

THE TRANSPORTATION AND DEPOSITION OF SEDIMENTS IN ESTUARIES

By

C. F. WICKER

Corps of Engineers, Philadelphia, Penna.

For the purposes of this paper, an estuary is defined as the tidal portion of a river in which the direction of flow reverses and the water-surface elevation rises and falls with a periodicity corresponding to that of the tide in the ocean. This definition excludes rivers, such as the Mississippi, that do not reverse their direction of flow anywhere along their courses, yet experience a tidal rise and fall in their reaches. Attention is directed to the use of the word river in the definition; arms of the sea such as fiords, bays and lagoons thereby being excluded also. This definition is not necessarily unique, but it is perhaps somewhat more restrictive than some students of tidal waterway matters would find acceptable.

Estuaries provide the only harbors for deep-draft vessels along the coastal-plain portions of many of the world's seaboards. They also yield bounteous harvests of seafood. It follows that sedimentation in estuaries is of enormous economic consequence. If it is uncontrolled, ship channels will shoal, anchorages in sheltered coves will disappear, and the estuary will gradually fill outward from the shores and ultimately become a worthless expanse of marsh traversed by a meandering stream carrying upland discharge to the sea. It must not be assumed that this process necessarily requires a geologic age for its accomplishment. It is a matter of historical record that numerous small estuaries that were of great value to the early colonists of our country are now mud flats. There is also evidence, according to Dr. H. H. Bennett, former Chief of the U. S. Soil Conservation Service, that the present rapid sedimentation of bays and estuaries is an abnormal condition that has developed after, or along with, the clearing, over-grazing and cultivation of land in the contributing watersheds. Whether or not this is so, it is likely that even the largest estuaries are not self-maintaining.

The sources of the sediments that shoal an estuary are the upland area drained by the river, the bed and banks of the estuary itself, organic material, and the littoral drift in motion along the ocean beaches adjacent to its mouth.

All rivers transport detritus to a greater or lesser extent, depending on the characteristics of the watershed, the distribution of the annual rainfall, and the hydraulics of the river. Nature is hard at work endeavoring to level the continents and her principal tool is water. Her success in the past is measurable by the great deposits of such sediments as shale, sandstone, and conglomerates that have been laid down in the geologic past, as well as the unconsolidated materials, such as gravel, sand, and silt, that have been deposited more recently. The sources of these materials obviously were the land masses of previous geologic ages. Her continuing, and perhaps greater, present success in accomplishing this purpose is attested to by many observers.

It is probable that much of this *primary* material was deposited initially in the upper reaches of the estuarine portion of the river, from whence it is moved gradually downstream during favorable hydraulic conditions that occur from time to time in the widely varying regimen that is characteristic of most estuaries. In the course of its slow movement, sorting and abrasion take place, and the fines eventually reach the lower portions of the estuary. These deposit more effectively in the quieter waters in coves and along the shore, and extraordinarily high tides build up the deposits to elevations sufficient for the establishment of vegetation and a teeming animal life. During periods of strong winds, these altered deposits are subjected to wave attack and the tidal currents may redistribute the material in portions of the estuary where the hydraulic characteristics would not permit the original material to remain. The cycle continues: the eroded deposits are rebuilt more rapidly than before by new material from the upland and gradually the mud flats creep out far from the original shoreline.

The marine sediment materials that shoal estuaries may play a decisive role in their deterioration. If the estuary enters the ocean in a locality where the shoreline is composed of unconsolidated deposits, littoral drift placed in motion by wave attack on that shoreline will transport material toward the mouth of the estuary. When the estuary is flooding, that is to say, its current is in the landward direction, much material will be carried into the waterway and

probably deposited on an inner bar at the end of the flood. When the estuary is ebbing, some of this material will be eroded from the bar and carried seaward, to meet other material brought to the mouth in the meanwhile by the continuing littoral drift. Some of this material will be carried far out to sea into deep water, some will pass the mouth completely and reach the leeward ocean beach, and the remainder will be deposited on a so-called outer bar that will obstruct the entrance. The combination of the inner and outer bars will seriously affect the tidal regimen of the estuary and accelerate the deposition of both upland and marine sediments.

