River Channel Patterns: Braided, Meandering and Straight

By LUNA B. LEOPOLD *and* M. GORDON WOLMAN

PHYSIOGRAPHIC AND HYDRAULIC STUDIES OF RIVERS

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SYMBOLS

A	area of cross section of flowing water
A_d	drainage area
b	exponent in relation of width to discharge when $w \propto Q^b$
C_s	sediment concentration, in pounds of sediment per pound of clear water
d	mean depth, defined as ratio of cross-sectional area to width
D_s	size of sediment particle
D_{50}	median size of sediment particle; subscripts 25, 75, or 84 refer to percent of sample finer than specified size
f	exponent in relation of depth to discharge when $d \propto Q^f$
f	Darcy-Weisbach resistance factor
g	acceleration due to gravity
k	numerical coefficient having a specific but undetermined value
L	sediment load, in units of weight per unit of time
m	exponent in relation of velocity to discharge when $v \propto Q^m$
P	wetted perimeter, in feet
Q	water discharge, in cubic feet per second (cfs)
R	hydraulic radius, in feet
s	slope of water surface
So	sorting coefficient of a granular mixture
T	temperature, in degrees Fahrenheit
v_*	shear velocity
v	mean velocity defined as quotient of discharge divided by cross-sectional area
w	width
γ	specific weight of water, or 62.4 pounds per cubic foot
ρ	mass density of water
τ_0	intensity of boundary shear

PHYSIOGRAPHIC AND HYDRAULIC STUDIES OF RIVERS

RIVER CHANNEL PATTERNS: BRAIDED, MEANDERING, AND STRAIGHT

By Luna B. Leopold and M. Gordon Wolman

ABSTRACT

Channel pattern is used to describe the plan view of a reach of river as seen from an airplane, and includes meandering, braiding, or relatively straight channels.

Natural channels characteristically exhibit alternating pools or deep reaches and riffles or shallow reaches, regardless of the type of pattern. The length of the pool or distance between riffles in a straight channel equals the straight line distance between successive points of inflection in the wave pattern of a meandering river of the same width. The points of inflection are also shallow points and correspond to riffles in the straight channel. This distance, which is half the wavelength of the meander, varies approximately as a linear function of channel width. In the data we analysed the meander wavelength, or twice the distance between successive riffles, is from 7 to 12 times the channel width. It is concluded that the mechanics which may lead to meandering operate in straight channels.

River braiding is characterized by channel division around alluvial islands. The growth of an island begins as the deposition of a central bar which results from sorting and deposition of the coarser fractions of the load which locally cannot be transported. The bar grows downstream and in height by continued deposition on its surface, forcing the water into the flanking channels, which, to carry the flow, deepen and cut laterally into the original banks. Such deepening locally lowers the water surface and the central bar emerges as an island which becomes stabilized by vegetation.

Braiding was observed in a small river in a laboratory. Measurements of the adjustments of velocity, depth, width, and slope associated with island development lead to the conclusion that braiding is one of the many patterns which can maintain quasi-equilibrium among discharge, load, and transporting ability. Braiding does not necessarily indicate an excess of total load.

Channel cross section and pattern are ultimately controlled by the discharge and load provided by the drainage basin. It is important, therefore, to develop a picture of how the several variables involved in channel shape interact to result in observed channel characteristics. Such a rationale is summarized as follows:

Channel width appears to be primarily a function of near-bankfull discharge, in conjunction with the inherent resistance of bed and bank to scour. Excessive width increases the shear on the bed at the expense of that on the bank and the reverse is true for very narrow widths. Because at high stages width adjustment can take place rapidly and with the evacuation or deposition of relatively small volumes of debris, achievement of a relatively stable width at high flow is a primary adjustment to which the further interadjustments between depth, velocity, slope, and roughness tend to accommodate.

Channel roughness, to the extent that it is determined by particle size, is an independent factor related to the drainage basin rather than to the channel. Roughness in streams carrying fine material, however, is also a function of the dunes or other characteristics of bed configuration. Where roughness is independently determined as well as discharge and load, these studies indicate that a particular slope is associated with the roughness. At the width determined by the discharge, velocity and depth must be adjusted to satisfy quasi-equilibrium in accord with the particular slope. But if roughness also is variable, depending on the transitory configuration of the bed, then a number of combinations of velocity, depth, and slope will satisfy equilibrium.

An increase in load at constant discharge, width, and caliber of load tends to be associated with an increasing slope if the roughness (dune or bed configuration) changes with the load. In the laboratory river an increase of load at constant discharge, width, and caliber resulted in progressive aggradation of long reaches of channel at constant slope.

The adjustments of several variables tending toward the establishment of quasi-equilibrium in river channels lead to the different channel patterns observed in nature. For example, the data indicate that at a given discharge, meanders occur at smaller values of slope than do braids. Further, at the same slope braided channels are associated with higher bankfull discharges than are meanders. An additional example is provided by the division of discharge around islands in braided rivers which produces numerous small channels. The changes in slope, roughness, and channel shape which accompany this division are in accord with quasi-equilibrium adjustments observed in the comparison of large and small rivers.

INTRODUCTION AND ACKNOWLEDGMENTS

From the consistency with which rivers of all sizes increase in size downstream, it can be inferred that the physical laws governing the formation of the channel of a great river are the same as those operating in a small one. One step toward understanding the mechanisms by which these laws operate in a river is to describe many rivers of various kinds.

This study is primarily concerned with channel pattern; that is, with the plan view of a channel as seen from an airplane. In such a discussion some consideration must also be given to channel shape. Shape, as we shall use it, refers to the shape of the river cross section and the changes in shape which are observed as one proceeds along the stream, both headward to the ultimate rills and downstream to the master rivers. Because the shape of the cross section of flowing water varies, depending upon whether the river is in flood or flowing at low flow, shape must take into consideration the characteristics of river action at various stages of flow.

The channel pattern refers to limited reaches of the river that can be defined as straight, sinuous, meandering, or braided. Channel patterns do not fall easily into well-defined categories for, as will be discussed, there is a gradual merging of one pattern into another. The difference between a sinuous course and a meandering one is a matter of degree and a question of how symmetrical are the successive bends. Similarly, there is a gradation between the occurrence of scattered islands and a truly braided pattern.

The interrelationship between channels of different patterns is the subject of this study. Because neither braided channels nor straight channels have received the attention in the literature that meanders have, our observations of these patterns precede the discussion of the interrelations between channels of different patterns.

The *flume experiments* described were conducted in the Sedimentation Laboratory of the California Institute of Technology during the time when the senior author was a visiting professor in the Division of Geological Sciences. For this opportunity, as well as for advice and encouragement, thanks are extended to Dr. Robert P. Sharp. The Division of Geological Sciences also financed the laboratory phase.

Dr. Vito A. Vanoni of the institute not only allowed the use of his laboratory for the work but generously offered his counsel. Assembly of the laboratory equipment would not have been possible without the expert craftsmanship of Elton F. Daly of the Hydrodynamics Laboratory of the institute.

An early draft of the manuscript was read by a number of friends in and out of the Geological Survey. For help at various stages of the work particular thanks are extended to Norman H. Brooks, Ronald Shreve, and John P. Miller.

For her careful work in compiling and computing data for this, as well as previous studies, we gratefully acknowledge the assistance of Ethel W. Coffay of the Geological Survey.

THE BRAIDED RIVER

INTRODUCTION

In 1877 when field parties of the Hayden Survey were making the geologic reconnaissance of west-central Wyoming, Peale (1879) was impressed by the manner in which tributaries joined the upper Green River. In streams which do not exhibit a braided pattern, a tributary usually discharges all of its flow through a single channel into the channel of the master stream. Peale observed that, in contrast, Horse Creek "flows out into a broad valley in which it is side by side with the Green, and finally, to use an anatomical term which exactly describes it, joins the latter by anastomosis. There are at least five islands formed by the two streams in the lower end of the broad valley" (p. 528).

The term "anastomosis" was apparently first applied to streams by Jackson (1834). Because it has occasionally been misapplied in the geomorphic literature, it is desirable here to recall its definition—the union of one vessel with another—or the rejoining of different branches which have arisen from a common trunk, so as to form a network. Successive division and rejoining with accompanying islands is the important characteristic denoted by the synonymous terms, braided or anastomosing stream.

A braided pattern probably brings to the minds of many the concept of an aggrading stream. Not until the work of Rubey (1952) was the problem of channel division and island formation discussed as one of the possible equilibrium conditions of a channel. The examples which are discussed here allow some elaboration of Rubey's idea and perhaps a somewhat more complete picture of the manner in which the channel division around islands proceeds.

HORSE CREEK: TYPE LOCALITY OF THE BRAIDED STREAM

It is appropriate to use as the first example of a typical braided river the same stream to which the term "anastomosing" was early applied. There has been but little change in the stream pattern between 1877 and 1942 when the modern topographic map was published. Figure 28 shows the area near Daniel, Wyo., as depicted by Peale and as shown on a modern map. The islands shown by Peale still exist with but minor changes in form.

Within a few miles of the point where Peale viewed the anastomosing reach of Horse Creek, 5 miles northwest of Daniel, Wyo., we mapped a reach of the river which includes a gaging station of the Geological Survey (fig. 29). At this place Horse Creek has a drainage area of 124 square miles and a mean discharge of about 65 cfs derived primarily from the headwater mountain area in the Wyoming Range. Though not so well developed here as downstream, the braided pattern is apparent. The reach near the gaging station was chosen for study because the channel pattern is typical and because the discharge data obtained at the station can be used to analyse the flow characteristics of the braided channel.

In figure 29 it can be seen that the reach at the gaging station has only a single channel, but within a few hundred feet downstream the flow divides and then again joins into a single channel. The division begins as a low gravel bar (marked C) near the left bank which grades downstream into a central ridge meeting the tip of a gravel island (marked D) supporting a willow thicket. In the left channel about 200 feet downstream from the upper tip of the island, a linear gravel bar (marked E in fig. 29 and pictured in fig. 30) extends for nearly 250 feet down the center of the channel. The bar ends near the junction of the main channels.

The two channels divided by the willow-covered island are about equal in width, 30 to 40 feet. The sum of these widths is 20 to 30 percent greater than the 50-foot width of the undivided reach. In the downstream part of the left channel where the central bar of gravel has been deposited, the width is only slightly greater than in the rest of the left channel where there is no central bar.

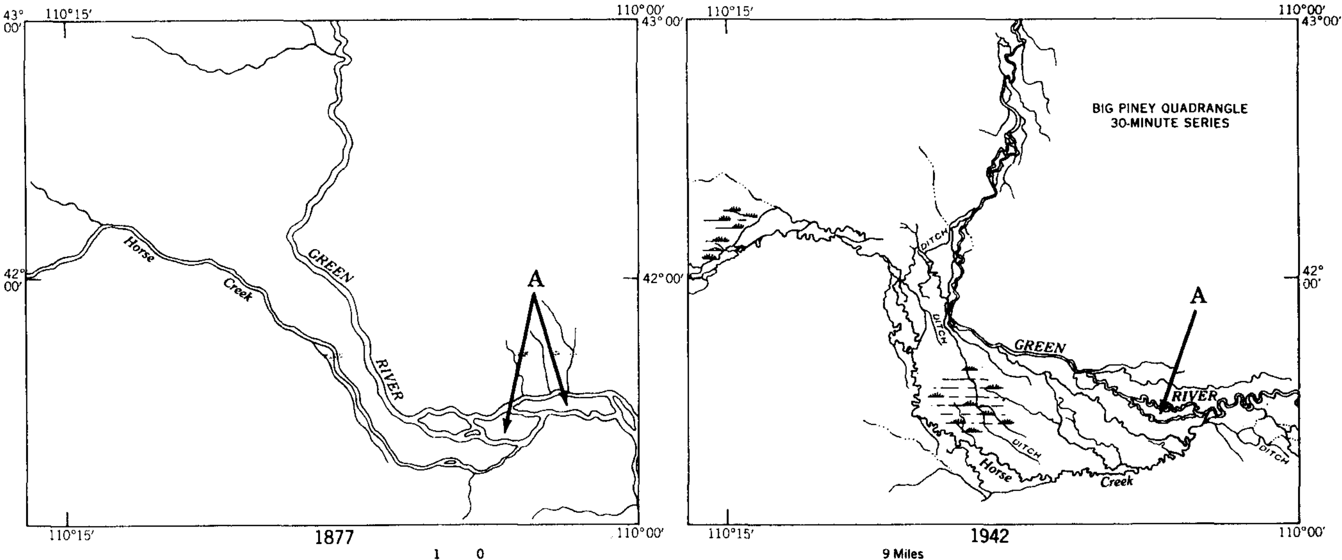


FIGURE 28. Maps of lower Horse Creek and the Green River near Daniel, Wyo., comparing a sketch made by Peale (1879, pl. L) in 1877 and a Geological Survey map of 1942. The islands (marked A) shown by Peale existed in 1942 with but minor changes in form. Note the successive dividing and rejoining of river channels.

Opposite the gravel island, and on the right side of the little valley, there is a slough which is alined with a grassed depression. During flood flow this slough and the depression undoubtedly carry water. The configuration of the slough and depression and their position in relation to the active right-hand channel indicate that they once joined as a continuous active channel which has subsequently been blocked by deposition. In its active stage this old channel was separated from the present right-hand channel by an island, similar in character to the gravel island now separating the two active channels.

The linear bar in the left channel is nearly bare of vegetation except at its most headwater tip where young willows have become established. This can be seen in figure 30, which looks downstream along the central gravel bar. The man stands by the young willow at the headwater tip of the linear bar. Two other bits of new growth on the bar can be seen 20 feet and 70 feet farther downstream.

The upstream end of the bar is gently rounded in cross section and lobate in form like a beaver tail. Downstream the bar becomes pointed, flat on top, and trapezoidal in cross section (figure 31).

When we first studied this linear bar there was no vegetation on the lower end. One year later some vegetation had sprouted on the formerly bare gravel surface as can be seen in figure 31. On 425 square feet of area there were 80 individual plants, or one on every 5 square feet approximately. The plants were:

Species	*Number of plants*
Red top (*Agrostis* sp.)	20
Sweet clover (*Melilotus* sp.)	17
Bluestem (*Agropyron Smithii*)	12
Foxtail (*Hordeum* sp.)	10
Dandelion (*Taraxacum* sp.)	7
Shepherd purse (Cruciferae)	4
Carrot weed (Umbelliferae)	3
Mint (Labiatae)	2
Timothy (*Phleum* sp.)	2

Two cross sections of the braided reach on Horse Creek are shown on figure 32. The valley bottom is

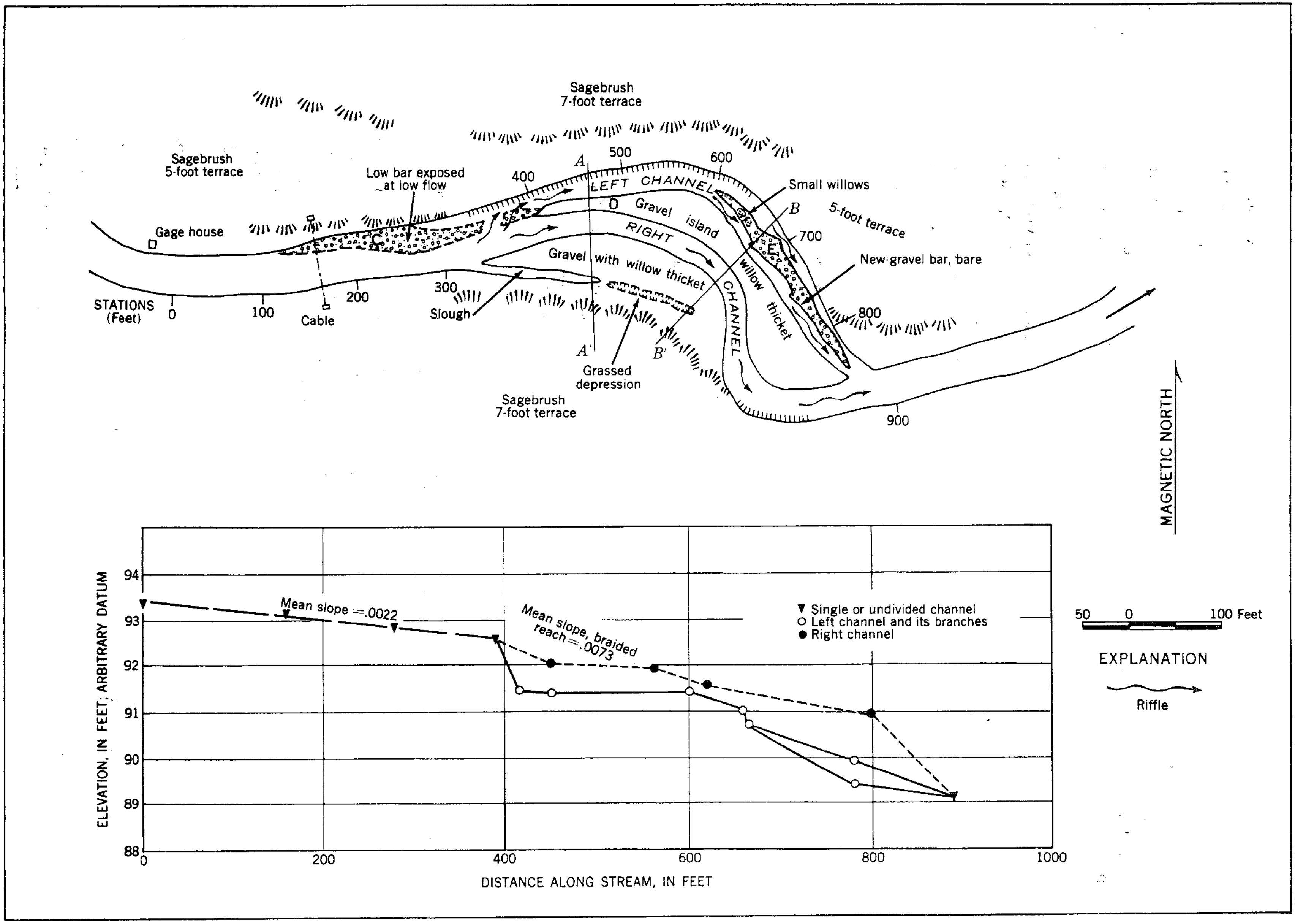


FIGURE 29. Plan and profile of Horse Creek near Daniel, Wyo., an example of a braided river. (Section shown in fig. 32.)

FIGURE 30.—View downstream along central gravel bar in left channel of Horse Creek; photograph taken from station 550 of the planimetric map of figure 29.

FIGURE 31.—Downstream end of central gravel bar in left channel of Horse Creek.

bounded by two low terraces, one 5 feet and another 7 feet above low water surface. Within the confining banks of the 5-foot terrace the gravel island and the adjacent gravel flat containing the abandoned channel lie at the same elevation. The new gravel bar generally is somewhat lower than the level of the adjacent island, though at a point about half way down the length of the bar the flat upper surface of the bar is at the same elevation as the surface of the island.

STAGES IN THE DEVELOPMENT OF A BRAID

These observations suggest a sequence of events in the development of a braided reach. In an originally single or undivided channel, a short, submerged central bar is deposited during a high flow. The head of the new gravel bar is composed of the coarse fraction of the bed load which is moving down the center of the channel bed. Because of some local condition not all the coarse particles are transported through this particular reach and some accumulate in the center of the channel. Most of the smaller particles move over and past the incipient bar, but part of the finer fraction is trapped by the coarser material and so deposited. Though the depth is gradually reduced, velocity over the growing bar tends to remain undiminished or even to increase so that some particles moving along the

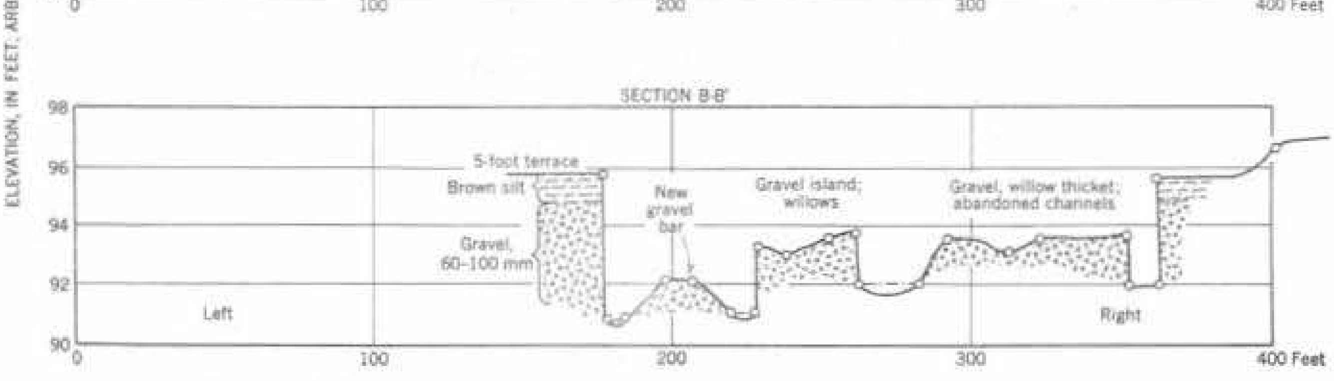


FIGURE 32.—Cross sections of braided reach of Horse Creek near Daniel, Wyo. (Lines of sections shown in fig. 29.)

bar near the center of the channel roll along the length of the new bar and are deposited beyond the lower end where a marked increase in depth is associated with a decrease in velocity. Thus the bar grows by successive addition at its downstream end, and presumably by some addition along the margins. The downstream growth is suggested by the fact that willows became established at the upstream tip while the downstream portions were still bare. A similar gradation in age of vegetation exists in many other islands studied.

The growth of the gravel bar at first does not affect the width of the stream, but when the bar gets large enough, the channels along its sides are insufficient in width to remain stable. Widening then occurs by trimming the edges of the central bar and by cutting laterally against the original sides of the channel until a stable width has been attained. At the same time, some deepening of the flanking channels may occur and the bar emerges as an island. The bar gradually becomes stabilized by vegetation. At some stage lateral cutting against the bar to provide increased channel width becomes just as difficult as against the banks of the original channel, and so the bar is not eliminated. The hydraulic properties of the channel during this process of island formation will be discussed in a later section.

After the island has been formed, the new channels in the divided reach may become subdivided in the same manner. As successive division occurs, the amount of water carried by an individual channel tends to diminish so that in some of these, vegetation prevents further erosion and, by screening action, promotes deposition.

The Horse Creek example demonstrates all of these features. The new gravel bar deposited in the left channel occupies the center of a channel not yet widened by stream action. The sequence of age of vegetation shows that the bar was extended downstream with time, and presumably was built in 2 or 3 years, for at the time the lower part of the bar was bare, the willows at the upstream tip were not more than 2 years old.

The gravel island separating the two main channels is considerably wider than the new gravel bar. The right channel is separated from the abandoned channel by a former island which also was wider than the new bar. When a central linear gravel bar is deposited, the bar may continue to increase in width, forcing the channels farther apart. One reason for this lateral cutting into the original banks can be seen by the direction of the flow at the tip of the gravel island. The low bar (marked C in fig. 29) just below the cable has built downstream until it actually joins the upstream tip of the much older gravel island (marked D). At low flow the water which gets into the left channel pours over the downstream tip of the low bar in a direction nearly perpendicular to the general stream course as indicated by the riffle symbols between the letters C and D in figure 29.

At high discharge the flow impinges against the left bank and subsequently produces a sharp bend in the streamlines to the right as they become alined again with the left channel. Thus the low bar and the upper tip of the gravel island force the flow into a reverse curve or S-shaped path. As a consequence the left bank would tend to erode where the flow impinged against it, while the inside of this curve would be a zone of deposition which would blunt or widen the upstream tip of the gravel island. It is reasoned that the widening of an initial linear bar is probably due mostly to the deposition on the inside of bends that results from obstruction by the bar.

The gravel island is interpreted as a stabilized and enlarged bar which had its origin in a manner typified by the new bar. The gravel in the bar and island are similar. The island has a thin layer of silt covering the surface of the underlying gravel; it is believed that during overbank flow, vegetation stopped the fine material and caused it to be deposited. Coarse material would ordinarily not be carried over the surface of the vegetated island for such material moves primarily in the swifter water of the established channels.

The initial vegetation which sprouts on a new gravel bar begins the screening process and the consequent deposition of thin patches of silt or fine sand promotes the stand of vegetation. Screening of fine material and the improvement of the stand of vegetation by altering the texture of the surface layer are reciprocal and perpetuating.

CHANGES ASSOCIATED WITH CHANNEL DIVISION

FLUME EXPERIMENTS

Experimental work in a flume at California Institute of Technology allowed us to test the hypothesis of bar deposition just outlined. The observations made in the laboratory provide some insight into not only the sequence of events leading to braiding but also into the hydraulic relations between the divided and undivided reaches of channel. First, the progressive development of braids in the flume will be discussed and compared with field examples. Second, the interrelations of hydraulic factors in both the laboratory and natural rivers will be analyzed.

The 60-foot flume had a width of about 3 feet and was filled to a depth of about 5 inches with a poorly sorted medium sand (identical to run 1, app. A). Initial channels of various shapes and sizes were molded by means of a template mounted on a moving

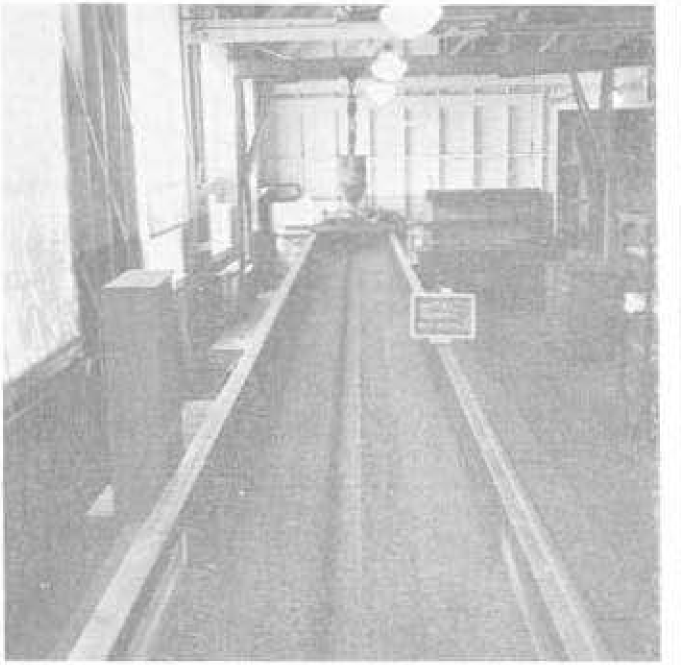


FIGURE 33.—Initial channel molded in the sand bed of the flume, California Institute of Technology.

carriage. One of the initial channels is pictured in figure 33. The traveling carriage also carried a point gage for measuring elevation to an accuracy of 0.001 foot vertically, and 0.005 foot horizontally. The slope of the flume was adjusted by a set of jacks which supported it, and slopes of 0.01 were possible. The flowing water itself altered the initial channel section and slope.

