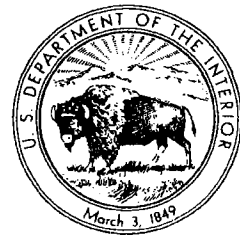


River Channel Patterns: Braided, Meandering and Straight

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

PHYSIOGRAPHIC AND HYDRAULIC STUDIES OF RIVERS

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SYMBOLS

<i>A</i>	area of cross section of flowing water	<i>L</i>	sediment load, in units of weight per unit of time
<i>A_d</i>	drainage area	<i>m</i>	exponent in relation of velocity to discharge when $v \propto Q^m$
<i>b</i>	exponent in relation of width to discharge when $w \propto Q^b$	<i>P</i>	wetted perimeter, in feet
<i>C_s</i>	sediment concentration, in pounds of sediment per pound of clear water	<i>Q</i>	water discharge, in cubic feet per second (cfs)
<i>d</i>	mean depth, defined as ratio of cross-sectional area to width	<i>R</i>	hydraulic radius, in feet
<i>D_s</i>	size of sediment particle	<i>s</i>	slope of water surface
<i>D₅₀</i>	median size of sediment particle; subscripts 25, 75, or 84 refer to percent of sample finer than specified size	<i>S₀</i>	sorting coefficient of a granular mixture
<i>f</i>	exponent in relation of depth to discharge when $d \propto Q^f$	<i>T</i>	temperature, in degrees Fahrenheit
<i>f</i>	Darcy-Weisbach resistance factor	<i>v_*</i>	shear velocity
<i>g</i>	acceleration due to gravity	<i>v</i>	mean velocity defined as quotient of discharge divided by cross-sectional area
<i>k</i>	numerical coefficient having a specific but undetermined value	<i>w</i>	width
		<i>γ</i>	specific weight of water, or 62.4 pounds per cubic foot
		<i>ρ</i>	mass density of water
		<i>τ₀</i>	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

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

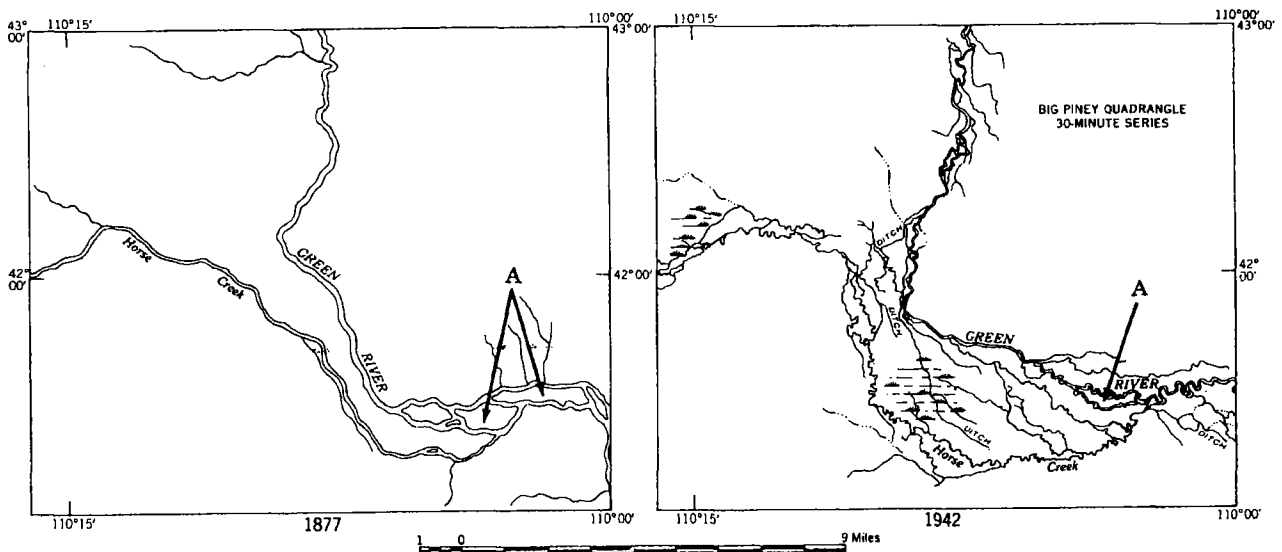


FIGURE 28. Maps of lower Horse Creek and the Green River near Daniel, Wyo., comparing a sketch made by Peale (1879, pl. L) in 1877 and a Geological Survey map of 1942. The islands (marked A) shown by Peale existed in 1942 with but minor changes in form. Note the successive dividing and rejoining of river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

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.

