Stability of Stream Channel Patterns

H. W. Shen, S. A. Schumm, and D. O. Doehring, Colorado State University, Fort Collins

Many stream channel classifications have been developed based on stability considerations. Previous classifications can be categorized grossly as based on characteristics of straight, meandering, and braided planimetric patterns. A classification scheme is presented that divides stream patterns into five types: (a) straight, (b) straight with sinuous thalweg, (c) meandering, (d) meandering with the development of midchannel bars, and (e) braided. In the proposed scheme, the observed relative stability of the various patterns decreases from pattern 1 to pattern 5. Observed stability can be explained by theoretical stability analysis, but basic theoretical rules must be applied with caution because of the complexity of stream behavior.

When highway engineers plan a bridge across a stream, a major problem is to assess the stability of that stream. Because all streams are undergoing continuous changes, it is valuable for the transportation engineer to know the relative stability of different stream channel patterns in order to assess the stability of the bridge crossing. A stable stream is defined as one whose bed and banks are spatially fixed. For transportation engineers, this means that a stable cross section can be treated as a rigid boundary for design purposes. The purpose of this paper is to discuss the relative stability of different channel patterns based on current knowledge.

Stream behavior is an extremely complex problem, and it is difficult to formulate rules that can be universally applied. The general stability relations described here should, therefore, be applied with caution.

Geomorphologists use field evidence to trace the history of channel developments, since they are particularly interested in long-term effects. Engineers, on the other hand, use a theoretical base to investigate what would happen to streams under certain conditions of change. From conceptual models, they predict short-term (100-year) effects. Geomorphologists usually try to determine why a stream changes from the way it changes (why from how). Engineers try to predict how a stream will change from theoretical considerations (how from why). In this paper, we first discuss stream stability from the observational, or geomorphologist's, viewpoint and then discuss stability analysis of stream channel patterns from the engineer's viewpoint.

STREAM CHANNEL PATTERNS

Stream channel patterns are the cumulative results of a combination of climatic, geologic, topographic, hydrologic, and human disturbance factors. Basically, there are only three types of patterns: straight, meandering, and braided.

1. A straight channel has straight and parallel banks, and flow within the channel is mainly in the longitudinal direction.
2. A meandering channel [see Figure 1 (1)] consists of many bends separated by short, straight reaches, or "crossings", between two bends. The secondary currents in each stream bend are significant enough to cause modifications of the bend. Usually, there are deep scour holes at the outer channel bend and the water near the inside bend is rather shallow. The channel bends may or may not be symmetrical.
3. A braided stream [see Figure 2 (1)] usually has a large width-to-depth ratio, and there are always many small channels that have developed within the main channel.

Both meandering and braided channels can develop into anabranched channels, which are subsidiary channels that diverge from a stream and eventually rejoin it.

Sometimes, the distinctions among these three basic channel patterns are not clear. For example, one reach of a stream can exhibit both meandering and braided patterns, or a stream may consist of straight, meandering, and braided reaches at different locations. A

Figure 1. Meandering reach of Clark's Fork of the Yellowstone River showing two recently formed oxbow lakes produced by meander cutoff.

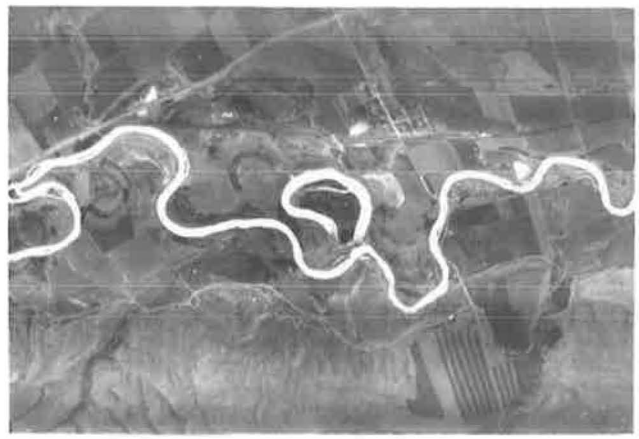


Figure 2. Braided reach of the Yellowstone River.

stream reach may appear to be braided at low flow stages, and yet its overbank flow may be contained within two relatively straight banks. In both cases the stream appears to be straight at flood stage. A few rivers are straight because they have stable banks and gentle gradients adjusted to the water and sediment load supplied—for example, the lower Mississippi River on the delta below New Orleans.