The water supply was recirculated from a storage sump from which it was pumped to an overhead tank equipped with a weir that permitted any desired discharge to be drawn at constant head. The excess water not drawn through the circulating system flowed over the weir and was returned to the sump. The discharge into the flume system was measured by a venturi meter. From the meter the water flowed into a 6-inch pipe which led to a stilling basin at the upper end of the flume, and thence through a honeycomb for smoothing out the turbulence. A 1-foot length of trapezoidal channel constructed of wood formed the transition from the stilling pool to the alluvial channel constructed with the template in the sand bed. Discharges used were in the range of 0.01–0.10 cfs.

At the downstream end of the sand channel was a trapezoidal weir, the elevation of which was kept approximately level with the sand bed of the stream. Below the trapezoidal weir was a stilling pool where the sand settled out, and from which the water was skimmed off and returned to the sump furnishing the water supply.

Sediment was fed into the system in the form of dry sand. From an overhead hopper at the upper end of the flume, the sand was carried out on a small endless belt and dropped into the flowing water in the short wooden flume immediately upstream from the sand channel. The rate of sand feeding was controlled by a variable speed motor which moved the endless belt. The rate of feed of the sand load could be varied from 0 to about 200 grams per minute. During the experiment three sizes of sand were used (see app. A).

In the experiment it was impossible to measure accurately the amount of sand delivered to the settling basin at the lower end. The rate of sand feeding could be accurately obtained by successive samples of the dry material coming off the endless belt. We were forced to rely on an inexact method of determining whether the system was in equilibrium: successive determinations of the longitudinal profile of water surface and dry stream bed. This method is sufficiently accurate under circumstances where the rate at which load is introduced is large relative to the volume of the river channel, for aggradation or degradation could be accurately measured during the progress of a run of reasonable duration. These were the circumstances for most runs, but a more refined method of determining equilibrium would be desirable.

It is important to emphasize the fact that the channel developed in the flume was not a model river but was the prototype of a small stream. The flume-river adjusted not only its slope, but also its depth and width. This can be seen in the tabulated data in appendix C. A period during which sand and water were delivered to the channel at constant rates lasted as long as 25 hours. During this period the flow was interrupted at intervals for measurement of cross sections. Such measurements and corresponding velocity and slope data are tabulated together and labeled a "run" in appendix C.

The first example showing the development of a braided reach is a set of runs (6a, b and 8) in which the initial channel cut by the template was 15 inches wide and 1½ inches deep. For these runs the flume was set at a slope of 0.0114. The discharge was 0.085 cfs, and load was introduced at the rate of 120 g per minute or a sediment concentration, C_s, of 830 ppm by weight. Customarily, the initial width of channel increased very rapidly through the action of the flowing water and attained a minimum value which was stable for the given discharge. In the river being discussed, the average stable width for a discharge of 0.085 cfs was 1.1 feet, The template channel being 1.25 feet (15 inches). slightly larger than the minimum stable value, there was no rapid adjustment. During 22 hours of flow (interrupted for purposes of measurement) a series of bars and islands developed in a 12-foot reach between stations 10–22. The lower end of the entrance box was at station 3, which means that the head of the braided reach was 7 feet downstream from the entrance.

The sequence of stages in the development of this braided reach is shown in figure 34, which includes sketches made of the pattern at various stages and detailed cross sections at one position or station along the flume. A photograph of this braid looking upstream is shown in figure 35. At the end of 3 hours of flow the development of a central submerged bar had proceeded so far that its lower end had caused some deflection of the flow toward the right bank. This resulted

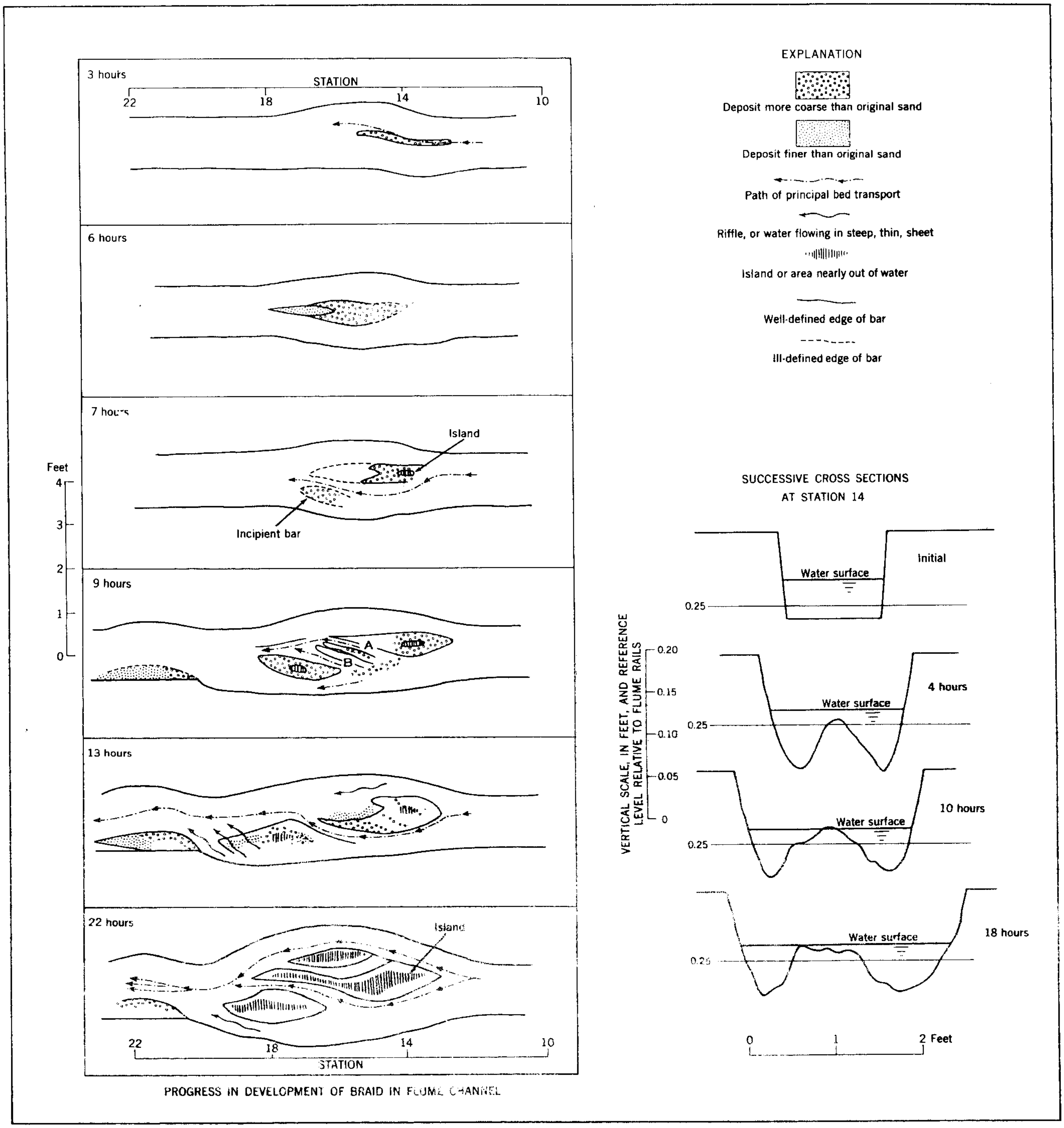


FIGURE 34.—Sketches and cross sections showing progress in development of braid in flume-river (February 16–22, 1954, runs 6–8.) (Profiles shown in fig. 38.)

in a small arcuate reentrant in the formerly straight bank. The head of the submerged bar had similarly caused some cutting on the left bank. The cross sections shown at the right of figure 34 were taken by means of the point gage on the traveling carriage after the load and water were temporarily stopped. The stopping and starting had little effect on the configuration of the bed.

The cross section at station 14 after 4 hours of flow shows the pronounced central ridge or submerged bar. It should be noted, however, that in the upper left diagram showing the plan view at 3 hours, the band of principal bed transport lies *on top of the submerged central bar.* The grain movement in the deeper parts of the channel adjacent to the central bar was usually negligible in the early stage of island development. The central bar continued to build closer to the water surface yet the principal zone of movement remained for a time along the top of the building bar. It was there that some of the larger particles stopped, trapping smaller particles in the building bar. These smaller grains could have been moved by the existing flow had they not become protected or blocked by larger grains.

The central bar in the flume-river was caused by local sorting, the larger particles being deposited in the center of the stream at some place where local competence was insufficient to move them. But, as explained, bar building by sorting does not imply that the deposit is composed only of grains too large to be moved further (see app. B). The sketches of the developing braided reach show an irregular distribution of well-sorted fine material, usually deposited near the toe or downstream edge of the bar where progressive bar development consisted of foreset beds as in a delta. The continual shifting of the channels, then, builds a heterogeneous bar consisting of patches of materials of different size and different degrees of sorting.

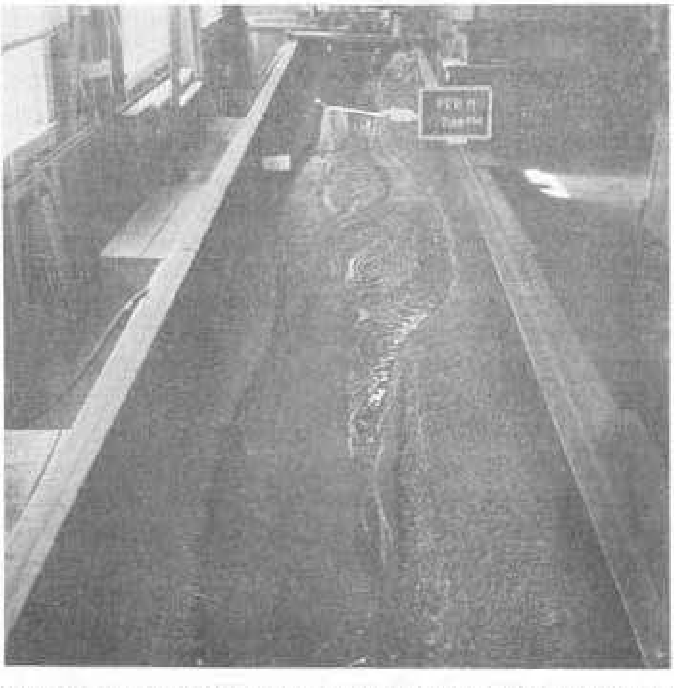


FIGURE 35.—Braided channel developed in flume (February 19, 1954, runs 6-8, 2 p. m.) Note similarity to Horse Creek, figure 30.

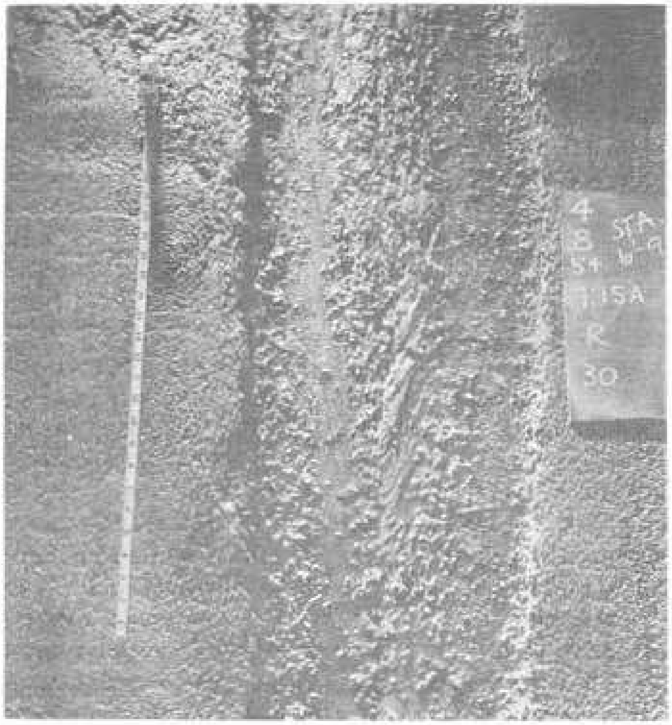


FIGURE 36.—Island formed in a braided reach of the flume-river (April 8, 1954, 7:15 a. m., run 30, stations 6-9.)

By the end of 7 hours of flow the central bar had been built so high that individual grains rolling along its ridge actually "broke" the water surface. Leopold and Miller had noted previously (1956, p. 6) that in arroyos, many large pebbles and cobbles were observed to roll in flows of depth only half the diameter of the rolling stone. By such a process a true island cannot be formed in uniform discharge. However, the deflection of the water by the central bar usually caused local scour in some part of the channels separated by the central bar, and this scour caused a lowering of the water surface which left the bar sticking out of the water as a real island. Such scour was observed in many of the runs and the islands which are indicated in the sketches in figure 34 emerged as a result of this process. This condition is also shown in figure 36, a photograph of a developing island.

The area designated as "incipient bar" in figure 34 at hour 7 had enlarged and emerged as an island by hour 9. Furthermore, after hour 9 of flow a linear bar had developed in the channel area between the two islands, bisecting the flow into two parts, marked A and B. By hour 13, continued bar building in channel A and subsequent lowering of the channel B diverted most of the water out of the old channel A and the primary zone of transport over the bar area was restricted to channel B.

Similar sequences continued to change the configuration of the braided reach, moving the principal zones of transport from one place to another, and at hour 22 there were three island areas. It should be understood that in the flume-river the constant discharge did not permit the islands to receive any increment of deposition after emergence so that an "island" actually represented merely the highest knob of a bar most of which remains submerged. The cross section of station 14 at hour 18 (bottom diagram, right side, fig. 34) illustrates this feature.

The succession of events observed in the flume are analogous to those postulated to account for the characteristics of the reach studied on Horse Creek. The central bar built closer to the water surface and extended itself downstream with time, channels were successively formed and abandoned, and the bars were made up of the coarser fractions of the introduced load but mixed with considerable fine material which had become trapped. The similarities between the field example and the flume can be seen by comparing the photographs in figures 30 and 35.

Nearly all observers who have recorded notes on the action of a braided stream have remarked on the shifting of bars and the caving of banks. Once a bar is deposited it does not necessarily remain fixed in form, contour, or position. This can be seen in the successive cross sections of four stations made during the run pictured in figure 37. Time changes at a particular position are arranged side by side and the downstream variation at a particular time can be seen in the vertical groups. A reference level is given for each section so that the changes of water surface elevation can be compared. The sections grouped on the uppermost horizontal line are at station 6. Comparing the sections from left to right it can be seen that station 6 underwent continued aggradation and the shape of the cross section changed radically, much more than did the area of the cross section.

The horizontally arranged group of sketches at station 10 illustrate the varying elevation of water surface which rose between hours 1½ and 4, fell from hours 4 to 6, and rose again from hours 6 to 11. The fall of water surface elevation is clearly due to the scour of the right-hand channel between hours 4 and 6.

The initial linear nature of the central bar is best illustrated at 6 hours where a central ridge is present through an 11-foot reach between stations 6 and 17. This is shown on the sketch of the plan view in the lower right part of figure 37 and on the cross sections for that time arranged vertically on the figure.

The growth and subsequent erosion of a central bar is also illustrated at station 10 (fig. 37). On the left-hand diagram of station 10 the shape of the initial channel molded by template is shown as a dashed line. After 1½ hours this shape had been altered by the building of a central bar and by slight degradation of the channels beside the bar. By the end of 4 hours the combination of lateral building and deposition on the bar surface had widended the bar and made a double crest. Bar building resulted in a diversion of most of the water into the right channel at station 10 which caused local scouring.

DIVIDED AND UNDIVIDED REACHES IN THE FLUME AND IN NATURAL RIVERS

In both natural streams and the flume-river the slope of the divided reach proved to be greater than that of the undivided reach. The steepening of the divided reach in the flume is very marked. Figure 38 shows the water surface profile data associated with runs 6a and b and 8, February 16–22, 1954. The measurements presented in the left part of the figure are interpreted diagrammatically on the right half of the figure. When considering the measurements it must be recalled that the elevation of the water surface was measured relative to a sloping datum. Thus, water surface profiles which rise downstream relative to the datum mean that the water surface became adjusted to a slope less than that of the flume rails. This can be seen by reference to the diagrammatic profiles on the right of figure 38 where the initial profile, shown as a heavy line, represents the slope of the water surface when the run began and the water started to flow down a channel parallel to the sloping rails. By the end of 9 hours, aggradation had taken place in the reach between station 6 and station 12, and also downstream from station 35. Degradation of the initial channel had occurred between stations 15 and 35 with the establishment of a steep reach in the divided or braided section.

Between hours 9 and 20 of flow, continued aggradation took place in the divided reach but, in general, the steep slope was maintained approximately parallel to that which existed at the end of hour 9. Similarly, the aggrading reach downstream from station 20 maintained nearly the same average slope as that which existed at hour 9, this slope being much flatter than that of the divided or braided reach. A similar sequence can be observed in the profiles presented in the lower left-hand part of figure 37 (associated with run 17, March 11–12). In figure 37 it can be seen that between hours 1½ and 4, the reach from station 10 to

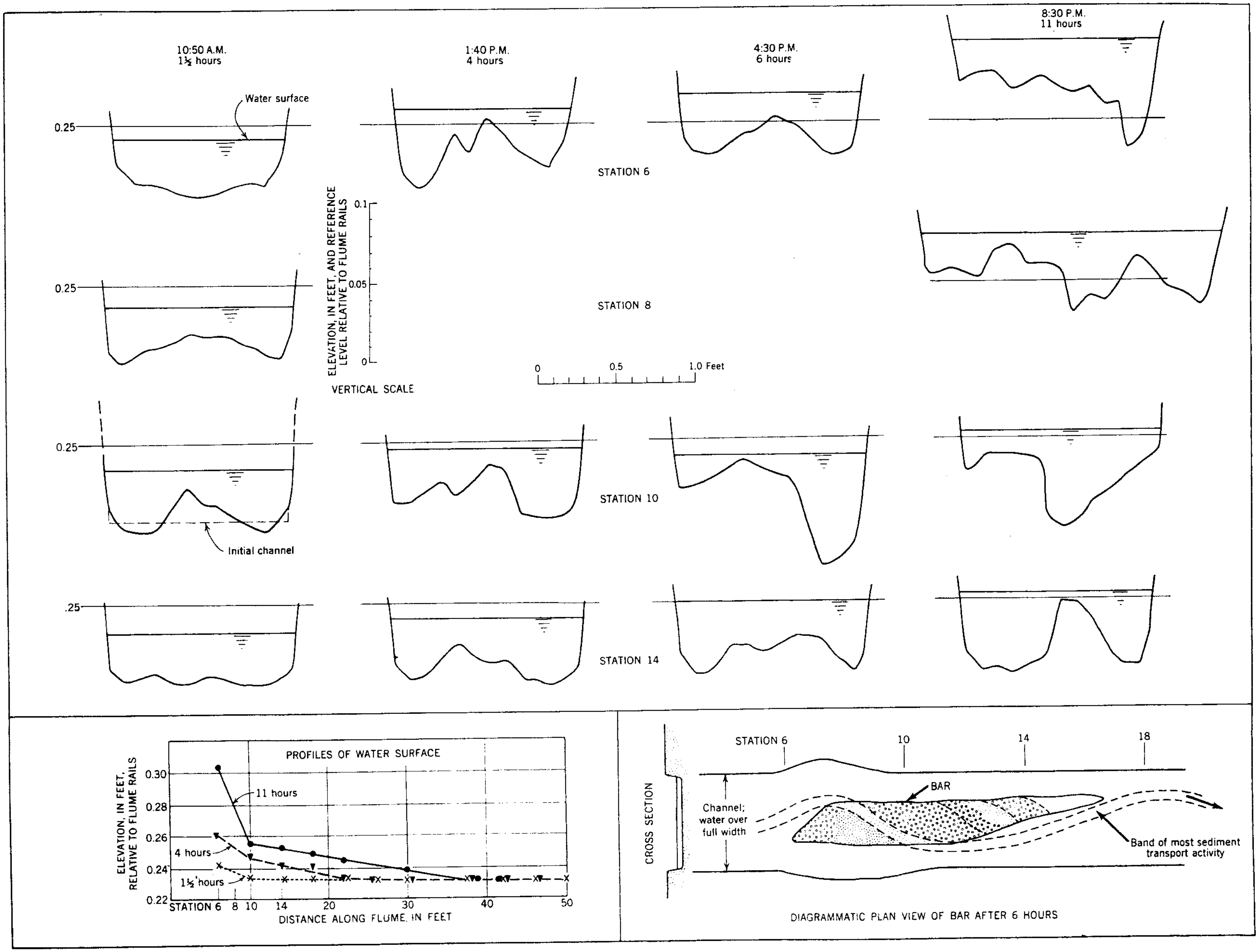


FIGURE 37.—Cross sections showing the progressive development of bars in a braided reach of the flume-river, profiles of water surface, and diagrammatic plan view of bar (March 11–12, 19[illegible])

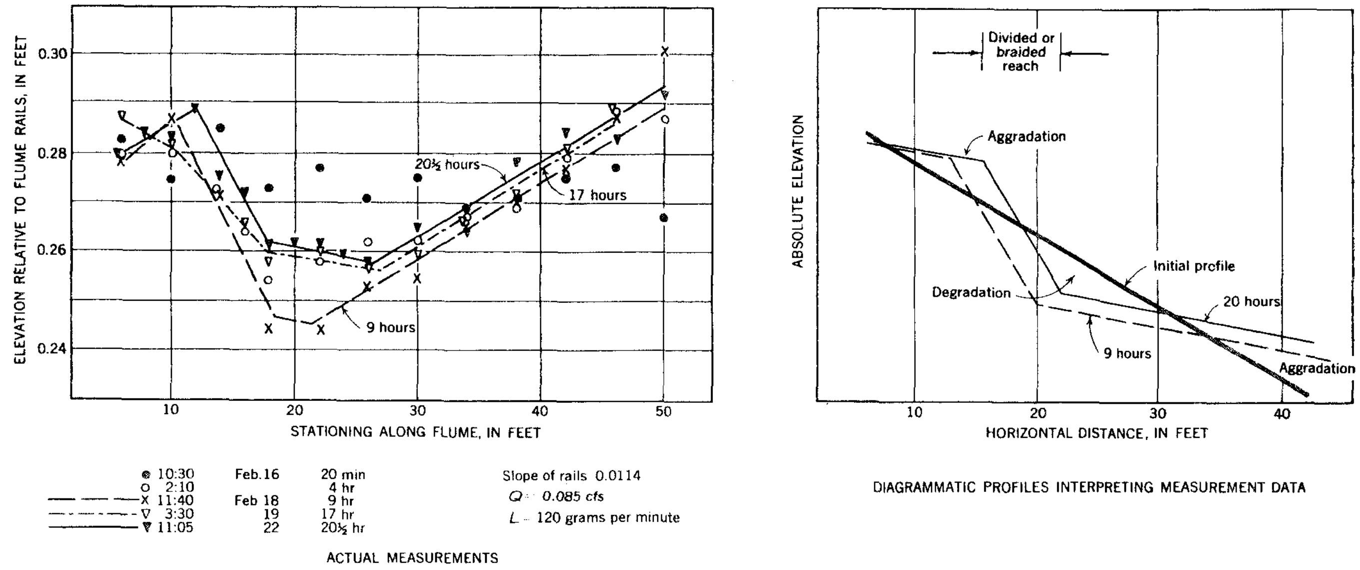


FIGURE 38.—Measured and diagrammatic profiles of flume-river during run of February 16–22, 1954. (Plan view and cross sections for these runs are shown in fig. 34.)

station 22 steepened markedly, but from hours 4 to 11 aggradation occurred at approximately the same slope which existed in this downstream reach at hour 4. In the braided reach upstream from station 10, however, continued aggradation was accompanied by continued steepening between hours 4 and 11.

It is important to note in these runs that *aggradation could take place at a constant slope* without braiding even when the total load exceeded the capacity of the channel for transport. Braiding is developed by sorting as the stream leaves behind those sizes of the load which it is incompetent to handle. If such sorting results in progressive coarsening of the bed material then the slope increases progressively If the stream is competent to move all sizes comprising the load but is unable to move the total quantity provided to it, then aggradation may take place without braiding. Hence, contrary to the assumption often made, the action in the flume river suggests that braiding is not a consequence of aggradation alone. This is brought out in flume runs 30a to 35 which are discussed later in relation to the adjustment of slope in natural channels.

Although the steepening of slope in the divided reach is one of the more obvious of the observed changes in the channel associated with division around an island, nearly all other hydraulic parameters are also affected. Detailed comparisons of an undivided channel and a channel divided around an island, or a potential island, are available for three river reaches and four runs in the flume-river. These comparisons are presented in table 1. (Complete data are tabulated in app. D). Comparisons are shown as ratios of the measurements in the divided reach to similar measurements in the undivided one. The width in a reach containing an island is the width of flowing water. The width of the undivided reach is the width of the water surface upstream or downstream from the island or where there is but a single channel.

TABLE 1.—*Ratio of hydraulic factors of divided to undivided reaches of braided streams (natural rivers and flume-river)*

	Green River near Daniel, Wyo.	New Fork River near Pinedale, Wyo.		Flume at California Institute of Technology			
		Reach 1 (1953)	Reach 2 (1954)	Feb. 15 Sta. 10 and 14	Feb. 16 Sta. 14 and 22	Feb. 18 Sta. 10 and 14	Mar. 5 Sta. 12 and 38
Area	1.3	1.03	1.6	0.94	1.08	0.78	1.07
Width	1.56	1.83	2.0	1.05	1.34	1.48	1.70
Depth	.88	.56	.79	.90	.80	.52	.63
Velocity	.77	.97		1.06	.93	1.27	.93
Slope	5.7	2.3	1.4	1.3	1.4	1.9	1.7
Darcy-Weisbach resistance factor	10.5	1.3		1.1	1.3	.63	1.25

All examples show that channel division is associated with increased width of water surface, increased slope, and with decreased depth. In the three comparisons from our measurements of natural rivers the sum of the widths of the divided channels ranges from 1.6 to 2.0 times that of the undivided one. In the four comparisons made in the flume the ratios vary from 1.05 to 1.70.

