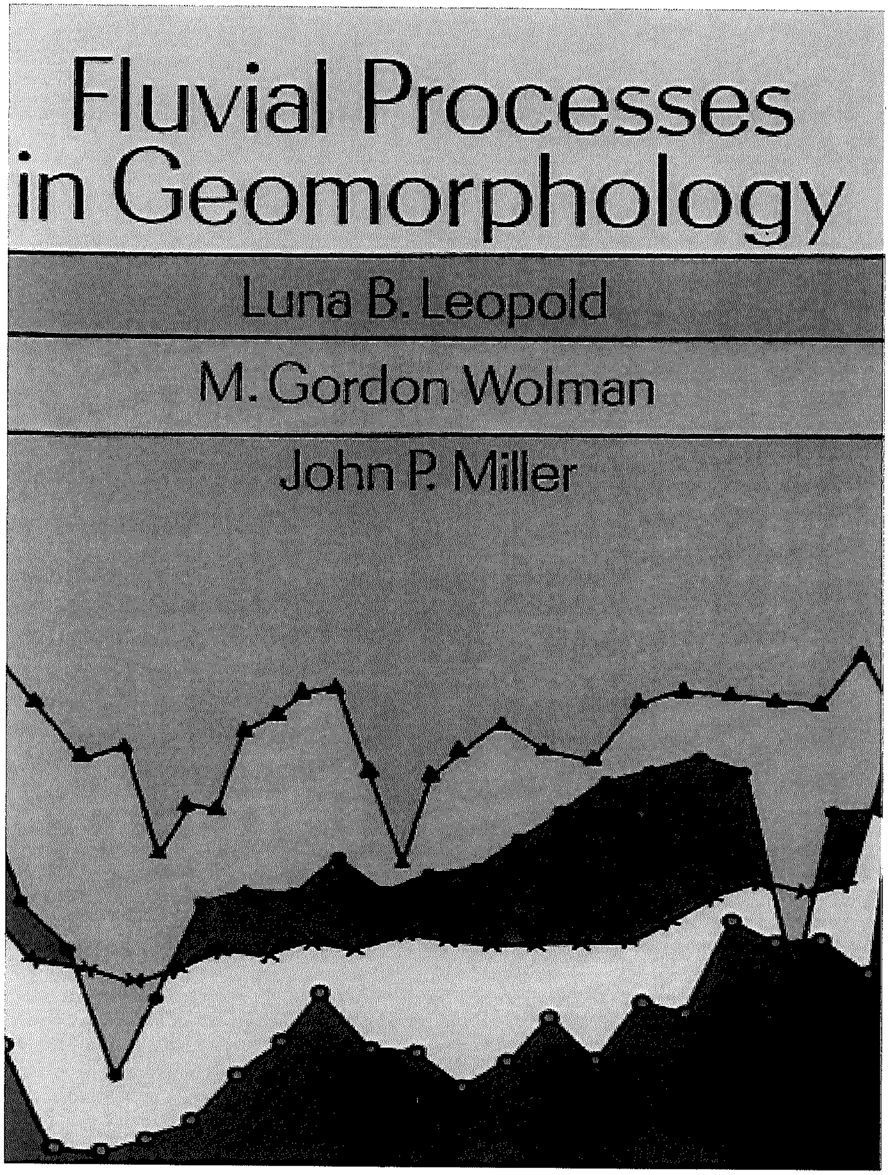
Fluvial Processes in Geomorphology
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FLUVIAL PROCESSES IN GEOMORPHOLOGY

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Figure 3-23.

Generalized relation of effective work done by events of different magnitude.

Landforms in Relation to Frequency of Climatic Events

Catastrophic events of rare frequency may have a great effect on the characteristics of particular landforms, even though rare occurrences may perform but a moderate proportion of the total work of moving materials out of the basin. The effect on surface form, however, is not easily studied. Rivers in flood are known to exercise tremendous force upon objects in their paths, but inhospitable and dangerous working conditions in the field have limited the number of direct observations made during such events. Most of the knowledge of the geomorphic effects of floods is built on observations made ex post facto—a definite disadvantage.