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

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 (<i>Agrostis</i> sp.)	20
Sweet clover (<i>Melilotus</i> sp.)	17
Bluestem (<i>Agropyron Smithii</i>)	12
Foxtail (<i>Hordeum</i> sp.)	10
Dandelion (<i>Taraxacum</i> sp.)	7
Shepherd purse (Cruciferae)	4
Carrot weed (Umbelliferae)	3
Mint (Labiatae)	2
Timothy (<i>Phleum</i> sp.)	2

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

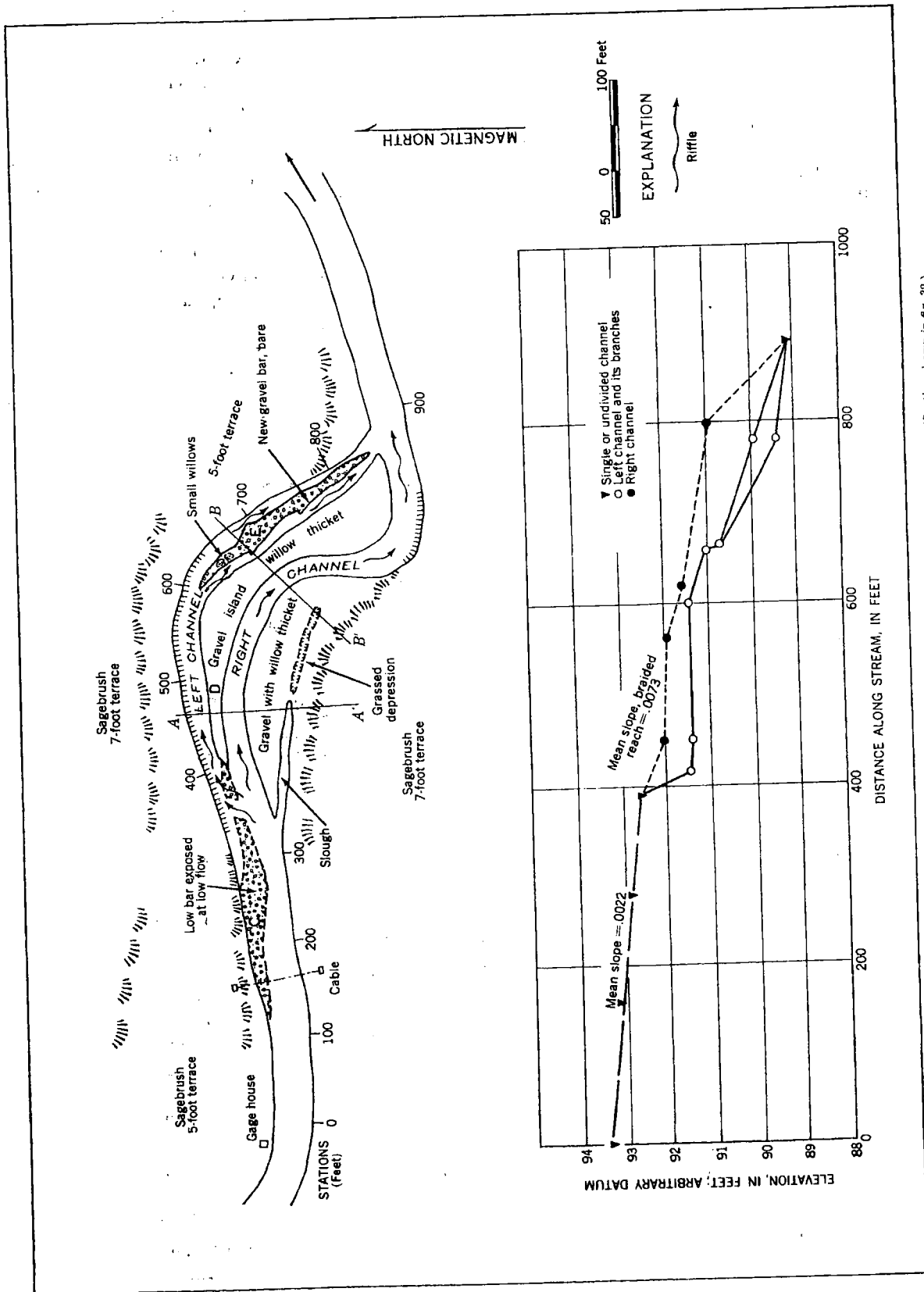


FIGURE 29. Plan and profile of Horse Creek near Daniel, Wyo., an example of a braided river. (Section shown in fig. 32.)

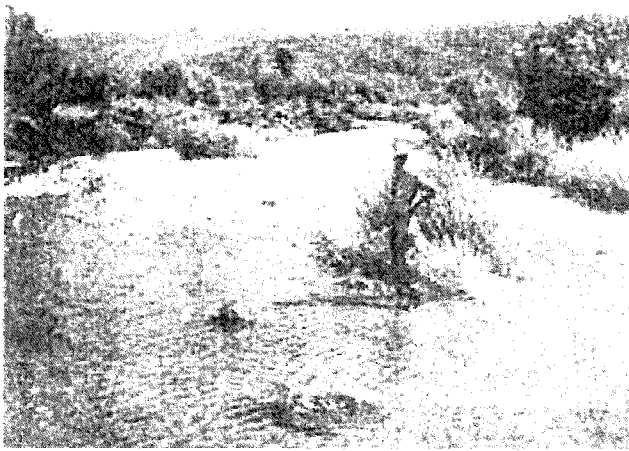


FIG. 1. Channel at the lower end of the reach.

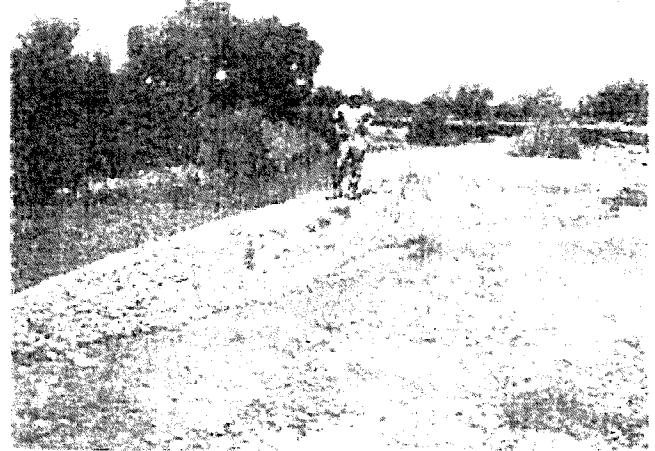


FIG. 2. Channel at the upper end of the reach.

braided by two low terraces, one 7 feet and the other 7 feet above the water surface. Within the lower up banks of the V-bed, across the gravel bar and, to a lesser extent, the remaining low alluvial channel bed, the same elevation. The gravel bed is generally somewhat lower than the level of the upper gravel bench at a point about half way down the reach. The same is the case with the surface of the gravel bar in the lower reaches of the reach.

STAGES IN THE DEVELOPMENT OF A BRAID

These observations suggest a sequence of events in the development of a braided reach. In a straight

reach, a channel, usually a river, composed of coarse sands, deposited by a high flow, is cut at a narrow bed bar, composed of the same particles, with low cut when water flows down the side of this narrow bed. Because of some local resistance, small gravel bars, composed of coarse sand, are formed at intervals of some 100 to 200 feet. Most of the kind of material, gravel, sand, and silt, deposited by a high flow, is composed of coarse sand, and the gravel bars tend to migrate upstream, especially in the lower reaches of the reach.

