

# TRANSITING COASTAL RIVER CHANNELS

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Rivers are the means and routes by which products of weathering are carried from the land surfaces to the oceans of the world (LEOPOLD, 1962). Since early times, man has utilized these avenues to explore new land and to transport the natural resources of the land from one area to another; more recently, he has used dams to harness these rivers for production of electrical power. Rivers vary greatly in size and occur in numerous topographic and geographic circumstances. Since this is the case, one might suppose that a wide variety of river types exists and that little can be said about general river characteristics. In actuality, however, a subtle unity exists, and this is probably the most important characteristic of river systems. In accomplishing the task of removing weathered materials from the continent, the water forms and maintains a highly organized system of physical and hydraulic features. Details of the interrelations in this organized system are highly complex, and it is difficult to visualize many of them simultaneously. Yet these same relationships constitute the distinctive characteristics of rivers, and some understanding of the basic types of rivers is necessary before man can utilize river systems to their greatest potential. For untold centuries man has navigated these major arteries of the continents, spreading his culture from one area to another. How did early explorers, lacking a thorough understanding of the complex processes that control such variables as exist in river channels, navigate unknown rivers? Perhaps the best answer is that most of the early penetrations of the river systems were conducted on a trial-and-error basis, an extremely time-consuming task. As certain pilots gained experience in one river, they applied the knowledge gained to traversing other rivers. Even at the present time, shipping companies allow river pilots, rather than their own captains,

to navigate their ships up and down the Mississippi River, even though the river is frequently charted. Most of the river pilots have been reared on the river and have learned through experience the numerous small, subtle features that indicate the thread of maximum current and hence a navigable channel. Mark TWAIN, the most famous of all pilots on the Mississippi, had considerable insight into transiting problems. He knew how to read the river. Most pilots have learned these lessons without understanding the basic principles governing them. Unfortunately, knowledgeable pilots are not found on all the large rivers of the world, and gaining such experience takes many years. In many instances today, time is just not available for the long process of learning by trial and error. In such cases, the basic knowledge gained from past river research must be applied and explanation must be made of the reasons such factors as water turbulence patterns, bankline shape, etc., can be used as aids to navigation in relatively uncharted rivers. Even in rivers that have been charted sporadically, changes resulting each year from flood passage make many of the charts out of date and the use of them hazardous.

## RIVER PATTERNS

Perhaps the most useful method of examining the characteristics of a river is to look first at the basic types. A river pattern is the appearance of its banks as viewed from above (i.e., in a plan view). If most of the major rivers of the world are thus examined, they can generally be grouped into three types: meandering, straight, and braided. These types have been thoroughly described by LEOPOLD and WOLMAN (1957) and are shown, along with typical cross sections, in figure 1. Although these three types represent the major divisions, it should be realized that continuous gradations exist between one type and another. Within a single river system, then, it is possible to find more than one type of pattern existing along its length.

### Meandering Channels

Meandering channels show more or less regular inflections in the direction of the channel and are generally quite sinuous in plan (fig. 1C). In such channels, deep scour pools are located very near the cut bank, while a broad, gently sloping bottom normally occurs on the opposite point bar. Between the points of maximum inflection of the meander loops are relatively straight portions of the channel, which in the Mississippi River are referred to as reaches. Meandering rivers have been the object of numerous studies, and many of the processes involved in river meandering have been well documented.

The flow pattern in a curved channel results in a slight elevation of the water surface against the cut bank. Thus, in a curve there are both

a downstream velocity component and a weaker, sideways component toward the cut bank at the water surface, but flowlines are about parallel on the stream bed. Maximum velocity and turbulence, during all but peak flood stage, are found near the steep cut bank, the speed of flow falling as the point bar is reached. During violent floods, however, this pattern is commonly reversed. The hydraulic gradient (slope of the water surface) is increased, and the flow seeks the shortest route to the sea, thus tending to straighten the channel (MATHES, 1941; RUSSELL, 1967). Material eroded from one meander loop (predominantly from the cut bank) is carried downcurrent and normally is deposited on the point bar of the next meander loop downstream. This leads to the migration of meander loops and rapid erosion on the cut bank. The cut banks of actively meandering streams tend to migrate rapidly; rates of up to 2 500 feet a year have been recorded for certain bends in the Ganges River of East Pakistan. Because of the flow patterns, however, it is relatively easy to predict both rate and direction of movement with a moderate degree of accuracy, even with a limited amount of information.

Profiles e-e' and f-f' in figure 1 are typical cross sections of a meandering stream. Profile e-e' is taken at the maximum point of inflection and shows a typical steep cut bank and associated scour pool. Quite often the scour pool lies close to the bank, and the navigable channel is extremely narrow. In many cases the bank above the water level will show numerous arcuate indentations, which are the result of local slumping of bank material caused by oversteepening. The closer the scour pool is to the cut bank, the greater the number of slumps that will generally occur. The bank opposite the cut bank, however, shows a gradual slope up to the point bar. The shape of this bank varies drastically during the changing flow regimes associated with the flood cycle. Profile f-f' is a cross section in the reach, or relatively straight area, of a meandering river. Unlike that at the point of maximum inflection, this profile shows a rather flat-bottomed, U-shaped section. Note also that the reach is generally considerably shallower than the section across the meander loop.

### **Straight Channels**

Straight channels are those which have, at bank-full stage, a negligible sinuosity over a distance many times the channel width (fig. 1B). The thalweg (line of maximum depth) of straight channels is generally sinuous in plan, moving from one bank to the other. The bends, however, are generally quite broad and not so tight as those of a meandering channel. As a consequence of the slight sinuosity, lateral bars are formed and are arranged alternately along the banks. The longitudinal profile down the center of the channel of such streams, therefore, shows an alternation of deep pools (opposite the lateral bars) and shallow riffles (between the lateral bars). This type of stream, although quite distinct, is essentially transitional, showing features comparable to both meandering and braided streams. The riffles correspond to a semibraided reach and the lateral bars and pools to a meander loop. Steep river gradients, large variations in stage,

aperiodic floods, and small bedload (although it might be quite coarse) are characteristic of straight channels. Very little factual data have been gathered on the hydraulic processes occurring in this type of river.

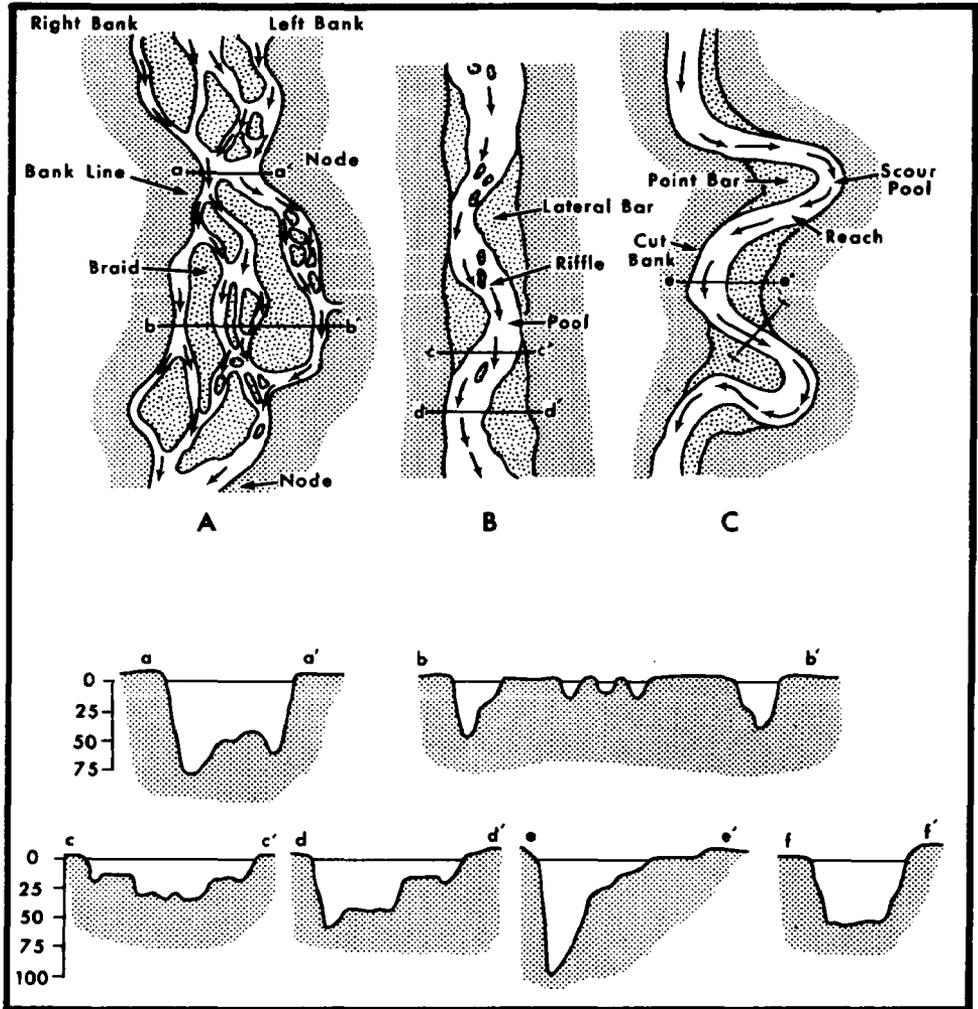


FIG. 1. — River channel patterns and typical cross sections.  
A. Braided. B. Straight. C. Meandering.

The cross sections  $c-c'$  and  $d-d'$  in figure 1 are typical of such a stream. A profile across the riffle area ( $c-c'$ ) shows a hummocky bottom; the area is generally quite shoal. Many small channels are present and in a plan view have an anastomosing pattern. The edges of the two lateral bars are quite evident. Profile  $d-d'$ , on the other hand, is across a pool. Here the river scours much deeper along the bank opposite the lateral bar. This profile closely resembles a cross section of a meandering river, except for

the small scour channel that also hugs the lateral bar side. However, a similar channel is often found in very broad meander loops. The lateral bars, although impressive and appearing stable on aerial photographs, are essentially ephemeral. They tend to migrate downstream and change orientation in a rather short period of time (20 to 50 years). In a straight channel, the banks are relatively stable and do not tend to migrate widely with time. Rather, the entire stream channel tends to shift to other areas within the valley. The most unstable portions of the river are the bars within the channel, which tend to move frequently. It is extremely difficult to suggest navigating aids, probably because of the lack of factual data relating to this type of river.