The basic causes that initiate meandering are still not entirely clear, but they are probably numerous. Shen (2) and Callander (3) have summarized these causes as follows:

1. Development of secondary currents as a result of (a) dynamic stability of flow (3), (b) rotation of the earth (4, 5), and (c) differences in roughness between bed and bank (6);
2. Disparity between hydrologic and topographic conditions [according to Schumm and Khan (7), if the valley floor on which the river flows is, as a result of past hydrologic conditions, steeper than necessary for the modern water and sediment load, meandering occurs as a natural way for flow to seek a lesser slope; they also found that the addition of 3 percent kaolinite in suspension would enhance and cause the development of a meandering channel];
3. A lateral disturbance, which can be caused by such factors as a tributary or a difference in the soil between the left and right banks (8); and
4. "Erosion-deposition processes tending toward the most stable form in which the variability of certain essential properties is minimized" (9).

According to Lane (10), there are two primary causes of braided streams:

1. The stream may be supplied with more sediment than it can carry (overloaded), and part of that sediment may be deposited.
2. Steep slopes and high sediment loads and velocity can cause a wide, shallow channel in which bars and islands readily form (11).

Shen and Vedula (12) have presented an explanation of braided channels based on consideration of bank erosion and sediment transport. The basic principle is that in a narrow stream the entire bed can act as a unit to aggrade or degrade according to the difference between the sediment supply and the capability of the flow to transport it. However, when a stream cross section is too wide (because of excess bank erosion during high flow or weak bank resistance or both), the entire channel cross section cannot act as a single unit, and thus part of the wide channel may be covered by numerous small channels and result in a braided stream.

PREVIOUS STUDIES OF CHANNEL PATTERNS AND OTHER PROPERTIES

Channel Patterns

Various investigators have classified channel patterns based on direct observation. Table 1 gives a brief summary of these studies and the specific items investigated.

Kellerhals and others (19) described channel patterns in a different manner, dividing them according to three main headings: (a) a type that consists of straight, sinuous, irregular, irregular meander, regular meander, and tortuous meander; (b) channel islands, subdivided into occasional, frequent, split, and braided islands; and (c) channel bars, subdivided into none, side bar, point bar, channel junction bar, midchannel bar, diamond bar, diagonal bar, and sand wave. Table 1 gives our arbitrary interpretation of their classification, according to the normal divisions of straight, meandering, transitional, and braided (Kellerhals and others actually classified the braided pattern as a subset of straight or meandering patterns).

Brice and others (20) suggested a new criterion by which a channel is classified into five categories: (a) equiwidth, point-bar stream; (b) wide-bend, point-bar stream; (c) braided, point-bar stream; (d) fully braided stream; and (e) anabranched stream (Table 1).

Other Channel Properties

In 1863, Ferguson noticed that meander wavelength bears a relationship to channel width. Since then, various channel properties, including width, depth, meander wavelength and amplitude, sinuosity, bend characteristics, and braiding, have been investigated by many researchers by using conventional statistical

Table 1. Classification of channel patterns by various authors and some specific factors investigated.

	Channel Pattern			
Author	Straight	Meandering	Transitional	Braided
Lane (10)		X		Caused by (a) steep slope and (b) aggradation
Leopold and Wolman (13)	X	X		X
Schumm (14)	X	Regular, irregular, tortuous	X	Straight (island)
Popov (15)	Alternate bars			Midstream bars
Culbertson and others (16)		Point bars (a) of uniform width and (b) wider at bends		Point bars, islands
Chitale (17)[a]	X	Regular, irregular, simple, compound	X	X
Garg (18)		Uniform width, point bar		Point bar, bar or island
Kellerhals and others (19)	X	Irregular, regular, tortuous	Sinuous, irregular	
Brice and others (20)[b]	Equiwidth, wide-bend	Equiwidth, wide-bend, braided	Equiwidth, wide-bend	Wide bend, with (a) braided and (b) fully braided

[a] Chitale (17) defines two major categories: single-channel (straight, meandering, and transitional) and multiple-channel (braided).
[b] Brice and others (20) also define another type of channel: anabranched.

Table 2. Channel properties investigated by various authors.