It is known that the size, shape, and pattern of river channels are closely related to the flows which they transmit. Although the mechanics involved in the adjustments of channel form, pattern, and discharge are not completely understood, there appears to be a close correlation between discharge and specific aspects of channel form. The wavelength of a meandering river, for example, is roughly proportional to some measure of discharge. It is reasonable to suppose that the pattern of the channel itself is formed by flows which apply sufficient force to mold the channel but are also retained within the channel, rather than by those which occupy the entire cross section of a valley during periods of flood. In many rivers the bankfull stage recurs on the average once each year or perhaps once every two years. Although a channel may be scoured during individual high flows, flows much above the bankfull stage and out of the channel cannot be responsible for the regular meandering pattern. Such flows often move downvalley directly across the pattern and not coincident with it.

Additional observations indicate that the cross section of a straight reach of channel is adjusted to a range of discharges which provide a shear stress balanced by the resistance of the banks. A meandering channel migrates both across and down its alluvial plain. The stability of the meandering channel is a function, then, of the shear stress on the outer bank and of the associated deposition on the inner or convex bank, a subject covered in some detail in Chapter 6. In either case, the channel is formed and reformed during a range of flows lying between the lower limit of competence and an upper limit at which the flow is no longer confined within the channel. The range so defined consists of flows which recur more often than once in a year or once in two years. Thus it appears that the channel-and pattern-forming discharge is one which recurs frequently. Although great erosion does occur during exceedingly large flows, in streams with developed meander patterns and floodplains the channel-forming discharge does not seem to be that associated with the infrequent or catastrophic events.

The process of channel formation and its relation to competence and to the time intervals during which the major portion of the work is done can be tied together by considering a particular river section. Seneca Creek near Dawsonville, Maryland, about 20 miles north of Washington, D. C., drains an area of 100 square miles. It lies within rolling farm country in the Piedmont province, in an area underlain by deeply weathered schist and sandstone lying outside the boundary of glaciation. A photograph of the reach is shown in Fig. 3-24.

At the measuring point the channel is 75 feet wide, the bed is gravelly, and banks of silt stand about 5 feet high. The mean flow is 100 cfs. Flow is less than the average value (less than 100 cfs) 66% of the time or 240 days per year. At the 50%

point of the duration curve the discharge is 72% of the mean flow, and at that stage the average depth is 0.7 feet Thus half the time the channel is less than 0.18 of its bankfull depth. The discharge at bankfull stage is approximately 1,330 cfs, and the recurrence interval of this discharge is 1.1 years.

Figure 3-24.

A. Seneca Creek near Dawsonville, Maryland, looking downstream at low flow; bar in middle ground is composed of gravel.

Over a period of 7 years of study of the reach of Seneca Creek it has been our observation that even sand grains do not move to any great extent at mean flow and below, probably because the cobbles on the bed protect the smaller grains from exposure to the flow. Cobble gravel bars which are out of water at mean flow are stripped of their surface rocks at less than bankfull stage and rocks of the same size replace those moved, for the gravel bars have not changed in position, form, or elevation after a bankfull flow has receded.

Wyoming, were measured at equal stages, when the river was rising and when it was falling; in both there was a dip or topographic trough in the cross profile, which otherwise was convex to the sky. R. M. Myrick, who made the measurements, noted that debris floating in the stream tended to be concentrated in this trough. Once caught in the topographic trough, such debris presumably could not escape and so tended to accumulate there. A trough was observed on both rising and falling stage, discounting the view sometimes heard that debris tends to collect in the center of the stream during rising stages and along the banks of the stream during falling stage. Others have suggested that a stream carries floating debris on the rising but not on the falling stage.

Despite their apparent simplicity, flow and sediment movements in straight natural channels are complex phenomena, requiring further detailed field observations.

Braided Channels

The separate channels of a braided stream are divided by islands or bars. Bars which divide the stream into separate channels at low flow are often submerged at high flow. Great areas of braided channels of proglacial streams (see Fig. 7-34) are in many ways similar to the braided channels that can be observed in the sandy detritus covering numerous short reaches of the concrete gutter at the edge of a city street. The building of central and lateral bars is an important part of the process of development and shifting of braided channels.

In a study of braided channels tributary to the Green River near Daniel, Wyoming, we noted the following characteristics. The several channels in a given reach were separated by vegetated islands whose upper surfaces tended to be at the same level as small unvegetated central bars obviously in the process of being built. The islands were composed of gravel essentially similar to that of the building bars, diameter 60—100 mm. The ages of vegetation taking hold on the new gravel bars indicated that the bars tend to build by additions at the downstream end and probably also on some parts of the lateral boundaries, but not on the upstream tip.

