. Agriculture began in both basins immediately following the first gold rush to Colorado in 1858. By 1895 there were 20 major irrigation diversions on the Arkansas River between Pueblo and the Kansas border, and similar diversions were occurring on the South Platte River.

The hydrologic nature and type of floodplain vegetation of both rivers changed appreciably. As water tables rose, stream flows became perennial, flood peaks decreased, and floodplains were able to sustain denser vegetation. According to early descriptions, woody vegetation was sparse along the rivers. However, the floodplains are now occupied by cottonwoods, and it is apparent that there is more vegetation along the rivers today. This increase in vegetation probably reflects a higher water table, a result of increased irrigation activity. In addition, salt cedars invaded the Arkansas River Valley. These hydrologic and vegetative changes produced major morphologic changes along both rivers.

Figure 10 depicts the manner of the South Platte River metamorphosis, which is characterized by stream narrowing and floodplain construction by vertical accretion. The thalweg did not aggrade, but a floodplain was formed adjacent to the thalweg by island construction (Figure 10*B*) and channel filling. When flood peak decreased, vegetation quickly colonized areas below the mean high water level of the channel (Figure 10*C*). In this way, newly formed bars were stabilized by vegetation and became islands. The channels, which surrounded these islands, no longer shifted, because vegetation had fixed the position of the banks and islands. Channel abandonment and island attachment to the floodplain followed (Figure 10*D*).

The former braided pattern can be seen on aerial photographs (Figure 9*A*). The ages of the largest cottonwood trees on the floodplain indicate that the islands were being colonized by woody vegetation at least 60 years ago. This suggests that thc metamorphosis began after 1900.

Figure 11 depicts the manner of river metamorphosis at Bent's Old Fort on the Arkansas River. The important characteristics of this model are point-bar stabilization and meander-loop enlargement. Perennial flows, flood-peak reduction, and especially dense salt-cedar growth were major factors leading to the metamorphosis. Salt cedars colonized the channel below mean high water level and stabilized the point bars during the drought of the 1930s. This process allowed meander loops to enlarge as channel width decreased.

The development of the meandering pattern at this reach of the Arkansas

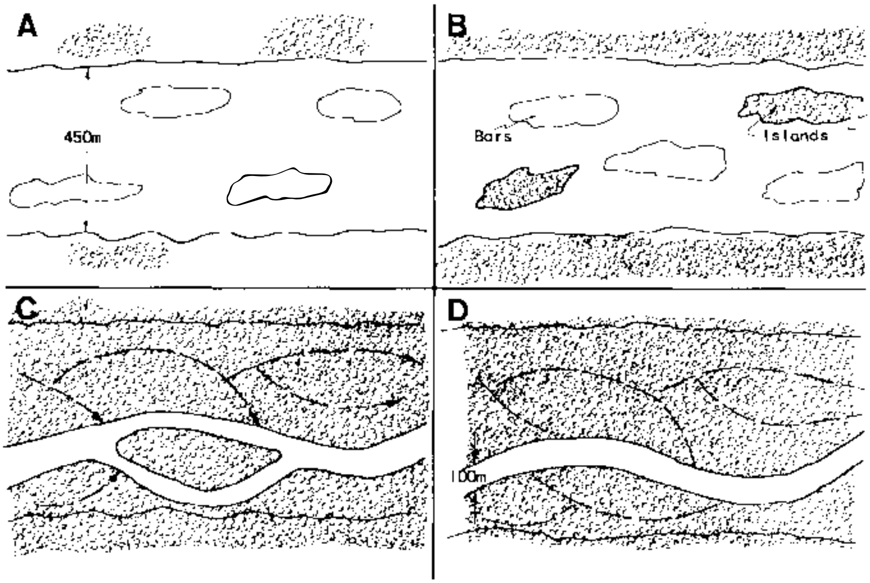

Figure 10 Model of South Platte River metamorphosis. *A* Early 1800s: discharge is intermittent, bars are transient. *B* Late 1800s: discharge is perennial, vegetation is thicker on floodplain and islands. *C* Early 1900s: droughts allow vegetation to establish itself below mean annual high water level, bars become islands, single thalweg is dominant. *D* Modern channel: islands attached to floodplain, braided patterns on floodplain are vestiges of historic channels. (From Nadler & Schumm 1981.)

was the result of an influx of fine sediment (suspended load) from a tributary (Timpas Creek) that incised deeply into the valley fill. The sediment influx converted the Arkansas River in this reach from a braided bed-load channel to a meandering mixed-load channel (Figure 3). Farther downstream, beyond the effects of Timpas Creek, the channel remained straight.