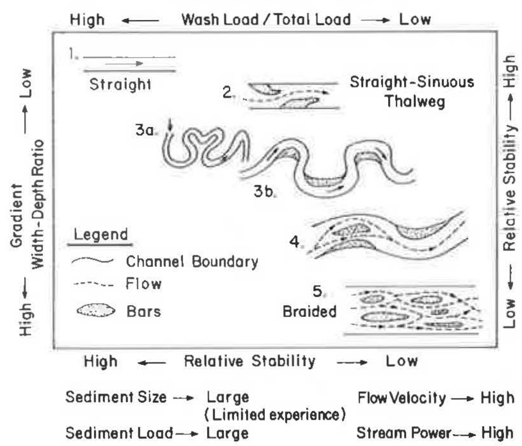
Property	Author	Property	Author
Channel width and depth	Schumm (14, 21-23) Leopold and Maddock (24) Bray (25)	Sinuosity	Langbein and Leopold (9) Schumm (14, 21-23) Chitale (17) Bray (25) Inglis (27) Ackers and Charlton (30) Ferguson (31, 32) Daniel (33)
Wavelength and amplitude of meander	Dury (11) Leopold and Wolman (13) Schumm (14, 21-23) Jefferson (26) Inglis (27) Ferguson[a] Carlston (28) Speight (29) Ackers and Charlton (30) Ferguson (31, 32)	Bend characteristics	Leopold and Wolman (13)
		Braiding	Inglis (27) Brice (34) Howard and others (35) Krumbein and Orme (36)

[a]See Inglis (27).

Table 3. Classification stability of alluvial channels.

Pattern No.	Channel Pattern	Channel Stability
1	Straight; equiwidth, with straight thalweg	Stable
2	Straight, with sinuous thalweg	Generally stable, but thalweg shift and bar migration occur
3a	Meander; equiwidth with small point bars	Stable; chute cutoffs can occur
3b	Meander; wide bends, with large point bars and cut bank outside of meander	Relatively stable because of chute and neck cutoffs and shift and growth of meander
4	Meander-braid transition; large point bars with frequent chute cutoffs	Unstable
5	Braided, with multiple thalwegs that shift and many shifting bars and islands	Unstable

Figure 3. Classification and stability of alluvial channels and variables that affect channel patterns.



methods. Some have attempted to establish empirical selection between channel morphology and hydrology. The channel characteristics studied are given in Table 2.

CLASSIFICATION AND RELATIVE STABILITY OF ALLUVIAL CHANNELS

There are three major categories of stream channels: (a) bedrock, (b) alluvial, and (c) partially controlled. The bedrock channel is fixed in bedrock and is stable over the time span that concerns engineers. The alluvial channel is formed in sediment that has been transported by the stream, and therefore channel morphology and the alluvium reflect the type of sediment load transported. It is this group of channels that is classified in this paper. The third group requires brief mention because it is predominantly an alluvial channel that encounters bedrock and older resistant alluvium in its course and is, at least locally, influenced by this encounter. For example, the channel may be locally fixed in position by resistant materials, which may significantly alter the local meander pattern.

Classification

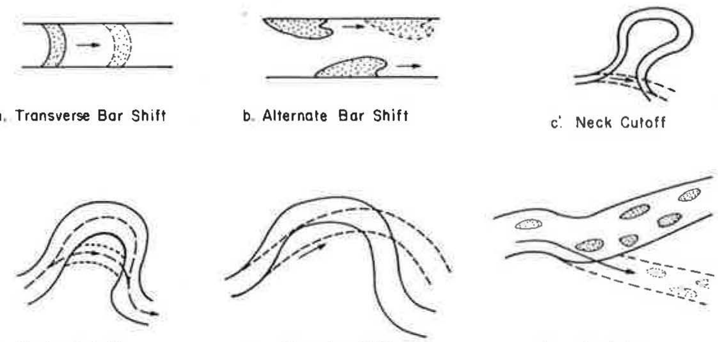
We propose a tentative classification of the patterns of alluvial stream channels that relates to the stability of the patterns. The five patterns given in Table 3 have been selected as including the types of streams common in the United States. Obviously, some channel types span a great range of patterns; for example, pattern 3 channels can have a wide range of sinuosity.

In order to provide information on the stability of alluvial channels, classification of such channels should be based not only on channel pattern but also on the variables that affect channel morphology. Many empirical relations demonstrate that channel dimensions are attributable mostly to water discharge, whereas channel shape and pattern are also related to the type and amount of sediment load that moves through the channel. Geomorphic history is also important because it can determine the slope of the valley floor or alluvial plain on which the stream flows. For example, some very straight rivers, such as the Illinois River and the Mississippi River below New Orleans, are flowing on alluvial surfaces that are relatively flat; on the other hand, the most sinuous reach of the Mississippi (Greenville Bends) is localized on the steepest part of the valley floor below the confluence of the Arkansas River (23).