The transportation of sediments from these sources is accomplished by the currents, waves, and density flows acting in concert. The currents found in estuaries have all the characteristics of those in upland rivers, but the system is vastly more complicated. Estuarine currents are primarily generated by the tide, their essential characteristics vary widely from cycle to cycle even in localities where the basic phenomenon is considered to be relatively simple. As an example, it is not unusual for the tide at the mouth of an estuary on the east coast of the United States to rise from an elevation two feet below mean sea level to three feet above that plane and return to one foot below during one cycle of 12.42 hours. The rise in this case amounts to five feet, the fall four feet, and the orientation of the entire cycle with respect to the plane of mean sea level is askew. It follows that much more water would flow into the estuary from the ocean during the flood phase of the cycle than would leave it during the ebb. The cause of such errancies on the East Coast is the weather. The vagaries of the weather are such that not only can there be a considerable difference between the rise and fall phases of a given cycle of the tide, but also successive rises can differ widely from each other and the fall of one cycle can be much different from the fall of the next. The effect of these variations in the tidal phenomena on the currents that they produce is proportionally as great. The tides on the East Coast are termed the semi-daily type — if the weather during one cycle is similar to that of the next, there will be only small differences between them. On the West Coast, even though given weather conditions prevail through a long period of time, the characteristics of one tide will be greatly different from those of the succeeding tide. Obviously, variable weather conditions will also modify the tide here, as on the East Coast. Although the West Coast tide is classified as the “mixed”

type for different reasons, the term seems to be an appropriate description of so variable a regimen. It is apparent that the currents generated by a tide that varies so erratically will likewise vary from one cycle to the next.

Returning to the less variable regimens of East Coast estuaries, the cycle of events during a tide that is not marred by erratic weather conditions is as follows: At the moment of low tide at the mouth, the current there will be ebbing. Its inertia will cause the flow to continue in that direction for some time after the tide has commenced its rise, of course decelerating as the slope it is ascending increases. When the deceleration is complete, i.e., the velocity is zero, the direction of flow at that point in the estuary will reverse and the flood phase of the current cycle will be entered. The current will accelerate to a peak velocity, then decelerate to zero velocity, after which the flow will again reverse and the ebb portion of the cycle will be reentered. Its characteristics will be similar to those described as occurring during the flood, that is, the velocity will increase to a maximum, then decrease to zero, completing the cycle. Sometime during the flood current, high tide will have occurred locally, but for an interval thereafter, flood current will continue, flowing uphill at a decreasing rate.

As the great wave generated by the tide in the ocean ascends the estuary, similar cycles of current events occur in its wake. Thus, at a given moment the current can be flooding at the mouth and ebbing upstream of the mouth. If the estuary is long and if its characteristics are such that the tide retains sufficient energy, it is possible for the current to be flooding at the mouth, ebbing for some distance above the mouth, and flooding in its upper reaches.

Likewise, it is possible for an estuary of considerable width and having materially greater depths in the midsection as compared with those along the shores to be in the flood phase of the cycle along the shore while the ebb phase continues in mid-channel. This condition occurs after the local passage of the low-water portion of the tide cycle, and a similarly complicated flow pattern will exist at the time of high tide. On the other hand, if the width is very great, the tide can be considerably earlier in mid-channel than near the shore and despite momentum differences, the local reversals of current direction can occur earlier in mid-channel than near the shore. Upstream in the narrower sections of the estuary, the reversals are likely to be simultaneous events from shore to shore.