Figure 7-34. Braided channel of the Muddy River, at a point about 23 miles north of Mt. McKinley, Alaska. The river heads in the Peters Glacier, which flows off the north side of Mt. McKinley. [Photograph by Bradford Washburn.]

In flume experiments conducted in a channel molded in moist but uncemented sand, the introduction into the flowing water of poorly sorted debris at the upper end produced, with time, forms similar in many respects to those observed in the field. After 3 hours a small deposit of grains somewhat coarser than the average introduced load had accumulated on the bed in the center of the channel (Fig. 7-35). This represented a lag deposit of the coarser fraction which could not be carried by the flow. These same grains had already been carried downstream several feet, which suggests that when mixed with smaller material large grains may be moved under flow conditions incapable of transporting them when concentrated with particles of similar size.

Lag deposits of material slightly coarser than average can also be observed in ridges separating small anabranches on alluvial fans in desert areas. These appear to be similar depositional bars or ridges. A photograph of such a gravelly ridge on a fan in Death Valley is shown in Fig. 7-36.

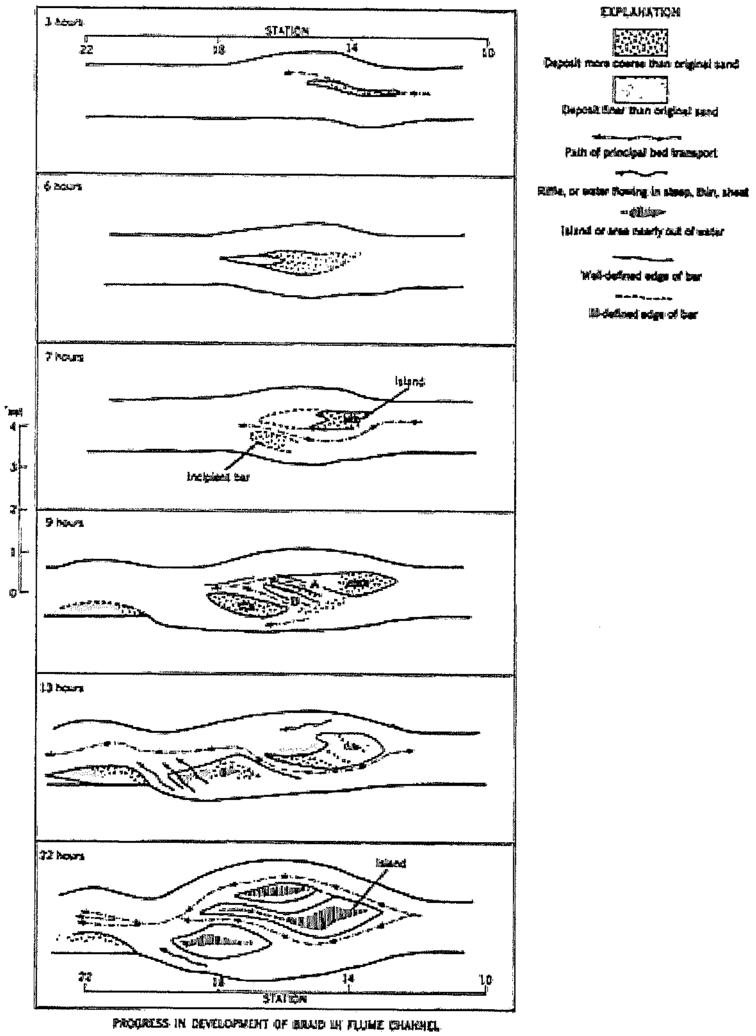
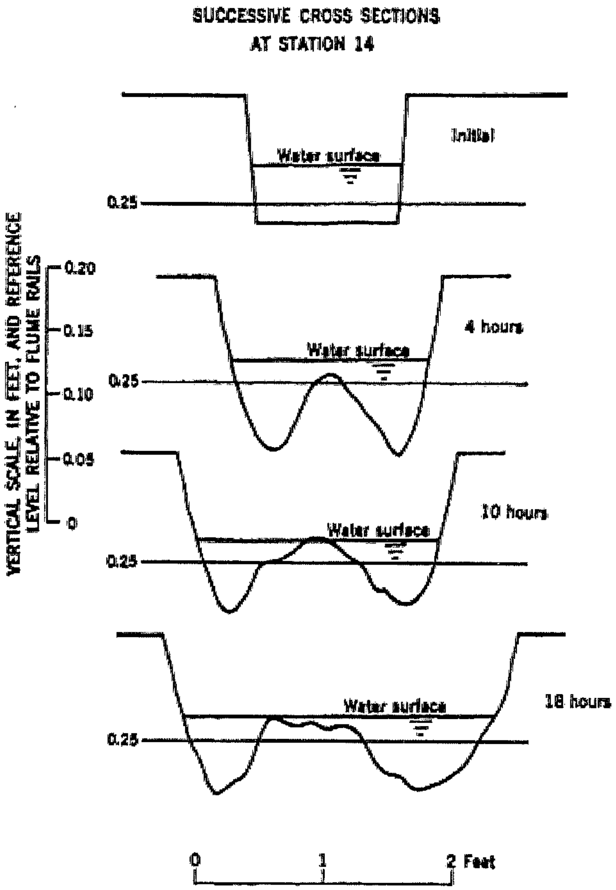