### **Braided Channels**

Braided channels are those marked by successive divisions and rejoinings of the flow around alluvial islands (fig. 1A). A braided river shows several islands in cross section, the islands being a product of the river itself and composed of both bedload and suspended sediment. In plan view, the islands are asymmetrically diamond-shaped or triangular, and one point of the triangle generally points upstream. In most large braided rivers, the islands are extremely unstable and change their location annually. In these circumstances, charts which are a year or so old are generally inaccurate. Under certain conditions, such as stabilization by a thick cover of vegetation, the islands become semi-permanent in location, their shapes changing only slightly from one flood to another. Because the islands tend to migrate and change their size, shape, and location frequently, they cause drastic changes in cross-sectional area at any one point from year to year. The result of this constant change in sectional area is rapid cutting and filling along the banks. Thus, banklines of most braided rivers are indistinct, and care must be taken in attempts to map banklines from aerial photographs.

Over long distances, the banklines of braided rivers are not simple, smooth, and parallel. Instead, bank width varies considerably along the river's entire length. These variations in width are not random, and the narrow widths, or node points, can be explained either one of two ways. First, the node points may simply be present because of stability or low erodibility of the bank material. If the banks are composed of clay or some consolidated or cemented material, they become relatively stable. Because the banklines are stable at such points, the river must scour deeper to accommodate flood discharges, and the scoured material causes a local sharp increase in transported load. Therefore, below node points the river tends to be extremely wide and shoal. Velocities decrease as they leave the narrow part of the channel, causing the increased sediment load to drop out and form islands. The islands reduce the cross-sectional area, and the river must cut its banks laterally to maintain a cross-sectional area that is in equilibrium with discharge. A nodal point formed by such resistant bank material is commonly stable and does not migrate on a short-term basis. Another type of nodal point is directly related to the formation of

the islands themselves. Although hydraulic reasons are poorly understood, local areas of slack current develop in a channel and cause rapid deposition of bedload. These shoal areas gradually build up to form an island which reduces the cross-sectional area, and the river accordingly must widen at the point where the island develops. This condition will also cause formation of node points both below and above the immediate area of the island formation which are independent of bank composition. Nodal points formed in this manner, however, are not stable, and over a short period of time tend to move downstream or disappear altogether.

As a direct result of the formation of nodal points, river scour depth does not maintain a constant value along the entire length of a braided stream. Scour and fill in a stream represent an attempt by the river to keep its energy grade line constant in slope by adjusting cross-sectional area. Thus, in narrow or constricted reaches, scour occurs with increasing flow and fill with diminishing flow. In expanding reaches, fill generally occurs during flood and scour may or may not occur during low flow. Thus, nodal points are areas of deep scour; the wide reaches have relatively low scour depths, or a tendency to fill. This is diagrammatically shown in cross sections a-a' and b-b' of figure 1. Profile a-a' is a typical cross section at a nodal point of a braided river. Here the river is narrow, and a single major channel, with no bars, exists. Note that the two deepest scour areas are adjacent to each bank. Profile b-b' is taken across a wide portion of the river. The most striking difference is the presence of several individual channels rather than a single major channel. The total wetted cross-sectional area of these channels combined should be similar to that of the cross-sectional area at the nodal point. Because of the multiple channels and the extreme width, the depth of scour in any single channel is much less than that at the nodal point cross section.

The detailed processes responsible for the formation of a braided channel are still poorly understood. Many published works deal specifically with the process of braiding, but little agreement can be found, and the hydraulic parameters of a braided stream are extremely complex. From the studies completed to date, it appears that braided channels occur in river systems having a relatively steep slope, an overabundance of transported load, or a combination of the two. In large alluvial rivers, such as the Brahmaputra in East Pakistan, extreme sediment load is the more important factor.

The above discussion simply points out some of the better understood major processes associated with the three major types of river patterns. It is obvious that in such a short discussion many important features have been omitted. For example, very little discussion was given concerning hydraulic regime, but so little data from large rivers are available that it would be virtually impossible to consider this factor in detail. It is important to recall, however, that any of the three types of river patterns can form in a single river system. In each type, navigation is quite different, and each reach of a river must be examined on its own basis. General rules can and will be given, but local conditions will cause variations from the generalities presented.

### CHANNEL MIGRATION

The major factor hampering navigation in an alluvial river is that most channels are constantly adjusting their cross-sectional area to differing flow regimes. A section of the river that is navigable during one part of the flood cycle may or may not be navigable during another part of the cycle. In a meandering river, the thalweg remains fairly stable throughout a flood cycle. It shifts slightly during flood, attempting to straighten its channel, but in general the shift is rather slow and the thalweg does not change drastically from day to day. A braided channel, on the other hand, is just the opposite, as the thalweg tends to migrate rapidly and by fits and starts (CHEIN, 1961). A 10-month field season in the Brahmaputra River in East Pakistan, completed in April of 1968, showed that the Brahmaputra is an actively braiding channel, and data gathered during one flood cycle will serve as an example of the magnitude of channel shifting that can be expected over a relatively short period of time.

Examination of aerial photographs of the Brahmaputra shows numerous channels, shoals, and islands, which indicate a river of low hydraulic efficiency and heavy sediment load. The maximum discharge recorded is 2 519 000 cusecs, while the lowest flow on record is on the order of 116 000 cusecs. Water level rises rather abruptly during the first part of June, fluctuates slightly during the next 3 months, and falls rapidly during the month of October. During flood stage, the river transports a huge volume of sediment; nearly 7 000 000 tons of suspended load per day has been measured consistently. Bedload is even greater, but at present no figures can be quoted. Even during periods of low flow, over 1 000 000 tons a day of suspended sediment is in active transit.

In a river so highly charged with sediment the bed configuration changes drastically under differing flow regimes. Deposition of sediment in one locality causes deepening scour in another area. Thus, the thalweg tends to wander continuously from one position to another within the river banklines. Figure 2 illustrates the magnitude and frequency of this migration for the 1966-67 flood cycle of the Brahmaputra. The upper graph shows a discharge curve, while the lower one indicates the magnitude of the movement of the thalweg from a stable reference point on the right bank. In May and June, during the rising stage, the amplitude of movement is rather large, on the order of 3 000 feet, but this movement is quite gradual, as it takes place over an entire month. During the peak of the flood, July through August, there is a relatively small amount of movement, and the thalweg remains nearly constant in location. In August and October, during the falling river stage, the thalweg moves in an irregular and sudden fashion. Within a period of a few days, the main channel wanders back and forth to an extent of several thousand feet. The low flow stage, November through March, is characterized by little movement of the thalweg. Thus, from low stage to low stage the position of the main channel shifted some 2 000 feet from its initial position, but, much more important,

during this period sudden shifts back and forth on a magnitude of 2 000 to 3 000 feet took place. There appears, however, to be a seasonal variability to the channel shifting, with the maximum magnitude of shifting taking place during the rising and falling stages. During the subsiding stage, the movement is more erratic and sudden, and it is during this period that navigation on the Brahmaputra is most hazardous. A similar observation was made on the braided Yellow River of China by CHEIN (1961).

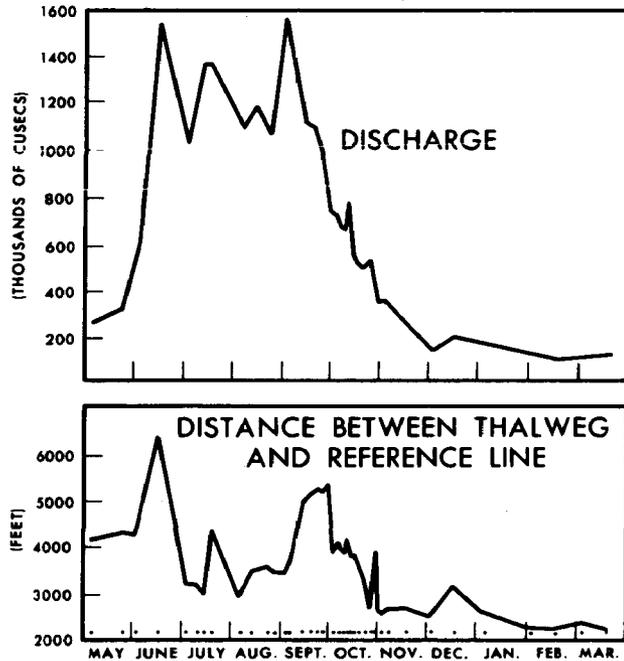


FIG. 2. — Discharge hydrograph and corresponding movement of the thalweg during the 1966-67 flood cycle on the Brahmaputra River. Data from Sirajganj Station. Dots on bottom graph indicate dates of measurements.

In the low-water stage, prior to the passage of the flood, the river is subdivided into numerous small channels; one of these generally serves as the main channel and carries a larger portion of the flow. This channel is commonly situated near one of the river banks and is slightly curved, moving from one bank toward the other. With the onset of the flood, the initial reaction is for the river to seek a path with little curvature. As a result, the thalweg tends to move toward the inside portion of the curvature. The rise in flood stage, however, is quite rapid, and the channel must widen and deepen to accommodate the large increase in discharge. The usual result is for migration of the thalweg in a transverse direction to be initiated. This type of channel shifting takes place gradually, usually over an entire month, but it may attain considerable amplitude.

The erratic and sudden shifting of the thalweg during falling stage is directly related to the movement and position of the sand bars and mid-channel islands. As flood waters subside, an excess of sediment is being

carried as bedload and in suspension. Velocities diminish, causing this material to be deposited. Deposition of the excess sediment results in a corresponding change in local flow direction, and the thalweg is in a state of constant movement. It is during this period that bed aggradation is the highest and many new channels are formed which function for a short time and are then abandoned. As flood waters continue to subside, one of the channels becomes dominant and the rate of wandering of the thalweg diminishes.

Thus, in a braided river the position and rate of migration of the main channel at any one time are directly related to the flow regime. During low stage the main channel can quite often be located by surface water turbulence patterns, which will be discussed later in the text. During rising stage the channel will be in a stage of migration, but a scalloped bank will quite often indicate that the thalweg is close to the bank, causing oversteepening and slumping. In the Brahmaputra, during flood the entire channel is usually navigable, and the only danger lies in running aground along the crests of large migrating sand waves. As will be explained later in the text, the position of these features can usually be spotted by turbulence patterns. During the falling stage the channel position changes erratically, and location of a navigable channel is quite difficult. In order to navigate safely, pilots must survey the channel almost continuously during the entire falling-stage period.

As mentioned previously, the thalweg in a meandering channel is generally not subject to such violent shifts during a flood cycle. Unfortunately, no data comparable to that gathered for the Brahmaputra has been compiled for other rivers.

### **BEDFORMS AND FLOW REGIMES**

Another major factor in determining both the position and depth of a river channel is the systematic change of the bottom topography that takes place under differing flow regimes. Sediment accretion or erosion on the channel floor is quite dependent on the relationships that exist between the size and quantity of sediment in transport and various hydraulic parameters. Thus, it is of special importance to understand how the channel bed is modified to achieve the most efficient balance between sediment and water discharge.