The average current velocity in the entire cross section at a given moment can be correlated approximately with the slope through a short reach of the estuary, which is a function of the amplitude of the tide cycle, and the acceleration or deceleration of the current. The peak flood velocity in that cross section correlates approximately with the range of the somewhat out-of-phase rising portion of the tide cycle; and likewise, the peak ebb velocity is related to the magnitude of the falling portion of the tide wave. Thus, the maximum velocity at a given point during a tide rising five feet will be approximately $5/6$ as great as that attained by another flood current at the same point when the accompanying tide rises six feet. Accordingly, the considerable variations of the tide at the mouth of the estuary are accompanied by approximately proportional variations in the current regimen of the estuary; it is unusual for the current velocities of one flood phase to be similar to those of the following flood, and the same remark is applicable to the ebbs.

By definition, all estuaries carry upland runoff to the sea. The effects of these discharges on the regimen of the estuary are of great importance and significance. They increase the duration of the ebb portion of the cycle and correspondingly shorten the flood. They also increase the strength of the ebb and conversely, decrease the velocity of the floods. These modifications of the tidal currents are much more pronounced in the upper reaches of the estuary than in the lower, as the proportion of upland discharge to the total discharge of the estuary decreases toward the sea. It follows that the current regimen for a given upland discharge is markedly different from that accompanying a greater discharge; the flood current in the upper portions of the estuary may be replaced by a weak ebb, which is followed by a much reinforced true ebb. Likewise, portions of the estuary that experienced a flood current, with the lower upland discharge, that was approximately equal to the strength and duration of the ebb, now exhibit a comparatively weak flood and a much stronger ebb.

Obviously, the water flowing into the estuary from the sea is saline, and, equally obviously, the upland discharges into the waterway contain only a small quantity of dissolved solids per unit of weight. The mixing of these waters can be completely accomplished within the estuary if the upland discharges are a minor fraction of the discharges emanating from the sea as a result of the tide. In such cases, there is a gradual decrease of salinity of the waters in

the lower reaches of the estuary as the distance from the sea increases, then a fairly rapid decrease in the middle reach, and finally a gradual decrease again until a point is reached beyond which the water has all the characteristics of the upland discharge as to dissolved solids content. On the other hand, the fluvial discharge can approach the magnitude of the tidal discharge, and it is then found that the mixing of salt and fresh water is far from complete in the lower sections of the estuary. The water at the surface can be fresh, even at the mouth, and the water on the bottom can have a salinity equal to that of the ocean. At the entrance to the estuary, it will be found that the depth of the fresh-water stratum below the surface will be small and conversely, the thickness of the stratum of saline water great. Upstream in the estuary, the height of the saline water above the bottom decreases, and, ultimately, the water is fresh from surface to bottom. This stratum of saline water, tapering from a maximum thickness near the mouth to zero at some point upstream, is appropriately described as the salinity wedge.

Although a well-defined salinity wedge is not found in all estuaries, at least a rudimentary form of the phenomenon must be expected. In the fully developed condition, it will be found that the surface water moves in the upstream direction feebly and briefly, if at all, and flows downstream strongly and throughout most, if not all, of the tidal cycle. The water at the bottom flows upstream during most of the tide cycle, the strongest flow occurring during the rising phase of the tide and the weakest during the falling. At the interface of the wedge, a very turbulent condition exists due to the combat between the outward flowing upper stratum of water and the inward flowing lower stratum. In the case of estuaries in which the mixing of saline and upland waters is accomplished within the waterway and the wedge is not well-defined, it is usually found that the mixing action is accomplished principally within a given reach of the waterway, the exact location of which depends upon the rate of upland discharge. Thus, during a great flood, most of the mixing will take place far down in the lower reaches of the estuary; during a low upland discharge, the mixing is largely accomplished at some section much farther upstream. Wherever this zone may be, the flow and saline characteristics during a portion of the tidal cycle bear a resemblance to those found in the wedge. The water at the surface in this principal mixing zone is never wholly fresh, however, nor is the water at the bottom as saline as the waters

of the ocean. The interface zone is very thick, so to speak, and, accordingly, there is no sharply defined point in the vertical at which the salinity changes abruptly from one value to another. Nevertheless, the density differentials are sufficient in this reach of the estuary to affect profoundly the currents. It will be found that the flood current begins earlier on the bottom than it does at the surface, and that the average strength of the flood portion of the cycle at the bottom is greater than that of the ebb. Conversely, the surface ebb commences a little earlier than the ebb at the bottom, has a greater duration, and attains a higher velocity than that of the succeeding flood at the surface.