Figure 7-35.

A. Successive views in plan of central bar formation in a laboratory flume. ***B.*** *Successive views in cross section of central bar formation in a laboratory flume.*



As the instantaneous velocities in turbulent flow are subject to fluctuation, a brief decrease in intensity allows some particles to come to rest. Large particles may have rolled into the stream from eroding banks upstream. Velocities required to keep them moving are less than those required to reinitiate movement after they have come to rest. Once concentrated, the large particles form a locus for continued deposition.

As shown in the sketch at 3 hours of flow (Fig. 7-35), the band of principal bed transport lay on top of the submerged central bar, whereas grain movement in the deeper parts of the channel adjacent to the central bar was negligible at this stage. The central bar continued to build closer to the water surface. By the end of 7 hours of flow the central bar had been built so close to the water surface that individual grains rolling along its ridge actually broke the water.

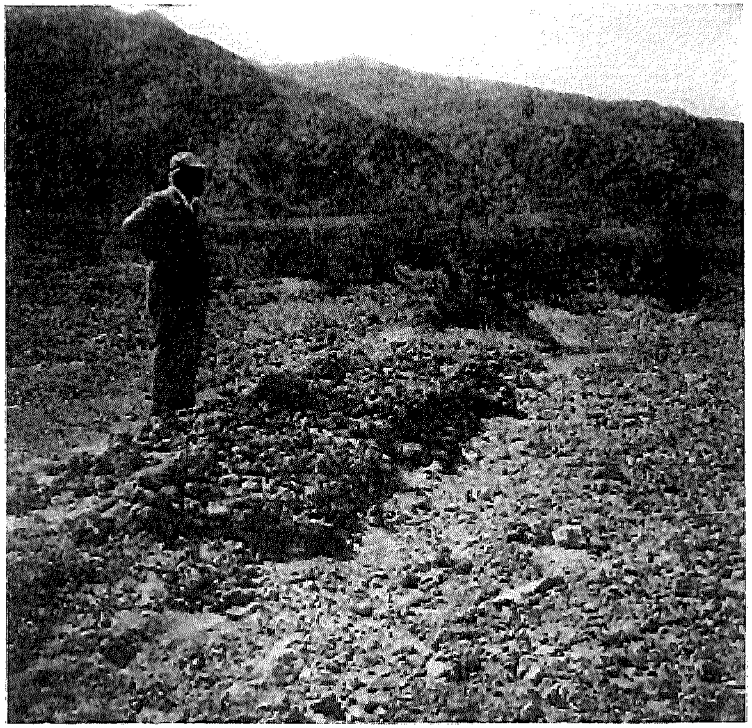


Figure 7-36.

Ephemeral channels on surface of desert fan in Death Valley, California, which have central bars or gravel ridges comparable to those in gravelly channels of braided perennial rivers.

The growth surfaceward of a central bar tends to concentrate flow in the flanking channels, which then scour their beds or erode their banks (or both), as can be seen in the plan and in the cross section of Fig. 7-35. As the cross section is enlarged, the water surface elevation is lowered, and the bar, formerly just covered with water, emerges as an island. In a natural stream the emergent bar may be stabilized by vegetation, which prevents the island from being easily eroded and in addition tends to trap fine material during high flow. Thus the gravel tends to become veneered with silt.