The vast bulk of the information available on molding of the channel bed under various hydraulic regimes has been obtained from laboratory flume studies. In flume studies, such parameters as water surface slope, discharge, water temperature, depth, velocity, sediment concentration, water viscosity, etc., can be controlled and measured quite accurately. In natural channels, however, there are usually additional complicating factors that cannot be artificially created or scaled down.

Flow in alluvial channels is classified into a lower flow regime and

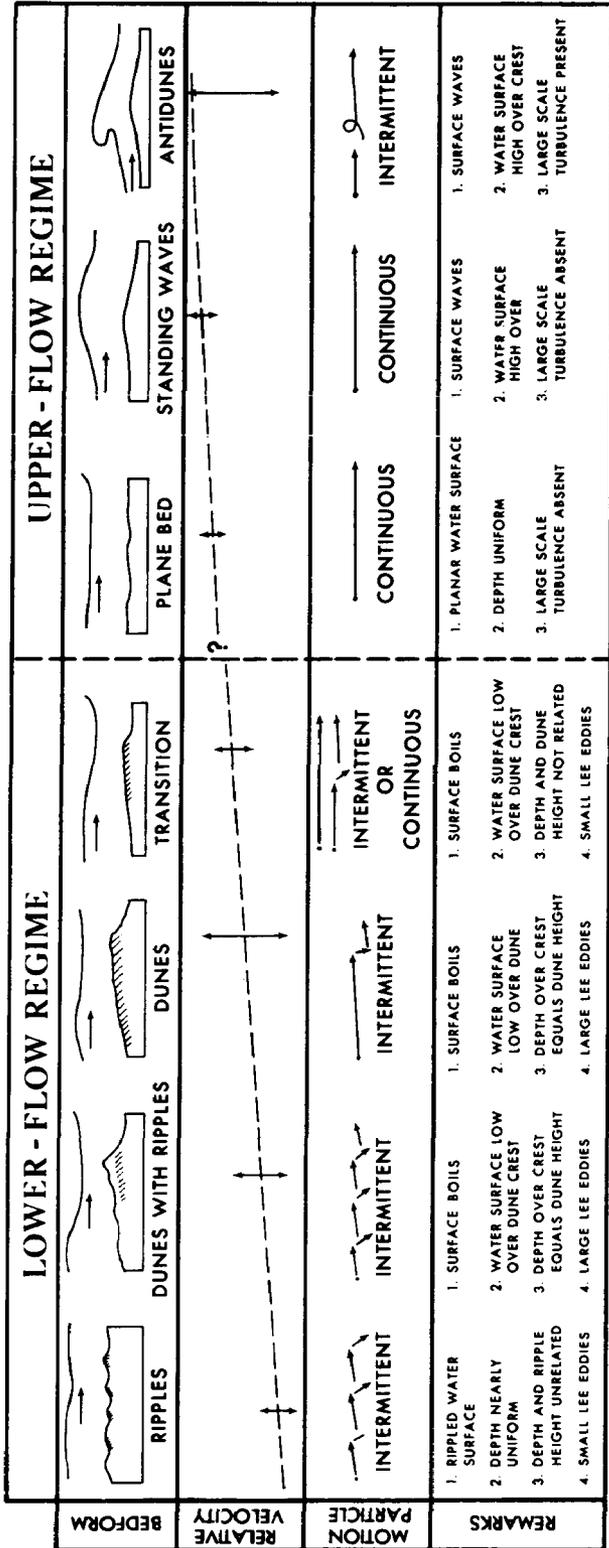


FIG. 3. — Flow regime diagram for sand beds. Modified from HARMS and FAHNESTOCK, 1965.

an upper flow regime, and there is a transition between. This classification by SIMONS and RICHARDSON (1961) is based on the form of the bed configuration, mode of sediment transport, process of energy dissipation, and phase relation between the bed and water surface. Although quite general, this classification offers a convenient way to describe bed roughness and hence resistance to flow. The concept of flow regime and its relationship to other factors is schematically represented in figure 3, which was modified from a similar diagram by HARMS and FAHNESTOCK (1965). As stream power increases, the bed is molded into a progressive sequence of bedforms, starting from plane bed without sediment movement and continuing to ripples, ripples on dunes, dunes, transition, plane bed, standing waves, and antidunes. In the lower flow regime, sediment particles move intermittently, rolling up the upstream slope of ripples and dunes and sliding down the slip face, where they will be deposited for a short time. They will be set in motion once more when subjected to local erosion as the bedform migrates. Bed material moves more continuously in the upper flow regime, and generally the entire bed is in transit except in the stage of antidunes, in which sediment again moves intermittently. Transport rate, therefore, is lowest in the lower flow regime, in which the movement of most of the particles is in steps that are as long as the ripple or dune length. Highest rate of movement is found in the upper flow regime, especially during the stage of antidune formation. Water surface undulations are out of phase with the bedforms during the ripple and dune stage but in phase with the bed roughness elements in the upper flow regime.

The two flow regimes are characterized by distinctly different turbulence patterns which are directly related to the bedforms. In the lower flow regime, eddies exist in the lee of ripples and dunes; small vortices are generally associated with shallow flow over a rippled bed, while large surface boils, commonly observed as upwellings of more turbid water, are more characteristic over dunes. In the upper flow regime, eddies or vortices are not conspicuous in flow over plane bed or standing-wave forms, and flow lines are more nearly parallel (HARMS and FAHNESTOCK, 1965). Dune height appears to be equal to or less than the depth of water over the crests of the dunes. This relationship between bedform height and water depth does not persist into the transition to upper flow regime or in ripples, where height and water depth are unrelated.

The above discussion has been based entirely on observations and measurements conducted in laboratory flumes and reported in the literature. Some of the observations, however, have been extended to the natural environment (NORDIN, 1963, 1964; HARMS and FAHNESTOCK, 1965; and others), but they have generally dealt with small streams. One of the basic aims in conducting flume experiments is to apply the results obtained to natural channels and to attempt to predict the characteristics of the channels as flow regimes change. It is important, therefore, to examine some of the relationships described above in a large, natural alluvial channel to see if they are comparable or different.

It has long been recognized that loose, granular bed material assumes characteristic forms under aqueous currents. Even after nearly 50 years

of investigation, little information exists on the genesis of these bedforms, and the terminology has of necessity been based on geometric form and size. Bedform terminology is unusually difficult in large river systems such as the Brahmaputra and Mississippi rivers, where wave heights of bedforms range from a few inches to over 45 feet. During the period of investigation on the Brahmaputra River, measurements such as wave height, wave length, foreset slope, ripple index, rate of movement, etc., were completed on over 1 500 individual bedforms during a single flood cycle. It soon became apparent that a systematic change occurred in the bedforms during the changing flow regimes. Thus, four groups could be identified: ripples, megaripples, dunes, and sand waves. These terms will be defined in the following discussion and used consistently throughout the text. It is not the writers' purpose to introduce specific terminology, but simply to define terms used in the paper.

### Ripples

The term *ripples* is applied to those forms that have a wave height ranging from a few inches to 1 foot. The ripple index ( $WH/WL$ ) is highly variable, ranging from less than  $1/5$  to over  $1/20$ . Under similar discharges, rate of movement is extremely variable, being dominantly controlled by the general slope of the bed. Movement is greatest as the slope increases and lowest when the bedforms are moving upslope.

### Megaripples

Megaripples have a wave height ranging from 1 to 5 feet and wave lengths of 10 to slightly over 500 feet. The ripple index ranges from approximately  $1/6$  to  $1/100$ . Figure 4 illustrates a typical fathometer trace taken in about 30 feet of water in the Brahmaputra River. On this particular profile, taken during rising stage, the average wave height is 3 feet and the wave length, approximately 25 feet. It was not uncommon to find the bed of the channel thus molded over a distance in excess of 2 miles. The rate of movement is very erratic, but megaripples have the

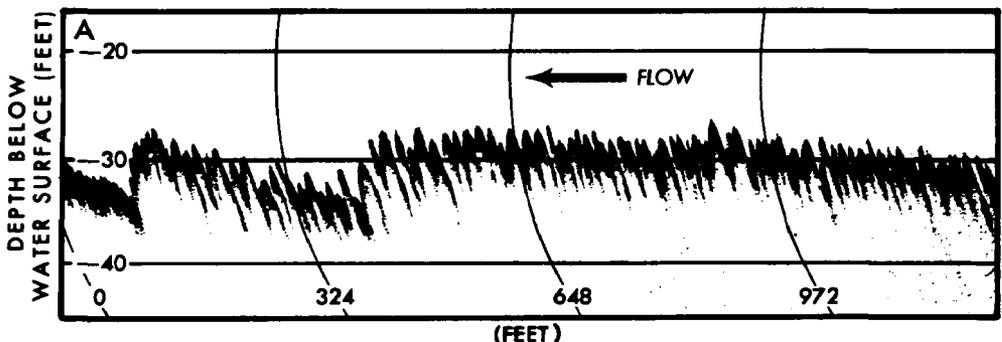


FIG. 4. — Fathometer trace showing megaripples that develop during rising stage, Brahmaputra River.

highest average rate of movement of all the bedforms measured. The rates during the flood cycle ranged from 80 feet per day to over 750 feet per day. The wave height is independent of water depth, as evidenced by the fact that similar-sized features can be observed in water depths ranging from 10 feet to over 90 feet. In shallow water, small, turbulent eddies can be observed just downstream of the crests of the bedforms, but in deeper water no surface turbulence is apparent.

### Dunes

Dunes range in wave height from 5 to 25 feet and are the most common active bedform found during peak flood. Wave lengths are extremely variable, ranging from 140 feet to over 1 600 feet. The ripple index, however, is quite restricted and ranges from 1/30 to 1/60. Figure 5 illustrates a typical dune bedform in the Brahmaputra during flood period. The height of the dunes also appears to be independent of water depth, as some of the larger ones (greatest wave height) were present in less than 12 feet of water. The rate of movement is quite consistent during flood, ranging from 100 to 370 feet per day with a high concentration at 220 feet per day. The dunes cause quite a disturbance in the flow, and the separation zone is large, producing large boils on the water surface just downstream of the crest. Directly over the crest the water surface is smooth and slick.