Stream channels form a continuum, from straight to meandering to braided, that can be illustrated by the five patterns shown in Figure 3. These patterns illustrate the range to be expected in nature. The variables that influence pattern characteristics and the relative stability of the patterns are also indicated in Figure 3.

Since this classification is designed to indicate the relative stability of a river, it should be especially useful to transportation engineers. For instance,

Figure 4. Typical types of channel changes.



although a pattern 1 straight channel may occur only rarely, when it is found it means that the banks are relatively stable and will erode slowly. In the case of a pattern 2 straight channel, the outer banks are relatively stable but the thalweg between them can shift. In designing a pier, the shifting of flow within the channel must be accounted for.

Channel patterns 3 and 4 are meandering channels in which the outer banks are not straight and parallel and may shift frequently. In this case, the shifting of the thalweg and the banks follows a more or less regular pattern. Most rivers meander, and we show the continuum of meandering channels by only three patterns: patterns 3a, 3b, and 4.

Some investigators have divided braided channels into several groups. For instance, Brice (34) has subdivided braided channels into those with submerged bars and those with islands. The changes of the thalweg within the cross section of a braided channel cannot be predicted, and bank cutting is usually relatively rapid. Submergence or emergence of an island is very much a function of the frequency of flow. Since all of these factors cause similar problems for highway engineers in designing bridges across streams, the braided category is not subdivided here.

The basis of classification is the type of sediment load transported by the channel. The absolute quantity of water and sediment that moves through the channel can be less important than the type of sediment load. For example, in nature there are large and small channels of each of the types shown in Figure 3, and in each case the large channel forms in response to a larger water discharge but the pattern itself and the shape of the channel depend on the proportion of the total sediment load (silt, clay, sand, and gravel) that is wash load (silt and clay) or bed-material load (sand and gravel) (23).

Observed Stability Tendencies

The following relations were established from investigations of the pattern, dimensions, and shape of sand-bed streams of the Great Plains of the western United States. A summary of the results can be found elsewhere (23).

When bed-material load is small, wash load is a large part of the total load and the channel is narrow and deep (with a width-depth ratio of <10) and, depending on valley slope, the channel can be straight (pattern 1) or very sinuous (pattern 3a). When the percentage of bed-material load is intermediate, the width-depth ratio is less and sinuosity is between about 2.0 and 1.3 (pattern 3b). This sandy channel may also be relatively straight, but the thalweg or the deepest part of the straight channel may be sinuous (pattern 2).

As the proportion of bed-material load increases, width-depth ratio increases (to >40) and sinuosity is low. There is a tendency for multiple thalwegs to form (pattern 4). The greatest development of channels and bars occurs in the braided channel (pattern 5) when the ratio of bed-material load to total load is high.

As Figure 3 shows, not only does the channel pattern change from pattern 1 to pattern 5 but other morphologic aspects of the channel also change; that is, for a given discharge, gradient and width-depth ratio increase. In addition, peak discharge, sediment size, and sediment load will probably increase from pattern 1 to pattern 5. Naturally, with such geomorphic and hydrologic changes, hydraulic differences can be expected, and flow velocity, tractive force, and stream power increase from pattern 1 to pattern 5. Obviously, then, channel stability decreases from pattern 1 to pattern 5, patterns 4 and 5 being the least stable.

In nature, there is a continuum of patterns between patterns 3 and 4 of decreasing sinuosity, increasing gradient and width-depth ratio, and decreasing bank and channel stability. A comparison of aerial photographs with Figure 3 should provide a means of evaluating the relative stability of river channels.

Suspended-load channel patterns 1 and 3a are associated with small amounts of bed-material load; as a result, the banks tend to be relatively stable because of their high silt-clay content and thus the channels are not characterized by serious bank erosion or channel shift. Bars may migrate through the channel of pattern 1 (Figure 4a), but this should not create undue instability. Neck cutoffs are characteristic of pattern 3a (Figure 4c); they can be anticipated by inspecting the shape of the meanders.

Channels with higher bed-material loads and banks that contain less cohesive sediment are less stable than suspended-load channels (patterns 3b and 4). Alternate bars migrate through the low-sinuosity channel (pattern 2), causing alternating reaches of stable and eroding banks. In these cases, meander growth and shift are characteristic (Figure 4c), and chute cutoffs (Figure 4d) reveal a tendency for the development of multiple thalwegs.