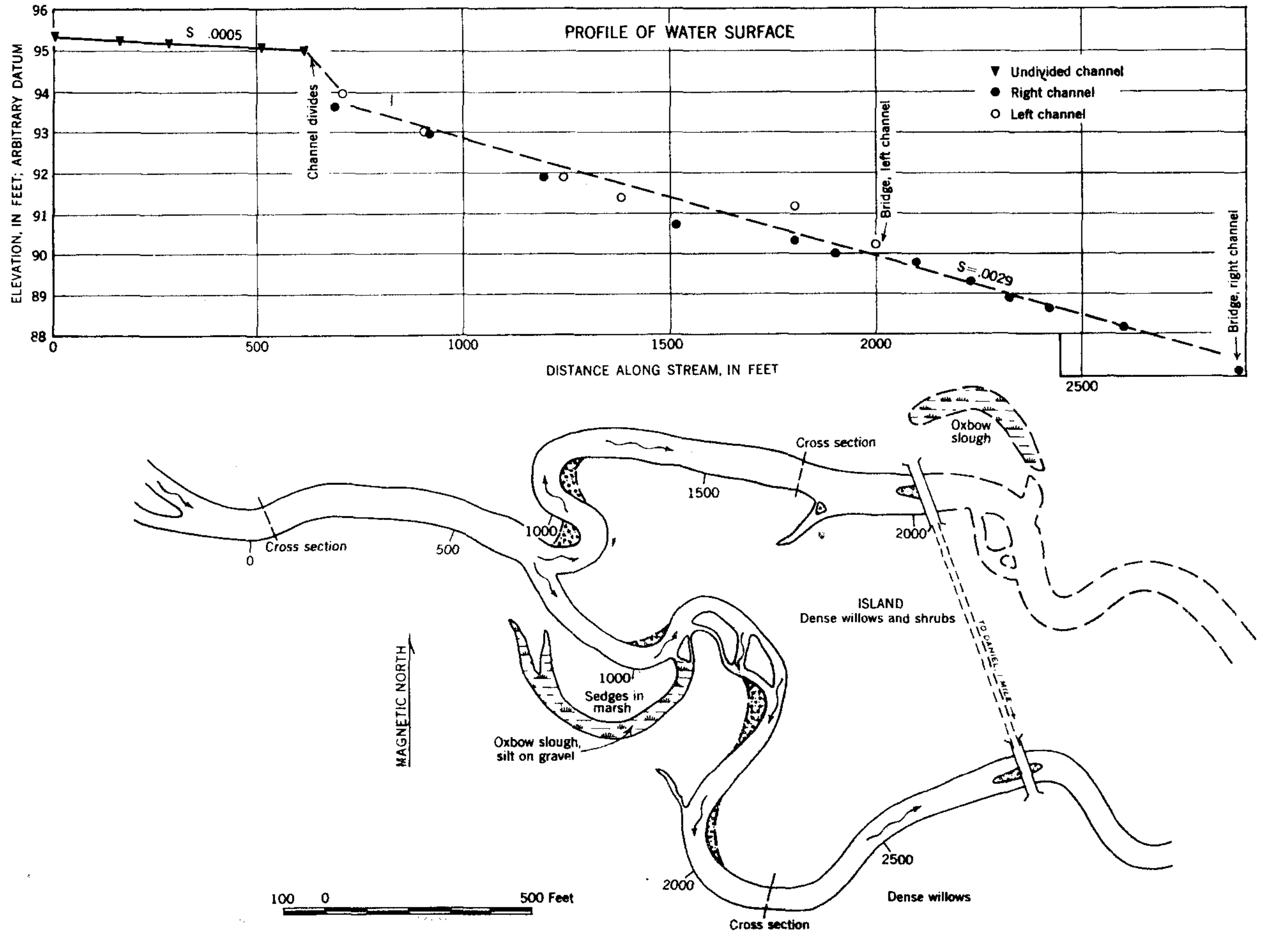
This increase in water surface width caused by development of a bar or an island is accompanied by a decrease in mean depth. The mean depth of the divided reach was computed by dividing the cross-sectional area of flowing water by the total width of water surface in the two channels. The ratio of depths in the divided reach to depth in the undivided reach varied from 0.6 to 0.9 in natural rivers and from 0.5 to 0.9 in the flume-river.

With regard to changes in slope, the profiles of Horse Creek in figure 29 show that the left channel is more conspicuously divided into pools and riffles than the right one, but the slope of each of these divided channels is unquestionably greater—in fact, it is three times as large—as the slope of the undivided part of the stream. The increased slope of the divided reach is even more marked on the profile of the Green River near Daniel, Wyo., where there is nearly a six-fold increase in slope after the river divides (fig. 39). In the example of the New Fork River (fig. 40), the steepening is less obvious primarily because there is a steep riffle between stations 200 and 500 which tends to increase the average slope of the upper 1,000 feet of the mapped reach. If, however, the divided reach between stations 1700 and 2400 is compared with the undivided reach from stations 1500 to 1700, steepening of the slope in the undivided part is again apparent (table 1).

In Rubey's analysis (1952, p. 126) of the division of the channel of the Illinois River by islands he was unable to show from the maps available to him any significant increase in slope in the divided reach, but the maps suggested that "on the average, the slope opposite islands is steeper by something like 5 to 10 percent."

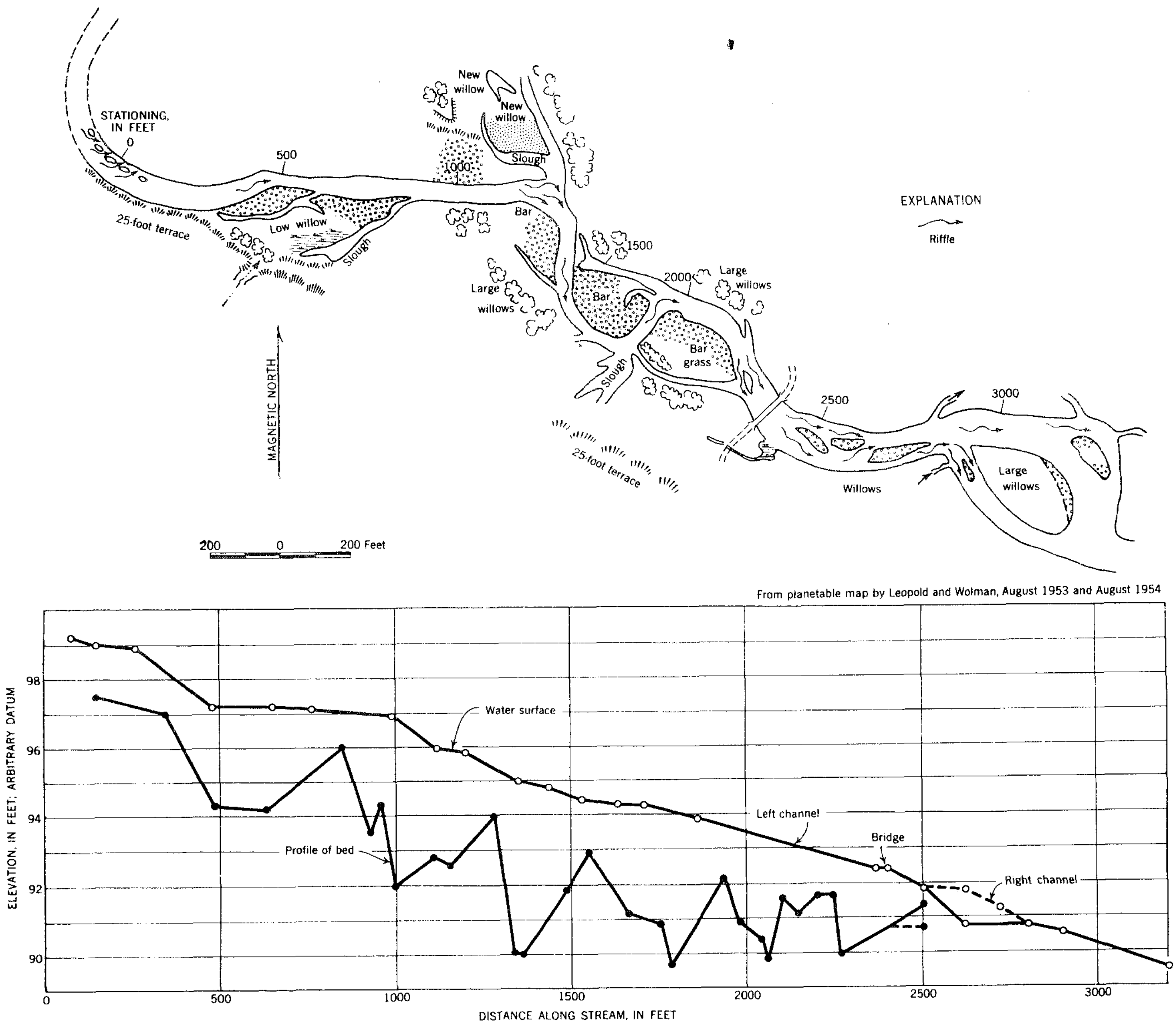
As table 1 shows, there is more variation in the ratios in slopes than there is in the ratios of widths and of depths in divided and undivided reaches. This is due primarily to one example in a natural river, the Green River near Daniel, for which the slope of the divided channel was nearly six times that of the undivided one. With the exception of this one large ratio, however, the natural rivers have ratios of 1.4 and 2.3, and the ratios in the flume ranged from 1.3 to 1.9

The changes in width, depth, and slope caused by island development in the flume-river are of the same order of magnitude as comparable changes in the natural rivers studied.



From planetable map by Leopold and Wolman, Aug. 12, 1953

FIGURE 39.—Map of Green River near Daniel, Wyo., showing a reach in which the channel divides around an island and is, therefore, braided; the individual divided channels meander.



From planetable map by Leopold and Wolman, August 1953 and August 1954

FIGURE 40.—Plan and profile of a braided reach of the New Fork River, 3.4 miles below Pinedale, Wyo. (American Gothic reach.)

The change of cross-sectional area depends upon the relative amounts of change of width and depth. The division by an island caused the cross-sectional area to increase in all three reaches of the natural rivers studied but in the flume there was an increase in cross-sectional area in two instances and a decrease in two instances. The velocity in the divided channels was somewhat less in the two natural rivers for which data are available, but in the flume division caused the velocity to increase in two reaches and to decrease in two others. Nonuniform changes caused by island growth can also be seen in the Darcy-Weisbach resistance factor *f* (table 1).

These data indicate that changes in nearly all the hydraulic parameters occur when a channel divides. In discussing this matter Franzius (1936, p. 38) assumed that conditions in channel division could be approximated by assuming that the width-to-depth ratio, slope, and roughness are identical in divided and undivided channels. Such assumptions would apply only in certain cases but could not be assumed generally applicable. Chien (1955) computed the characteristics of divided channels, using the Einstein bedload equation (1950) and assuming that no change of grain size accompanied channel division. This assumption is more likely to be fulfilled in natural channels than those of Franzius, but both the flume data and the streams studied by us in the field indicate that selective deposition of coarse fractions of the load in the braiding process tends to result in coarser material in the beds of the separate channels than in the undivided channel.

The adjustment of various hydraulic factors to any change in the independent factors may take the form of any one of many possibilities. The adjustments are interdependent and it is difficult to specify in advance how an alteration of conditions will be taken up by the dependent factors.

New islands form and channels often change too rapidly for complete adjustment to equilibrium conditions, but some reaches of braided rivers are very stable indeed, as judged by the size and age distribution of vegetation. The island shown on Peale's map of the Green River near Daniel still exists 70 years later, as can be seen in figure 28. Presumably, in such instances, a closer approach to equilibrium is possible than in transitory channel division. Nevertheless we interpret our observations presented above as indicative that a braided pattern as well as other patterns can indeed be one of the possible conditions of quasi-equilibrium.

SUMMARY: THE BRAIDED RIVER

A braided river is one which flows in two or more anastomosing channels around alluvial islands. This study indicates that braided reaches taken as a whole are steeper, wider, and shallower than undivided reaches carrying the same flow. A mode of formation of a braided channel was demonstrated by a small stream in the laboratory. The braided pattern developed after deposition of an initial central bar. The bar consisted of coarse particles, which could not be transported under local conditions existing in that reach, and of finer material trapped among these coarser particles. This coarse fraction became the nucleus of the bar which subsequently grew into an island. Both in the laboratory-river and in its natural counterpart, Horse Creek near Daniel, Wyo., gradual formation of a central bar deflected the main current against the channel banks causing them to erode.

The braided pattern is one among many possible conditions which a river might establish for itself as a result of the adjustment of a number of variables to a set of independent controls. The requirements of channel adjustment may be met by a variety of possible combinations of velocity, cross-sectional area, and roughness. Braiding represents a particular combination, albeit a striking combination, of a set of variables in the continuum of river shapes and patterns.

Braiding is not necessarily an indication of excessive total load. A braided pattern once established, may be maintained with only slow modifications. The stability of the features in the braided reaches of Horse Creek suggests that rivers with braided patterns may be as close to quasi-equilibrium as are rivers possessing meandering or other patterns.

STRAIGHT CHANNELS

In the field it is relatively easy to find illustrations of either meandering or braided channels. The same cannot be said of straight channels. In our experience truly straight channels are so rare among natural rivers as to be almost nonexistent. Extremely short segments or reaches of the channel may be straight, but it can be stated as a generalization that reaches which are straight for distances exceeding ten times the channel width are rare.

THE WANDERING THALWEG

Figure 41 shows in plan and profile a reach of Valley Creek near Downingtown, Pa. For 500 feet this channel is straight in a reach where the alluvium of the valley is 30 feet thick. Its sinuosity (ratio of thalweg length to valley length) is practically 1.0.

The thalweg, or line of maximum depth, is indicated by a dashed line in the upper portion of figure 41. Though the channel itself is straight, the thalweg wanders back and forth from positions near one bank and then the other. This is typical of a number of nearly straight reaches which we have studied. The wandering thalweg is easier to see in the sketch shown in the lower part of figure 41 in which the position of the thalweg relative to a channel of uniform width is plotted.

Along with the wandering thalweg it is not uncommon to find deposits of mud adjacent to the banks of straight channels. These commonly occur in alternating (as opposed to "opposite") positions. A similar observation has been made by Schaffernak (1950, p. 45). The alternating mud "bars" are related to a thalweg which also moves alternately from bank to bank. In an idealized sense, this plan view of straight channels appears to bear a remarkable resemblance to a meander.

In a straight flume Quraishy (1944) observed that a series of alternating shoals formed in the channel. These he referred to as "skew shoals" (p. 36). Similarly, Brooks (1955, p. 668–8) called the condition in which low channel bars formed alternately adjacent to the left and right walls of his straight flume a "meander" condition.

POOLS AND RIFFLES

Another characteristic of natural streams even in straight reaches is the occurrence of pools and riffles. This has been noted by Pettis (1927), Dittbrenner (1954), and Wolman (1955). Figures 40, 42, and 43, respectively, the New Fork River near Pinedale, Wyo., the Middle River near Staunton, Va., and the Popo Agie near Hudson, Wyo., present plans and profiles for a braided reach, a straight reach, and a meandering reach. Profiles of these three examples are compared

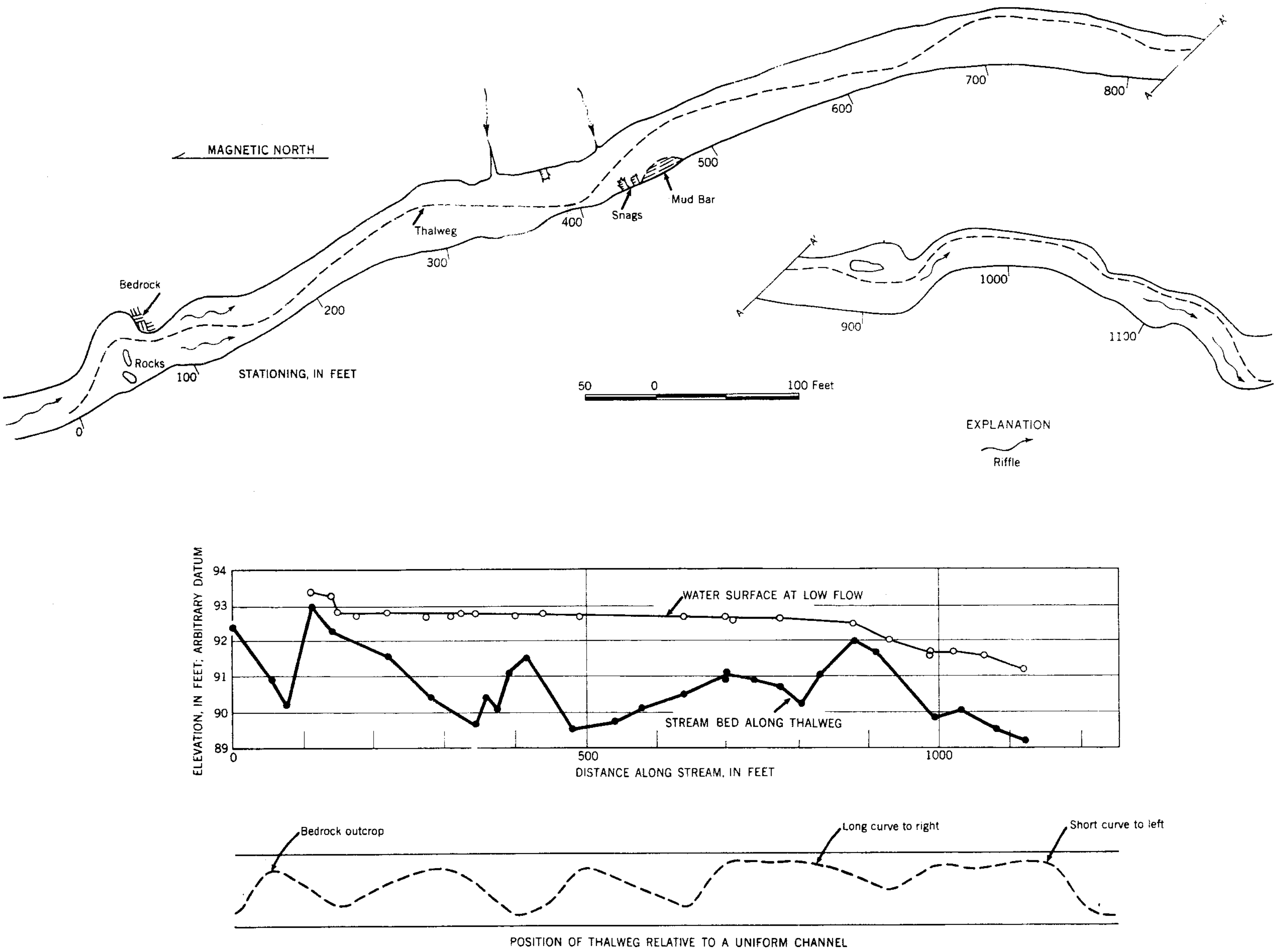
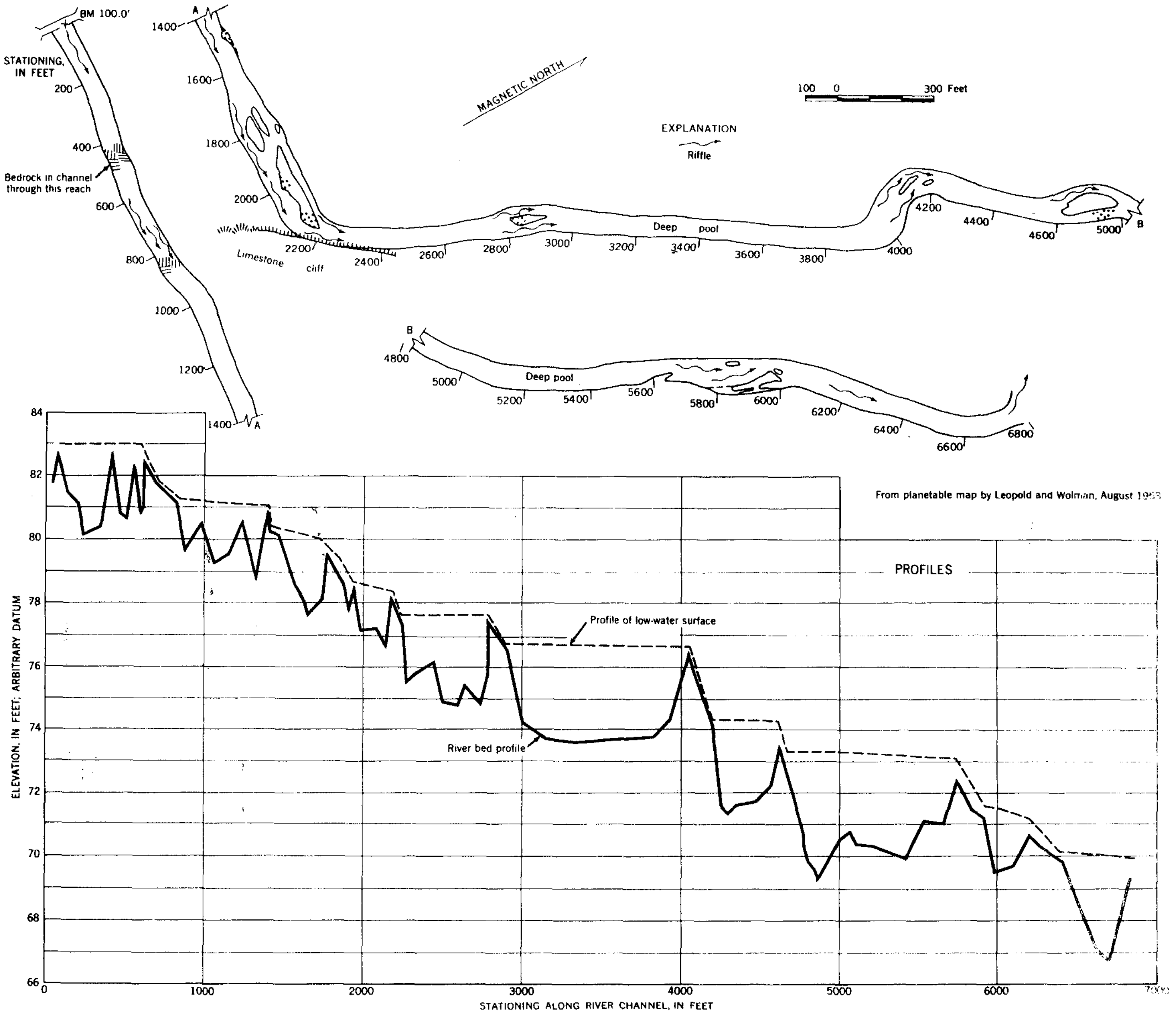


FIGURE 41.—Plan and profile of Valley Creek at Sugar Ridge farm, near Downingtown, Pa.



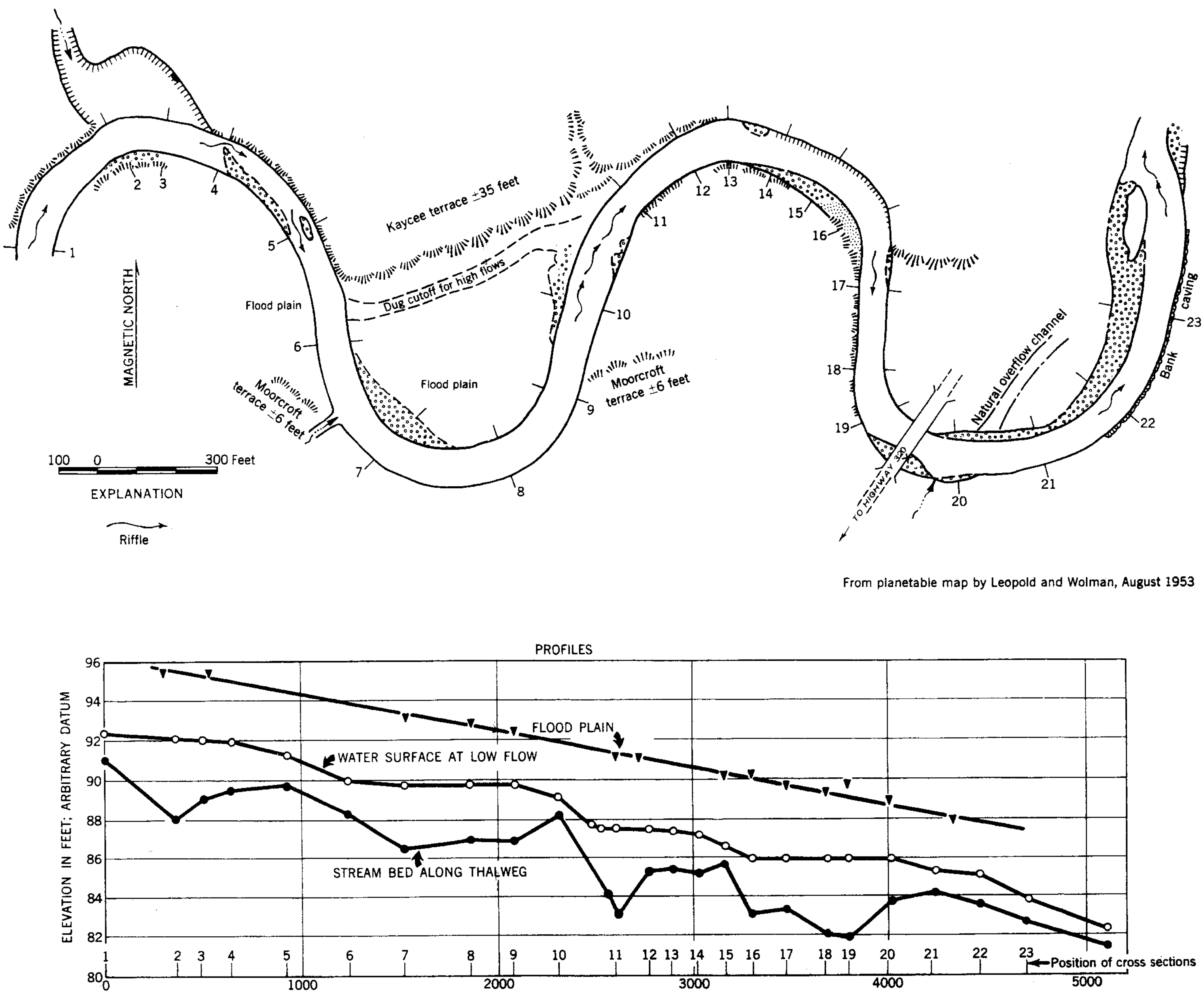
From planetable map by Leopold and Wolman, August 1953

FIGURE 42.—Plan and profile of a reach of the Middle River near Staunton, Va.

in figure 44 which reveals a similarity in the profiles of streams possessed of very dissimilar patterns. Thus, *a straight channel implies neither a uniform stream bed nor a straight thalweg.*

As demonstrated first by Inglis (1949, p. 147), the wavelength of a meander is proportional to the square root of the "dominant discharge." One wavelength (a complete sine curve or 2π radians) encompasses twice the distance between successive points of inflection of the meander wave. It is well known that meandering channels characteristically are deep at the bend and shallow at the crossover or point of inflection. Thus, twice the distance between successive riffles in a straight reach appears analogous to the wavelength of a meander and should also be proportional to $Q^{0.5}$. As an initial test of this hypothesis, bankfull discharge, which we consider equivalent to "dominant discharge" of the Indian literature, has been plotted in figure 45*A* against wavelength of meanders. The figure includes data from straight reaches for which "wavelength" is twice the distance between successive riffles.

The data in figure 45, tabulated in appendix E, include measurements of rivers in India from Inglis (1949), our own field measurements, and some flume data from Friedkin (1945) and Brooks (1955 and personal communication). The wavelengths in Brooks' data obtained in a fixed-wall flume (no. 259, appendix E) represent, as in the nonmeandering natural channels, twice the distance between the "riffles," or low bars, which he observed.



From planetable map by Leopold and Wolman, August 1953

FIGURE 43.—Plan and profile of a meandering reach of the Popo Agie River near Hudson, Wyo.