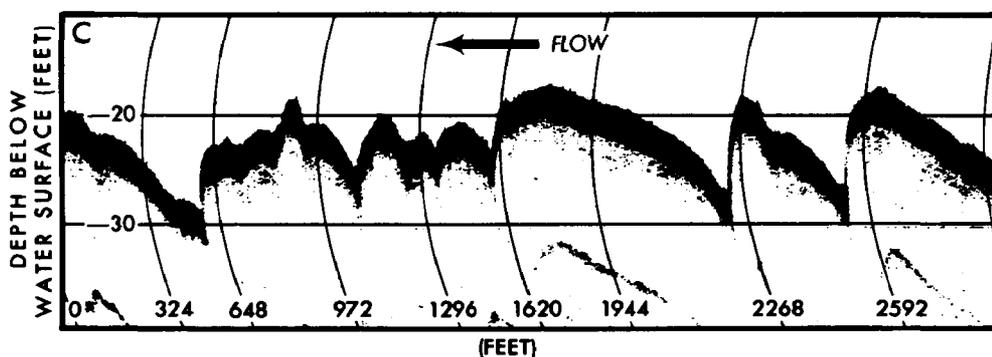


FIG. 5. — Fathometer trace showing dunes that develop during the latter part of rising river stage, Brahmaputra River.

### Sand Waves

The most spectacular type of bedform is the large sand waves that form during peak flood (fig. 6). These bedforms have wave heights ranging from 25 to 50 feet. Wave lengths are highly variable, ranging from 600 feet to well over 3 000 feet. Wave height is completely independent of water depth, as in many cases only 8 feet of water occurred over the crest, while in other areas features of similar height had well over 90 feet of water over the crest. When these features are present in shallow water, they form hazardous traps for navigation. The rate of movement of the sand waves

is quite often extreme. The fathogram in figure 6 shows the position of the crest of a sand wave on September 8, while the dotted line is a trace of a fathogram run 24 hours earlier. This sand wave had migrated downstream a distance of 2 100 feet in a 24-hour period. Such movements of the sand waves are the main reason for the rapid changes in bar position, quite commonly cited in the Brahmaputra. At the crest of the sand wave, the flow separates from the boundary and a stable eddy is formed. Large, turbulent boils break the surface downstream from the crestline. These turbulent cells reach extreme dimensions, some having a diameter of 800 feet. The boils will generally raise the water surface a height of 1 foot or more from its general level and can have disastrous effects on small boats. Handling of larger craft is extremely difficult.

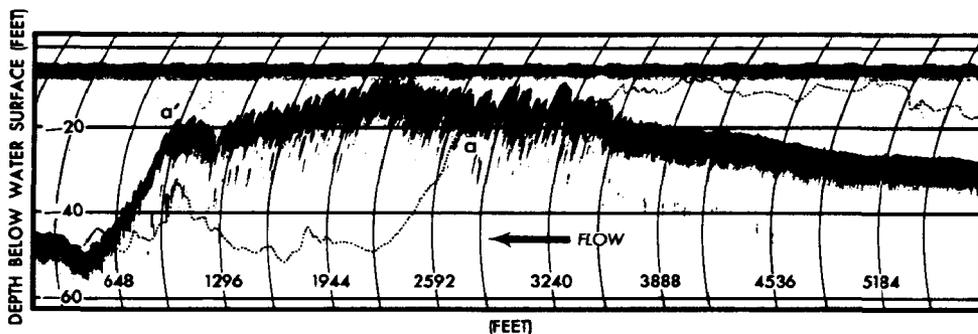


FIG. 6. — Fathometer trace showing sand wave developed during flood stage, Brahmaputra River.

The dotted line represents the trace of this same profile line run 24 hours earlier and indicates a migration of this bedform some 2 100 feet during the 24-hour period. All positioning obtained by Decca Fix Navigation System.

The nature of the bedforms encountered during a flood cycle on the Brahmaputra and the relative high rates of movement lead to significant changes along a particular reach over a short period of time. From studies in other river systems (Mississippi River, Rio Grande River, Burdekin River, etc.), it is apparent that such features are common and control local bottom topography. These features also produce telltale evidence (turbulent cells) on the water surface, and observations of such surface turbulence can be utilized to gain a crude approximation of bed topography.

### BEDFORMS AND WATER TURBULENCE PATTERNS

SIMONS and RICHARDSON (1963) have shown that in flume experiments lower and upper flow regimes are characterized by distinctly different water surface turbulence patterns and that these patterns are directly related to the bedforms. The observations were later tested under field conditions in the Rio Grande (HARMS and FAHNESTOCK, 1965); in general, patterns similar

to those observed in the flume studies were indicated. In the lower flow regime, small eddies and vortices exist in the lee of ripples, while surface boils appear as upwellings of more turbid water in the lee of dunes. In the upper flow regime eddies or vortices are not conspicuous in the flow over a plane bed. During the flood cycle in the Brahmaputra, observations on turbulence patterns were made in conjunction with other hydrologic measurements to see if the above relationships held true in a large river, where bedforms attain sizes several factors larger than those in the Rio Grande. The size of the Brahmaputra channel presented many problems, and it was only by aerial reconnaissance that an overall picture of the turbulence patterns and their distribution could be recorded and correlated with bedform configuration. Large-scale aerial photographs (scale 1/8 000) were exceedingly helpful in mapping the distribution of the turbulent boils breaking the water surface. Because of the large area to be covered, the time factor, and observation during only one flood cycle, data presented should be considered tentative and as a building block for more detailed studies in the future.

In June, the river stage rises rapidly, most commonly reaching flood level toward the end of the month. Flood conditions are maintained for approximately 3 months. During this period the initial bed configuration is gradually molded into several distinctive types. Although the sequence of bedforms remains similar to that described by HARMS and FAHNESTOCK (1965) in the Rio Grande, the shift from one bedform to another is hastened or retarded by changes in any one of the many hydraulic variables. It was also noted that separate reaches within the river were undergoing different changes simultaneously. Depth of water, local slope, velocity, sediment concentration, etc., all contribute to the lateral changes. Nevertheless, a general progression could be recognized at any one reach during progressively increasing discharge. In the early stages of the increasing discharge, the bed is characterized by a variety of small-scale ripples and larger megaripples (fig. 4). Even at this stage, larger bedforms are beginning to take shape. The water surface remains relatively smooth and only a few small, turbulent cells break the surface. Within a few days the discharge can increase from 600 000 cusecs to over 1 500 000 cusecs (discharge curve, fig. 2). During this period of rapid rise of water level, dunes develop very quickly. The profile of the bedforms, however, is extremely complex, and many different-sized bedforms exist along a single profile. Troughs and crests are at extremely differing levels and the entire bed surface is very irregular. Surface turbulence patterns become apparent everywhere on the water surface but have no recognizable pattern. On aerial flights during the period, surface boils appeared randomly, breaking first in one place, then in another.

Once peak flood is reached and the variation in discharge becomes low, well-developed dune fields begin to appear. Dune shapes become similar and troughs and crests of individual bedforms along a single longitudinal profile attain similar depths (fig. 7). It is also at this stage that surface turbulence begins to assume a fairly consistent pattern. Figure 8 shows the distribution of surface boils as mapped from large-scale

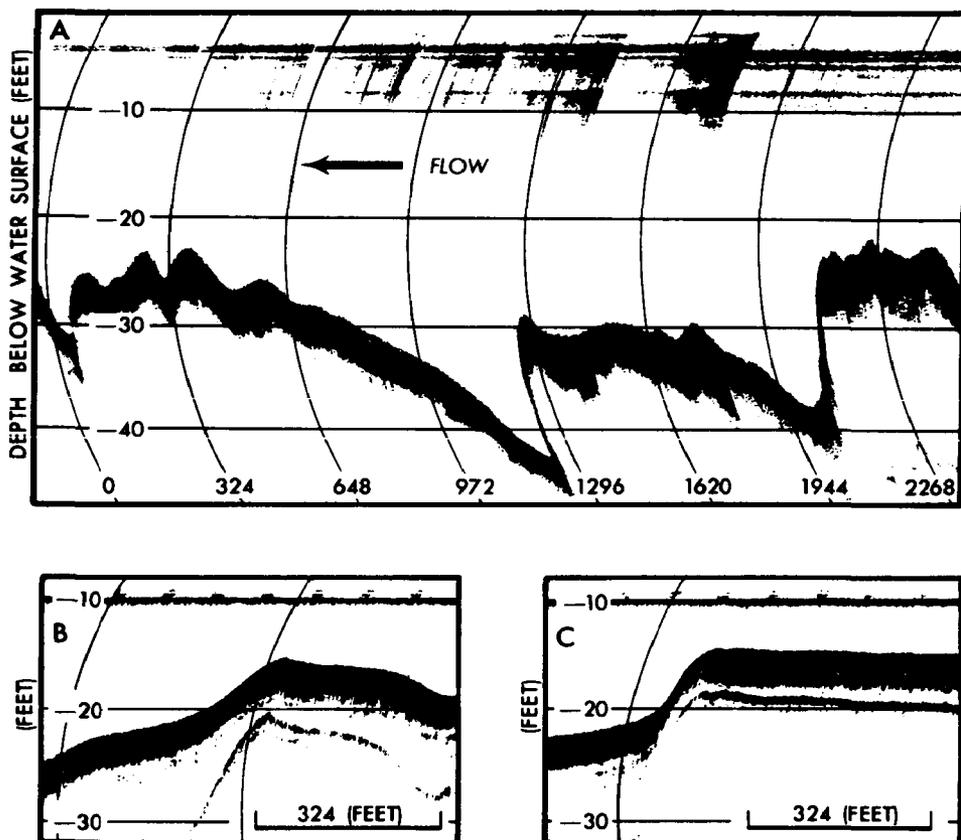


Fig. 7. — Fathometer traces of river bed during rising stage, Brahmaputra River. A. Longitudinal profile showing well-developed dunes. B. Transverse profile oriented at right angles to A. C. Transverse profile 2000 feet downstream of B.

aerial photos. Note that the cells appear to be aligned in rows at an approximate right angle to the current flow. Although in observation an individual cell would break the water surface and last for only 10 seconds or so, the position of the cells did not move randomly. Rather, the cells began to appear in similar areas over quite a long period of time. The position of the row of surface boils was just downstream of the crest of the dunes, while the water surface was smooth over the crests. As the depth of water became greater, the boils would break farther downstream from the dune crest. Cross sections oriented essentially perpendicular to the current flow indicate a rather smooth bed, and the only relief apparent is when the profile cuts across a dune at a high angle (fig. 7B and C). As flood conditions persist and flow velocity increases, the bed is gradually built up into extremely large bedforms (sand waves). As described earlier, these features have wave heights ranging from 25 to a maximum of 50 feet and are spaced from 600 to 3000 feet apart. These large bedforms are not present everywhere in the channel but are more confined to the straight reaches between large curvatures in the thalweg. Once they are formed,