Similar processes have been described in maps and by time-lapse photography on the White River, a braided stream emanating from the Emmons Glacier on Mount Rainier in Washington State (Fahnestock, 1963). Flowing on an average slope of about 0.04, the White River changes with great rapidity in response both to random deposition of cobbles and boulders and to diurnal fluctuations in discharge accompanying glacial melting.

For example, within a period of 2 months during the summer melting season, in a single cross section carrying an estimated flow of about 200 cfs, at one time there were 5 distributary channels, four times there were 4 channels, three times there were 2 channels, and once there was only 1 channel (cross section No. 5).

As another example, Fahnestock noted that during a period of 8 days the water in a given reach shifted or switched a lateral distance of about 400 feet from one side of the valley to the other.

As in the laboratory, flow is often on elevations rather than depressions in the alluvial plain, and natural levees confine the channel in places (Fahnestock, 1963). Downstream from local chutes or channels of concentrated flow, deposition takes place, forming fanlike noses as the flow diverges in the area of deposition (Fig. 7-37). The levees and noses may also contribute to shifting the channel alignment by imposing barriers across active anabranches. In both field and laboratory, deposition on top of the bar often continues even as the depth of the water becomes exceedingly shallow.

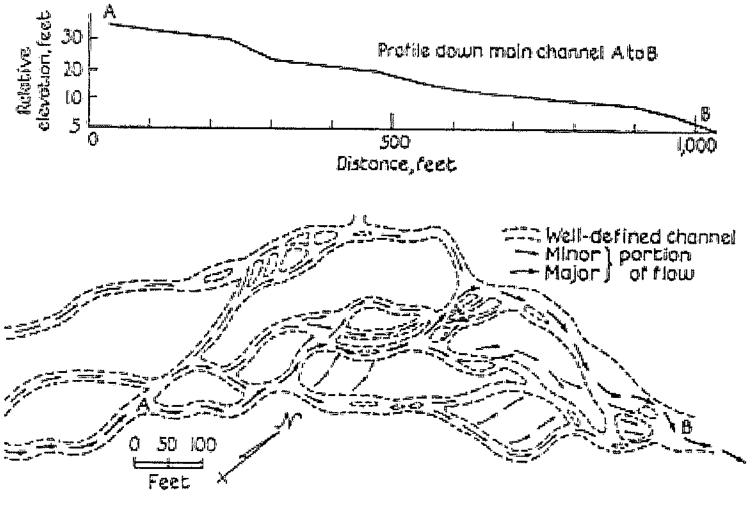


Figure 7-37. Pattern of flow on gravelly valley train below Emmons Glacier, Washington. Note the dividing and joining of channels at obtuse angles. [From Fahnestock, 1963.]