This is a very general picture of the hydraulic regimen of a typical estuary subject to a relatively simple tide. It is vastly more complicated than the hydraulics of even a great upland stream, and the stage on which the complexities are displayed is often of heroic proportions. The estuarine portion of the St. Lawrence, exclusive of the Gulf, is approximately 450 miles long and has an average width of 40 miles; the small Thames estuary has an average width of over a mile and a maximum of 10 miles in its approximately 45-mile course to the sea; and the Delaware, also a relatively small estuary, experiences a maximum discharge at its mouth, during a mean tide, that is greater than the peak discharge of the greatest flood of record in the Mississippi at New Orleans.

Under these conditions, quantitative sediment discharge data having an accuracy corresponding to that ordinarily obtained in upland streams cannot be obtained easily. In fact, an effort to do so would necessarily assume prodigious proportions as the discharge is rapidly variable during one phase of a given tide; an entirely different but again varying regimen is set up during the next phase of the same tide, when the direction of flow is reversed; successive tide cycles may be, and usually are, quite different; and the density of the water in some reach of every estuary is not constant, nor is the variation constant. The great widths of the cross sections to be studied in themselves greatly magnify the job of obtaining satisfactorily reliable data on sediment discharges.

As a consequence, studies of shoaling problems in estuaries are based on a general knowledge of the regimen, the characteristics of the materials contained in the shoals and the sources of such materials, also observations of the sediments in motion in a given vertical in the cross section during favorable weather conditions. (In

the wider sections of an estuary, storms produce conditions that are untenable for small craft.) The discussion which follows is therefore necessarily qualitative in nature.

Sediments brought into an estuary by the upland, or fluvial, discharge are transported seaward with decreasing efficacy as the distance from the non-tidal portion of the waterway becomes greater. In an estuary of steadily increasing cross-sectional area and a constant mean depth that receives an unvarying upland discharge of sediment and water, and which is subject to one identical tide cycle after another (such an estuary does not exist in nature), it will be found that all of the sediments except the very finest and lightest have deposited in a given reach extending downstream from the point where a reversing flow is first found in the waterway, i.e., the head of the estuary. The coarsest and heaviest particles will be found at that point, and the shoal will be composed of ever lighter and finer particles as successive sections downstream of that point are examined. The length of the section will depend upon the length of time that the regimen described — constant upland discharge of sediment and water and repeating identical tide cycles — has been in existence. As this laboratory regimen continues, the shoal at the head of the estuary will assume proportions that will modify the currents in that locality. A reversing flow will no longer occur; the unidirectional flow that takes its place will vary from a minimum velocity at the time when flood flows would have been experienced in a clear channel to a maximum that will be greater than that which was attained at full ebb in the clear channel, due to the reduction of the cross-sectional area. Particles having the characteristics of those that formerly would deposit in this reach are carried farther downstream before settling out permanently, and those that previously would have deposited in these downstream reaches travel even farther. As this "laboratory" regimen continues, the headwaters shoal will creep downstream, but at a decreasing rate as the width of the estuary increases.