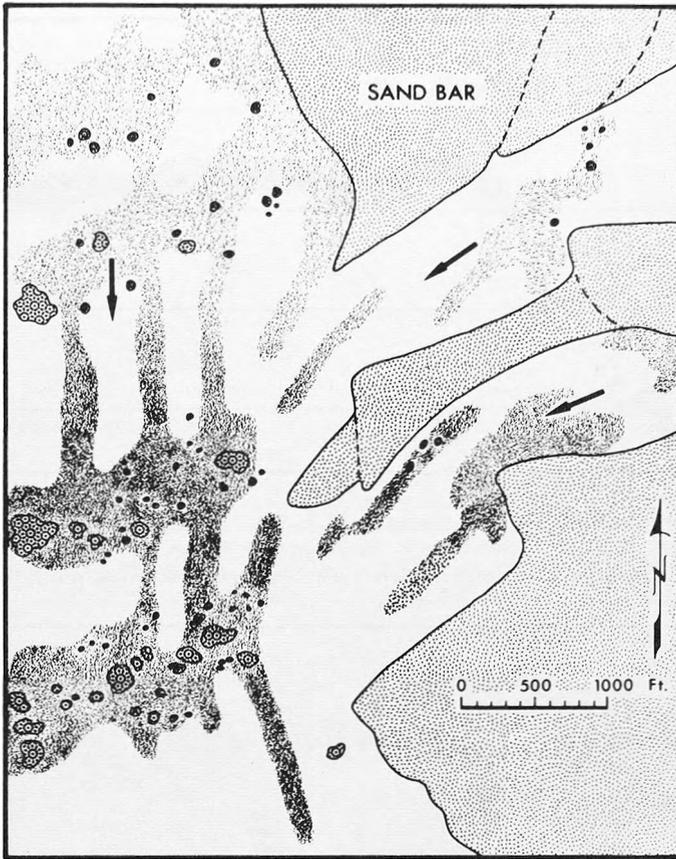


FIG. 8. — Plan view of surface water turbulence patterns taken during rising river stage, Brahmaputra River.

Stippled pattern on the water surface indicates areas of turbulent water, which generally occur over the crests of large bedforms. The roughly circular patterns represent boils.

they generally persist for the entire flood and for a time during the falling stage. Figure 9 illustrates a fathometer trace across one of the large sand waves. The crest of this feature lay in approximately 15 feet of water, and the form was migrating at the rate of 1 800 feet a day. The water surface displayed extremely large turbulent cells arranged in a very definite pattern. Figure 10 illustrates this type of pattern as traced from aerial photographs. Note that the boils form elongate rows which are at right angles to the current flow. The spacing of the rows is generally the same as the spacing of the sand waves. The boils do not form exactly over the crests of the sand waves, but because of current flow they are located slightly downstream of the crests. Individual boils attain rather larger dimensions, some reaching a diameter of 800 feet. Much more common are the smaller ones, which range in size from 50 to 150 feet in diameter. When the turbulent cell breaks the surface, it will raise the water level as much as 2 feet above the adjacent level. These features are large enough to have disastrous effects on small boats.

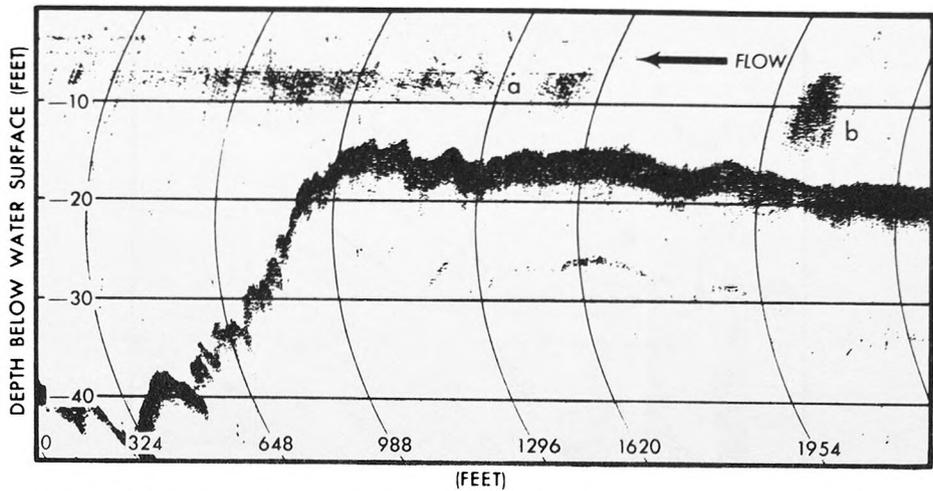


FIG. 9. — Fathometer trace of longitudinal profile during peak flood showing large sand wave, Brahmaputra River.

"a" and "b" are highly sediment-laden turbulent cells recorded on fathometer trace.

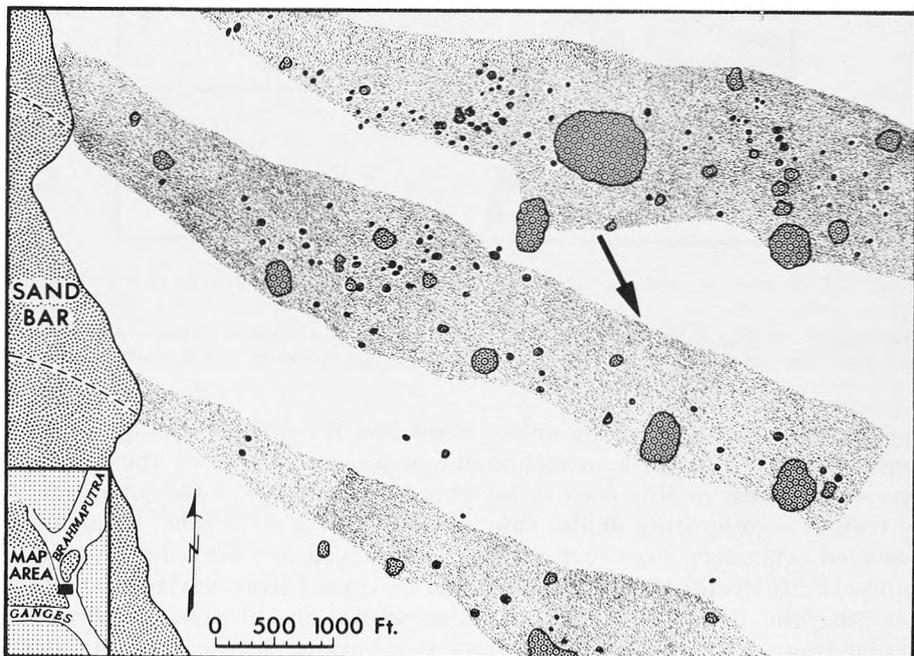


FIG. 10. — Plan view of surface water turbulence patterns during peak flood, when the dominant bedforms are sand waves (Brahmaputra River).

Stippled pattern represents turbulent water over large sand waves. Large boils (roughly circular patterns) parallel the crests of the bedforms.

As peak flood continues and flow velocity reaches a maximum, many portions of the channel assume a plane bed configuration (fig. 11A). This obviously occurs rather rapidly, as in one area a profile showed well-

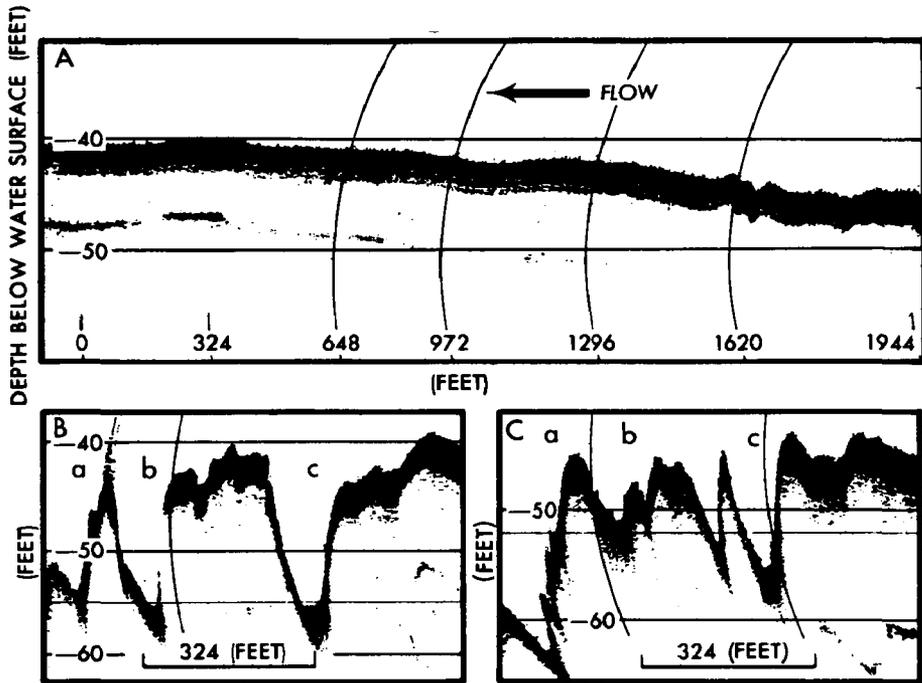


FIG. 11. — Fathometer traces of river bed during peak flood, Brahmaputra River. A. Longitudinal profile showing plane bed condition existing during upper flow regime. B. Transverse profile oriented at right angles to A. C. Transverse profile 2 000 feet upstream of B.

developed dunes on one day and 24 hours later the bed was planar. The flow had changed from the lower flow regime to the upper flow regime and bedforms had disappeared. The longitudinal section shown in figure 11A illustrates such a bed condition. The water surface existing during the plane bed, however, showed small turbulent cells, but the features were arranged in rows parallel to the current rather than at angles such as existed when bedforms were present. Figure 12 illustrates a plan view traced from aerial photos showing the distribution of the surface boils. Cross sections (at right angles to current flow) run during the plane bed stage show an unexpected feature. The bottom is extremely uneven in a transverse section, and large, elongate scour pools exist parallel to the current flow. Figure 11B and C illustrates a small section of two cross profiles. The upper fathometer trace is located 2 000 feet upstream from the lower trace illustrated. Note that the elongate scour pools can be correlated on both profiles (a, b and c, figure 11 B and C). A longitudinal profile, on the other hand, indicates a plane bed. These elongate scours probably cause the turbulent cells to develop and assume an orientation parallel to the current flow. During the flood period, two such instances were observed. Whether the elongate scours are always associated with plane beds or not still remains questionable. It appears, however, that when the turbulent cells assume an elongate pattern parallel to the flow the scour features probably exist. In the examination of the large-scale aerial