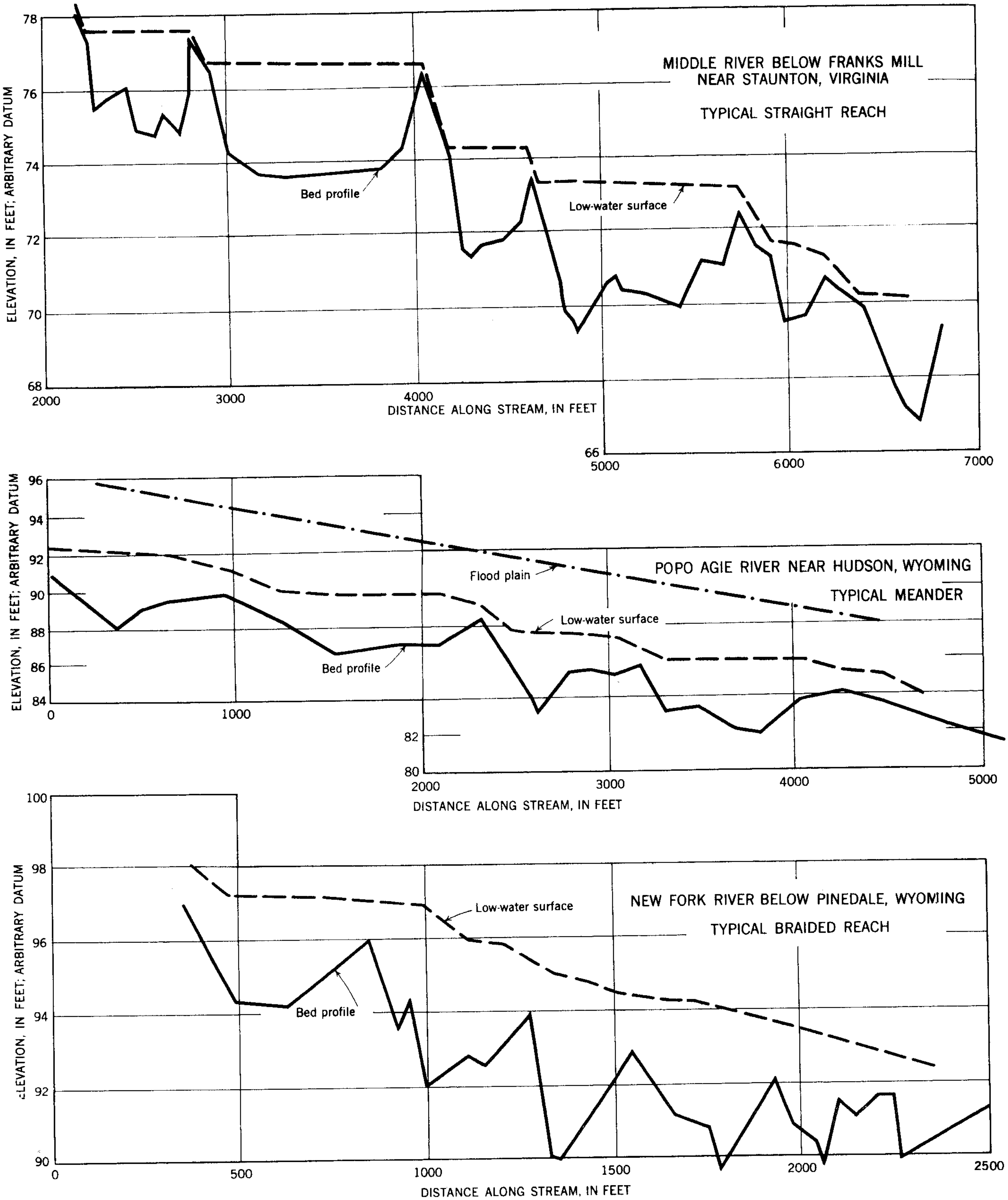


FIGURE 44.—Profiles of three rivers including straight, meandering, and braided reaches.

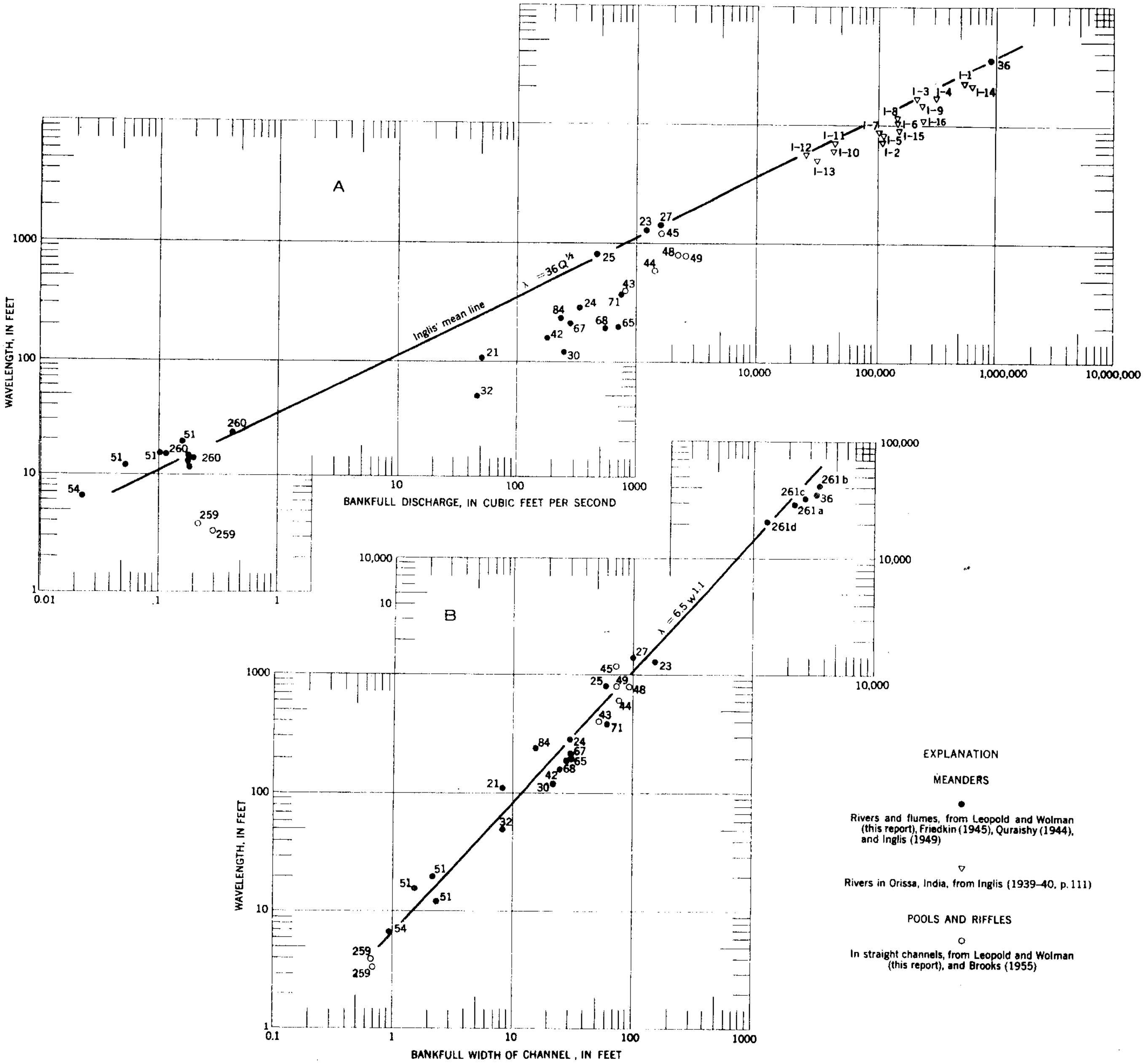


FIGURE 45.—Wavelength of meanders and of riffles as functions of bankfull discharge and channel width.

Figure 45A demonstrates that, with considerable scatter, a relation between wavelength and discharge exists through a 10^8 variation in Q. The data for straight channels do not vary from the average relation any more than those for meanders.

Inglis (1949, p. 144) had called attention to the fact that since width is also proportional to the square root of discharge, wavelength is a linear function of stream width. Inglis did not mention the fact, illustrated in figure 45*B*, that the scatter of points in the width-wavelength relation is less than that in the discharge wavelength relation. The relation in figure 45*B* is quite consistent though it includes straight channels as well as meanders, and the widths range from less than 1 foot in the flume to 1 mile in the Mississippi River. The line drawn through the plotted points in figure 45*B* indicates that in general, the ratio of wavelength to bankfull width varies from about 7 for small streams having widths of 1 to 10 feet, up to 15 for large rivers having widths in excess of 1,000 feet.

Dr. T. M. Prus-Chacinski has told us that European engineers have a rule-of-thumb that the meander wavelength is 15 times the channel width. That our ratio is 1:15 only for large rivers may possibly be influenced by the fact that our data show bankfull width rather than width at some lower stage. Our data indicate that the relation is not a constant ratio but a power function having an exponent slightly larger than 1.0, specifically $\lambda = 6.5w^{1.1}$.

Comparison of figures 45*A* and 45*B* leads us to postulate that in terms of the mechanical principles governing meander formation and the formation of pools and riffles, the wavelength is more directly dependent on width than on discharge. It is argued later in this paper that in general, at a constant slope, channel width follows from discharge as a dependent variable. We suggest, therefore, that wavelength is dependent on width and thus depends only indirectly on discharge. That this relation describes both the distance between riffles in straight channels and the wavelength of meanders leads us to conclude that the processes which may lead to meanders are operative in straight channels.

SUMMARY: STRAIGHT CHANNELS

The observations discussed lead us to three tentative conclusions. First, pools and riffles are a fundamental characteristic of nearly all natural channels and are not confined to meanders. Second, river curves all tend to have a wavelength that is a function of stream width and thus indirectly a function of discharge. Third, even straight channels exhibit some tendency for the flow to follow a sinuous path within the confines of their straight banks.

THE CONTINUUM OF CHANNELS OF DIFFERENT PATTERNS

The physical characteristics of the three specific channel patterns discussed in the preceding section suggest that all natural channel patterns intergrade. Braids and meanders are strikingly different but they actually represent extremes in an uninterrupted range of channel pattern. If we assume that the pattern of a stream is controlled by the mutual interaction of a number of variables, and the range of these variables in nature is continuous, then we should expect to find a complete range of channel patterns. A given reach of river may exhibit both braiding and meandering. In fact, Russell (1954) points out that the Meander River in Turkey, which gave us the term "meandering," has both braided and straight reaches.

This conception of transition in pattern or interrelation of channels of diverse pattern is supported by the data in figure 46 in which the average channel slope is plotted as a function of bankfull discharge (data tabu-

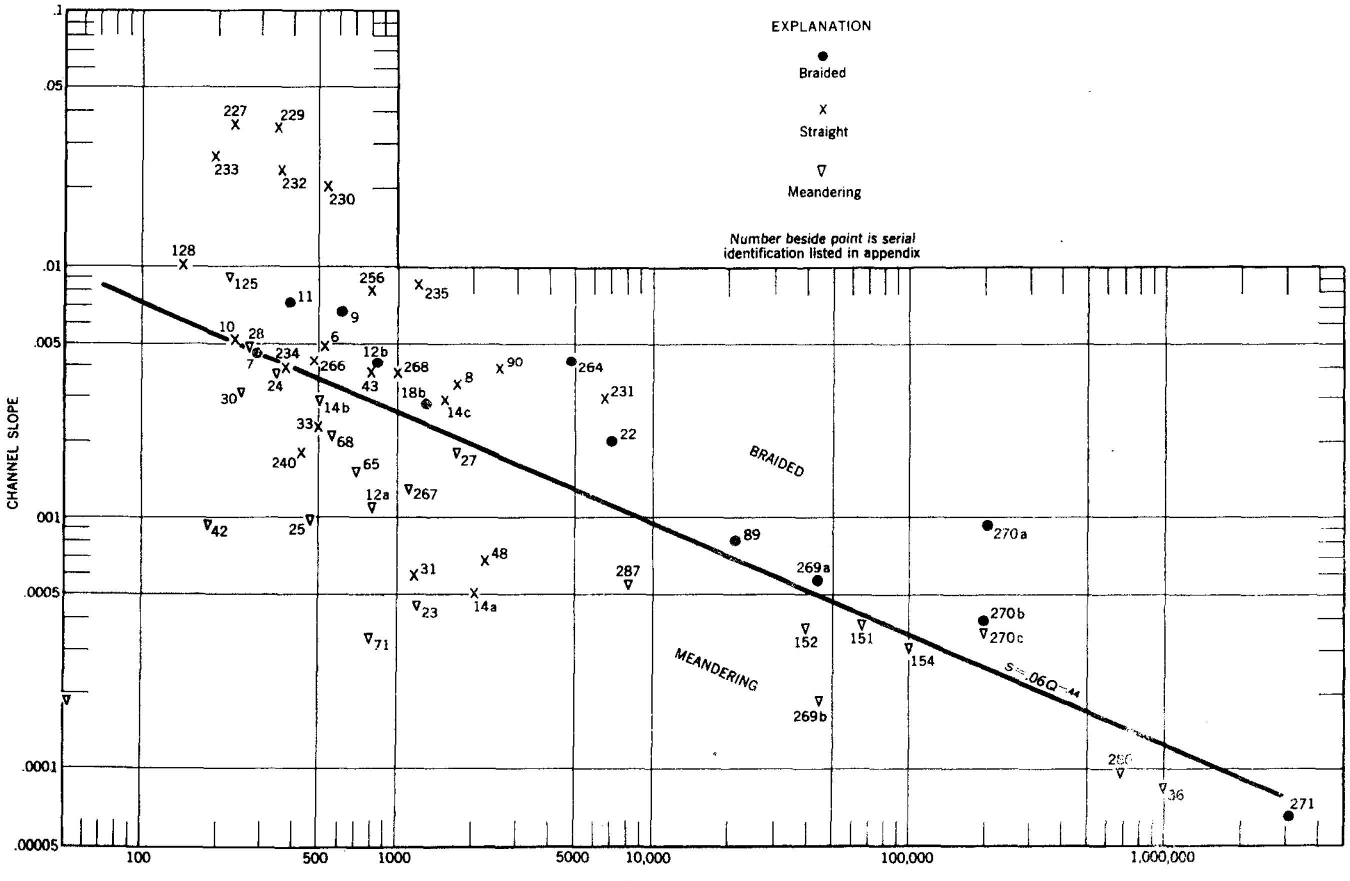


Figure 46.—Values of slope and bankfull discharge for various natural channels and a line defining critical values which distinguish braided from meandering channels.

lated in app. F). Meandering, braided, and straight channels are designated by different symbols. The reaches which have been called meanders are those in which the sinuosity, the ratio of thalweg length to valley length, is equal to or greater than 1.5. This value is an arbitrary one but in our experience where the sinuosity is 1.5 or greater, one would readily agree that the stream is a true meander. Many channels which appear to the eye to be very tortuous actually have rather low sinuosity ratings. The reader may be helped in visualizing these values by inspecting the map of the Popo Agie River near Hudson, Wyo. (fig. 43). This meander on the Popo Agie, the most symmetrical that we have seen in the field, has a sinuosity of 1.73.

The term "braid" is applied here to those reaches in which there are relatively stable alluvial islands, and hence two or more separate channels.

The data in figure 46 indicate that in the rivers studied the braided channels are separated from the meanders by a line described by the equation

$$s=0.06\ Q^{-.44} \qquad (1)$$

For a given discharge, meanders, as one would expect, will occur on the smaller slopes. At the same slope a braided channel will have a higher discharge than a meandering one. The figure shows, moreover, that straight channels, those with sinuosities less than 1.5, occur throughout the range of slopes. This supports the view that the separation of a true meander from a straight channel is arbitrary. Study of the sinuosities of these channels does not reveal an increasing sinuosity with decreasing slope; that is, greater tortuosity is not necessarily associated with decreasing slope. A diagram similar to the one in figure 43 has been plotted by Nuguid.[1] His designation of meanders was not based upon a particular sinuosity but was apparently an arbitrary designation based upon the plan or map of the channel. Nuguid indicated that what he calls normal, or straight, channels have a smaller value of slope than meanders for any given discharge. The present data do not demonstrate such a distinction.

In considering figure 46 it is important to keep in mind that these data describe certain natural channels. In natural channels specific variables often occur in association. For example, steep slopes are associated with coarse material. In a system which contains, as we have pointed out, a minimum of seven variables, a diagram such as figure 46 which treats only two of these cannot be expected to describe either the mechanism of adjustment or all theoretically possible conditions. Because it is drawn from nature, however, it does describe a set of conditions which are to be expected in many natural channels.

Two ideas that will be explored more fully are inherent in figure 46. First, at a given discharge various slopes are associated with varying channel shapes and patterns. Second, in considering an individual bifurcating channel, we are concerned with a division of discharge comparable to the comparison of a downstream point with an upstream point in a river channel system.

Cottonwood Creek near Daniel, Wyo., is a striking illustration of an abrupt change from one stream pattern to another (fig. 47). Above the gaging station, Cottonwood Creek is a very sinuous meander. Immediately below the gage it becomes a braid. The character of the channel where braiding begins is shown by the photograph in figure 48. As the profile in figure 47 shows, the meander reach has a slope of 0.0011, while the braided section occurs on a slope of 0.004. The difference in slope is accompanied by a change in the median grain size from 0.049 foot in the meander to 0.060 foot in the braided reach.

Data for this reach are plotted in figure 46. At a discharge of 800 cfs points 12a and 12b represent, respectively, the meandering and the braided parts of the reach of Cottonwood Creek pictured in figure 47. In changing from a meander to a braid at a constant discharge we should expect the two conditions on Cottonwood Creek to be represented by points on different sides of the line of figure 46, and indeed this expectation is fulfilled.

It is clear that through the short reach of Cottonwood Creek discharge is the same in both meandering and braided parts, for no tributaries enter. The load carried is the same in both meandering and braided parts. There is no indication of rapid aggradation or degradation, and to the extent that this is true, if the meandering reach is assumed to be in quasi-equilibrium, then the braided reach is also. The braided pattern here is not due to excessive load but appears to be a channel adjustment caused by the fortuitous occurrence of a patch of coarser gravel deposited locally in the valley alluvium, the bulk of which was probably laid down in late Pleistocene time.

A reach of the Green River near Daniel, Wyo., is shown on the map in figure 39. Here the transition from undivided to divided channel involves a change of slope, and by reason of the individual channels, a change in discharge. The river at this point has a drainage area of 600 square miles and a bankfull discharge of about 2,000 cfs. It flows in a broad alluvial plain about 2 miles wide. There are myriad sloughs and marshes with a dense growth of sedges and willows. In the reach mapped in figure 39 the main channel divides into two channels about one-quarter

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[1] Nuguid, C. P. 1950, A study of stream meanders: Iowa State Univ., master's thesis.

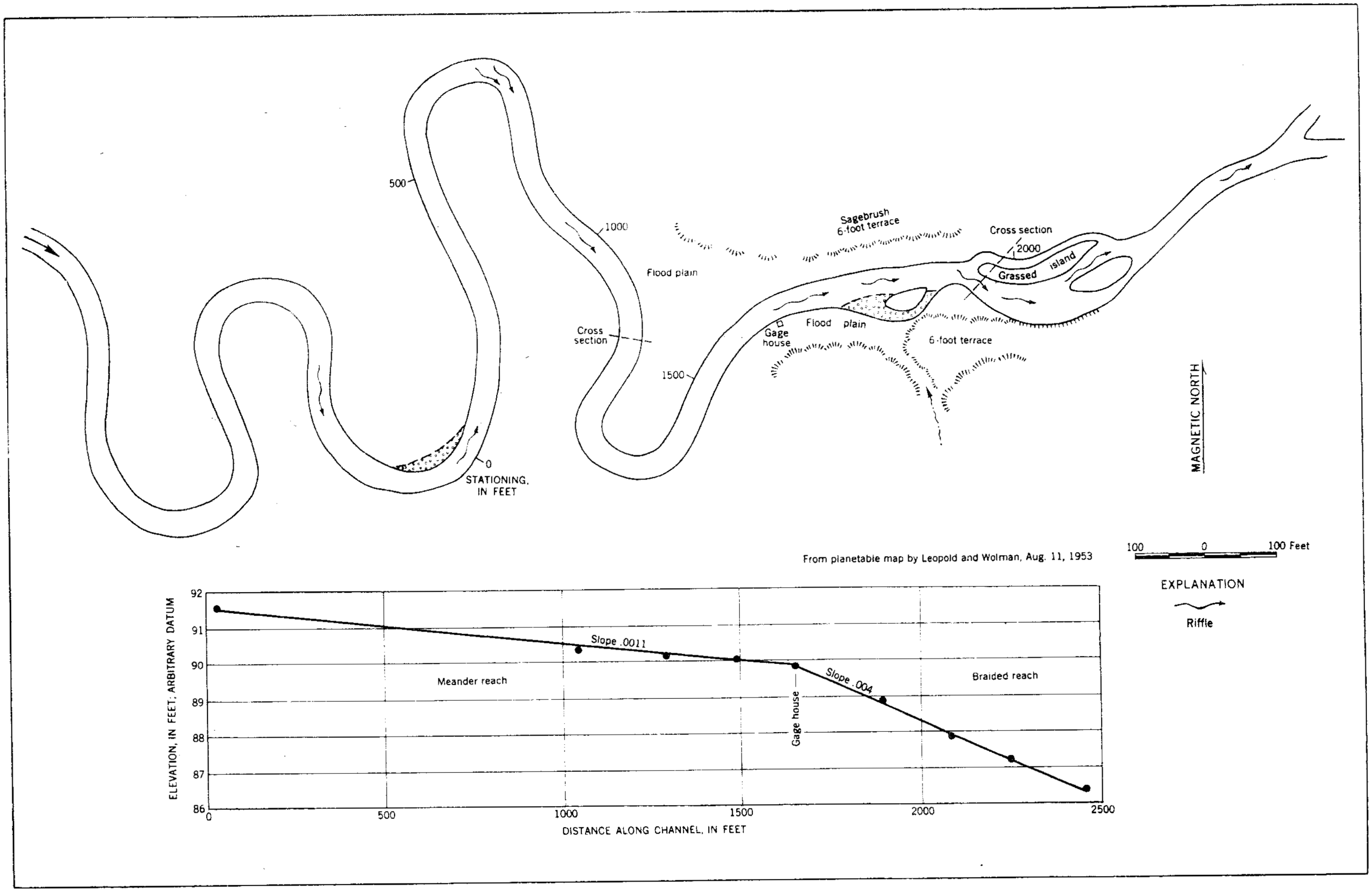

FIGURE 47.—Plan and profile of Cottonwood Creek near Daniel, Wyo. In this reach the river changes its pattern from meander to braid.

FIGURE 48.—Views upstream of the braided part of Cottonwood Creek near Daniel, Wyo. *A* indicates gaging station house where pattern changes from meander to braid. At *B* the first meander bend upstream can be seen.

mile above U. S. Route 189. At the time the map was made the undivided channel carried a discharge of 425 cfs. Below the division the left channel had a discharge of 305 cfs and the right 120 cfs. Flowing on a slope of 0.0005 the undivided channel has a grain size of 0.056 foot, while in both the right and left channels the slope is 0.0029 and the grain size 0.18 foot.

Assuming that the proportion of the discharge flowing in each channel remains the same at the bankfull stage, the three channels for the Green River at Daniel are plotted in figure 46 (points 14a–c, appendix F). In this figure the divided reaches of the channel are considered separately in terms of their local slope and discharge. The undivided part is also considered over a short reach. Thus, the short undivided reach of the Green River at Daniel (point 14a) is given the symbol of a straight river in figure 46. The slopes of the divided channels are equal but their discharges are different. From figure 46 (points 14b, c) we should expect the left channel to be braided and the right to be meandering. As the map in figure 39 shows, the right channel is definitely meandering. The left channel has too small a value of sinuosity to be called a meander. It does include some islands, but it is not a clear case of braiding and should be classified as straight.

Other examples of the relation of channel pattern to discharge and slope can be chosen from rivers in various parts of the world. The great rivers traversing the plain of the Ganges in the State of Bihar, India, provide illustrations. The Kosi River (maximum discharge about 800,000 cfs), rising near Mount Everest, flows out of the Himalayas and over a broad, flat debris cone to join the Ganges. The Kosi is braided in the first 75 miles after it leaves the mountain front and this braiding is associated with deposition of the coarser fractions of its debris load, just as in the flume experiments described earlier. The pattern changes from braiding to meandering at the foot of the debris fan and remains meandering to the junction with the Ganges.

Data on discharge are meager on the Bihar rivers. The mean annual flood for the Kosi, roughly equivalent to the bankfull stage, is about 200,000 cfs. Some decrease of the peak discharge can be expected from channel storage in the 75-mile reach over the debris fan and this is probably compensated by an increment provided by the Bagmati and Kamla Rivers which enter the Kosi at the foot of the fan. As a reasonable generalization, we assume that the bankfull discharge remains constant from the foot of the Himalayas to the junction with the Ganges.

The river slope decreases from about 0.001 near the apex of the debris fan to about 0.00035 in the meandering reach. The values of slope and discharge on figure 46 appear as points 270a–c, (app. F). The meandering reach (point 270c) plots somewhat above the tentative line we have drawn to separate braids from meanders.

Point 271 represents the Ganges River near Patna, and again the discharge is only approximate. This point falls somewhat too low for the line dividing braids from meanders. Though the data are approximate the Kosi and Ganges examples are included because they represent cases of braiding at very large discharge.

The Son River, a northward-flowing tributary, joins the Ganges near Patna. Owing to the great breadth of the Gangetic plain, which in the central portion was constructed principally by the Ganges, the Son flows on a gradient greatly influenced by the Ganges itself. Where the Son joins the Ganges, both rivers flow at approximately the same gradient. The Ganges, having a much larger discharge than the Son, has a braided pattern, while the Son meanders. This illustrates the principle shown in figure 46, that at a given slope, the braided pattern will be associated with a large discharge and the meandering pattern with a small one.

Besides differences in slope and discharge between meanders and braids our observations indicate that in general, at constant slope braided channels are also characterized by higher width : depth ratios than are meanders.

When a channel divides around an island in a braided reach, the separate channels have a smaller discharge, a larger grain size, and a steeper slope than the undivided channel. These changes are not peculiar to braids alone but are in the same direction as the ones we usually find in a comparison of small and large channels with increasing discharge in the downstream direction.

The relation of channel pattern to slope and discharge is of particular interest in connection with the reconstruction of the alluvial landscape from profiles of terrace remnants and from alluvial fills. Changes of climate such as occurred in the Pleistocene might be accompanied by changes in precipitation and runoff. Such variations in streamflow might produce changes in the stream pattern without any accompanying change in the quantity or caliber of the load. An increase of flow could result in a meander becoming a braid; a decrease in discharge could make a braided channel a meandering one. Yet, a change in the character of the load, such as an increase in caliber which the presence of a valley glacier might provide, could result in an increase in slope and a change from meandering to braiding without any change in the precipitation or discharge. The presence, then, of material of different sizes in successive valley fills suggests that at different periods in its history the river which occupied the valley may have had several distinctive patterns. As the pattern of major rivers in an area is a significant feature of the landscape, the application of such principles to historical geology may prove of some help in reconstructing the past.