It must not be assumed that the movement of sediments is unidirectional throughout their journey to that portion of the estuary wherein they finally deposit. Nearly all of the load is dropped at each slack water, some of it only temporarily. As the current in the opposite direction increases its strength, a scouring velocity for some of the particles is attained; these move along with that current until it in turn has passed its maximum and has decreased until the

velocity is insufficient to move these particular particles, whereupon deposition will again occur. Similarly, coarser particles deposit before slack water and must await the advent of a flow in the opposite direction having a higher velocity than that necessary to move the first class of particles considered. Thus, fine particles will travel a given distance downstream with an ebb before depositing a somewhat shorter distance upstream with the ensuing flood. They then resume their downstream journey and settle out at or near the end of the period of the next ebb at a point somewhat farther downstream than the point of deposition at or near the end of the preceding ebb. Coarser and heavier particles will not travel as great a distance during the complete cycle of upstream and downstream movement, but a net downstream advance will probably occur nevertheless. The coarsest and heaviest particles will remain where deposited at slack water.

It also must not be assumed that the very fine or light particles will necessarily be advanced via the above-described back and forth motion through the estuary and out to sea under this "laboratory" regimen. Once the particles reach the saline portion of the estuary, the peculiar currents of that region will not permit particles traveling the lower strata of water to accomplish a net advance seaward at the end of each cycle. These peculiarities are due to the salinity wedge; they exist to a greater or lesser extent according to the degree of development of the wedge, but even a very rudimentary form of wedge will prevent the passage to sea of particles moving in the lower strata for the "laboratory" regimen under discussion.

The saline water in this reach will produce a flocculation of the particles in transport, causing some of them to settle out. A shoal will form and grow until its dimensions have assumed proportions sufficient to modify the cross section appreciably. The resultant higher current velocities can "defloc" the particles and move them about, but flocculation will reoccur when favorable circumstances again exist. In fact, it is likely that the particles will be flocculated and deflocculated many times as the shoal forms and gradually reduces the tidal prism by impeding the passage of the tide.

As stated before, an estuary in a locality where the coast is composed of unconsolidated deposits is subject to shoaling by these sediments. They are transported to the mouth by the so-called littoral processes, and are deposited there as inner and outer bars. Both of these features are extremely adverse to the regimen of the estuary

as they impede the entrance of the tide wave and reduce the tidal prism.

Thus, the "laboratory" estuary is shoaled in three localities: At its headwaters, where the coarser and heavier particles deposit and gradually reduce the length of the estuary; in the region where the salinity wedge modifies the distribution of current velocities in the vertical, and where the finest and lightest particles are flocculated and prevented from completing their journey to the sea; and at the mouth where the littoral materials form great bars. All of these deposits work towards the same end, the elimination of the tidal fluctuations and the currents they generate and thus the destruction of the estuary. The waterway will become a river of dimensions adequate to carry the upland discharges of water and sediments to sea, meandering along its course through vast marshlands.

Of course, no estuary possesses the ideal physical characteristics discussed and a regimen of such constancy cannot exist anywhere except in the laboratory. In nature, it will be found that the cross-sectional areas vary erratically, although tending to increase towards the mouth, and mean depths will certainly not be constant throughout the course. Also, the entry of tributaries will seriously interfere with the pattern of sedimentation described, and, finally, the infinite variety of hydraulic conditions that exist by virtue of variable upland discharges and tides will have a profound effect on the transport and deposition of sediments.

Variations of cross-sectional areas that are not in consonance with the ideal rate of increase, and errancies in the mean depths, will cause variations in the current velocities of both floods and ebbs. The velocities attained in a cross section of excessive area or deficient mean depth will be less than those found at a corresponding phase of the current cycle at a cross section of deficient area or excessive mean depth. The latter can be sufficiently strong to scour the bed, thus adding to the volume of material from the upland that is in transport and accordingly accelerating the rate of shoaling in sections in which the current velocities are low. As a result, it is likely that the shoaling will not be concentrated in the upper reaches, the region affected by the salinity wedge, and at the mouth, but will be found also in the many other sections where the physical characteristics depart from those that are dictated by the ideal form. The unfavorable cross sections will not be adjusted properly by the shoaling or scouring, and the deterioration of the estuary will be

found to proceed more rapidly than was the case in the ideal estuary.