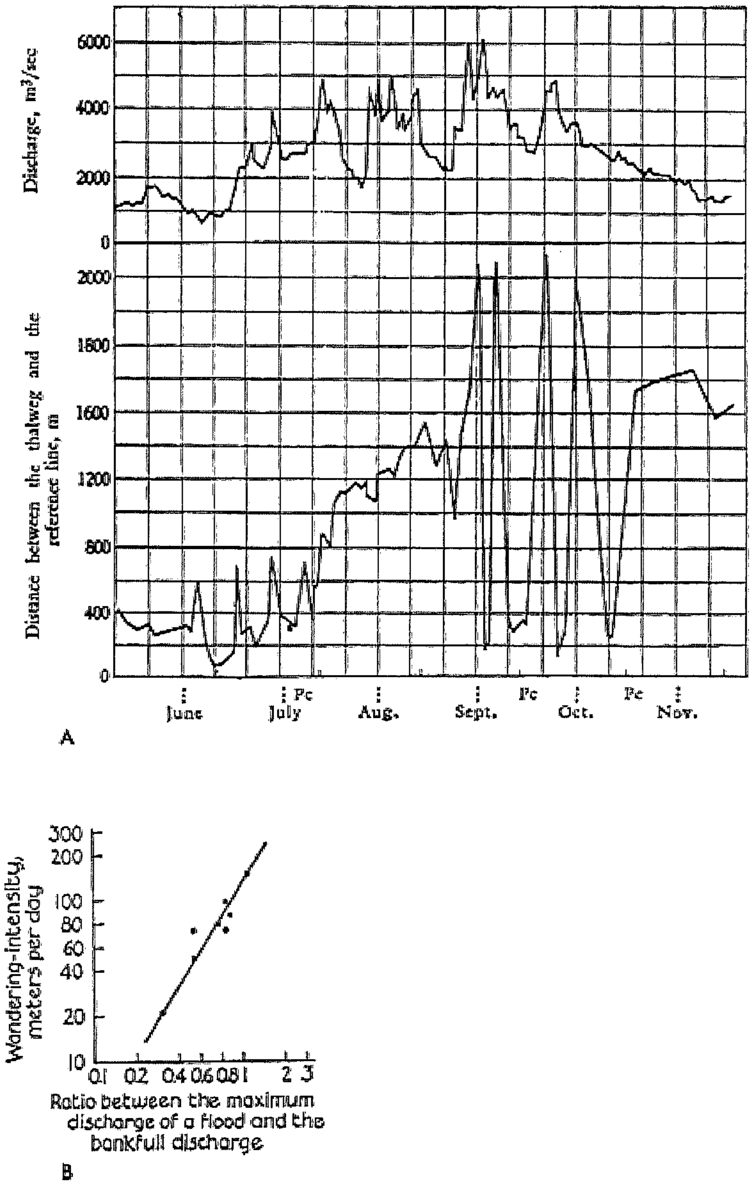


Figure 7-38.

Changes in braided river pattern, Yellow River. [From Chien, 1961.] **A.** *Shifting of the thalweg in a zone of convergence.* **B.** *Channel shifting as a function of the ratio of maximum discharge to bankfull discharge.*

Large braided rivers are also characterized by wide channels, rapid shifting of bed material, and continuous shifting of the position of the river course. An example for which observations are available over a considerable period is the Kosi River, a tributary to the Ganges in Bihar, India. The river rises in Nepal in the vicinity of Mt. Everest, and near Chatra emerges from the mountains at the apex of a flat cone built by the deposited sediments, with a gradient of .0009 near the apex, flattening to .0002 near Dhamaraghat. In the flood season the average discharge is about 160,000 cfs. Through this whole distance of 130 miles over the cone the river is braided. The last two centuries have witnessed a westward movement of the river over this cone, a lateral distance of some 70 miles. The movement has not taken place gradually but sporadically; the river is known to have shifted 12 miles laterally in a single year. The lateral movement of the Kosi River channel, on a line passing through Bhelhi and Puenea, is tabulated for various periods of specific observation.[5]

DATES	PERIOD (years)	DISTANCE MOVED (miles)
1736-1770	34	6.7
1770—1823	53	5.8
1823-1856	33	3.8
1856—1883	27	8.0
1883-1907	24	11.5
1907-1922	15	6.8
1922-1933	11	18.0
1933-1950	17	11.0

On the Yellow River, Chien (1961, p. 738) has shown that channel shifting varies with fluctuations in discharge (Fig. 7-38), and that the amount of shifting—that is, the lateral movement—is controlled by the spacing of constrictions or control points along the river. Likening the braided stream to a long elastic band along which oscillations will be propagated by a disturbance at any one point, Chien (p. 745) points out that by controlling the displacement at several points on the band the amplitude of the oscillations is reduced. Controls limited to bedrock or resistant strata on the bank only, as at the outside of a bend, may be effective only at stages below overflow, but control points such as bedrock narrows, bridges, or revetments are effective at all stages.

If a reach of river possessing a single channel is compared with an otherwise similar reach in which the channel is divided by a bar or island, the braided portion will have a steeper slope (Fig. 7-39, A). This increase in slope is analogous to the variation of slope with discharge in a downstream direction as indicated in the hydraulic geometry. The undivided channel is comparable to the larger downstream channel, and each of the anabranch channels represents a stream with smaller discharge flowing on similar bed material. The ratio of slopes of divided to undivided channels was found to range from 1.4 to 2.3 in field situations and 1.3 to 1.9 in the flume (Leopold and Wolman, 1957, p. 51). The sum of the widths of the anabranches is also greater than the width of the undivided channel, the ratio varying from 1.6 to 2.0 in field examples and 1.05 to 1.70 in the flume.