When channels have large loads of coarse sediments, bank sediments are easily eroded, gravel bars and islands form and migrate through the channel, and avulsion (Figure 4f) may be common (pattern 5). As the channel straightens, meander shift and cutoffs are absent.

Because the preceding discussion relates entirely to stable alluvial channels, the changes indicated for each channel type are typical and can be expected under all conditions. However, when the sediment load or the discharge transmitted by channels is altered, channels respond by either eroding or depositing sediment, and they become unstable. But, because channels are composed of sediments of different degrees of stability and because the ways in which they erode and deposit and transport sediment are different, their responses to an altered hydrologic regime are also different (23). In each case, a reduction of sediment load will tend to produce scour and perhaps an increase in sinuosity. As load increases, aggradation and braiding occur, and meander cutoffs cause a decrease in sinuosity.

Channel patterns are frequently altered by human intervention, usually by straightening the channel by means of cutoffs or complete channelization. The straightened channel can then be very unstable as it attempts to resume its former gradient and pattern. Care should therefore be taken in evaluating the stability of straight channels: Natural channels should be stable, but artificial channels may have a propensity for major change.

An anastomosing, or anabranched, system is actually a multiple-channel system (23, p. 155), and such a system can be composed of any of the channel types shown in Figure 3. The anabranches will be sinuous or alluvial plains, straight deltas, and braided or alluvial fans. Therefore, the class function of Figure 3 can also be applied to an anastomosing or anabranched pattern.

Analysis of Stability Tendencies

Strictly speaking, the rate of sediment transport cannot be correlated with channel stability but, as a general rule, streams that have high transport rates tend to be relatively less stable. As Figure 3 shows, the type of sediment load, sediment size (with which there is only limited experience), flow velocity, stream power, width-depth ratio, and channel gradient is related to channel pattern and the relative stability of alluvial channels. In this section, additional, variable factors are examined from the viewpoint of the mechanics of flow. For convenience, the order of the factors is changed slightly. Width-depth ratio can be treated as a result of instability and is not commented on here.

Sediment Transport

In sediment load we include flow conditions, channel gradient, and sediment size. A completely stable channel is one in which the flow is not able to move the sediment on either the banks or the bed. However, aggradation could alter the shape of the channel.

The rate of sediment transport can be determined by using the following ratio:

$$R_1 = F_1/F_2 \qquad (1)$$

where F_1 is the fluid force acting with a particle and F_2 is the resistance force of the particle to flow. R_1 can also be shown as a Froude number based on shear velocity and sediment particle size. Shields (37) determined that, if $R_1 < 0.06$ in turbulent flow with cohesionless sediment, no sediment particles can be moved by the flow. In any case, a low R_1 value indicates a low rate of sediment transport and a relatively stable channel, whereas a high R_1 value indicates a relatively high rate of sediment transport and a relatively unstable channel.

For a relatively narrow range of sediment sizes (e.g., the channel used in Figure 4), an increase in flow velocity and stream power will have the same effect as an increase in the rate of sediment transport, and channel stability will decrease. This situation may be worsened if an increase in flow rate carries the flow into "upper-regime flow", where the occurrence of antidunes creates a great deal of turbulence and further weakens the channel banks. There were no upper-regime flows in the observations used to formulate Figure 3.

An increase in channel gradient has almost the same effect as an increase in the Froude number of the flow. It is quite reasonable, therefore, that an increase in sediment load, flow velocity, stream power (increasing stream power is almost the same as increasing flow velocity), or channel gradient would have the same effect on channel stability as an increase in the rate of sediment transport. The few observations of a decrease in channel stability with an increase in sediment size are not easily explained. Several other factors may be involved in these cases.

Type of Sediment Load

The influence of type of sediment load on the stability of a stream can be analyzed as follows:

1. The patterns shown in Figure 3 are dimensionless and therefore do not depend on the quantity of water and sediment moved through the channel. If discharge were constant for each pattern, however, the quantity of bed load moved through the channels would indeed be related to the channel pattern. For the great range of channels of greatly differing dimensions, the significant factor is the proportion of wash load and bed load moved through the channels (14, 23) and the type of load. A high ratio of wash load to total load indicates that the proportion of bed load to total load is small, and a narrow, deep, straight channel (patterns 1 and 2) or a sinuous, low-gradient channel (pattern 3) can move the sediment load. When the ratio of wash load to total load is low, the proportion of bed load to total load is high, and a shallow, wide, relatively straight channel (pattern 4) or a braided, steep-gradient channel (pattern 5) is required for transport of this sediment load.
2. The type of sediment load determines the nature of the sediment that composes the bed and banks of a channel. When the ratio of wash load to total load is high, the bank will contain large amounts of silt and clay and they will be cohesive. A channel with cohesive banks is relatively stable.
3. According to Simons and others (38), the presence of fine sediment will have the same effect as a change of fluid viscosity because both will affect the fall velocity of sediment. When there are very large concentrations of fine material, the dune bed (in the lower flow regime, when $R_1 \leq 0.10$) may become plane. A reduction in the transport of bed material will occur, and the channel could become more stable, as shown in Figure 3. In the upper flow regime, the reduction in fall velocity of sediment particles that results from the addition of fine sediment may change a standing-wave flow to an antidune flow or increase the activity and turbulence of an antidune flow. These changes increase resistance to flow, increase the transport of bed material, and decrease channel stability. This case is outside the range of observations used in determining Figure 3.

Additional Factors

Other factors that affect channel stability are not discussed here in detail since their influence varies from site to site. These factors include the ratio of bank resistance to bed resistance, the ratio of fluid force to resistance, gradation of sediment material, bank seepage, vegetation, and water temperature. Any of these factors may be of paramount importance at specific sites, and their importance can be determined by thorough design investigations.

METHODS OF IDENTIFYING AND EVALUATING CHANNEL PATTERNS

Several techniques of identifying channel patterns and evaluating their stability are available to the transportation engineer. These methods can be grouped according to whether they are based on existing conditions, historical information, or prediction. Essentially, two kinds of pattern changes may occur: (a) intrinsic (changes inherent in the stream system itself, such as cutoffs, channel migration, and avulsion) and (b) extrinsic (changes that are the result of external factors such as changes in sediment supplies and human intervention).

Existing Conditions

Existing channel patterns and possible pattern changes are determined by using the following methods:

1. Direct observation—Low-altitude flights and ground visits are necessary to identify existing channel patterns. Aerial photography is probably the least expensive way of studying channel patterns.
2. Analysis of data—Analysis of bank stability, geologic setting, variation of flow magnitude, sediment transport characteristics, and geomorphic factors can be useful in determining possible changes in channel patterns.

Historical Information, Records, and Research

The following types of information can be used to identify changes in channel patterns:

1. Records such as newspaper reports, railroad company files (if there was a railroad nearby), church records, and court cases are possible sources.
2. Several sets of aerial photographs taken at different times will clearly document channel changes. In many areas, aerial photography was begun in the mid-1930s.
3. Visits with local residents can be helpful in determining previous channel changes. Many of these "stories" should be verified with other sources if possible.

Predictions

Of utmost importance to the transportation engineer is the ability to predict changes in the pattern and location of streams. Rather rapid and otherwise unexpected changes are likely to occur in response to natural and human disturbances of the fluvial system. Among the disturbances that should be considered in making predictions are the following:

1. Natural disturbances include (a) geologic processes that are discontinuous with respect to time and (b) short-term episodic phenomena. Examples of the former include large-magnitude flooding, mass wasting, and stream capture. Another problem area is engineering design based on nonrepresentative data that result from short-term climatic cycles. It is difficult to anticipate channel changes produced by these disturbances.
2. Man-made changes in the drainage basin (land-use changes), in the stream channel (engineering projects), and in retention areas (reservoirs) may cause significant response in a channel. Alteration of vegetation, surface materials, and landforms and the installation of storm sewers change water yield, the timing and magnitude of flood peaks, sediment yield, channel geometry, snow accumulation and melt, the water table configuration, and other important components of the hydrologic cycle. In this regard, land use can be expected to have potentially profound downstream effects on stream channels. Alteration of stream courses by channelization, straightening, and the construction of streamside structures (e.g., dikes, levees, and bridges) can be expected to affect the channels and has the potential for changing stream patterns. Interbasin water transfer projects and impoundments of water in reservoirs can be expected to increase the erosion of stream beds and banks by increasing annual runoff and decreasing upstream sediment load, respectively.

Accurate predictions for a specific reach of channel can only be made after thorough analysis by engineers and geomorphologists. The actual methods of analysis are beyond the scope of this paper.

SUMMARY

This paper proposes a scheme to classify alluvial channel patterns into five types. The observed relative stability of these various types of patterns is given, and the applications of the classification are presented. Although it has been shown that the observed stability can be explained by theoretical stability analysis, readers must be cautious in applying these rules because stream behavior is extremely complex.

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