CONTROLS

Alluvial rivers arc open channels that clearly are fashioned by the water conveyed by the channel. Therefore, an explanation of channel patterns should be largely hydrologic. However, all types of channels are formed at similar average discharges in the field and in the laboratory by changes of valley slope and sediment supply. The bankfull, average, or mean-annual discharge determines to a large extent channel dimensions such as width, depth, meander amplitude, and meander wavelength, but the quantity of water moving through a channel does not affect the basic pattern. Neverthcless, under otherwise similar conditions a river that has flashy

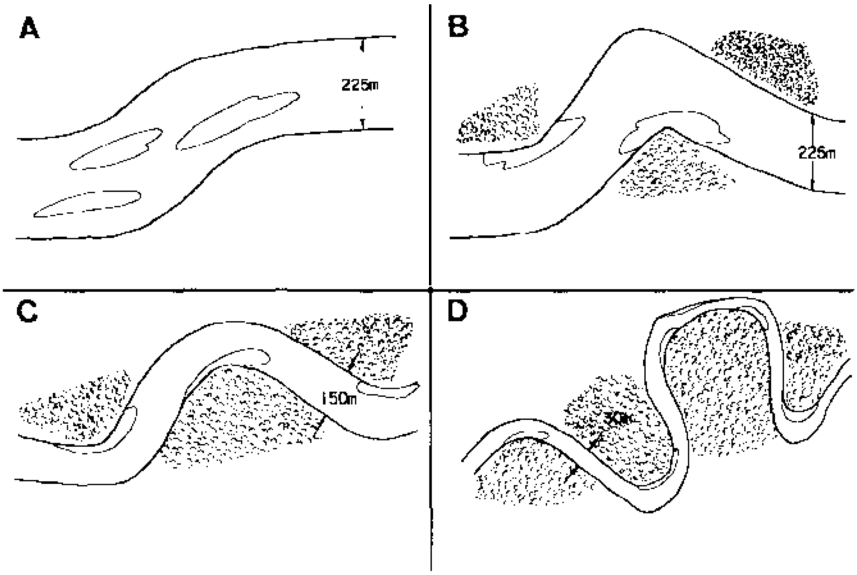

Figure 11 Model of Arkansas River metamorphosis at Bent's Old Fort. *A* Pre-1900 channel. *B* 1926 channel. *C* Channel between 1926 and 1953. *D* Modern channel. (From Nadler & Schumm 1981.)

discharge (high peak discharge to mean discharge ratio) can be braided, in contrast to the channel with a more regular or uniform discharge. Therefore, under some conditions the hydrologic character of the fluvial system is significant (Schumm 1977).

The type of sediment load transported by the river also plays a role (Table 1, Figure 3). Channels that transport relatively low sand-and-gravel (bed load) loads are more likely to be sinuous, and they are not braided. Studies of Great Plains rivers show that channels with a low ratio of bed load to suspended load are relatively narrow, deep, and sinuous, whereas when the ratio is high, the channels are relatively wide, shallow, and straight (Schumm 1977). These differences can occur without a change in the size of the sediment on the channel bed. Therefore, the suggestion that braided rivers are a result of coarse sediment alone is incorrect.

Part of the difficulty in explaining river patterns is that both convergence and divergence are significant. Convergence means that similar landforms (river patterns) can be developed by different causes or processes, and divergence means that different landforms can be developed by similar causes or processes. The fact that a braided river can be caused by high flood peaks, by high bed-load transport, and by aggradation is an example of convergence (Schumm 1984). With these complications, the explanation for the variety of river patterns must necessarily be elusive.

Another problem is that although much has been written concerning river patterns, the emphasis has been upon meandering. Even Albert Einstein (1926) contributed to this literature. The repetitive patterns of curves, and the significant deviation from a straight line, are puzzling. If nature is efficient, why does a meandering river take a long and inefficient course to its destination? The jet stream meanders, the Gulf Stream meanders, and streams on ice and on glass plates meander (Gorycki 1973). The conclusion is that the meandering tendency is inherent in fluid. Hydraulic engineers show that fluid flow patterns develop instability as a result of bank and bed friction and internal shear and turbulence within the flow (Callander 1978); this instability then leads to the formation of alternate bars (Figure 3*b*). The helicoidal flow in bends has been cited as a cause of meanders (Ikeda 1980). However, in other channels these secondary flow patterns do not cause meandering. Experimental studies reveal that major flow deflection caused by the introduction of water into the head of a flume at an angle may produce excellent meander patterns, whereas at the same discharge but under lower energy conditions meanders do not form (Schumm & Khan 1972). These experiments suggest that there is a limited range of hydraulic conditions at which meandering occurs. Therefore, part of the difficulty in explaining meandering is that the full range of river patterns is not normally considered; that is, the question "Why do rivers meander?" can be supplemented by the question "Why are some rivers straight?"