There is a close relationship between braiding and meandering: a braided channel may exhibit curves that have a characteristic relation of radius to channel width, and the river has at least some reaches that would be called meandering. In other instances, as in Fig. 7-39, A, the anabranches of a braided stream definitely meander while the undivided channel does not. In overall plan, however, the channel course of the braided river is usually very much less sinuous than a meandering river of comparable size. Although the channels may meander at low stages, at overbank flow the braided river often moves nearly straight down its valley. Figure 7-39, B, shows that when two rivers of a given size of river (same discharge) are compared, braided channels occur on steeper slopes than meanders. Steeper slopes contribute to sediment transport and to bank erosion and are often associated with coarse heterogeneous materials. All these are conditions which contribute to braiding.

Where coarse material is available, braiding may result from the selective deposition of the coarser material, causing formation of a central bar and thus diverting the flow and increasing erosional attack on the banks. This was observed in the flume, in the gravelly channels studied by us in Wyoming, and in braided proglacial rivers described by Fahnestock (1963) and others. Even in fine material, however, irregular deposition of bars and bank erosion may produce a braided pattern. The shifting channel may move gradually during low flows, but during floods major changes in the position of the thalweg can be produced. Because deposition is essential to formation of the characteristic braided pattern, it is clear that sediment transport is essential to braiding. It is also evident, however, that if the banks were unerodible and the channel width confined, the capacity of the reach for the transport of sediment would be increased, reducing the likelihood of deposition. In addition, any bars which formed would be removed as flow increased, since bank erosion could not take place. Thus, for the bars to become stable and divert the flow, the banks must be sufficiently erodible so that they rather than the incipient bar give way as the flow is diverted around the depositing bar. Sediment transport and a low threshold of bank erosion provide the essential conditions of braiding. Rapidly fluctuating changes in stage contribute to the instability of the transport regime and to erosion of the banks; hence they also provide a contributory but not essential element of the braiding environment. Heterogeneity of the bed material in the same way creates irregularities in the movement of sediment and thus also may contribute to braiding.