As the gravel bars migrate, the gravel bars tend to migrate upstream, especially in the lower reaches of the reach, especially in the lower reaches of the reach.

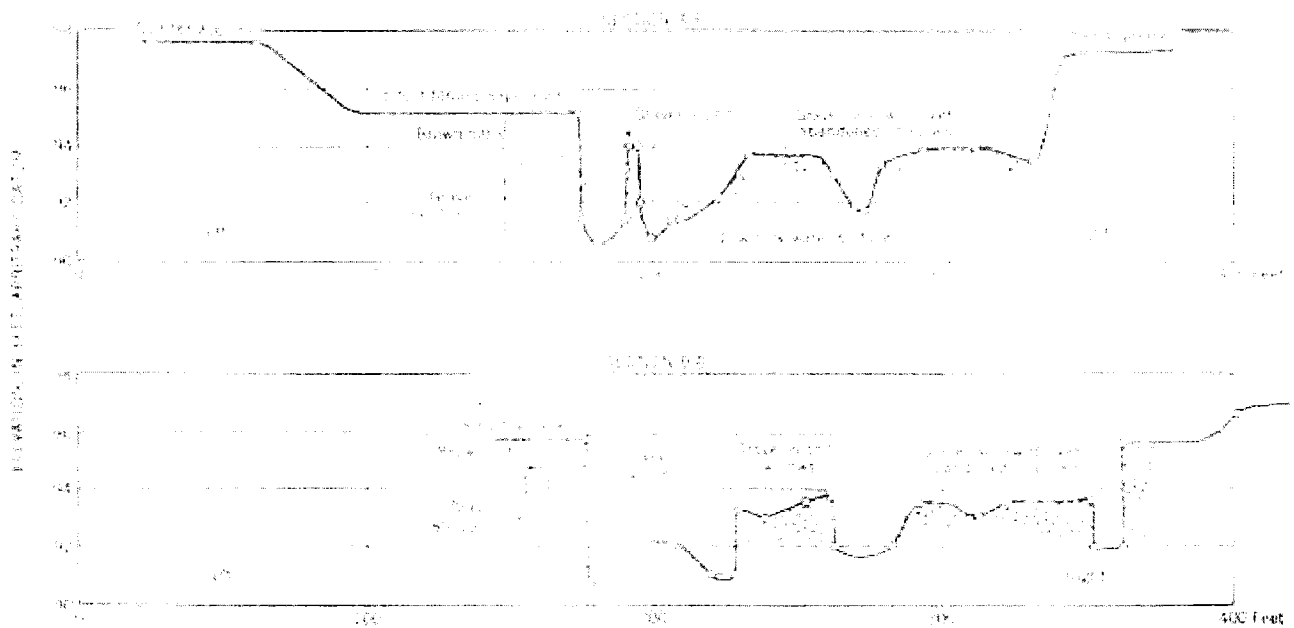


FIG. 3. Cross-sections of the reach. (The system in the lower reach is the same as in Fig. 1.)

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 aligned 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



Fig. 1. Channel flow experiment apparatus.

channel. A constant flow rate of polymer solution was maintained by the flow controller. The flow rate was measured by a flowmeter and recorded on a strip chart recorder.

The flow rate was controlled by a flow controller which was set to maintain a constant flow rate. The flow rate was measured by a flowmeter and recorded on a strip chart recorder.

The channel depth was measured at three points and varied from which it was prepared to an average of 1.0 cm. A paper with a well that permitted a constant flow rate change to be made at such a point. The channel depth was measured at three points and varied from which it was prepared to an average of 1.0 cm. A paper with a well that permitted a constant flow rate change to be made at such a point. The channel depth was measured at three points and varied from which it was prepared to an average of 1.0 cm. A paper with a well that permitted a constant flow rate change to be made at such a point.