SUMMARY: THE CONTINUUM OF CHANNEL PATTERNS

The observations described above demonstrate the transitional nature of stream patterns. A braided stream can change into a meandering one in a relatively short reach. Individual channels of a braided stream may meander. A tributary may meander to its junction with a braided master stream.

When streams of different patterns are considered in terms of hydraulic variables, braided patterns seem to be differentiated from meandering ones by certain combinations of slope, discharge, and width-to-depth ratio. Straight channels, however, have less diagnostic combinations of these variables. The regular spacing and alternation of shallows and deeps is characteristic, however, of all three patterns.

This continuum of channel types emphasizes the similarity in physical principles which determine the nature of an individual channel. The next section discusses some aspects of these principles. Although our understanding of them is far from complete, the analysis does indicate the complex nature of the mechanisms controlling diverse natural channels.

THE NATURE OF CHANNEL ADJUSTMENT TO INDEPENDENT CONTROLS

Many geologists accept the idea that geology, climate, and interrelated hydrologic factors are the ultimate determinants of river morphology. Nevertheless, the details of how this control is exercised, particularly with respect to the hydraulic mechanisms, have not been fully described.

It is the purpose of this final section of the present report to illustrate, from our field and laboratory observations, some parts of the process by which the river channel is ultimately controlled by geology and climate through the effect of these factors on discharge and load.

The shape and pattern of the river channel are determined by the simultaneous adjustment of discharge, load, width, depth, velocity, slope, and roughness. In order to study the behavior of any of the variables separately, the remaining ones must be kept constant. Obviously, this seldom occurs in nature. Nevertheless, it has been possible to make some observations in natural channels in the field and in the flume under conditions in which several of the variables do remain constant. These observations of isolated parts of the mechanism of adjustment in river channels are presented in the following section. Each example is a simplification of the general case involving simultaneous adjustment of all of the variables. Segregated into a sequence of actions and responses, the process of adjustment is somewhat easier to visualize.

DEVELOPMENT OF RIVER WIDTH

During a flood the process of bank caving and cutting takes place with relative rapidity. One high flow can make more change in channel shape in the direction of increasing width than many succeeding days of lower flows can alter. It is reasonable to suppose, however, that the quasi-equilibrium width of the channel is determined not by those floods which occupy the entire valley, but rather by discharges which attain or just overtop the banks of the channel (Wolman and Leopold, 1957). If the width is larger than necessary for quasi-equilibrium, the unused parts of the wide channel are taken over by vegetation which not only tends to stabilize the places where the roots are present, but the vegetation itself induces deposition. The establishment of vegetation in unused parts of a natural channel provides a slow but effective way of reducing a width which has been made excessive during high flows. The deposition of root-bound mud lumps seen on the bars of braided streams in Wyoming is one way vegetation tends to become established. It is well known that plant seeds are frequently included in flood debris deposited along high-water marks. As described by Dietz (1952), lines of even-age vegetation can often be observed marking the zone of deposition of seeds on sloping river banks.

We have noted in natural channels and in the flume that the wandering thalweg of a straight reach provides an additional mechanism for decreasing the width of the channel. Deposition of material on the insides of these thalweg bends tends to reduce the channel width. These areas of deposition may also be associated with the loci of vegetation mentioned above.

The width of a river is subject to constant readjustment if the banks are not well stabilized by vegetation. The magnitude of the readjustment depends on the nature of the banks and the amount and type of vegetation they support. In the eastern United States river banks generally tend to be composed of fine-grained material having considerable cohesiveness, and large trees typically grow out from the bank and lean over the stream. Their roots are powerful binding agents, and under these conditions width adjustments are small and slow. Only the large floods are capable of tearing out the banks. In the semiarid West width adjustments appear to be greater owing to generally more friable materials making up the banks and to less dense vegetation. Though examples for which adequate data are available are not numerous, a few may be mentioned.

The Verde River in Arizona has experienced in the last half century several floods of considerable magnitude. The flood of 1891 widened the channel greatly but in subsequent years vegetation became established and the width gradually became restricted. The Gila River in Arizona has not experienced a great flood since 1916 and vegetation and deposition have tended to narrow the channel in the subsequent years

After construction of Hoover Dam the channel of the lower Colorado River changed considerably. Data on changes of width at Yuma, Ariz., were analysed by Leopold and Maddock (1953) who showed that the new width is much smaller than existed before the higher flows were eliminated.

If these lines of reasoning are correct, it might be supposed that if rivers from a great diversity of geographic areas were considered, flood discharge would correlate more closely with river width than it would with any of the other channel factors such as depth, velocity, slope, or grain size, because the latter are apparently less directly controlled by discharge. Data from such diverse rivers as the arroyos in New Mexico, Brandywine Creek, Pa., the Yellowstone and Bighorn Rivers, and the upper Green River indicate that such is is the case. There is, of course, considerable variation in width of streams having equal discharges of a similar frequency. Nevertheless, the variation between streams at a particular discharge is small relative to the change in width with increasing discharge in the downstream direction. The difference in width between streams having equal discharge appears to be related to sediment concentration and to the composition of the bed and banks.

The close relation between channel width and discharge is also shown by several runs in the flume (table 2). Runs 23b and 30d each had a discharge of 0.033 cfs. Despite the fact that the bed material in run 30d was 6 times as coarse as that in run 23b, and the slope about 10 times as steep, each run developed the same width.

TABLE 2.—*Comparison of channel factors in two flume-runs at equal discharge*

[California Institute of Technology flume, 1954]

	Run	
	23b	30d
Discharge cubic feet per second	0.033	0.033
Median grain size feet	.00059	.0036
Load pounds per second	.00121	.00202
Width feet	.66	.67
Hydraulic radius feet	.0555	.0320
Velocity feet per second	.68	1.36
Slope	.00175	.0117
Darcy-Weisbach resistance factor	.0575	.0523

The rapidity with which the width of the channel in the flume adjusted to the discharge indicates the close association of the two. When the water was first turned on, if the initial channel shape molded by the template was not in equilibrium with the discharge, the adjustment of shape took place very rapidly indeed. More than 20 runs were made in which the initial channel shape was not wide enough for quasi-equilibrium with the discharge, and in all of these runs the adjustment of the channel width by bank erosion and the consequent change of mean depth took place, on the average, in less than 5 minutes. The runs lasted not less than 5 hours and often as long as 30 hours. After the initial adjustment in channel width within the first 5 minutes, no subsequent change in width took place during the rest of the run. In interpreting this flume observation, it should be noted that the channel within the flume was composed of completely uncemented sand without any clay for binding the channel banks. An inspection of the cross sections of figure 37 shows that the sand banks above the water line stood nearly vertical for the duration of a run without any tendency for caving or progressive widening.

When a template was used which established a channel wider than that which the water would have cut—that is, wider than necessary for quasi-equilibrium—there was little or no adjustment of the channel to a narrower width except gradually in connection with tendencies for general aggradation or degradation.

From the evidence presented we tentatively conclude that the width is primarily a function of discharge.

The magnitude of the effective discharge to which the width is adjusted is considered in another paper (Wolman and Leopold, 1957) where we argue that it occurs about once a year.

CHANNEL ROUGHNESS AND RESISTANCE

One of the ways by which the lithologic character of a basin affects river morphology is the size of the particles contributed to the debris load. To relate this effect to the hydraulic mechanisms by which the channel is adjusted, it is necessary to consider the interaction of grain size with other hydraulic factors.

Engineers are familiar with the concept (Rouse, 1950) that at high Reynolds numbers the Darcy-Weisbach resistance coefficient,

$$f \propto \frac{gRs}{v^2} \tag{2}$$

is a function of relative roughness. Where the roughness is controlled by the grain size, relative roughness may be defined as the ratio of grain size to the depth of flow.

For flow in pipes empirical relations between resistance coefficient and relative roughness have been obtained, and in these relations the "grain size" term has usually been defined on the basis of a uniform sand size. The size of roughness elements of pipes of various materials are often expressed in terms of "equivalent grain size," that is, uniform grains which gave comparable resistance.

RESISTANCE CONTROLLED BY SIZE OF BED MATERIAL

The beds of natural rivers are often characterized by a wide range of particle size, particularly where the bed material is gravel. Because of both organized and random variation of grain size-distribution over the channel bed, the sampling problem is in itself important. Furthermore, even when an adequate sampling procedure is adopted, one must choose some representative size or some characteristic of the size distribution to typify the bed material.

Thus far no completely satisfactory method has been developed for relating grain size in natural rivers to resistance. Our approach to the problem has been an empirical one. The size-distribution of grains making up the beds of several river reaches was measured, using a method described by Wolman (1954). Some of the size-distribution data are included in appendix G, and the values of median grain size determined by the same method are shown in appendix H for a more extensive list of river locations.

In our attempt to relate grain size to resistance, the grain size parameter chosen is D_{84}; that is, 84 percent of the material on the cumulative curve is finer than the size D_{84}. The 84 percent figure is one standard deviation larger than the median size, a choice guided by our experience that this size gave the best correlation with resistance.

Figure 49 shows an empirical relation between a resistance parameter $\frac{1}{\sqrt{f}}$ (where f is the Darcy-Weisbach coefficient) and relative smoothness (the ratio of mean depth of water, d, to grain size D_{84}). The data in figure 49 are for a number of reaches of Brandywine Creek, Pa., (data from Wolman, 1955). The equation for the straight line drawn through the points is

$$\frac{1}{\sqrt{f}}=\left(\frac{d}{D_{84}}\right)^{0.5} \tag{3}$$

The data from Brandywine Creek include measurements of the slope of the water surface which, in conjunction with the measurements of the bed material size, are available for very few locations elsewhere. To be correct, the slope used in the computation of f should be the slope of the energy grade line. Our data indicate, however, that for the purposes of this generalized analysis, the difference between the water surface and energy slopes is not significant.

For streams other than Brandywine Creek, our data do not include water surface slope but only the mean slope of the channel bed. The latter is usually a rough approximation to water surface slope but its use constitutes an additional source of variance. It is not astonishing, therefore, that when such data are added to those for Brandywine Creek as has been done in figure 50, the scatter is greater than in figure 49. Nevertheless, the mass of points encompass the points for Brandywine Creek alone and these two figures indicate in a general way how geology, through its effect on grain size, may influence the river channel properties.

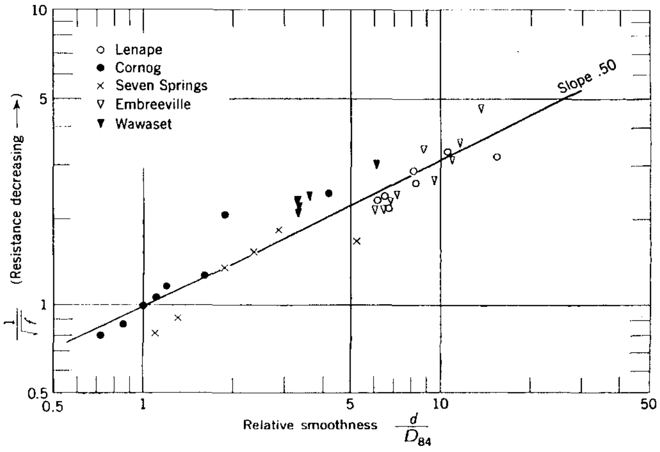

FIGURE 49.—Relation of relative smoothness and a resistance factor for data collected on Brandywine Creek, Pa.

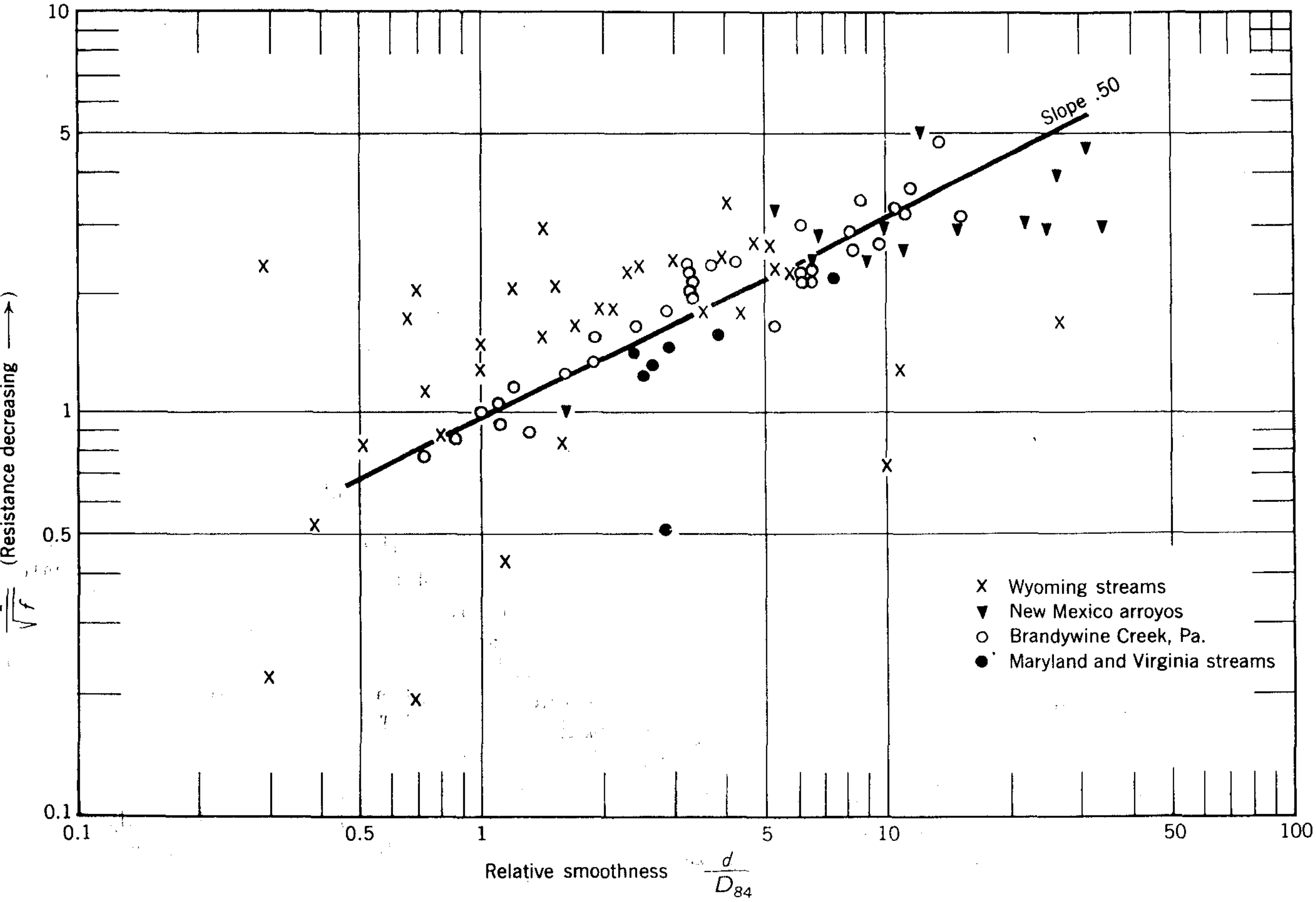

FIGURE 50.—Relation of relative smoothness to a resistance factor for all of the data collected by the authors.

One reason the empirical relation presented above is defined only poorly is that the computed resistance is probably not solely a function of the size of the bed material. Although the data largely represent streams with coarse beds in which the ratio of width to depth is usually greater than 20 to 1, the resistance in some of them may be affected by vegetation, channel alinement, or other factors not attributable to grain roughness. In the event that grain size is not the dominant factor controlling the resistance, the relation shown in figures 49 and 50 would not apply.

RESISTANCE RELATED TO BED CONFIGURATION

In many natural channels with beds of fine material the roughness of the channel is related to the dunes and ripples which form on the bed rather than to the size of the discrete particles themselves. This relation is illustrated by an example from the flume.

The photograph (fig. 51) of the bed of the channel in run 23b shows the size and spacing of dunes. These dunes were characteristic of all runs in which the bed was composed of fine sand, D_{50} equal to .00059 foot. As table 2 shows, in run 30d the grain size was 6 times as large as it was in run 23b. Figure 57 shows the bed in run 30d. When each was experiencing the same discharge, however, the resistance factor in run 23b was approximately equal to that in run 30d. Thus, the adjustments in velocity, depth, and slope which accompanied the changes in the configuration of the bed of fine sand resulted in a resistance in the bed of fine material equivalent to that in the much coarser channel. Where bed configuration is important, the channel roughness can no longer be considered even partially independent. Roughness is controlled by changes which take place in velocity, depth, and slope in response to changes in discharge and load. Detailed studies of sediment transport by Brooks (1955) support this conclusion.

SEDIMENT TRANSPORT, SHEAR, AND RESISTANCE

The complexity of the problem indicated by the brief observations on bed configuration and resistance leads directly to a consideration of some illustrations of the interrelation of resistance, shear, and sediment transport.

In some of the runs made in the flume, a deep

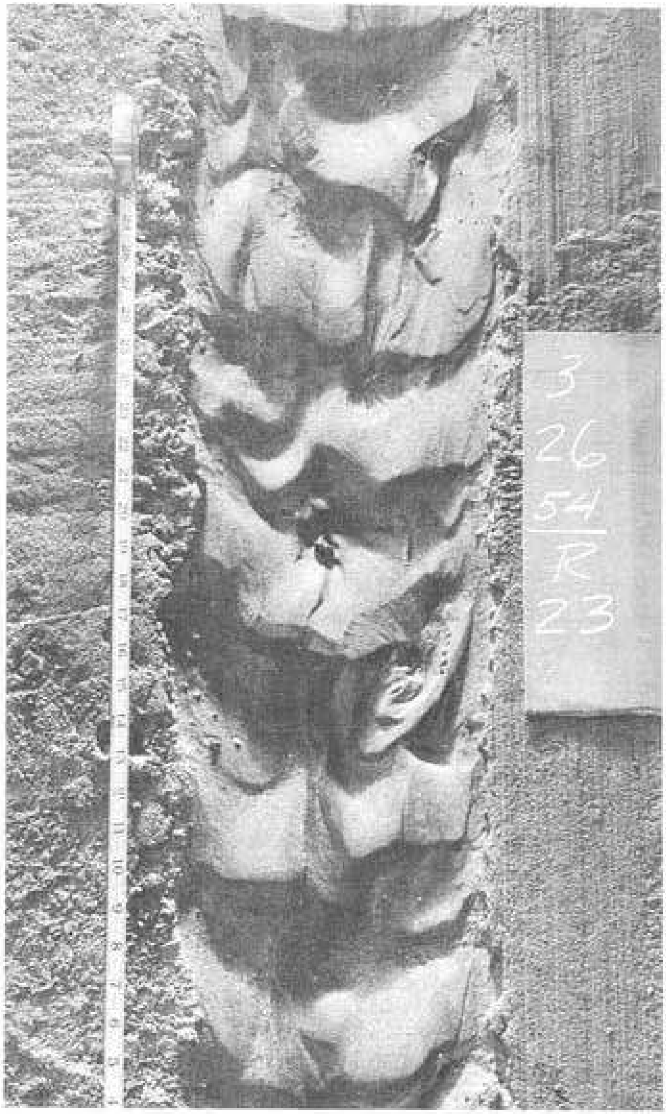

FIGURE 51.—Dunes in fine material on bed of flume-river (March 26, 1954, run 23b.)

trapezoidal channel (template E, run No. 20a, b, c, was molded in the sand. Though the discharge nearly filled the channel, the sand making up the bed of the flume was not moving. Load fed at the upper end of the flume tended to move downstream as a front, sediment deposited in a given reach building up the bed and gradually reducing the depth and increasing the velocity in the reach. When the depth was decreased sufficiently, the grains passed over the new deposit and were carried downstream where they rolled over the end of the new deposit like foreset beds being deposited in a delta.

TABLE 3.—*Comparison of reaches of channel before and after passage of sediment front*

[California Institute of Technology flume, March 18, 1954]

	Run		
	20a	20b	20c
Station	9	13	26.
Time	8:00 a. m.	3:50 p. m	3:50 p. m.
Position of front relative to the station	1 foot downstream.	5 feet downstream.	8 feet upstream.
Discharge .... cubic feet per second	0.086	0.086	0.086.
Load .... pounds per second	.00253	.00253	No movement.
Velocity .... feet per second	1.18	1.18	0.66.
Hydraulic radius .... feet	.064	.062	.120.
Slope	.0068	.0041	.0018.
Shear ($\tau_0 = \gamma Rs$)	.027	.016	.014.
Darcy-Weisbach resistance factor	.080	.047	.130.

In run 20, (table 3) stations 9 and 13 are upstream from the depositional front, and station 26 is downstream from the front. The data in the table show that passage of the front through a given reach was accompanied by an increase in velocity and slope and by a decrease in hydraulic radius. The shear (computed as γRs) at station 26 in which no sediment was moving, however, very nearly equaled the shear at station 13 through which sediment was moving. The movement of sediment, however, at station 13 was associated with a much lower resistance.

At the outset of run 17 no sediment was being removed from the bed of the channel until sand introduced at the head of the flume moved down the channel. As the run progressed the sediment load introduced into the flow moved progressively downstream as a thin sheet of material along the bed. After passage of this sheet, movement on the bed was continuous. Vertical velocity profiles taken at station 36.8 before and after passage of the sheet are shown in figure 52. The grain size remained constant and the rate of change of velocity with depth was greater when sediment was not moving on the bed. As the rate of change of velocity with depth is directly proportional to the shear velocity and the Von Karman kappa, it is tentatively assumed that the transport of sediment alters the value of kappa as found by Vanoni (1946).

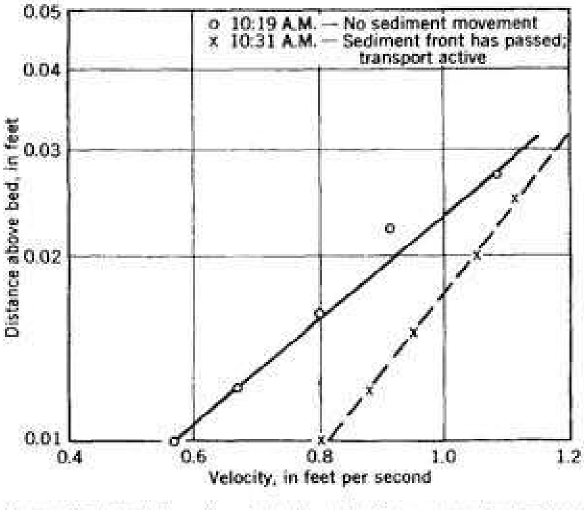

FIGURE 52.—Vertical profiles of velocity in the flume-river showing that at a given grain size, shear velocity is not the sole determinant of bed transport.

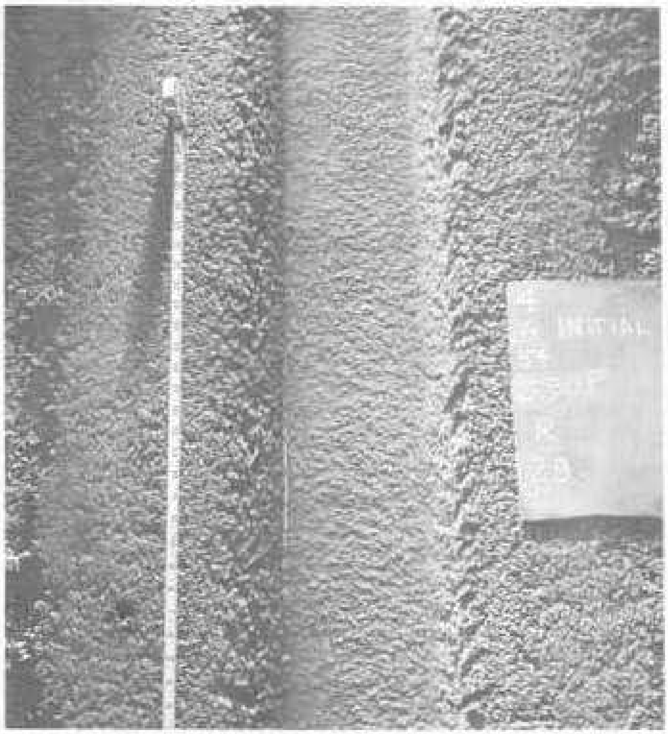

FIGURE 53.—Initial channel molded in flume bed (April 6, 1954, run 29, 3:30 p. m.)

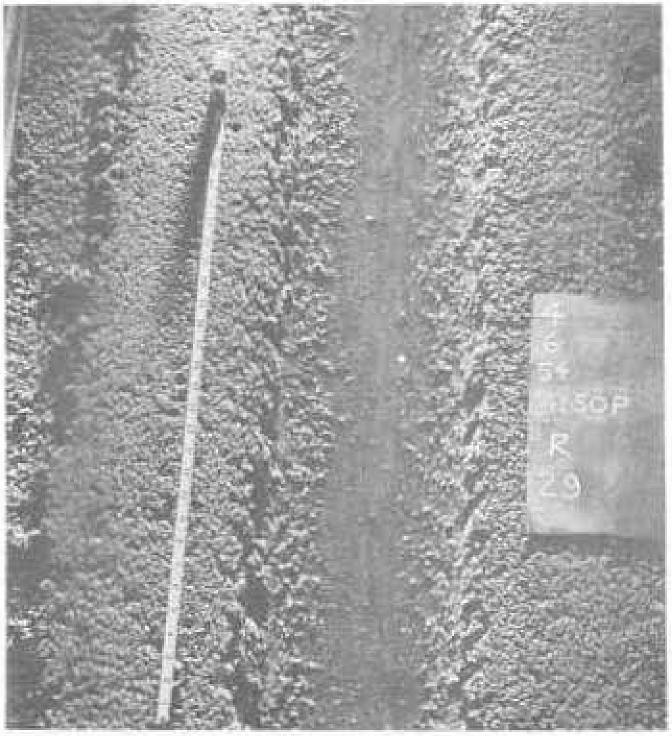

FIGURE 54.—Bed of flume-river after 1½ hours of flow with no load being introduced (April 6, 1954, run 29, 4:50 p. m.)

A series of runs in the flume was designed to show the effect of various rates of introduction of sediment load under constant conditions of discharge, flume slope, and template size. The initial channel was molded with a trapezoidal section having a top width of 9 inches and a depth of 2½ inches. Experience had shown that a discharge of 0.033 cfs would require no readjustment of this width. This initial channel is shown in figure 53. The flume slope was set at 0.0103. In the first run in the series no load was introduced. There was a gradual winnowing of the bed during which there was active movement over the central 3½ inches of the total bed width of 7 inches. The central band of sand movement at station 20 after 1 hour and 20 minutes can be seen in figure 54. After 18 hours of flow with no load being introduced, the whole channel became winnowed of finest grains and further degradation had in effect ceased. The condition at station 20 after 18 hours is shown in figure 55.