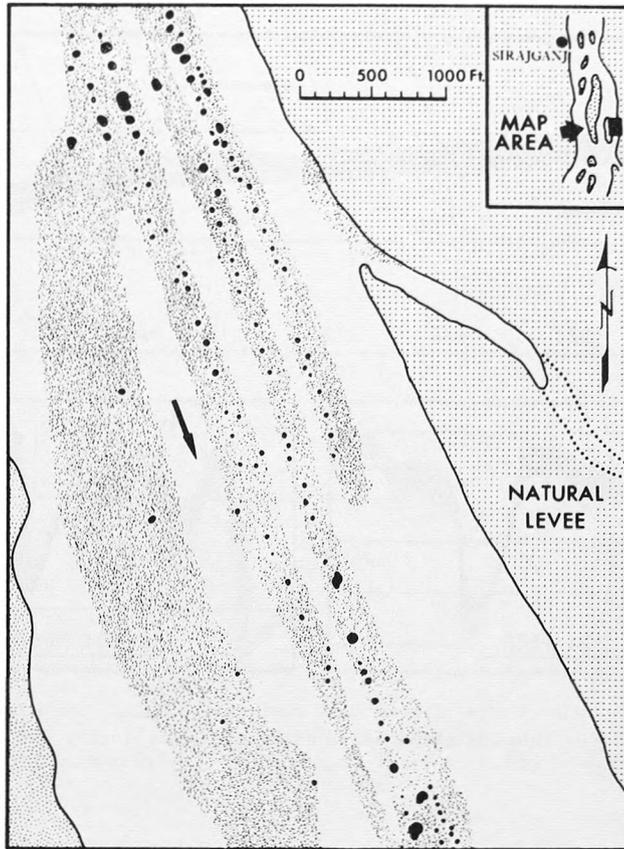


FIG. 12. — Plan view of surface water turbulence patterns that develop during plane bed phase of peak flood, Brahmaputra River.

Stippled areas represent turbulent regions but their parallel orientation with the current indicates general absence of large bedforms.

photographs of the river over a distance of some 50 miles, this type of turbulent pattern is found to be very common and generally to occur in narrow necks where current velocity should be the highest.

In summarizing the results of the hydrologic regime of the river and its relationship to bedforms, there is sufficient evidence to indicate that during the period of increasing discharge and velocity the bed undergoes a definite sequence of changes. At first the smaller bedforms (megaripples) are present and water surface is relatively smooth. Dunes appear as discharge increases, but at first they are poorly developed and the bed is extremely irregular in both transverse and longitudinal sections. The water surface is randomly broken by small surface boils. After a period of time, a well-developed dune field exists, and surface turbulence assumes a regular pattern controlled by the position of the dune crests. When velocity reaches a maximum, larger bedforms (sand waves) develop in some areas, whereas in other areas a plane bed exists. Water turbulence reaches its maximum intensity and forms a regular pattern, oriented

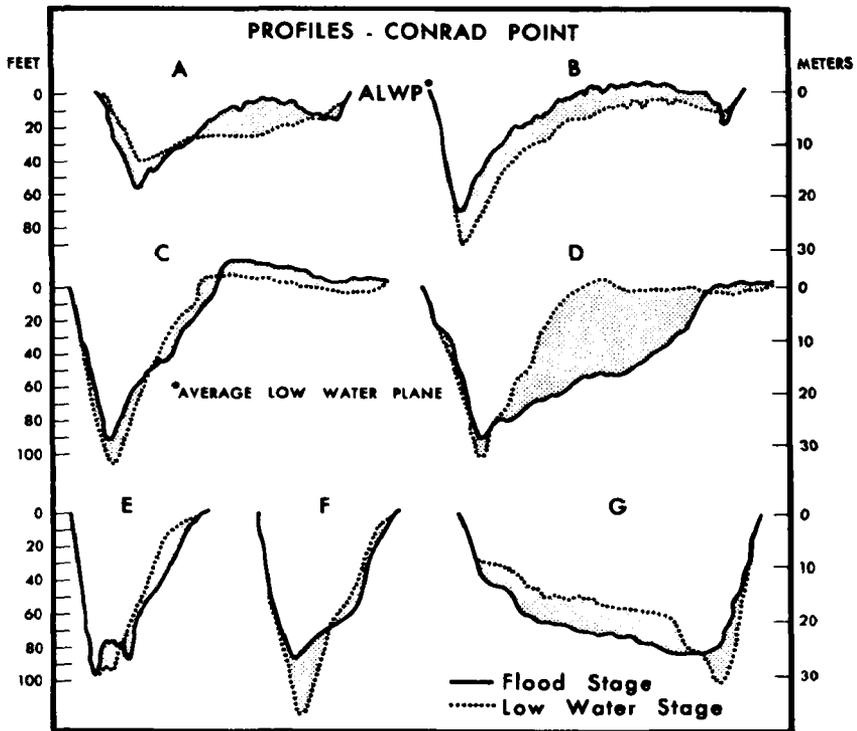
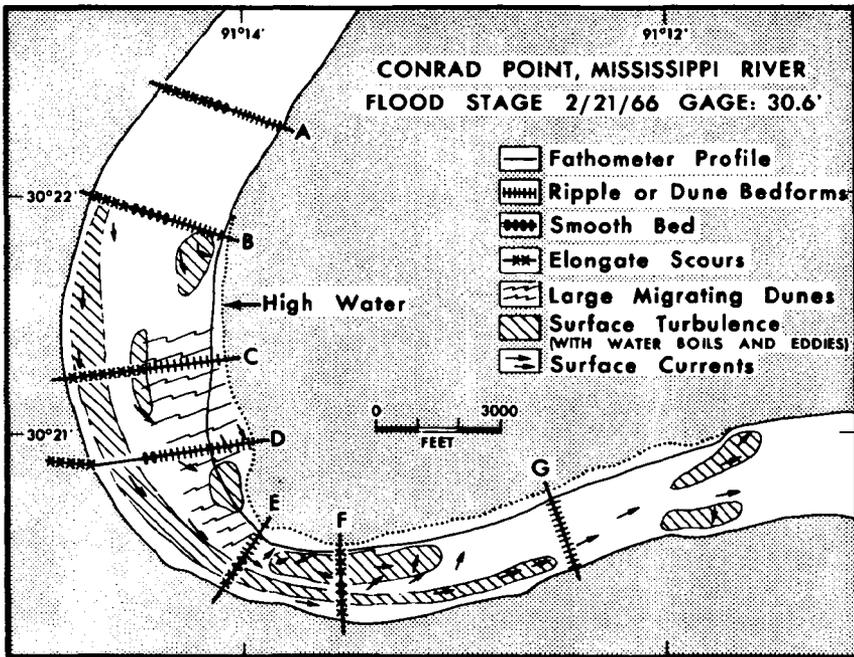


FIG. 13. — Mississippi River meander loop near Baton Rouge, Louisiana, showing surface water turbulence patterns, bedforms, and seasonal changes of channel cross section.

parallel to the bedform crests when sand waves are present. In areas of plane bed, turbulence is not quite so intense, but the pattern is oriented parallel to the current flow and is probably controlled by large, elongate scours that exist in the bed. This sequence is similar in many respects to that indicated by SIMONS and RICHARDSON (1963) from flume studies. The scale is quite different, but the repetitive nature is apparent.

Similar observations have been made of relationships between bottom topography and water turbulence patterns in a meandering channel, but not in as great detail as those described from the Brahmaputra River. Figure 13 shows some of the correlations that exist between general bed topography and water turbulence on Conrad Point, Mississippi River. The lower part of the diagram illustrates both low-water and flood-stage cross sections for this particular meander loop. Note that the areas of highest turbulence, especially those characterized by circular or reverse eddies, are generally in the deeper parts of the channel. Figure 14 is a low-angle, oblique, aerial photograph that illustrates these reverse eddies (A, fig. 14) that so characteristically form over the scour pool that hugs the cut bank. The view of the photograph is upstream. Note the relatively smooth water in the area labeled "B". This is the slick water that commonly overlies the crests of large bedforms. Note that in this case the slick area bends in a downstream direction, following the crest of a bedform. The boat in the background is



FIG. 14. — Low-angle, oblique, aerial photograph of water turbulence patterns, Thomas Point, Mississippi River.

View upstream during peak flood; "A" indicates edge of point bar; "B" is the turbulent zone near the point bar edge; "C" is the zone of cut bank vortices; "D" is the complex turbulence zone over deep channels; and "E" represents area of turbulence over crest of point bar bedforms. Slick water lies over the remainder of the shoal point bar.

navigating the edge of the bar (outlined by the dotted line), avoiding the rough, turbulent area of the cut bank. The large eddies formed along the cut bank often cause considerable difficulty in handling of craft. However, if the craft moves too close to the point bar side of the bend, it will run aground on some of the crests of the large, migrating bedforms. Figure 15 is a low-angle, oblique, aerial photograph of Thomas Point, a tight meander loop on the Mississippi River just upstream of the city of Baton Rouge. The view of the photograph is upstream. Note how the bar is easily discernible and outlined by relatively smooth water (A). The cut bank side of the meander loop, on the other hand, is highly turbulent and shows a very patchy pattern on the photograph (B). The proper path for navigation is shown by the dashed lines in the photograph.



FIG. 15. — Low-angle, oblique, aerial photograph showing distribution of water turbulence during flood stage, Thomas Point, Mississippi River. The letter symbols indicate the same zones as shown on figure 14. Dashed line indicates the deep-water channel.

Thus, as shown by the discussion above, water surface turbulence patterns offer the navigator some clues to proper navigation and also some insight into local bottom topography. Some of the reasons for this correlation have been discussed, but many factors remain unknown. If some correlation could be found between size of bedforms and depth of water in which turbulence on the surface is not apparent, navigation in uncharted waters would be made much simpler. It is hoped that future work on the Mississippi River will answer some of these questions.

## NAVIGATION HAZARDS IN COASTAL AND RIVER WATERS

Certain natural phenomena, not indicated on charts and ordinarily not fully described in aids to navigation, at times pose serious obstacles to transiting of coastal and river waters. From the sea, coasts are subjected to tides, waves, surges of various kinds, and changes in current directions and velocities. Characteristics of sea state change between deeper offshore areas and the irregular shallow bottoms near shore. Physical and chemical properties of the water, such as salinity, density, turbidity, temperature, and acoustical properties of nearshore zones, also differ markedly from those displayed farther offshore. Such changes may be abrupt and may occur within short distances from the coast. Meteorological changes, with such factors as storms, winds, rain, fog, and haze, bring irregular daily and seasonal contrasts. Most confusing is the fact that these diverse conditions, instead of appearing singly, may be present in many different combinations, all of which must be taken into account by pilots operating craft in coastal and river waters.