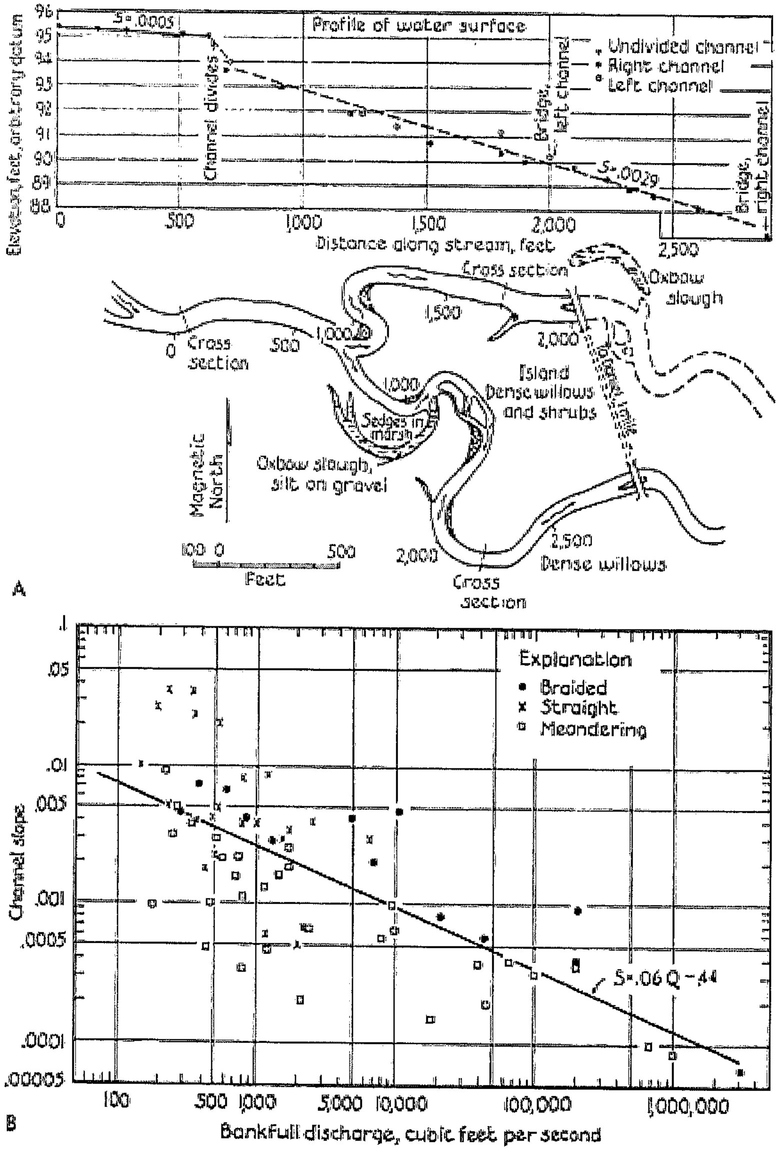


Figure 7-39.

Relation of discharge to slope in braided and nonbraided rivers. A. Plan view and profile of a channel which divides around an island, showing how the individual divided channels are steeper than the single one, Green River near Daniel, Wyoming. ***B.*** *Relation of discharge to slope and a line which separates data from meandering and braided channels. [After Leopold and Wolman, 1957, and Balek and Kolar, 1959.]*

Because the braided reach is wide and shallow and the channel banks are unstable, the rate of sediment transport per unit width of channel may be relatively low. As we noted earlier (p. 201), anabranches of some braided channels appear to be near the threshold condition of equilibrium. In addition, deposition in such reaches is characteristic. Braided channels then may be associated with aggradation. It is also clear, however, that this need not be the case. Although deposition takes place it may be local and transient only. Deposits left at one moment are moved in the next. The timing may involve minutes or days, as Fahnestock so vividly showed on the White River, or months or seasons on rivers subject to periodic annual or seasonal floods. Transient as the individual channels may be, the reach as a whole may be stable, aggrading or degrading (Stricklin, 1961; Fahnestock, 1963). Several kinds of observations support the concept that braiding is a valid equilibrium form.

On Horse Creek near Daniel, Wyoming, for example, the stability of the channel pattern is demonstrated by the fact that islands separating anabranches have changed in outline but little in 60 years. Cottonwood Creek near Daniel, Wyoming, changes abruptly from a meandering to a braiding pattern. Through the short reach where this change occurs, no tributaries enter, and discharge and load are the same in both meandering and braided portions. There is no evidence of rapid aggradation or degradation. If the meandering reach may represent an equilibrium condition, then the braided must also do so.

When bedload in transport cannot all be carried through a particular reach for some reason—such as a local deficit in shear—it is logical that the largest particles are deposited. If this results in the growth of a central bar, the divided channels will be characterized by a larger width and greater slope but probably only a modest increase in mean velocity, if any. These are adjustments, then, which tend to increase the ability of the same discharge to carry a larger amount of bedload, a generalization supported by flume data and by inference from field experience which was summarized by Leopold and Maddock (1953, p. 29).

It appears, therefore, that braiding is a type of adjustment that may be made in a channel possessing a particular bank material in response to a debris load too large to be carried by a single channel. Braiding then represents a response or adjustment among the controlling variables which may provide an equilibrium condition over a period of time. The pattern in itself is not evidence that the channel is "overloaded." (This usually implies aggradation, which, it has been shown, need not be the case.)

Braiding is therefore considered to represent a particular combination of variables in a continuum of river shapes and patterns. Once established, the braided pattern may be maintained with only slow modification, and the braided river may be as close to equilibrium as are rivers possessing meandering or other patterns.

Geometry of Meanders

Nearly all natural channels exhibit some field conditions, keeping in mind that mathematical and conceptual models are only steps in analysis and are in themselves neither proofs nor end products.

To summarize, theoretical models of hillslope evolution involving a degradation term proportional to the angle of slope provide reasonable resemblances of hillslopes found in many regions. These are primarily concave-convex. Superficially this erosional profile is not distinguishable, however, from profiles formed by erosion of the crest slope and deposition at the foot slope. In regions where weathering and weathering removal of rock waste unaided by running water are the principal mechanisms of denudation of slopes, the geometric models produce hillforms comparable to those found in nature. Like all such models, however, the mere agreement of natural form and model-derived form is not proof of the validity of the assumptions made in constructing the model. Such proof depends upon matching observation of process and form with the reasoning and assumptions of the model.

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