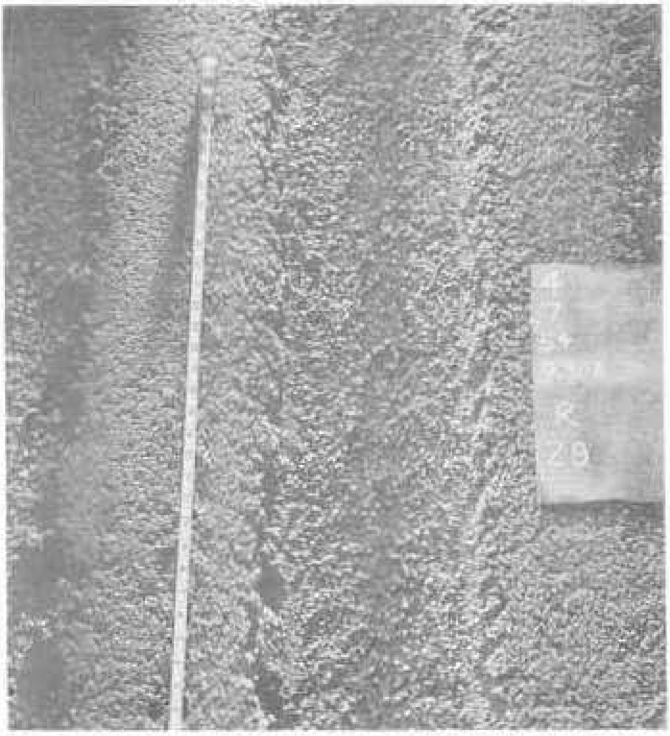

FIGURE 55.—Bed of flume-river after 21 hours of flow with no load being introduced (April 7, 1954, run 29, 9:30 a. m.)

During this degradation the slope flattened slightly and the bed coarsened until little or no movement occurred. At this discharge the stream became unable to move the material on its bed; thus, this discharge was analogous to low flow in a natural river with a coarse bed. Because the discharge was too low to be effective, the slope could not be altered.

Runs were made at the same discharge and initial slope introducing load at the rate of 24 grams per minute and 55 grams per minute. In each run there was some steepening of the reach farthest up stream as in previous instances in which a braided channel developed. The principal part of the flume, however, through which moved the bulk of sediment minus part of the coarse fraction deposited in the developing island, remained relatively stable. The slope of this lower reach became 0.0117 in the run (No. 30d) during which 55 grams per minute was introduced, and 0.0112 in the run (No. 31) of 24 grams per minute.

The most striking difference between these two runs (Nos. 30d and 31) in which different quantities of load were introduced, was the width of the band of moving sediment in the long reach below the developing braid. As can be seen by comparing the photographs in figures 56 and 57, the larger introduced load (run 30d, fig. 57) was associated with movement of the load over most of the bed width. With the smaller introduced load the movement on the bed was confined to a narrow band in the center of the channel.

This same effect was shown by another series of runs in which all particles coarser than 3.32 mm had been sieved out of the introduced sand load (app. A). The width of the moving band of sediment appeared to depend on the rate of introduction of load, as shown in table 4.

In summary, the bed sediment movement in the flume tended to concentrate in the center of the bed, not only when the bed was flat, but even after a central ridge began to develop. When no central ridge was being built, the width of the band of moving sediment increased with the amount of load coming into the reach.

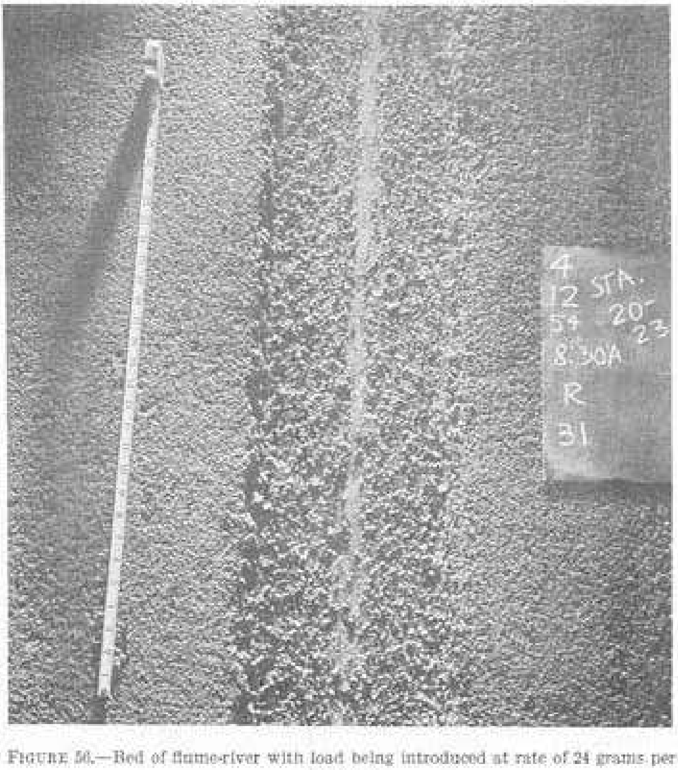

FIGURE 56.—Bed of flume-river with load being introduced at rate of 24 grams per minute.

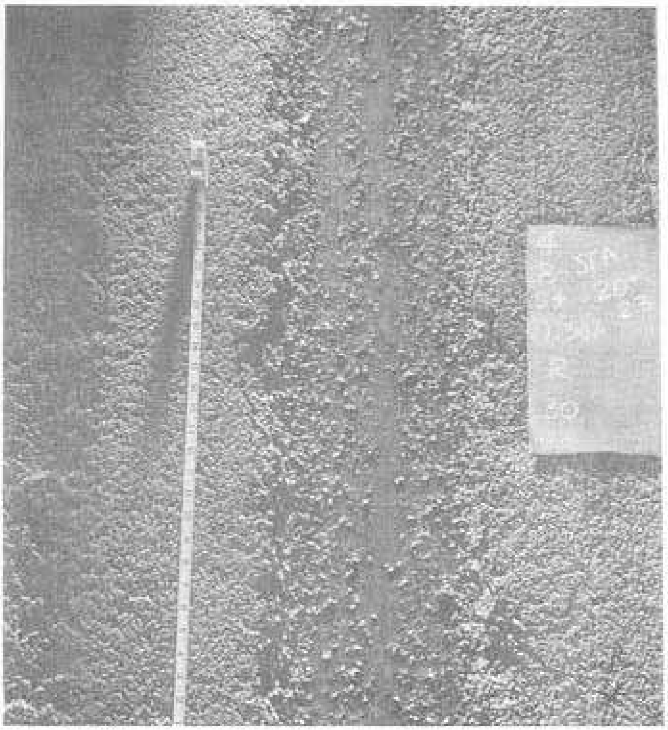

FIGURE 57.—Bed of flume-river with load being introduced at rate of 55 grams per minute.

TABLE 4.—*Relation of width of moving band of sediment to rate of introduction of load*

Measured at station 22, California Institute of Technology flume, 1954]

Run	*Rate of load introduction (grams per minute)*	*Width of band of moving bed sediment (inches)*
32	56	2¼
33	115	3½
34	175	4½

RESPONSE OF SLOPE TO CHANGES IN LOAD IN THE FLUME

Another series of runs in the flume was designed to test the relation between sediment load and slope at a constant discharge. The cross section remained practically constant during the series. The following data (table 5) were obtained under constant initial conditions except rate of introduction of load. All material coarser than 3.32 mm had been screened from the introduced load, and as a result no island or bar appeared. When the load was introduced at various rates at the same discharge (runs 32 to 35) the slope became adjusted to nearly the same value whether the reach was stable or aggrading. Aggradation was characterized by a gradual and uniform rise of the bed all along the flume.

TABLE 5.—*Effect of changing load on stream slope, all other conditions being kept constant*

[California Institute of Technology flume, 1954]

Run	*Discharge (cubic feet per second)*	*Load introduced (grams per minute)*	*Slope*	*Condition of channel*
32	0. 033	56	0. 0105	Nearly stable.
33	. 033	115	. 0105	Slow aggradation
34	. 033	175	. 0109	Aggradation.
35	. 033	212	. 0110	Rapid aggradation.

Despite a fourfold increase in load, slope remained essentially constant. Although this appears to conflict with Gilbert's conclusion (1914), analysis of Gilbert's data shows that the increase in slope which took place with increasing load in his experiments was also accompanied by an increase in roughness. In our experiment there was but a relatively small change in either slope or resistance.

Though slope was little affected by changes of total load in the flume experiments, there was some indication that at constant grain size, relatively steep slope is associated with small discharge and flat slope with large discharge. The data do not permit a definite statement on this relation. Considering the downstream rate of change of velocity, depth, and width with discharge in an average river (Leopold and Maddock, 1953, p. 26) under the assumption of constant roughness (*f*), slope must decrease with discharge as

$$s \propto Q^{-0.20} \tag{4}$$

The part which changing cross-sectional area downstream plays in this relation is unknown. Tentatively, it is believed that at constant grain size, river sections having different effective discharges should differ in slope, larger discharges being associated with flatter slopes.

OBSERVATIONS OF ADJUSTMENTS IN NATURAL CHANNELS

Measurements in the flume are complemented by examples drawn from larger rivers illustrating the same principles of adjustment. Table 6 indicates the nature of the adjustments which accompany changes in sediment load at constant discharge. Unfortunately, there are few rivers for which data on the flow parameters, including slope, are available and the data for these few suffer because suspended load but not bed load was measured.

In table 6 the flow characteristics of the Elkhorn River, which are compared at a discharge of 6,000 cfs, represent the rising and falling sides of a hydrograph. The rising stage was typified by a lesser depth and lesser slope, and a greater velocity and greater load than the falling stage. The elevation of the bed remained the same. The larger load of the rising stage was associated with lesser roughness. This lower resistance led to a greater velocity and a lesser depth despite the slightly lesser slope. The product of depth times slope, which is directly proportional to the shear, was less in the rising stage, and thus the larger load was associated with the lesser shear. It is presumed that the increase in velocity associated with the lesser roughness was of greater importance than the relatively small difference in shear in promoting equilibrium with the large load.

Also in table 6, the data on the Rio Grande at Bernalillo show another type of adjustment. The rising stage was characterized by a lesser depth, greater velocity, and greater load than the falling stage. In the falling stage, slope was somewhat less, and thus the smaller load was associated with the lesser shear. Here, then, the greater shear was associated with the larger load, but, as in the Elkhorn River, the total resistance was less when the load was large.

TABLE 6.—*Examples from river data of adjustments of depth, velocity, and slope to changes in suspended load at constant discharge and width*

Stage	Elkhorn River near Waterloo, Nebr., March 26 to April 9, 1952		Section A–2, Rio Grande at Bernalillo, N. Mex., April to June, 1952	
	Rising	Falling	Rising	Falling
Discharge ---- cubic feet per second	6, 000	6, 000	4, 700	4, 700
Width ---- feet	255	263	275	275
Velocity ---- feet per second	4. 90	4. 56	5. 5	5. 0
Depth ---- feet	4. 8	5. 0	3. 1	3. 4
Slope	. 00038	. 00046	. 00094	. 00084
Suspended load ---- tons per day	96, 000	74, 000	46, 000	21, 000
Elevation of bed above arbitrary datum ---- feet	7. 8	7. 8	3. 2	3. 2
Shear ($\tau_0 = \gamma ds$) ---- pounds per square foot	. 114	. 143	. 182	. 178
Resistance factor $\left(f = \frac{8\ gds}{v^2}\right)$	. 019	. 028	. 025	. 029
Grain size, suspended material ---- D_{50} (mm)	. 03	. 04	. 13	. 13
Grain size, bed material ---- D_{50} (mm)	------	------	. 32	. 32

SUMMARY AND INTERPRETATION

From these diverse observations on the nature of channel adjustments to independent controls we draw several tentative conclusions: 1. Channel width is largely determined by discharge. The effective discharge we believe to be that corresponding approximately to bankfull stage. 2. Where resistance is controlled by the roughness provided by discrete particles on the bed of a channel, the resistance factor may be correlated with the size of the particles. 3. Where the configuration of the bed enters into the determination of roughness, the resistance is a function of the discharge and load and represents a simultaneous adjustment of velocity, depth, and slope. 4. The load transported at a given discharge is not solely a function of shear and grain size. At a constant shear decreased resistance appears to be associated with greater transport. The resistance is not necessarily governed by caliber of the load but may be determined principally by bed configuration. 5. In the flume-river the width of the band of moving sediment was often less than the width of the channel, and width of the band was related to the quantity of load being transported. If such bands exist in natural channels, errors might result from estimates of total load based on computations of load per foot of width multiplied by the total width. 6. Where no change in roughness occurs at constant discharge, a large increase in load is not accompanied by an appreciable increase in slope. Both aggradation and degradation may occur, therefore, without change in slope.

We shall now attempt to construct a general though oversimplified picture of the way in which the shape and pattern of a natural channel may be determined by the river itself within the framework provided by the climate, rocks, and physiography of the region in which it lies.

In a given region the magnitude and character of the runoff are determined by climate and lithologic factors quite independent of the channel system. The amount and distribution of precipitation, and characteristics which affect the runoff, are functions of the climate. The topographic and lithologic character of the drainage basin helps to determine, in conjunction with vegetation, not only the characteristics of the runoff, but of equal importance, it greatly helps to determine the load of debris delivered to the channel system from the interstream areas and from the stream margins. Both quantity and nature of the load are greatly influenced and often are primarily governed by geologic factors.

Exceptional runoff is accompanied by conditions which increase the movement of soil and rock debris. Of particular importance are relatively large amounts of rainfall, often at high intensity, and saturated soils. Moreover, large volumes of runoff are associated with relatively large depths of flow both in rills and in overland flow. These depths are accompanied by relatively high flow-velocity and increased transport of debris to the channel system. For such reasons large flows are usually accompanied by large loads.

In a given period of time there are far fewer large flows than small or moderate ones. An intermediate range of discharge includes flows that occur often enough in time and possess sufficient vigor to constitute the effective discharge (Wolman, 1956). During these flows the river can move the material on its bed and in its banks and thus is capable of modifying its shape and pattern.

It is within the framework of these characteristics of runoff of water and sediment that channel systems develop. The water and load, including their time and space distribution as well as quantity, that are delivered to the channel system are functions of the climate and geology. The water and load carve the channels that transmit them downstream. To the water and debris, therefore, the channels ultimately owe their shape and pattern, but processes within the channel itself effect specific modifications.

Channel width is primarily determined by discharge. Widening is rapid relative to other changes and the channel generally tends to become adjusted at the width provided by large flows near the bankfull stage.

The roughness of any reach of a channel is governed, initially at least, by the geologic character of the bed material supplied by the drainage basin. Although abrasion and sorting may modify the material on the bed, the rock character partly determines the extent of such modification. The roughness may be primarily grain roughness. Alternatively, owing to the size distribution of the particles and their movement, the rugosity may be due to the configuration of the dunes, ripples, or waves in which the particles on the bed arrange themselves.

The roughness of the boundary affects the stress structure and the velocity distribution in the flowing water. In addition, turbulent eddies near the bed produced by the roughness elements lift particles of debris off the bed. These alternately move forward in the current and settle back to the bed under the influence of gravity. Not only the resistance then, but also the movement of debris through turbulence and shear is related to roughness.

At a given discharge, with width fixed thereby, velocity, depth, and slope become mutually adjusted. To visualize the nature of this adjustment, one may assume temporarily a value of slope. With slope given, velocity and depth must mutually adjust to meet two requirements: The first is that the product of width, depth, and velocity is equal to the value of discharge, or

$$Q=wdv \qquad (1)$$

The second is the relation of resistance to depth, slope, and velocity, which is expressed by the equation for the Darcy-Weisbach coefficient,

$$f \propto \frac{gRs}{v^2} \qquad (2)$$

The resistance f can be assumed to be fixed by the materials in the bank and on the bed.

These two equations must be satisfied. They contain six factors, but where four of the factors are fixed or temporarily assumed, these two equations fix the remaining two variables.

At a given discharge width is considered fixed. Resistance is determined by the nature of the material in bed and banks, channel configuration, and bed condition. Slope has been temporarily assumed. Hence, velocity and depth become determined by these two equations.

If this combination of depth, velocity, and slope constitute a channel that will transmit the given discharge and load without erosion or deposition, the slope is not altered. If the hydraulic factors of the channel are not in equilibrium with the imposed load, erosion or deposition will occur. By such action the slope of relatively long reaches of the channel is altered and as the alteration occurs, the velocity and depth also are changed.

This explanation provides a perspective of how the several variables interact to make the channels which are observed in nature. These variables are interdependent, but their relative order of importance is believed at this time to be generally as outlined above. If correct reasoning about the relations of geologic and other factors to fluvial processes is to be achieved, it is necessary to determine the relative independence of these variables.

In further explanation we reason that if, for example, a river is able to move the size of material in the load but is unable to transport the total quantity of load brought into the reach, deposition may take place along the reach with little or no change in slope. During a flood in an alluvial river if deposition occurs on the bed, this deposition at a constant width is customarily accompanied by a decrease in depth and consequent increase in velocity through reduction in cross-sectional area. The increase in velocity at the expense of depth implies that deposition on the bed does not cause an equal rise in elevation of the water surface and of the bed.

Our studies indicate that an increase in load at a constant discharge is usually accompanied by a decrease in bed roughness which serves to increase the velocity. The adjustment in depth then, and the smoothing of the bed are inextricably related. It is, of course, possible that the increase in capacity resulting from the increase in velocity is still inadequate to transport the total load, in which event both the bed and the water surface will rise.

If a stream can move only some of the sizes in the load provided to the reach, the process of adjustment is similar to the one described above save for the fact that by winnowing from the bed certain sized fractions only, the mean size of the bed material is increased. This increased size will be associated with an increased slope over the entire reach, thereby increasing the total capacity for transport of all movable sizes.

APPLICATION OF OBSERVATIONS ON CHANNEL ADJUSTMENT TO THE PROBLEM OF CHANNEL PATTERN

As explained, eight and possibly more variables enter in a consideration of natural stream channels: discharge, amount of sediment load, caliber of load, width, depth, velocity, slope, and roughness. Each of these factors varies as a continuous function; that is, within the limits of observed values, any intermediate value is possible. The factor having the largest range of values is discharge, for in natural channels it can vary from 0 to any amount less than 10,000,000 cfs. Load, expressed as concentration by weight, varies from nearly 0 to about 500,000 ppm. Caliber of load, expressed as median grain size, may vary from a value near 0 to 10-foot boulders. Width of natural channels varies between a few tenths of a foot to about 20,000 feet, mean depth from 0 to an amount less than 80 feet, mean velocity from near 0 to less than 25 feet per second, slope from near 0 to 1.0, and resistance, expressed as the dimensionless Darcy-Weisbach number, from about 0.001 to about 0.30.

Combinations observed in nature are far more restricted than the permutations of the values of the eight variables. To our knowledge, for example, rivers capable of discharging more than 1,000,000 cfs do not have slopes in excess of 0.0009 and usually less than 0.0002.

Channel patterns, braided, meandering, and straight, each occurs in nature throughout the whole range of possible discharges. Some of the largest rivers in the world are braided; for example, the lower Ganges and Amazon. More are meandering, of which the lower Mississippi is the best known example. Meanders are common in very small creeks, and braids are common in many small ephemeral streams. Both meanders and braids have been observed in the laboratory at discharges less than 0.1 cfs. The straight pattern occurs at all discharges.

Our observations indicate that braids tend to occur in channels having certain combinations of values of the flow factors, and that meanders occur in different combinations. The straight pattern can occur in either. Specifically, at a given discharge, braids seldom occur in channels having slopes less than a certain value, while meanders seldom occur at slopes greater than that same value.

These considerations together with the details discussed earlier in this study lead to one of the principal points of the present discussion: There is a continuum of natural stream channels having different characteristics that are reflected in combinations of values of the hydraulic factors. The channel patterns, braided, meandering, and straight, each is associated with certain of these combinations. The combinations of hydraulic factors that exist in most natural channels are those which represent quasi-equilibrium between the independent factors of discharge and amount and caliber of load, and the dependent factors of form and hydraulic characteristics of the channel. Braided, meandering, and straight patterns, in this conception, are among the forms of channels in quasi-equilibrium.

This conception fits the observations that a given channel can change in a short distance from a braid to a meander or vice versa, that the divided channels of a braid may meander, and that a meandering tributary may join a braided master stream. Such changes in a given channel or such different channels in juxtaposition can be attributed to variations in locally independent factors.

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APPENDIX

Appendix A.—*Analyses of sizes of sand used in flume experiments and fed into flume-river, 1954*

[California Institute of Technology flume]

	Median size (mm)	Percent finer than given size (millimeters)—					
		.078	.156	.312	.625	1.25	2.50
Medium sand:							
Run 1, February 12	0.90	----------	3	15	36	61	80
Run 10, February 26	.82	----------	3	15	37	64	83
Run 12, March 5	.72	----------	3	17	44	69	86
Run 17, March 11	.65	----------	3	17	48	73	89
Run 18, March 15	1.00	----------	2	12	32	56	78
Run 20, March 18	.73	----------	3	17	44	68	85
Fine sand:							
Run 22, March 24	.17	6	42	93	98.6	----------	----------
Medium sand screened of all particles >3.32 mm:							
Run 34, April 16	.64	----------	6	20	49	77	95

Appendix B.—*Data on size characteristics of sand on channel bed and on bars in flume-river, 1954*

[California Institute of Technology flume]

	Median size mm)	Percent finer than given size (millimeters)—						D_{50} (median)	Size in millimeters		
		.078	.156	.312	.625	1.25	2.50		D_{75}	D_{25}	$So=\sqrt{\frac{D_{75}}{D_{25}}}$
Bar or island in braided reach:											
Station 6, February 12	2.10	----------	1.2	7	20	35	58	----------	----------	----------	----------
Station 10, February 12	1.45	----------	3	14	28	45	65	----------	----------	----------	----------
Channel bed, unbraided:											
Station 16, February 12	1.30	----------	5	19	35	49	69	----------	----------	----------	----------
RUN 12, MARCH 5											
Braided reach:											
Station 11, coarse material from surface of bar	----------	----------	----------	----------	----------	----------	----------	3.00	4.20	1.75	1.55
Station 12, bed of right-hand channel	----------	----------	----------	----------	----------	----------	----------	1.75	3.60	.48	2.74
Station 12, fine material from surface of bar	----------	----------	----------	----------	----------	----------	----------	.48	1.30	.27	2.21
Station 12, bed of left-hand channel	----------	----------	----------	----------	----------	----------	----------	.75	2.25	.33	2.60
Unbraided reach:											
Station 26, bed of channel	----------	----------	----------	----------	----------	----------	----------	1.80	3.75	.57	2.56
Station 38, bed of channel	----------	----------	----------	----------	----------	----------	----------	1.25	3.20	.38	2.90

APPENDIX C.—*Summary of data for flume experiments at California Institute of Technology, 1954*

[Station refers to distance along the 60-foot flume where cross section was measured. Slope of water surface is slope of flume plus or minus deviation of water surface from slope of flume; load is rate of sand introduction at upstream end of flume; zero load means no load introduced; area is cross section of flowing water.

Observations on dunes or other bed configuration are not complete. Where original notes are definitive, indication of bed configuration is noted as follows:

S	smooth bed.
A	antidunes (definite movement upstream).
SA	stationary antidunes, alternating forming and breaking, but not moving upstream.
D	dunes, moving downstream. Number after the letter designation is wavelength, in inches, thus D 3½ signifies dunes 3½ inches from crest to crest.