Onshore winds raise water levels along the coast and for varying distances up river channels. The amount of rise depends on fetch, velocity, duration of wind, and the slope of the nearshore bottom. If winds of 20- or 30-mile velocity blow for several days, coastal water levels may be raised a foot or more. Storm surges accompanying typhoons raise levels significantly higher and may inundate lowlands for many miles inland, an effect that commonly lasts for several days. Extent of flooded land, though of intense concern to the rural inhabitant, is not of much interest to the navigator, but the consequence of flooding on water velocities in channels may be extremely important.

Offshore winds tend to lower water levels below those predicted by amounts which increase according to wind velocity and duration. Decreased depths of shoals in coastal waters may cause difficulties, particularly during falling tide and, of course, most acutely during low spring tides. When river stage is high, the combination of offshore wind and ebbing tide may create outflow currents with troublesome velocities.

Ordinary land breezes during early mornings or sea breezes during afternoons have comparatively little effect on water levels because of their short duration and alternations in direction. With limited fetch, such as a maximum of 15 to 30 miles, these winds are of little effect, except to sailing craft making use of them, as is common among boats used by local fishermen.

Changes in visibility are highly significant along low deltaic coasts, where conspicuous landmarks may be rare and where low relief and extensive water surfaces dominate the land- or sea-scape. Difficulties arise as a result of rain, fog, or haze.

Fog is likely to occur as blankets offshore from river mouths and for some distance upstream. Fog which forms in mouths is likely to persist

longer after sunrise than does fog formed as a result of nighttime radiation. Trees along natural levees tend to restrict fog to air above the stream channel, both because fog particles are heavier than surrounding air and because the trees break the force of light breezes that might carry fog away.

Reduced visibility in fog poses serious problems to navigators. Fog is likely to be densest and most persistent over river-mouth bars, where navigation is most difficult even under the best circumstances. Craft without radar and other precision equipment are in such danger of running aground that they should not attempt to cross fog-enshrouded waters near river mouths. Rather, they should anchor and await clearing weather. A particularly dangerous condition along river channels is faced by craft headed downstream, where considerable forward momentum is necessary in order to maintain steerageway.

There is another characteristic of fog that deserves mention. Although horizontal visibility may be greatly reduced, a thin blanket of fog may have little effect vertically. Stars may be visible even though an object a few hundred feet away is hidden completely. To persons in aircraft a boat surrounded by fog may be a "sitting duck", helpless to escape aerial attack.

Temperature and salinity changes in the water itself impose subtle effects on sediment transport and behavior. The effects result primarily from density and chemical differences between the contrasting waters. Although not directly important to navigation, the interaction between salt water and colloidal (minute, individual particles) material carried by streams results in the accumulation of ooze which may impede river traffic. RUSSELL (1967, p. 19) points out the pertinent characteristics of this phenomenon as they relate to the Mississippi River :

"Colloidal materials remain in suspension indefinitely. Some are actually buoyant, so along with logs and branches of trees, etc., constitute part of the floating load. On drifting from fresh to somewhat saline water, many colloids are affected by electrolytic processes that flocculate them, causing settling and accumulation of ooze that eventually becomes organic clay. Jellylike masses of ooze commonly occur in lakes and stagnant channels of coastal marshes."

The arguments advanced indicating "sludge" as a major transiting problem at river mouths have been based on commonly observed acoustic fathometric reflections from 10 or more feet above the bottom. Systematic observations of these reflections by WRIGHT (1970, pp. 12-18 and 47) at South Pass, Mississippi River, revealed them to be associated solely with the saltwater-freshwater interface at times of maximum stratification. Variations in water surface slope (hydrostatic gradient), river stage, and tide are significant factors controlling current and discharge within the channel and hence are important in transiting the lower reaches of a river. During flooding tide there is a pronounced upstream flow within the salt wedge which reduces and occasionally reverses the seaward water surface slope in the river mouth. Consequently, the velocity of seaward water surface flow in the overriding freshwater layer is substantially reduced. Although velocities are reduced, density contrasts between freshwater-

saltwater layers reach a maximum. Craft transiting river mouths under these conditions frequently encounter a "dead water" effect and experience a loss of power. This effect occurs when the depth of the ship's keel coincides with the depth of the freshwater-saltwater interface. Interfacial waves are generated and the drain on the ship's power is proportional to the power required to generate the waves.

At ebb tide, increased seaward velocities occur within the freshwater layer. Turbulence created at the freshwater-saltwater interface decreases the density contrasts between the two layers, which diminishes conditions for power loss from interfacial waves. However, increased seaward currents produce another hazard for navigating lower reaches of rivers. Underpowered craft often lose steerageway because of rapid currents or interfacial waves, whereas high-powered craft could more easily negotiate rapid current but could experience difficulty during high flood tides, when interfacial contrasts are sharp.

Farther upstream, location of the most navigable channel in an uncharted river is complicated by the possibility that there may be numerous bars, and only one channel around each is more navigable than the others. This channel is determined by the amount of discharge each receives and by the overall and local configuration of the river system. In addition, ephemeral bars may develop and either dissipate or relocate with changing water levels and current direction. In the areas of shifting bars and channels, fish traps provide one of the few relatively permanent features that may be useful as navigation guides and reference points if aerial photographs are available. The traps usually consist of long rows of poles pushed or driven into the river bottom and used to support nets. The poles are usually arranged in distinctive v-shaped patterns that funnel the fish into collecting nets or traps. At the apex of the "v" larger platforms are constructed for raising the traps and nets.

The channel position in reaches and bends of meandering streams can be generally predicted (fig. 16A and B). Figure 16 represents examples of meandering sections of the Mississippi and Mekong rivers. RUSSELL (1967, pp. 4-8) discussed these relationships and showed that :

" Along straight segments of these channels (reaches) they are likely to have rather flat bottoms and steep submerged banks. Cross sections, however, are different on bends and vary according to the abilities of turbulent flow to entrain bed materials; steeper banks being typical in clay and wide shoal sections in coarse sediments.

" At times of flood, highest stage, there is ordinarily maximum floating load because trees and non-floating objects are introduced into the channel by bank caving, and also, much debris is swept away from the sides of channels. Floating load tends to work its way toward the sides of the channel with a sudden drop in stage and thus litters the newly exposed parts of the banks with driftwood. This is also true of sediment load being carried along below the surface, commonly leaving soft mudflats. Optimum conditions for bank caving occur after a flood crest has passed, particularly if the stage falls rapidly...

" The thread of maximum surface velocity (fig. 16 A and B), during

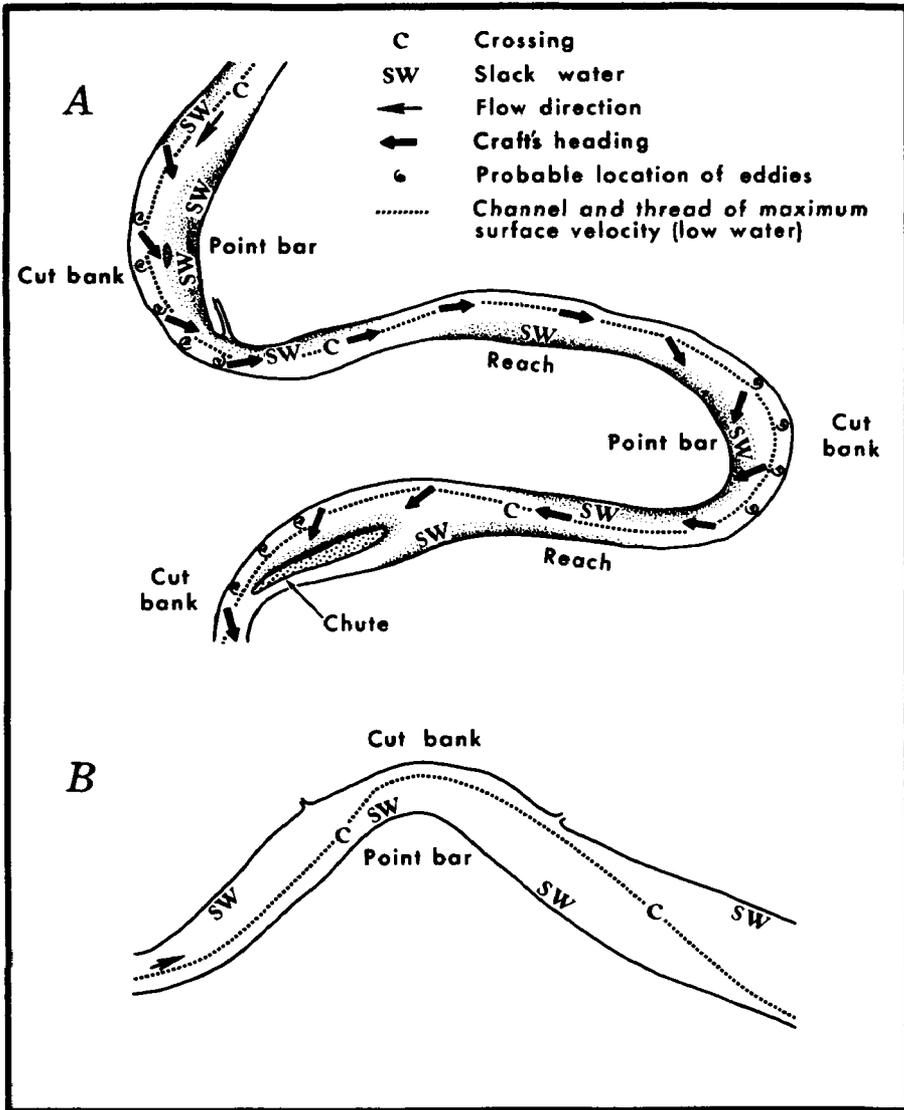


FIG. 16. — Meander river patterns and channel relationships at mean low water of (A) Manchac Point, Mississippi River, and (B) near the coast on the Song Cua Tieu, Vietnam. After GAGLIANO and McINTIRE, 1968.

all but high flood stage, ordinarily swings from the concave bank side of the bend next upstream, across the reach immediately upstream, to the concave bank of the bend under observation. It follows the bend a short distance away from the bank. The water surface is somewhat elevated toward concave banks (similar to slopes along a winding, well-banked highway). Pilots of boats headed upstream keep as far away as practicable from the thread of maximum surface velocity in order to economize on fuel and maximize speed, hence they run as close to bars as depths permit, then cross the channel on the next reach

upstream in order to take advantage of the less intense current close to the next bar. This pattern, that boats cross the channel on reaches, is so commonly followed that in the terminology of American river pilots, reaches are called crossings (boats cross from one convex bank to the next, and the thread of maximum current velocity crosses in the opposite direction, from one concave bank to the next).