In Schumm & Khan's (1972) experimental study the full range of channel patterns developed at the same discharge (Figure 8). At low slopes and with low sediment loads (i.e. low velocity and low stream power), the experimental channels remained straight, even when the water was introduced into the flume at an angle, which should have forced the channel to meander. It appears that although secondary flow patterns exist under these low-energy conditions, they are not powerful enough to move sediment across the channel to form alternate bars, and thus bank attack is minimal. As the slope of the surface on which the experimental channel flowed was increased, velocity, stream power, and sediment transport all increased. Bank erosion became important, and a sinuous pattern with alternate bars developed. At the highest slopes, with high energy and high sediment load, the channel became braided. The momentum of the flow in the downstream direction prevented the development of alternate bars by cross-channel flow, and increased bank erosion also prevented the formation of alternate-bar patterns.

It is clear that there are ranges of energy or stream power, for a given discharge and for a given size of sediment, at which different river patterns develop (Chang 1979). The explanation for these patterns, therefore, seems to be purely hydraulic. However, flow conditions depend on hydrologic conditions, and indeed it is well known that stream gradient depends on water discharge and sediment load. Therefore, the pattern at a given location depends upon hydrology and sediment supply from the upstream watershed. In addition, any changes of valley-floor slope by active tectonics can significantly affect channel patterns (Burnett & Schumm 1983).

It is apparent that there are multiple explanations for river patterns, and much depends upon local circumstances that influence sediment load and energy. All explanations of channel patterns are correct under certain circumstances. Certain hydraulic conditions and bed instability cause meanders, but these hydraulic conditions may be dependent upon valley-floor slope or upon watershed conditions that determine the amount of water and the quantity and type of sediment delivered to a river reach.

APPLICATIONS

Alluvial channels are dynamic and subject to change, but these changes are of different types and occur at highly variable rates. Therefore, rivers with different patterns behave differently, and their other morphologic characteristics (e.g. channel shape, gradient) are different. Hence, pattern identification can be the first step toward evaluating river stability and identifying potential hazards.

River patterns may be stable at one extreme or in the process of total change as a part of metamorphosis at the other. The change of river planform may be natural or in response to man-induced changes of hydrologic regimen.

The mode of pattern change can be very important when property or political boundaries follow the bank line or thalweg of a river. If a river changes position slowly by bank erosion and lateral accretion, as with meander growth or shift (Figure 4*e*), then the boundary shifts with the river. However, if the channel changes position rapidly by avulsion and meander cutoff (Figures 4*c*,*f*), then the boundary remains fixed. Clearly, an understanding of river patterns and river behavior is an important aspect of boundary law and forensic geomorphology.

The suggestion made here is that if one can identify the range of patterns along a river, then within that range the most appropriate channel pattern and sinuosity can probably be identified. If so, the engineer can work with the river to produce its most efficient or most stable channel. Obviously, a river can be forced into a straight configuration or can be made more sinuous, but there is a limit to the changes that can be induced, beyond which the channel cannot function without a radical morphologic adjustment (as suggested by Figures 3, 5, 6, and 7).

A clear understanding of the relation of channel pattern to river stability is required in the design of channels for mined-land reclamation and in the planning for channel modification. If a designed channel is too sinuous, it will not transport the water and sediment delivered to it and will aggrade. If the designed channel is too straight, it will degrade or erode its banks. The pattern must be adjusted to the gradient required by the discharge and sediment load. The practice of channelization, the replacement of a sinuous channel with a straight one to reduce flood hazards, has in many cases resulted in channel incision and long-term instability (Schumm et al 1984). When the channel gradient is steepened significantly by straightening, the channel will deepen, widen, and eventually evolve to a new condition of stability; however, this may take many years and cause major problems of bank erosion and high sediment transport. Brice (1983) has demonstrated that the response can be large or small depending upon the extent of the pattern alteration and the nature of the channel. It is now recognized that a major pattern alteration can create problems worse than those the alteration was designed to solve, and engineers are now considering alternatives to excessive channelization that will produce a straight channel (Schumm et al 1984, Bhowmik 1981). Again, the success of any design will depend on channel pattern (Figure 3), which in turn is dependent upon hydrology, sediment type, and valley morphology (Richards 1982).

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