Template sizes, in inches (all templates trapezoidal):

	Top width	*Bottom width*	*Depth*
A	15	13¾	1½
B	9	6½	2½
C	5½	3	2¼
D	3	1½	1½
E	9	3	3⅓
F	6½	3	3]

Run No.	Date	Channel pattern	Station	Discharge (cfs)	Slope flume	Slope deviation	Slope of water surface	Load (g per min)	Load (lb per sec)	Sediment concentration (*Cs*)	Mean velocity (fps)	Area (sq ft)	Width (ft)	Wetted perimeter (ft)	Hydraulic radius (ft)	Shear velocity (fps)	Darcy-Weisbach resistance factor	Intensity of boundary shear (lb per sq ft)	Sand 50 percent finer than— (ft)	Temperature (°F)	Template	Bed configuration
Runs using medium sand																						
1	Feb. 10	------	10	0.063	------	------	0.0085	100	0.00367	0.000934	1.21	0.0520	0.88	------	0.052	0.119	0.078	0.0276	0.00275	------	B	------
2a	Feb. 16	Braided	14	.085	------	------	.0133	125	.00459	.000865	1.24	.0684	1.60	------	.0371	.126	.083	.0308	.00275	------	A	------
2b	do	Undivided	22	.085	------	------	.0095	125	.00459	.000865	1.34	.0631	1.19	------	.0467	.119	.064	.0277	.00275	62	A	SA
4	Feb. 15	Braided	10	.085	------	------	.0104	118	.00433	.000817	1.37	.0619	1.38	------	.0386	.113	.055	.0250	.00275	------	A	------
4a	do	Undivided	14	.085	------	------	.0079	118	.00433	.000817	1.29	.0657	1.32	------	.0410	.102	.050	.0202	.00275	------	A	------
6a	Feb. 18	do	10	.085	------	------	.0081	120	.0044	.000830	1.20	.0708	1.28	------	.0485	.112	.070	.0245	.00275	------	A	------
6b	do	Braided	14	.085	------	------	.0157	120	.0044	.000830	1.53	.0553	1.90	------	.0254	.113	.044	.0249	.00275	------	A	------
8	Feb. 19	------	20.2	.085	------	------	.0093	120	.0044	.000830	1.24	------	1.20	------	.0497	.122	.077	.0288	.00275	------	A	------
9a	Feb. 25	------	10	.030	0.0103	+0.0032	.0135	80	.00294	.00157	1.39	.0216	.72	0.80	.0270	.108	.0485	.0228	.00263	------	C	------
9b	do	------	26	.030	.0103	+.0011	.0114	70	.0026	.00137	1.29	.0233	.56	.68	.0342	.112	.0560	.0243	.00263	------	C	D 3½
11	Mar. 2	------	22	.053	.0103	+.00083	.0111	105	.0038	.00116	1.20	.0440	.80	.96	.0457	.128	.091	.0316	.00263	------	C	------
12	Mar. 5	Braided	12	.093	.0103	+.0062	.0165	290	.0107	.00184	1.24	.0748	2.15	2.39	.0313	.129	.0865	.0322	.00229	------	A	SA
12a	do	Undivided	38	.093	.0103	−.0008	.0095	290	.0107	.00184	1.33	.0699	1.27	1.41	.0496	.123	.0686	.0293	.00229	------	A	------
14	Mar. 10	------	22	.040	.0103	+.0012	.0115	100	.00366	.00147	1.11	.0359	.77	.90	.0399	.122	.096	.0286	.00229	------	C	A
17	Mar. 12	------	26	.01	.0103	0.00	.0103	47	.00173	.00278	.88	.0114	.35	4.38	.0260	.0925	.0884	.0167	.00246	------	D	------
18a	Mar. 15	------	10	.040	.0103	+.0072	.0175	141	.00516	.00207	1.21	.0329	.68	.778	.0423	.154	.130	.0462	.00328	------	C	------
18b	do	------	38	.040	.0103	+.0010	.0113	140	.00516	.00206	.77	.0422	.68	.79	.0521	.137	.280	.0368	.00328	65	C	------
19	Mar. 17	------	22	.082	.0015	0	.0015	(1)	(1)	------	.61	.1351	.89	1.25	.1085	.0723	.113	.0102	.00328	63	B	------
20a	Mar. 18	------	9	.086	.0015	+.0053	.0068	69	.00253	.000472	1.18	.0729	.98	1.14	.0639	.118	.0805	.0272	.00328	63	E	------
20b	do	------	13	.086	.0015	+.00262	.00412	69	.00253	.000472	1.18	.0731	1.00	1.172	.0623	.0894	.0470	.0160	.00328	63	E	------
20c	do	------	26	.086	.0015	+.00033	.00183	(1)	(1)	------	.66	.130	.87	1.08	.120	.084	.130	.0137	.00328	63	E	------
Runs using fine sand																						
22	Mar. 24	------	21	.018	.00175	0	.00175	5.3	.000194	.000173	.733	.0245	.54	.68	.036	.0449	.030	.00394	.00059	------	C	D 7
23a	Mar. 26	------	10	.033	.00175	+.00287	.00462	33	.00121	.000588	.92	.0360	1.09	1.290	.0279	.0644	.0395	.0080	.00059	65	F	D 4½
23b	do	------	26	.033	.00175	0	.00175	33	.00121	.000588	.68	.0486	.66	.874	.0555	.056	.0575	.0061	.00059	65	------	D 4½
24	Mar. 29	------	22	.017	.00288	+.0005	.00338	4.6	.00017	.000160	.422	.0402	.61	.79	.051	.0745	.228	.0107	.00059	65	F	D 5
25	do	------	20	.030	.00288	+.00037	.00325	5	.00022	.0001	.63	.0476	.97	1.25	.0381	.0631	.0805	.00772	.00059	64	(2)	D 4
26	Mar. 30	------	22	.031	.00288	−.00012	.00276	0	0	------	.60	.0520	.85	1.18	.0441	.0623	.087	.0076	.00059	62	F	D 8
27	Mar. 31	------	21	.052	.00288	+.00022	.00310	8.0	.00029	.00009	.57	.0907	1.22	1.52	.0597	.0771	.146	.0115	.00059	69	(3)	D 5
Runs using medium sand, constant discharge, varying load																						
29	Apr. 6	------	20	.033	.0103	−.0005	.0098	0	0	------	------	.0299	.64	.77	.0388	.110	.0806	.0237	.00328	62	B	A 3½
30a [4]	Apr. 7	------	12	.033	.0103	+.003	.0133	55	.00202	.00098	1.27	.0259	.66	.76	.0341	.121	.0723	.0283	.00328	------	B	------
30b [4]	do	------	22	.033	.0103	0	.0103	55	.00202	.00098	1.27	.0259	.66	.76	.0341	.121	.0723	.0283	.00328	------	------	------
30c [5]	Apr. 8	------	12	.033	.0103	+.0045	.0148	55	.00202	.00098	1.32	.0250	.76	.84	.0293	.119	.0651	.0275	.0046	------	------	------
30d [5]	do	------	22	.033	.0103	+.0014	.0117	55	.00202	.00098	1.36	.0243	.67	.76	.0320	.110	.0523	.0234	.0036	------	------	------
31	Apr. 12	------	22	.033	.0103	+.0009	.0112	24	.00088	.000427	1.10	.0300	.63	.77	.0390	.119	.093	.0272	.00315	64	B	------
Runs using medium sand screened of particles greater than 3.32 mm																						
32	Apr. 13	------	22	.033	.0103	+.0002	.0105	56	.00206	.0010	1.21	.0272	.66	.78	.0349	.109	.0645	.0228	.0032	------	B	------
33	do	------	22	.033	.0103	+.0002	.0105	115	.0042	.00204	1.27	.0260	.66	.76	.0342	.108	.0575	.0224	.0032	70	(6)	------
34	Apr. 15	------	22	.033	.0103	+.0006	.0109	175	.0064	.00312	1.20	.0275	.67	.77	.0357	.112	.0638	.0243	.0032	------	B	A 3¼
35	Apr. 17	------	22	.033	.0103	+.0007	.0110	212	.0078	.0038	------	------	------	------	------	------	------	------	.0032	------	(7)	------

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[1] No movement.

[2] Increased *Q* in channel left from run 24.

[3] Increased *Q* and added load in channel left from run 26.

[4] After 4 hours of flow.

[5] After 20 hours of flow.

[6] Increased load in channel left from run 32.

[7] Increased load in channel left from run 34.

APPENDIX D.—*Comparison of hydraulic characteristics of undivided and divided reaches of braided streams*

Hydraulic factor	Green River near Daniel, Wyo.			New Fork River near Pinedale, Wyo.						Flume at California Institute of Technology, 1954							
	Braided reach		Undivided reach	Reach 1 (1953)			Reach 2 (1954)			Feb. 15		Feb. 16		Feb. 18		Mar. 5	
	Left	Right		Braided reach		Undivided reach	Braided reach		Undivided reach	Sta. 10	Sta. 14	Sta. 14	Sta. 22	Sta. 14	Sta. 10	Sta. 12	Sta. 38
				Left	Right		Left	Right		Braided reach	Undivided reach	Braided reach	Undivided reach	Braided reach	Undivided reach	Braided reach	Undivided reach
Area..........square feet..	152	70	169	25	82	105	64	19	52	0.0619	0.0657	0.0684	0.0631	0.0553	0.0708	0.0748	0.0699
Discharge..........cubic feet per second..	305	120	425	35	290	325	--------	--------	--------	.085	.085	.085	.085	.085	.085	.093	.093
Width..........feet..	65	44	70	35	64	54	64	24	43	1.38	1.32	1.60	1.19	1.90	1.28	2.15	1.27
Mean depth..........feet..	2.3	1.6	2.4	.7	1.3	1.94	1.0	0.8	1.2	.045	.050	.050	.053	.029	.055	.035	.055
Velocity..........feet per second..	2.0	1.7	2.5	1.46	3.5	3.1	--------	--------	--------	1.37	1.29	1.24	1.34	1.53	1.20	1.24	1.33
Slope..........	.0029	.0029	.0005	.00286	.00286	.00125	.00294	.00294	.00214	.0104	.0079	.0133	.0095	.0157	.0081	.0165	.0095
Resistance factor..........	.43	.41	.04	.24	--------	.065	--------	--------	--------	.055	.050	.083	.064	.044	.070	.0865	.0687
Shear velocity..........feet per second..	.46	.41	.49	.25	--------	--------	--------	--------	--------	.113	.102	.126	.119	.113	.112	.129	.123

APPENDIX E.—*Data on wavelength of meanders, bankfull discharge, and bankfull width*

[e estimated, pattern: M meander, S pool-and-riffle spacing in straight channels]

Serial No.	Location	Estimated bankfull discharge [1] (cubic feet per second)	Wavelength (feet)	Bankfull width (feet)	Pattern	Source of data
21	Duck Creek, near Cora, Wyo	50	110	8	M	Authors.
23	Buffalo Fork, near Jackson, Wyo. (Flybox reach)	1,200	1,300	150	M	Do.
24	Wind River, near Dubois, Wyo. (Dumb Cowboy reach)	340	290	30	M	Do.
25	Du Noir Creek, near Dubois, Wyo	470	800	60	M	Do.
27	Popo Agie River, near Hudson, Wyo. (Joyful reach)	1,700	1,400	100	M	Do.
30	Watts Branch, Viers pasture near Rockville, Md	246	120	22	M	Do.
32	Crooked Run, near State College, Pa. (Save the Meander reach)	e 45	50	8	M	Do.
36	Mississippi R., near Blytheville, Ark. (Tamm Bend reach)	1,000,000	34,000	3,400	M [2]	H. M. Eakin, unpublished.
42	Baldwin Creek, near Lander, Wyo	180	160	25	M	Authors.
43	Brandywine Creek, near Cornog, Pa	780	400	53	S	Wolman (1955).
44	At Seven Springs, Pa	1,400	600	79	S	Do.
45	At South Downingtown, Pa	1,600	1,200	72	S	Do.
48	Embreeville, Pa	2,200	800	92	S	Do.
49	Wawaset, Pa	2,500	800	74	S	Do.
51	Friedkin flume	.15	20	2.1	M	Friedkin (1945).
51	do	.10	16.2	1.5	M	Do.
51	do	.05	12.4	2.3	M	Do.
54	Quraishy flume	.021	6.8	.92	M	Quraishy (1944).
65	Christians Creek, near Staunton, Va. (Orange bridge reach)	690	e 200	31	M	Authors.
67	Barterbrook Creek, Route 254 near Staunton, Va	280	e 215	31	M	Do.
68	Middle River, at Bethlehem Church near Staunton, Va	560	190	29	M	Do.
71	South River, near Lipscomb, Va. (Black Bull reach)	800	380	60	M	Do.
84	Slab Cabin Creek, near Lamont, Pa	230	240	e 15	M	Do.
259	Brooks' flume	.28	3.4	.66	S	N. H. Brooks, personal communication.
259	do	.21	4.0	.66	S	Do.
260	Meander model, Central Board Irrigation Expt. Sta., Poona, India.	.175	14		M	Inglis (1949, p. 150).
260	do	.175	12.5		M	Do.
260	do	.175	14.5		M	Do.
260	do	.175	14		M	Do.
260	do	.40	24		M	Do.
260	do	.10	16		M	Do.
261a	Mississippi R., above Cairo, Ill		29,000	2,270	M	Corps of Engineers maps.
261b	Below Tiptonville, Ill		41,700	3,600	M	Do.
261c	Near Blytheville, Ark		32,700	2,800	M	Do.
261d	Missouri R., at Bismark, N. Dak		20,600	1,320	M	Do.
	RIVERS IN ORISSA, INDIA					
I 1	Mahanadi, below Jobra	610,000	21,600			Inglis, (1940, p. 111).
I 2	Berupa, below weir	112,000	7,500			Do.
I 3	Mahanadi, below Chitertola	237,000	16,200			Do.
I 4	Chitertola	338,000	16,800			Do.
I 5	Pyka	112,000	8,000			Do.
I 6	Nuna	155,000	10,500			Do.
I 7	Chitertola, below Nuna	111,000	8,400			Do.
I 8	Katjuri, below Surua head	159,000	10,800			Do.
I 9	Surua	260,000	14,400			Do.
I 10	Bhargovi	46,000	7,200			Do.
I 11	Daya	47,500	7,500			Do.
I 12	Bhargovi, below Achhutpur	29,000	5,700			Do.
I 13	Daya, below Belmora escape	34,000	4,800			Do.
I 14	Brahmini	650,000	21,600			Do.
I 15	Kharsua	162,000	9,000			Do.
I 16	Baitarani	260,000	10,800			Do.

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[1] For method of estimating bankfull discharge see footnote to corresponding serial number in appendix F.

[2] At gage height, 20 ft.

APPENDIX F.—*Data on estimated bankfull discharge at various stream sections*

[Pattern: B braided, M meander, S straight]

Serial No.	Stream and location	Drainage area (square miles)	Pattern	Slope	Estimated bankfull discharge (cubic feet per second)
6	Little Popo Agie R. near Lander, Wyo	108	S	0.0049	[1] 520
7	New Fork R., Jenkins Ranch near Cora, Wyo	45	B	.0047	[1] 260
8	Green R., at Warren Bridge near Daniel, Wyo	468	S	.0034	[1] 1,700
9	Beaver Creek, near Daniel, Wyo	141	B	.0066	[1] 620
10	New Fork R., below New Fork Lake near Cora, Wyo	36	S	.0051	[1] 230
11b	Horse Creek, near Daniel, Wyo	124	B	.0073	[1] 380
12a	Cottonwood Creek, near Daniel, Wyo	204	M	.0011	[1] 800
12b	do	204	B	.0041	[1] 800
14a	Green R., at Daniel, Wyo. (undivided)	660	S	.0005	[1] 2,000
14b	—— (right channel)		M	.0029	[1] 500
14c	—— (left channel)		B	.0029	[1] 1,500
18b	New Fork R., at American Gothic Reach near Pinedale, Wyo	372	B	.0029	[1] 1,300
21	Duck Creek, near Cora, Wyo	5	M	.00019	[1] 50
22	Snake R., below mouth of Hoback R., near Jackson, Wyo	3,440	B	.0021	[1] 7,000
23	Buffalo Fork, Flybox reach near Jackson, Wyo	345	M	.00045	[1] 1,200
24	Wind R., Dumb Cowboy reach above Dubois, Wyo	55	M	.0037	[1] 340
25	Du Noir Creek, above Dubois, Wyo	93	M	.00098	[1] 470
27	Popo Agie R., Joyful reach near Hudson, Wyo	700	M	.00184	[1] 1,700
28	Little Pipe Creek near Avondale, Md	8	M	.00473	[2] 260
30	Watts Branch, Viers pasture, near Rockville, Md	4	M	.0031	[2] 246
31	Seneca Creek, at Dawsonville, Md	100	S	.0006	[2] 1,160
33	Seneca Creek, at Riffleford near Rockville, Md	15	S	.0023	[3] 500
36	Mississippi R., at Tamm Bend near Blytheville, Ark		M	.000089	[4] 1,000,000
42	Baldwin Creek near Lander, Wyo	21	M	.00093	[1] 180
43	Brandywine Creek, at Cornog, Pa	26	S	.0038	[2] 780
48	—— at Embreeville, Pa	117	S	.00068	[2] 2,200
65	Christians Creek, at Orange bridge near Staunton, Va	24	M	.0015	[3] 690
68	Middle R., at Bethlehem Church near Staunton, Va	18	M	.0021	[3] 560
71	South R., Black Bull reach south of Mt. Vernon Church near Lipscomb, Va	69	M	.00034	[1] 800
89	Yellowstone R., at Billings, Mont	11,600	B ?	.00083	[2] 21,400
90	Wind R., near Burris, Wyo	1,220	S	.004	[1] 2,500
125	Middle Piney Creek below South Fork near Big Piney, Wyo	34	M	.0091	[1] 220
128	Little Sandy Creek, near Elkhorn, Wyo	21	S	.010	[1] 150
151	Kansas R., at Lecompton, Kans	58,420	M	.000379	[2] 65,000
152	—— at Ogden, Kans	45,240	M	.000379	[2] 40,000
154	—— at Wamego, Kans	55,240	M	.000316	[2] 102,000
227	Fall Creek, near Pinedale, Wyo	37	S	.036	[1] 230
229	West Fork Rock Creek below Basin Creek, near Red Lodge, Mont	60	S	.035	[1] 350
230	Rock Creek, near Red Lodge, Mont	100	S	.021	[1] 540
231	Clarks Fork, near Edgar, Mont	2,115	S	.00295	[1] 6,500
232	Clear Creek, near Buffalo, Wyo	120	S	.024	[1] 350
233	North Fork Clear Creek, near Ranger station near Buffalo, Wyo	29	S	.028	[1] 190
234	Red Fork, near Barnum, Wyo	142	S	.0038	[1] 380
235	Rock Creek, at Roberts, Mont	[4] 270	S	.0086	[1] 1,200
240	Pole Creek, ½ mile below Little Half Moon Lake near Pinedale, Wyo	87	S	.0018	[1] 430
256	Bull Lake Creek, near Lenore, Wyo	222	S	.0081	[1] 800
264	Snake R., near Wilson, Wyo	2,000	B	.0043	[1] 4,700
266	Big Sandy Creek, near Leckie ranch, Wyo	95	S	.00425	[1] 460
267	Hams Fork, near Frontier, Wyo	298	M	.0013	[1] 1,100
268	North Fork Powder R., near Kaycee, Wyo	980	S	.0038	[1] 1,000
269a	Bagmati R., above Dhang, India		B	.00057	[4] 45,000
269b	—— below Dhang, India		M	.00019	[4] 45,000
270a	Kosi R., above Dhamarghat, India	23,000	B	.00095	[4] 200,000
270b	—— above Dhamarghat, India		B	.00038	[4] 200,000
270c	—— below Dhamarghat, India		M	.00038	[4] 200,000
271	Ganges R., near Patna, India		B	.000066	[4] 3,000,000
286	Yukon R., near Holy Cross, Alaska		M	.000095	[4] 685,000
287	Chena R., near Fairbanks, Alaska		M	.00054	[4] 8,000

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[1] Estimated from generalized regional relations of discharge of 1.16-year recurrence interval plotted against drainage area.

[2] From rating curve; value of bankfull stage estimated in field.

[3] Interpolated in regional curve relating known bankfull discharge to drainage area.

[4] Estimated.

APPENDIX G.—*Distribution of bed-particle size in various stream cross sections*

Serial No.	Stream and location	Percent finer than (millimeters)—														50 percent finer than (feet)—	84 percent finer than (feet)—
		.25	.50	1	2	4	8	16	32	64	128	256	512	1024	2048		
6	Little Popo Agie R., near Lander, Wyo				5	9	13	22	46	80	95	100				0. 11	0. 24
8	Green R., at Warren bridge near Daniel, Wyo		5	6	8	9	9	9	10	16	48	84	100			. 46	. 84
9	Beaver Creek, near Daniel, Wyo	3	3	5	5	6	13	24	49	82	96	100				. 10	. 21
11a	Horse Creek, near Daniel, Wyo				2	5	7	22	55	88	100					. 09	. 20
12a	Cottonwood Creek, near Daniel, Wyo. (meander)		10	18	21	29	34	52	71	92	99	100				. 05	. 16
12b	Daniel, Wyo. (braid)		10	10	11	17	27	42	77	96	100					. 06	. 12
14b	Green R., at Daniel, Wyo				2	2	2	2	12	58	96	100				. 18	. 60
18a	New Fork R., at American Gothic reach near Pinedale, Wyo			4	12	15	15	23	31	88	100					. 12	. 20
23	Buffalo Fork, Flybox reach near Ranger station, Jackson, Wyo							2	25	83	100					. 14	. 21
24	Wind R., Dumb Cowboy reach near Sheridan Ranger station above Dubois, Wyo			2	4	4	5	20	41	73	96	100				. 13	. 27
25	Du Noir Creek, above Dubois, Wyo				10	23	37	82	100							. 035	. 056
26	North Popo Agie R., near Lander, Wyo			3	5	5	8	8	12	17	42	90	98	100		. 49	. 79
30	Watts Branch, Viers pasture near Rockville, Md		3	3	6	9	14	31	46	72	93	99	100			. 082	. 31
31	Seneca Creek, at Dawsonville, Md					2	3	29	69	97	100					. 075	. 15
33	At Riffleford near Rockville, Md		1	6	19	31	48	70	92	100						. 026	. 079
37	Brandywine Creek, at Lenape, Pa			11	17	18	26	40	61	89	99	100				. 072	. 18
43	At Cornog, Pa				7	9	14	21	32	48	75	97	100			. 22	. 48
44	At Seven Springs, Pa			4	5	6	9	13	26	49	77	94	99	100		. 21	. 49
45	Near South Downingtown, Pa			9	11	11	12	14	24	39	64	86	98	99		. 34	. 84
48	At Embreeville, Pa				5	7	14	40	64	91	100					. 072	. 17
49	At Wawaset, Pa				4	5	9	17	33	66	92	100				. 16	. 33
65	Christians Creek, at Orange Bridge near Staunton, Va	6. 5	7. 4	14	21	24	29	41	58	74	91	100				. 075	. 29
66	At Rt. 254 near Staunton, Va				4	11	23	37	61	82	97	100				. 085	. 21
67	Barterbrook Creek, at Rt. 254 near Staunton, Va	5	11	24	36	52	66	78	94	97	100					. 0125	. 069
68	Middle River, at Bethlehem Church near Staunton, Va		15	16	20	27	32	39	59	81	98	100				. 076	. 24
69	Eidson Creek, near Mt. Tabor Church near Staunton, Va		13	16	25	31	37	51	74	92	98	99	100			. 049	. 15
89	Yellowstone R., at Billings, Mont			1	1	1	1	5	16	39	77	99	100			. 27	. 47
90	Wind R., near Burris, Wyo								20	35	68	98	98	100		. 27	. 60
125	Middle Piney Creek, below South Fork near Big Piney, Wyo					1	3	5	12	29	68	100				. 31	. 58
128	Little Sandy Creek, near Elkhorn, Wyo			1	4	7	9	11	16	31	71	82	88	98	100	. 29	. 95
182	Rio Galisteo, at Cerrillos (Lamy), N. Mex	27	42	46	60	67	79	86	94	100						. 0038	. 042
183	Rio Santa Fe, at Old Albuquerque Rd., west of Santa Fe, N. Mex	1	4	34	61	68	76	90	96	100						. 0046	. 039
184	Arroyo de los Chamisos, near Mt. Carmel Chapel (Sunmount) at Santa Fe, N. Mex		6	26	52	72	86	94	97	99	100					. 0066	. 0227
185	Cañada Ancha (Euler), near El Rancho Montoso near Santa Fe, N. Mex	9	17	39	59	83	93	96	98	100						. 0046	. 0132
186	Ancha Chiquita, near El Rancho Montoso south of Santa Fe, N. Mex	2	14	48	78	87	93	97	98	98	100					. 0033	. 0101
187	Tributary to Hermanas Arroyo, near Las Dos, northwest of Santa Fe, N. Mex	1	11	37	54	70	81	89	97	99	100					. 0057	. 037
189	Rio Galisteo, at Domingo, N. Mex	11	36	71	91	96	96	100								. 0022	. 0046
227	Fall Creek, near Pinedale, Wyo						2	4	4	6	26	68	90	100		. 69	1. 25
228	Green R., Fontenelle, Wyo								8	16	84	100				. 29	. 42
229	West Fork Rock Creek, near Red Lodge, Mont						2	2	2	9	22	44	73	95	100	. 88	2. 4
230	Rock Creek, near Red Lodge, Mont								2	6	30	62	82	94	100	. 67	1. 93
232	Clear Creek, near Buffalo, Wyo					1	2	5	8	19	41	61	79	96	100	. 58	2. 15
233	North Fork Clear Creek, near Ranger station, Buffalo, Wyo							3	10	22	45	78	100			. 47	1. 0
234	Red Fork, near Barnum, Wyo							12	42	80	98	100				. 12	. 21
235	Rock Creek, at Roberts, Wyo								7	32	80	99	100			. 27	. 46
240	Pole Creek, ½ mile below Little Half Moon Lake near Pinedale, Wyo				1	3	3	5	10	23	51	78	93	100		. 42	. 51
256	Bull Lake Creek, near Lenore, Wyo									3	22	61	82	97	100	. 69	1. 92
266	Big Sandy Creek, at Leckie ranch, Wyo				7	12	14	15	22	38	66	88	99	99	100	. 25	. 72

APPENDIX H.—*Values of hydraulic factors at various stream cross sections*

[e, Estimated. For definition of *b*, *f*, and *m* see page IV; for discussion see Leopold and Maddock, 1953]

Serial No.	Stream and location	Drainage area (square miles)	At mean annual discharge				Slope		Median bed size (feet)	*b*	*f*	*m*	Gage height at bankfull stage (feet)
			Discharge (cubic feet per second)	Width (feet)	Depth (feet)	Velocity (feet per second)	Map [1]	Field [2]					
1	North Platte R., North Platte, Nebr.	32,000	2,300	540	1.7	2.4	0.00135	0.0014	0.0006	0.35	0.48	0.18	
2	Near Sutherland, Nebr	31,300	537	340	.92	1.7	.00115	.0011	.0005	.48	.34	.20	
3	Near Lisco, Nebr	26,900	1,137	400	1.35	2.1	.00105	.00125	.0016	.26	.50	.21	
4	Near Douglas, Wyo	14,300	1,493	310	1.7	3.0	.00095	.00095	.02	.05	.65	.28	
5	Wind R., at Riverton, Wyo	2,320	1,106	160	2.0	3.6		.0038	.16	.05	.65	.31	
6	Little Popo Agie R., near Lander, Wyo.	108	e 100	39	1.1	2.7		.0049	.11	.04	.48	.47	6
7	New Fork R., Jenkins ranch near Cora, Wyo.	45						.0047	e .023				
8	Green R., at Warren Bridge near Daniel, Wyo.	468	509	120	1.8	2.4		.0034	.46	.12	.34	.52	
9	Beaver Creek, near Daniel, Wyo	141	32.1	42	.88	.86	.0066	.0014	.097	.10	.40	.50	
10	New Fork R., below New Fork Lake near Cora, Wyo.	36.2	50					.0051	.017				
11a	Horse Creek, near Daniel, Wyo	124	63.2	61	.64	1.6		.00227	.09	.12	.42	.43	
11b	do.[3]	124						.0073					
12a	Cottonwood Creek near Daniel, Wyo.	204						.0011	.049				
12b	do.[3]	204	67.4	43	.8	1.8		.00405	.06	.30	.26	.44	
14a	Green R. at Daniel, Wyo	660						.0005	.056				
14b	do.[3]							.0029	.18				
14c	do.[3]							.0029	.18				
18a	New Fork R. at American Gothic reach near Pinedale, Wyo.	372						.00125	.121				
18b	do.[3]							.00286					
18c	do.[3]							.00286					
21	Duck Creek, near Cora, Wyo	5						.000193	e .004				
22	Snake R., below mouth of Hoback R. near Jackson, Wyo.	3,440						.0021					
23	Buffalo Fork, Flybox reach near Jackson, Wyo.	345					.00071	.000455	.14				
24	Wind R., Dumb Cowboy reach near Sheridan Ranger station above Dubois, Wyo.	55						.0037	.131				
25	DuNoir Creek, above Dubois, Wyo	93						.00098	.035				
26	North Fork Popo Agie R., near Lander, Wyo.	140	103	41	1.75	1.5		.0070	.49	.13	.20	.65	
27	Popo Agie R., Joyful reach near Hudson, Wyo.	700						.00184	.10				
28	Little Pipe Creek, near Avondale, Md.	8						.00473	.049				5.5
29	Rock Creek, Rt. 115 near Redland, Md.	7.4							.13				
30	Watts Branch, Viers pasture near Rockville, Md.	4.2	e 4.2	13.1	.52	.62		.0031	.082	.03	.47	.50	3.3
31	Seneca Creek, at Dawsonville, Md	100	93	53	1.06	1.7	.00133	.0006	.075	.18	.50	.30	5.1
32	Crooked Run ("Save the Meander Farm") near State College, Pa.	.53						.0005					
33	Seneca Creek at Riffleford near Rockville, Md.	15.5						.0023	.026				
36	Mississippi R., at Tamm Bend near Blytheville, Ark.	1,000,000?	e 580,000					.000089	e .002				
39	Northwest branch of Anacostia R., near Colesville, Md.	21	21.5	26	.92	.84				.19	.42	.42	
42	Baldwin Creek, near Lander, Wyo	21						.00093	.09				
57	Belle Fourche R., below Moorcroft, Wyo	1,730	79	38	1.5	1.4	.000947			.30	.42	.28	
58	At Hulett, Wyo	2,800	60.5	50	.8	1.8	.00126			.18	.48	.45	
59	At Wyoming-South Dakota State line		150				.000947						
61	Near Elm Springs, S. Dak	7,210	447	112	1.5	2.7				.38	.35	.32	
62	Near Fruitdale, S. Dak						.00118						
63	Arikaree R., at Haigler, Nebr	1,460	31.7	45	.5	1.4	.00189			.30	.45	.30	
64	Seneca Creek, near Woodfield, Md. (1 mile north of Woodfield)	2.1						.0092	.06				
65	Christians Creek, at Orange Bridge near Staunton, Va	24						.0015	.075				
66	Christians Creek, at Rt. 254 near Staunton, Va	82.5						.0030	.085				
67	Barterbrook Creek, at Rt. 254 near Staunton, Va	6.8						.0023	.0125				
68	Middle R., at Bethlehem Church near Staunton, Va	18						.0021	.076				
69	Eidson Creek, near Mt. Tabor Church near Staunton, Va	2.2						.0093	.049				
70	Tributary to Christians Creek, near St. James Church near Fisherville, Va	1.6						.0067					
71	South R., Black Bull reach south of Mt. Vernon Church near Lipscomb, Va	69.2						.00034	.00327				
72	South Fork Tye R., above Nash, Va	14.2						.051	1.15				
73	Tye R., culvert-bridge near Staunton, Va	6.4						.067	1.31				
74	Picnic reach near Staunton, Va	12.3						.068	1.65				
75	Below Nash, Va	31.4						.026	.75				
76	Campbell Creek, above Tyro, Va	1.1						.11	1.77				
77	Stony Run, above mouth at Little R. near Staunton, Va	1.1						.083	.31				

See footnote at end of table.