“ During violent floods, however, these rules reverse. Not only does river stage rise but the water surface steepens, increasing the hydraulic gradient, and the velocity increases. For the reason that the alluvial lands in the vicinity have been created by deposits reaching them mainly during times of flood, the valley gradient, or general downvalley slope of the flood plain in proximity to the river, is approached most closely by the hydraulic gradient (slope of the water surface). On many rivers the hydraulic gradient during floods more than doubles that at medium river stage. The greater velocities associated with steepened gradient bring effects that tend to straighten the channel. The flow is concentrated in a less sinuous pattern. The thread of maximum surface velocity moves out from concave banks toward bars, deepening the channel toward the convex bank. Pilots of boats headed upstream run from one concave bank to the next. If the flood is extreme, some of the flow may actually cross parts of bars, scouring channels called chutes. These are common on some rivers, as along the Mekong. ”

Transiting river bends with tows, flat-bottomed craft require the utilization of the sets (current direction) which circumvent the loop (fig. 16 A and B). On the approach to bends the craft is held into the current with the bow pointed in the general direction of the next point bar. This is to compensate for drift and to maintain headway while utilizing the current for both vessel control and power. As the craft comes out of the bend the orientation, as aligned with the set, is reversed. As it comes into the bend, checks should be made to assure that the craft is making headway rather than sliding with the current.

Eddies (vortices, whirling or circular motion), which form relatively permanent features where the thread of maximum surface velocity lies close to the cut bank, comprise danger areas and should be avoided (fig. 16A). These phenomena develop best during rising water but under certain bank and current conditions may persist throughout the changing river stages.

The greatest danger with eddies comes when a craft is moving upstream and the stern slides into the whirls. The circling motion tends to pull the stern bankward and to swing the bow into the set, which drives the craft around in the opposite direction. In this situation an additional hazard exists when a heavy rudder must be applied. Power consumed in making the turn may result in loss of headway motion and consequent temporary loss of control.

On tight bends where near right angles are approached (fig. 17A) much larger vortices may be present. The Scott Bluffs eddy in the Mississippi just north of Baton Rouge extends for approximately one-quarter mile along the bank and averages between 100 and 200 yards in width. During

high water it covers nearly one half the width of the channel. The size of these whirls limits the width of the navigable channel and with large craft it may be necessary to reverse course one or more times in addition to utilizing the set to swing the bow downcurrent, as is indicated in figure 17 A.

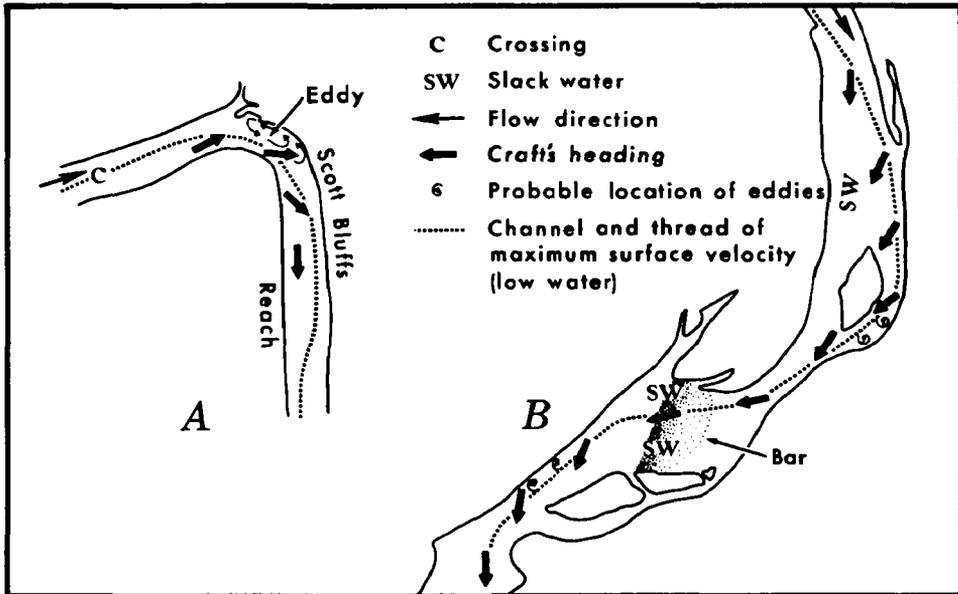


FIG. 17. — Mississippi River mean low water channels at (A) Scott Bluffs, Louisiana, and (B) in Arkansas near the Tennessee border.

After GAGLIANO and McINTIRE, 1968.

Another dangerous situation develops if the craft maneuvers too close and parallel to the bank while under strong power. The vessel may slide into the bank unless headway is reduced. Pilots on the Mississippi River refer to this situation as "bank suction". They reason that when the vessel moves critically close and parallel to shore, propeller action results in lowering water level between the craft and the bank, allowing the boat to move shoreward. Cutting the power on the propeller nearest shore when the danger appears evident is the usual practice by Mississippi River boatmen to correct the situation. Once against the bank, the bow or stern must be maneuvered into a v-angle from shore, creating a funneling effect to utilize the current to free the vessel.

Maintaining proper relative speeds between craft and current in transiting downstream bends constitutes an additional consideration. At times when the two speeds are nearly equal the vessel floats "dead with the current" with loss of rudder control. For surveillance in maintaining speed control in critical situations, Mississippi River boatmen employ a free-floating flanking buoy suspended in the water where it can be seen from the helm.

Channel location and bottom conditions in braided streams are less predictable than those which have a meandering pattern (fig. 17B). The

figure represents a braided section of the Mississippi River and is typical of low-stage channel conditions in many streams. Individual bars, islands, and opposite banks become the point bar and cut bank small-scale equivalents of meandering streams. In the wide sections, coalescing sand bars form across the channel, constituting an obstacle referred to as "reefs" by Mississippi River pilots (fig. 17B). At low river stage approximately 6 feet of water covers the crest along the downstream edge. As the craft moves upstream across the bar, speed and position must be exactly right with respect to the set, or the vessel will ground. In approaching the turn across the bar, the craft must reduce speed to pick up the downcurrent on the bow. If the turn is delayed too long and the current strikes the craft broadside, the vessel will be pushed against the opposite bank, whereas if the turn is started too soon the downcurrent will force the craft against the bar. Once the turn is made into the downcurrent, power is increased to "mount the reef". Too much power applied while crossing the shallow bar may result in striking bottom. Excess power applied in shoal water in general results in "bottom suction", a condition in which the propeller pulls water from between the stern and the stream bed and grounds the craft. In such situations, when the engines begin to labor speed should be reduced. An additional lowering of the water level occurs in shoal areas as a result of the craft's forward motion, which builds a head of water pushed forward in the form of waves in front of the bow, leaving less water to float the stern. Reduced speed allows the craft to rise.

Bars similar to the type indicated across the channel in figure 17B crest along the downstream edge, forming a reef or sill. From the crest they slope gently upstream but fall off sharply downstream with slopes corresponding to the angle of repose for sediment being transported. If a vessel plows into a bar while moving upstream, it usually jars to a halt against the reef, whereas while traveling downstream if the craft touches bottom it can usually slide over the reef or with a slight thrust of power can skim the reef crest and reach deep water.

Most subaqueous bars and subaerial islands (figs. 16 A and 17 B) in rivers possess similar form characteristics, a fact which aids in transiting over or by them. Their downcurrent edges slope off steeply into deeper water, a characteristic which corresponds to the bar described in figure 17B. Conversely, their upcurrent equivalents slope gently upstream, forming broad shoals. The island and its associated subaqueous bars shown on figure 16A illustrate characteristics of these features when the island is aligned with the channel. The bar edge forms a relatively straight line along its downcurrent steep side, but upstream of the island it descends gently, spreading laterally over a broad area.

Boatsmen navigating upstream in low water often utilize the slack, deep water paralleling the bar, but when they reach the descending upper end, where it broadens, they veer out into the channel. The statement among river pilots concerning bars when transiting upstream that "when the bar leaves you, you leave the bar" has merit.

Water surface roughness under certain conditions aids in identifying the channel, bars, and shoals. Rapid currents, eddies, and boils reflect

water movement contiguous with channels. Eddies, which were previously discussed, are easily recognized by their circular motion and associated turbulence. The color of the water or density of the concentration of suspended sediments may also indicate the general position of the channel. Obviously, the greatest concentration of suspended sediments and darker colors would be expected in proximity to the channel, where turbulence is greatest.

Subaqueous bars are often indicated on the water surface by a discontinuity between the roughened surface over deep water and smooth surface over shoals. The rim of the bar is well defined by a wave or ripple line which runs along the edge (fig. 15). Water lying over shoals is usually relatively smooth and often displays a slick surface. Slick areas almost always lie over shoals and should be avoided.

Wind blowing against a current at the right angle can form similar discontinuities on the water surface which are called "wind reefs" by boatmen. The pseudo reefs bear no relationship to underlying bottom forms and consequently can be misleading.

Both the "wind reef" and the roughened water surface outlining the subaqueous bar appear as long, straight lines from a distance, and both are prevalent during low water. They can be distinguished in most cases by the roughened water on the lee side of the "wind reef" as opposed to the smooth or slick surface over shoals.

Bank characteristics provide additional clues concerning adjacent shoals or deep water. Banks on the cut bank side of bends are steeper and higher than those on opposite point bars. Channels lie close to the former, and bank steepness in most cases is maintained by slumping and caving. In contrast, the low point bar slopes gently toward the channel, forming an extensive shoal area. Even though streams are more complicated than to warrant description as simply a sequence of uniform bends, the concept of cut bank-point bar can be applied to the smallest stream segment.

In anastomosing streams each bend around a bar or island, or local indenture where the current impinges against the bank, has its equivalent cut bank and point bar. In the channel on figure 16 it is readily observable that the set impinges against or moves near the reach bank, where ideally the channel should be in the center of the stream and opposite banks should possess uniformity. Where impingement of the current occurs, the bank will be locally steep, possessing the characteristic of a cut bank. On the upstream side of the cut bank a bar usually forms in the slack water, and the immediate offshore area will be shoal. If the set veers away from the bank another bar will form in the slack water downstream from the cut bank.

New sand deposits devoid of vegetation indicate recent deposition and active bar formation. On the Mississippi River different levels of tree vegetation (willow and poplar) attest to annual bar development in some favored localities. Likewise, freshly cut banks indicate active slumping and the fact that the channel occupies a position near the bank. If slumping is prevalent, it is likely that the river stage is lowering.

Along stream sections where neither bars nor cut banks are present the channel lies toward the middle of the river and approximates reach conditions.

Observing or "reading the banks" and noting differences in roughness of the water surface as they relate to underlying bedforms indicate danger areas and provide useful aids to river navigation.

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