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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

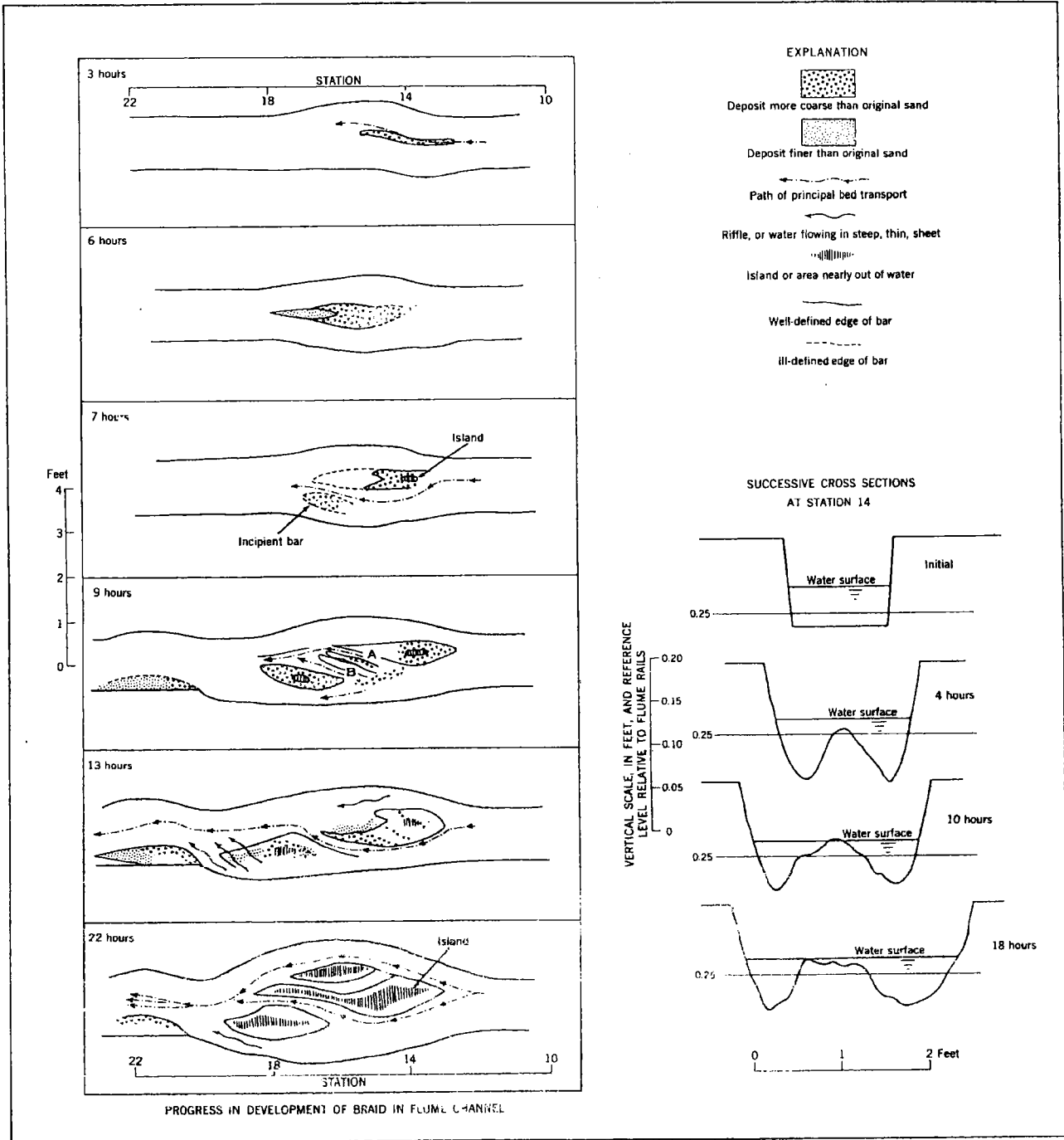


FIGURE 34.—Sketches and cross sections showing progress in development of braid in flume-river (February 16-22, 1954, runs 6-8.) (Profiles shown in fig. 38.)