APPENDIX H.—*Values of hydraulic factors at various stream cross sections*—Continued

Serial No.	Stream and location	Drainage area (square miles)	At mean annual discharge				Slope		Median bed size (feet)	*b*		*m*	Gage height at bankfull stage (feet)
			Discharge (cubic feet per second)	Width (feet)	Depth (feet)	Velocity (feet per second)	Map [1]	Field [2]					
78	Mines Run, at mouth near Staunton, Va	2.8						0.038	0.22				
79	Skidmore Fork, Rt. 95 near Staunton, Va	4.8						.025	.25				
80	Little R., Grooms Ridge near Staunton, Va	16						.0048	.26				
81	North R., near Stokesville, Va	23.4						.015	.38				
82	North River Gap near Stokesville, Va	66.4						.0091	.43				
84	Slab Cabin Creek, west of Lamont, Pa	16						.0032					
86	Big Horn R., at Manderson, Wyo	11,900	1,950	258	2.5	3.0	0.000947			0.06	0.55	0.35	
87	Wind R., near Crowheart, Wyo	1,920	1,315	155	2.4	3.6				.07	.48	.40	
89	Yellowstone R., at Billings, Mont	11,600	6,331	420	4.6	3.2	.00152	.00083	.27	.06	.47	.46	
90	Wind R., near Burris, Wyo	1,220	853	130	2.7	2.5	.004		.27	.05	.32	.62	
91	Near Dubois, Wyo	233	179	68	1.4	1.9	.0063			.02	.38	.59	6
92	Little Bighorn R., at State line near Wyola, Mont	199	152	29	2.0	2.5	.0095			.00	.37	.64	
93	North Platte R., at Wyoming-Nebraska State line, Wyo	22,100	767	270	1.4	2.1	.00118			.22	.6	.16	
94	At Saratoga, Wyo	2,880	1,204	210	2.8	2.0	.00146			.10	.33	.57	
95	Medicine Lodge Creek, Hyattville, Wyo	86	37	25	.9	1.7				.15	.31	.52	3.4–3.9
96	Gooseberry Creek, near Grass Creek, Wyo	155	19	19.5	.6	1.9	.0099			.09	.45	.43	
97	North Fork Owl Creek, near Ancher, Wyo	58.2	16	17	.58	1.7	.0114			.31	.24	.47	7.3–8.8
98	Yellowstone R., at Corwin Springs, Mont	2,630	2,950	242	3.4	3.6	.00237			.06	.49	.45	
99	Near Sidney, Mont	69,450	11,860	308	11.9	3.2	.000189			.04	.37	.58	
100	Little Bighorn R., below Pass Creek near Wyola, Mont	429	202	57	1.5	2.4	.00316			.02	.55	.45	
101	Near Crow Agency, Mont	1,190	294	96	1.2	2.5	.00118			.04	.44	.50	
102	Republican R., near Bloomington, Nebr	20,800	724	230	1.7	1.8	.00086			.08	.52	.40	16
103	Laramie R., near Ft. Laramie, Wyo	4,600	185	60	1.4	2.2	.00167			.17	.40	.40	
104	South Platte R., at Paxton, Nebr	23,700	438	140	1.5	2.0	.00158			.20	.58	.22	
105	North Platte R., near Keystone, Nebr	30,000	340				.00118			.58	.25	.15	
106	Platte R., near Grand Island, Nebr	59,500	960	670	.8	1.8	.00126			.05	.72	.22	
107	Near Odessa, Nebr	58,800	937	550	.96	1.8	.00126			.22	.53	.23	
108	Near Overton, Nebr	58,400	2,583	780	1.55	2.2	.00126			.07	.65	.27	
109	North Platte R., near Mitchell, Nebr	24,300	1,495	280	2.0	2.6	.00118			.50	.37	.12	
110	Below Whalen, Wyo	16,350	1,111				.00111			.42	.22	.32	
111	Below Casper, Wyo	12,600	1,358	250	1.9	3.0	.00080			.25	.25	.20	
112	Popo Agie R., near Riverton, Wyo	2,010	683	123	3.3	1.7	.00126			.02	.35	.62	
113	Greybull R., near Basin, Wyo	1,130	200	90	.95	2.4	.00663			.10	.50	.37	
114	Near Meeteetse, Wyo	690	364	87	1.4	3.0	.00947			.25	.35	.35	
115	Owl Creek, near Thermopolis, Wyo	484	45.5	26	.9	1.9				.20	.29	.50	
116	Missouri R., at St. Joseph, Mo	424,300	35,440	863	11.5	3.6	.000227			.05	.42	.58	
117	At Hermann, Mo	528,200	69,170	1,578	14.5	3.0	.000189			.05	.42	.50	
118	At Pierre, S. Dak	243,500	22,080	962	9.1	2.5	.000189			.10	.41	.47	
119	At Kansas City, Mo	489,200	43,710	1,093	11.7	3.4	.000146			.05	.55	.37	
120	At Bismark, N. Dak	186,400	20,320	1,202	6.1	2.9	.000227			.01	.50	.45	
121	East Fork R., near Big Sandy R., Wyo	79.2	103	70	1.3	1.15				.06	.41	.50	
122	North Piney Creek, near Mason, Wyo	58	60.3	29	.94	2.2				.12	.46	.42	
123	Boulder Creek, below Boulder Lake near Boulder, Wyo	130	196	130	1.8	.84		.0008	e 66	.08	.40	.47	
124	Silver Creek, near Big Sandy, Wyo	45.4	43.4	29	.8	1.9				.18	.49	.27	
125	Middle Piney Creek below South Fork near Big Piney, Wyo	34.3	26.7	23	.68	2.0		.0091	.31	.10	.40	.48	7.7
126	New Fork R., near Boulder, Wyo	552	403	98	1.8	2.2				.20	.48	.30	
127	Fontenelle Creek, near Fontenelle, Wyo	224	64.6	42	.95	1.7				.20	.28	.50	
128	Little Sandy Creek, near Elkhorn, Wyo	20.9	22	19	1.5	.76		.010	.29	.23	.41	.33	
129	Pecatonica R., at Freeport, Ill	1,330	906	140	6.2	1.03				.20	.35	.43	
130	Iroquois R., near Chebanse, Ill	2,120	1,609	330	3.2	1.5				.05	.60	.35	15
131	Catheys Creek, near Brevard, N. C	11.7	34	25.3	.9	1.5	.00947			.10	.20	.67	
132	Watauga R., near Sugar Grove, N. C	90.8	154	64	1.8	1.3				.10	.45	.50	
133	Davidson R., near Brevard, N. C	40.4	125	55	1.6	1.4	.00374			.05	.40	.53	
134	Noland Creek, near Bryson City, N. C	13.8	42.8	30.1	1.9	.8				.08	.27	.65	
135	Tennessee R., at Knoxville, Tenn	8,934	12,820	933	14.4	1.0	.000095			.06	.68	.28	
136	French Broad R., near Newport, Tenn	1,858	2,764	346	5.3	1.5	.00237			.05	.33	.65	10
137	At Calvert, N. C	103	335	92	1.8	2.0	.00108			.02	.55	.45	
138	At Rosman, N. C	67.9	229	77	2.0	1.5	.00252			.10	.52	.45	
139	At Bent Creek, N. C	676	1,589	296	2.8	1.9				.01	.55	.47	
140	Buttahatchee R., near Caledonia, Miss	823	1,066	152	13.0	.5	.000663			.20	.07	.75	
141	Tombigbee R., at Aberdeen, Miss	2,210	2,863	142	11.5	1.8	.000142			.10	.50	.38	
142	Near Leroy, Ala	19,100	26,250	513	26.0	2.0	.000019			.10	.31	.60	
143	Near Coatopa, Ala	15,500	21,450	458	22.3	2.2	.000076			.16	.45	.35	
144	Near Columbus, Miss	4,490	5,791	270	11.9	1.8	.000095			.18	.37	.52	
145	Sipsey R., near Elrod, Ala	515	715	93	7.0	1.1		.00063		.23	.45	.30	

See footnotes at end of table.

APPENDIX H.—*Values of hydraulic factors at various stream cross sections*—Continued

Serial No.	Stream and location	Drainage area (square miles)	At mean annual discharge				Slope		Median bed size (feet)	b	f	m	Gage height at bankfull stage (feet)
			Discharge (cubic feet per second)	Width (feet)	Depth (feet)	Velocity (feet per second)	Map [1]	Field [2]					
146	Republican R., at Clay Center, Kans	24,570	1,093	272	2.0	2.0	.000541	----	----	.37	.45	.20	15
147	Smoky Hill R., at Elkader, Kans	3,555	36	41	.6	1.5	----	----	----	.17	.58	.30	----
148	At Lindsborg, Kans	8,110	292	80	2.4	1.5	.000545	----	----	.22	.56	.20	----
149	At Enterprise, Kans	19,200	1,419	102	7.2	1.9	.000303	----	----	.10	.17	.72	----
150	Kansas R., at Bonner Springs, Kans	59,890	5,874	563	5.9	1.8	.000379	----	----	.06	.45	.48	----
151	At Lecompton, Kans	58,420	7,838	728	4.6	2.3	.000379	----	----	.07	.70	.25	----
152	At Ogden, Kans	45,240	2,514	342	3.8	1.9	.000379	----	----	.02	.55	.40	----
153	At Topeka, Kans	56,710	4,655	481	4.6	2.1	.000430	----	----	.07	.61	.30	21
154	At Wamego, Kans	55,240	4,114	525	4.1	1.9	.000316	----	----	.17	.55	.25	----
156	Flathead R., near Columbia Falls, Mont	1,553	2,855	290	2.5	4.0	----	----	----	.30	.32	.38	----
157	At Columbia Falls, Mont	4,464	9,112	450	7.1	2.9	----	----	----	.04	.40	.55	----
158	Near Polson, Mont	7,096	11,330	444	7.6	3.4	----	----	----	.08	.40	.50	----
159	Clark Fork R., at St. Regis, Mont	10,500	7,341	346	6.0	3.55	----	----	----	.09	.45	.44	----
160	Above Missoula, Mont	5,740	2,659	232	4.7	2.42	.00158	----	----	.05	.42	.51	----
161	Below Missoula, Mont	8,690	4,897	370	5.8	2.2	----	----	----	.03	.20	.77	----
162	Near Plains, Mont	19,900	18,690	495	14.3	2.6	----	----	----	.04	.27	.69	----
163	Near Heron, Mont	21,800	20,400	328	12.0	5.3	.00079	----	----	.20	.38	.36	----
164	Pend Oreille R., below Z Canyon, near Metaline Falls, Wash	25,200	26,190	293	11.7	7.6	----	----	----	.30	.34	.34	----
167	Embarrass R., at St. Marie, Ill	1,540	1,229	110	4.8	2.3	----	----	----	.20	.60	.20	18
168	Kankakee R., at Momence, Ill	2,340	1,818	430	2.3	1.8	----	----	----	.15	.44	.38	----
169	Rock R., at Como, Ill	8,700	5,174	500	3.6	2.87	----	----	----	.10	.48	.45	----
172	Sangamon R., at Riverton, Ill	2,560	1,806	125	6.0	2.5	----	----	----	.35	.55	.15	----
173	Connecticut R., at First Connecticut Lake near Pittsburgh, N. H	83.0	198	57	1.25	2.6	.01136	----	----	.10	.34	.56	----
174	At North Stratford, N. H	799	1,570	160	3.7	2.7	.00189	----	----	.15	.28	.58	----
175	Near Dalton, N. H	1,514	2,902	380	4.0	2.0	.00189	----	----	.08	.52	.42	----
176	At White River Junction, Vermont	4,092	7,217	485	4.2	3.5	.00063	----	----	.04	.66	.30	----
178	At Montague City, Mass	7,865	13,670	450	11.5	2.6	.00034	----	----	.08	.42	.46	----
179	White R., near Bethel, Vt	241	487	160	1.3	2.3	.00189	----	----	.08	.55	.36	12
180	At West Hartford, Vt	690	1,169	235	4.1	1.2	.00114	----	----	.05	.38	.57	----
181	Arkansas R., at Salida, Colo	1,218	622	104	2.0	3.0	----	----	----	.04	.45	.49	----
182	Rio Galisteo, at Cerrillos, N. Mex	e 100	----	----	----	----	----	.0059	.0038	.13	.56	.29	----
183	Rio Santa Fe, at Old Albuquerque Rd. west of Santa Fe, N. Mex	e 175	----	----	----	----	----	.0151	.0046	.25	.44	.35	----
184	Arroyo de las Chamisos, near Mt. Carmel Chapel (Sunmount) at Santa Fe, N. Mex	2.5	----	----	----	----	----	.025	.0066	.09	.61	.26	----
185	Cañada Ancha (Euler), near El Rancho Montoso near Santa Fe, N. Mex	1.52	----	----	----	----	----	.0175	.0046	.39	.30	.28	----
186	Ancha Chiquita, near El Rancho Montoso, south of Santa Fe, N. Mex	.09	----	----	----	----	----	.0286	.0033	.13	.60	.32	----
187	Tributary to Hermanas Arroyo, near Las Dos, northwest of Santa Fe, N. Mex	.06	----	----	----	----	----	.032	.0057	.32	.24	.43	----
188	Rio Puerco, near Cabezon, N. Mex	360	----	----	----	----	----	----	----	.27	.35	.36	----
189	Rio Galisteo, at Domingo, N. Mex	e 600	----	----	----	----	----	.0055	.0022	.32	.39	.24	----
190	Rio Puerco, at Cabezon, N. Mex	----	----	----	----	----	----	----	----	.34	.35	.34	----
191	Meet John Wash, near Casper, Wyo	----	----	----	----	----	----	----	----	.22	.33	.45	----
192	Shell Rock R., near Northwood, Iowa	380	141	100	1.25	1.1	----	----	----	0	.56	.46	----
193	Turtle Creek, near Austin, Minn	144	65	46	1.5	.85	----	----	----	.21	.48	.29	----
194	Cedar R., at Cedar Rapids, Iowa	6,640	3,093	460	2.8	2.3	----	----	----	.06	.56	.34	----
195	Near Conesville, Iowa	7,840	4,259	430	4.7	2.0	----	----	----	.33	.40	.22	----
196	Iowa R., at Wapello, Iowa	12,480	6,135	480	8.1	1.6	----	----	----	.40	.23	.41	----
197	Cedar R., near Austin, Minn	425	172	94	1.35	1.3	----	----	----	.09	.54	.39	----
198	Lime Creek, at Mason City, Iowa	535	209	94	1.9	1.19	----	----	----	.04	.53	.42	----
199	West Fork Shell Rock R., at Finchford, Iowa	860	461	112	2.4	1.7	----	----	----	.22	58	.17	10
200	Cedar R., at Janesville, Iowa	1,660	675	190	1.6	2.3	----	----	----	.25	.51	.19	----
201	At Waterloo, Iowa	5,190	2,988	440	2.3	2.9	----	----	----	.07	.66	.27	----
202	Tributary to Seneca Cr., at Hawkins Creamery rd. near Damascus, Md	0.8	----	----	----	----	----		.060	----	----	----	----
203	Seneca Creek, at Holstein pasture near Woodfield, Md	7.9	----	----	----	----	----	.00467	.056	----	----	----	----
204	At Poison Ivy reach, Brunt road bridge near Woodfield, Md	----	----	----	----	----	----	.00345	.074	----	----	----	----
205	At Pretty Flood Plain near Prathertown, Md	26	----	----	----	----	----	.0016	.037	----	----	----	----
206	Kankakee R., at Davis, Ind	506	470	75	3.6	1.75	----	----	----	.24	.61	.14	----
207	At Shelby, Ind	1.800	1.518	130	5.6	2.0	----	----	----	.12	.58	.29	----
208	Auglaize R., near Defiance, Ohio	2,329	1,598	285	3.7	1.5	.000189	----	----	.08	.48	.45	8
209	Near Fort Jennings, Ohio	333	278	100	2.8	1.0	.000413	----	----	.24	.48	.28	17
210	Blanchard R., near Dupont, Ohio	749	452	120	5.4	.7	.000090	----	----	----	----	----	----
211	Near Findlay, Ohio	343	219	92	1.5	1.6	.000237	----	----	.08	.56	.32	----
212	At Glendorf, Ohio	643	548	77	3.7	2.0	.000146	----	----	.18	.58	.22	----
213	Maumee R., at Antwerp, Ohio	2,049	1,547	202	4.3	1.7	.000271	----	----	.17	.45	.38	----
214	Near Defiance, Ohio	5,530	3,612	620	3.1	1.85	.000189	----	----	0	.50	.50	----
215	At Waterville, Ohio	6,314	4,269	670	2.1	3.1 (	.000947	----	----	.16	.59	.28	----
216	*Ottawa R., at Allentown, Ohio*	168	119	52	1.0	2.45	.000631	----	----	.26	.34	.40	----
217	At Kalida, Ohio	315	141	80	1.6	1.1	.000473	----	----	----	----	----	----

See footnotes at end of table.

APPENDIX H.—*Values of hydraulic factors at various stream cross sections*—Continued

Serial No.	Stream and location	Drainage area (square miles)	At mean annual discharge				Slope		Median bed size (feet)	*b*	*f*	*m*	Gage height at bankfull stage (feet)
			Discharge (cubic feet per second)	Width (feet)	Depth (feet)	Velocity (feet per second)	Map[1]	Field[2]					
218	St. Joseph R., near Blakeslee, Ohio	369	292	95	2. 8	1. 1	. 000210	--------	--------	--------	--------	--------	--------
219	Scioto R., at Chillicothe, Ohio	3, 847	3, 289	200	9. 2	1. 8	. 000316	--------	--------	. 12	. 30	. 53	17
220	Near Circleville, Ohio	2, 635	1, 815	280	10. 8	. 6	. 000271	--------	--------	. 10	. 21	. 64	--------
221	At Columbus, Ohio	1, 624	1, 386	280	3. 7	1. 35	. 000473	--------	--------	. 02	. 52	. 46	--------
222	Near Dublin, Ohio	988	797	205	2. 0	1. 95	. 00094,	--------	--------	. 18	. 40	. 40	--------
223	At La Rue, Ohio	255	198	90	3. 8	. 6	. 000316	--------	--------	. 13	. 32	. 50	--------
224	Near Prospect, Ohio	571	489	130	2. 5	1. 5	. 000237	--------	--------	. 08	. 50	. 42	--------
225	Tiffin R., near Brunerburg, Ohio	766	448	85	3. 9	1. 4	. 000105	--------	--------	--------	--------	--------	--------
226	At Stryker, Ohio	444	292	77	5. 6	. 69	. 000189	--------	--------	. 20	. 32	. 43	--------
227	Fall Creek, near Pinedale, Wyo	37. 2	36. 2	24. 5	. 35	. 42	--------	. 036	. 69	--------	--------	--------	8. 5
228	Green R., near Fontenelle, Wyo	3, 970	1, 838	250	3. 2	2. 3	--------	. 0002	. 29	. 05	. 35	. 60	7. 1
229	West Fork Rock Creek, below Basin Creek near Red Lodge, Mont	60	85	33	1. 25	2. 0	--------	. 035	. 88	. 04	. 36	. 58	--------
230	Rock Creek, near Red Lodge, Mont	100	166	28. 5	2. 4	2. 3	--------	. 021	. 67	0	. 29	. 71	--------
231	Clark Fork, near Edgar, Mont	2, 115	1, 008	115	4. 2	2. 0	--------	. 00295	. 21	. 08	. 31	. 60	3. 0
232	Clear Creek, near Buffalo, Wyo	120	70	42	. 9	1. 8	. 0316	. 024	. 58	. 14	. 37	. 48	--------
233	North Fork Clear Creek, near Buffalo (near Ranger station), Wyo	29	16	23	. 8	. 8	--------	. 028	. 47	--------	--------	--------	--------
234	Red Fork R., near Barnum, Wyo	142	29	21	. 97	1. 34	. 0038	--------	. 12	--------	--------	--------	--------
235	Rock Creek, at Roberts, Mont	e 270	--------	--------	--------	--------	--------	. 0086	. 27	--------	--------	--------	--------
236	Illinois R., at Kingston Mines, Ill	15. 200	14, 220	600	15. 0	1. 6	--------	--------	--------	. 16	. 32	. 54	--------
237	At Marseilles, Ill	7, 640	11, 670	620	4. 1	4. 5	--------	--------	--------	. 03	. 55	. 40	--------
238	At Meredosia, Ill	25, 300	20, 950	900	11. 5	1. 9	--------	--------	--------	. 08	. 57	. 35	--------
239	Kankakee R., near Wilmington, Ill	5, 250	4, 009	840	2. 4	2. 0	--------	--------	--------	. 04	. 50	. 46	--------
240	Pole Creek, ½ mile below Little Half Moon Lake near Pinedale, Wyo	87. 5	108	60	1. 23	1. 4	--------	. 0018	. 42	--------	--------	--------	5. 3
245	Cedar Creek, near Winchester, Va	101	86. 7	60	1. 1	1. 2	--------	--------	--------	. 06	. 58	. 35	--------
247	North Fork Shenandoah R., at Mt. Jackson, Va	509	368	110	2. 7	1. 2	--------	--------	--------	. 10	. 33	. 52	--------
248	Near Strasburg, Va	772	575	160	2. 4	1. 5	--------	--------	--------	. 13	. 52	. 35	--------
249	South Fork Shenandoah R., at Front Royal, Va	1, 638	1, 671	275	3. 2	1. 9	--------	--------	--------	. 04	. 42	. 54	--------
250	Near Luray, Va	1, 377	1, 264	315	4. 7	. 87	--------	--------	--------	. 04	. 33	. 59	--------
251	Near Lynnwood, Va	1, 076	1, 020	109	2. 9	1. 9	--------	--------	--------	. 06	. 53	. 38	--------
252	South R., at Harriston, Va	222	237	86	1. 5	1. 8	--------	--------	--------	. 10	. 30	. 60	--------
253	South R., at Waynesboro, Va	144	146	78	1. 4	1. 34	--------	--------	--------	. 04	. 43	. 50	--------
254	Stony Creek, at Columbia Furnace, Va	76	e 74	70	1. 2	. 9	--------		--------	. 20	. 45	. 31	--------
255	Antietam Creek, near Sharpsburg, Md	281	258	72	2. 7	1. 3	--------	. 00055	--------	. 05	. 35	. 57	--------
256	Bull Lake Creek, near Lenore, Wyo	222	285	92	1. 65	1. 9	--------	. 0081	. 69	. 14	. 33	. 50	--------
257	Cheyenne R., at Edgemont, S. Dak	7, 134	126	90	. 8	1. 9	--------	. 0013	e. 00016	--------	--------	--------	--------
258	Lance Creek, at Spencer, Wyo	2, 070	30. 7	43	. 53	1. 4	--------	. 00073	e. 0099	. 13	. 53	. 34	7. 5
264	Snake R., near Wilson, Wyo	2, 000	--------	--------	--------	--------	. 0043	--------	--------	--------	--------	--------	--------
266	Big Sandy Creek, near Leckie ranch, Wyo	95	--------	--------	--------	--------	--------	. 00425	. 25	--------	--------	--------	5. 5
267	Hams Fork R., near Frontier, Wyo	298	--------	--------	--------	--------	--------	. 0013	. 086	--------	--------	--------	3. 8
268	Middle Fork Powder R., near Kaycee, Wyo	980	--------	--------	--------	--------	. 0038	--------	. 15	--------	--------	--------	4. 6–5. 1
272	Bighorn R., near Custer, Mont	22, 350	4, 441	390	4. 65	2. 4	--------	--------	--------	. 10	. 50	. 40	--------
273	Near St. Xavier, Mont	e 20, 000	3, 758	264	4. 9	2. 8	. 00271	--------	--------	--------	--------	--------	--------
274	Missouri R., at Toston, Mont	--------	5, 322	370	4. 5	3. 2	--------	--------	--------	. 04	. 47	. 48	--------
275	Powder R., near Locate, Mont	12, 900	727	165	1. 6	2. 8	. 000947	--------	--------	. 28	. 42	. 30	--------
276	At Moorhead, Mont	8, 030	511	124	1. 7	2. 5	. 00114	--------	--------	--------	--------	--------	--------
277	Middle R., near Grottoes, Va	360	314	84	3. 0	1. 3	--------	--------	--------	. 15	. 34	. 53	--------
278	North Fork Shenandoah R., at Cootes Store, Va	215	187	73	1. 4	1. 8	--------	--------	--------	. 30	. 28	. 42	--------
279	Passage Creek, at Buckton, Va	87	70. 1	40	1. 75	. 95	--------	--------	--------	. 26	. 28	. 47	--------
280	Shenandoah R., at Millville, W. Va	3, 040	2, 561	460	3. 85	1. 4	--------	--------	--------	. 04	. 40	. 56	--------
281	Bighorn R., at Kane, Wyo	15, 900	2, 413	175	3. 8	3. 35	. 000947	--------	--------	. 06	. 51	. 43	--------
282	At Thermopolis, Wyo	8, 080	1, 900	210	2. 7	3. 33	. 00189	--------	--------	. 08	. 35	. 59	--------
283	Powder R., at Arvada, Wyo	6, 050	410	112	1. 27	2. 77	. 000947	--------	--------	. 44	. 27	. 29	--------
284	At Sussex, Wyo	3, 090	134	100	. 82	1. 85	. 000842	--------	--------	. 44	. 20	. 30	--------
285	South Fork Owl Creek, above Curtis ranch at Thermopolis, Wyo	139	29. 1	21	. 84	1. 65	--------	--------	--------	. 21	. 24	. 52	--------

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[1] Slope measured from topographic map.
[2] Slope determined by field survey.
[3] Divided channel.

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