Tributaries entering the estuary introduce sediments having characteristics differing from those already in transport in the main stream at the point of confluence. They may resemble those originally introduced by the main upland river, but the sorting process has resulted in the loss of the coarser and heavier particles in the upper reaches, leaving only the fines in transport at the cross section where the tributary enters. The regimen of the estuary may be inadequate to cope with the added burden, particularly if it contains a considerable quantity of coarser and heavier particles, and the rate of shoaling at the point of confluence may be quite large. It must be remembered that the regimen of the estuary may be such that the tidal components are preponderant; the addition of the water discharge of the tributary is not then of significance to the regimen of the main stem, but the sediments carried with it can constitute a considerable addition to the sediment load of the estuary at the point of confluence.

A complication of even greater importance than the natural physical characteristics, the errancies, and the occurrence of tributaries exists. As previously mentioned, the regimen of an estuary is characteristically variable. The diverse conditions that exist as a result of variations in the upland discharges and the tide have profound effects on the transportation and deposition of sediments. Depending upon the hydrology of the watershed, the upland water discharges into the estuary can vary from a small fraction of the mean to figures many times greater, and the sediment discharges will range through an even greater spread. The tidal currents can be completely obliterated in the upper reaches of the estuary if the upland discharges are very great, or they can be strongly reinforced by the abnormally high ranges of tide that occur if strong winds work in concert with the astronomical generators of the tide.

Thus, the materials that would deposit and remain indefinitely in the upper reaches of the estuary under a regimen of constant upland discharge and a succession of identical tidal cycles might be distributed widely by the powerful seaward flows that are generated by high upland discharges and "blowout" tides. (This perhaps colloquial but nevertheless descriptive term is applied to conditions that prevail when strong winds in the downstream and offshore direction depress the elevations of the water surfaces of the estuary

and sea far below normal levels.) It is unlikely that such materials would move through a considerable portion of the total length of the estuary as a result of one such occurrence of the extraordinary conditions described, but a series of them spaced over the centuries will move quite coarse and heavy particles derived from erosion of the upland down to the mouth. There they will join the littoral material derived from the erosion of the sea coast and brought to the mouth by the littoral currents, and be deposited on either the inner or outer bars. It is practically certain that the upland materials that can be identified on the bars at the mouths of estuaries do not reach there by the operation of the so-called normal regimens.

The great upland discharges and the occasions of extraordinarily powerful tidal currents, acting either singly or in concert, also greatly affect the hydraulics of the region ordinarily occupied by the salinity wedges. Saline water may be extruded entirely from the estuary. During its absence, the strength and duration of the flood current will be less than those of the ebb current from surface to bottom, rather than only in the upper strata, as when the wedge is present. This will permit a downstream movement of some of the flocculated material that could not take place if the wedge were present. In estuaries where the salinity wedge exists in rudimentary form only, it is likely that materials that were prevented from further seaward travel by the salinity "front" can find conditions making such travel possible if they are pushed by a strong ebb past the locality usually occupied by the front. In such estuaries, it is found that the waters downstream of the front are always nearly constant in density from surface to bottom, and the strengths and durations of the ebb currents, surface to bottom, are somewhat greater than those of floods generated by corresponding tides. The fines thus are gradually worked seaward, via a back and forth motion, through this region below the normal location of the front. They do not deposit at the mouth permanently, as the practically continuous wave action there keeps them in suspension until they are moved seaward into quieter water far offshore.

Extraordinary tidal and upland discharges can cause scour of the bed at reaches where the cross-sectional areas are deficient for such flows, and they will certainly accelerate scour at reaches that are deficient for normal discharges and are composed of erodible materials. It is also certain that the great upland discharges bring a much greater volume of sediments into the estuary. However, al-

though the estuary is confronted with much more sediment to combat as a result of the extraordinary discharges, it is likely that the beneficial results of such a regimen over-balance its deleterious effects. Shoals that accumulate during normal discharges are flushed away, and some sediments may be carried to sea under such conditions, thus slowing the pace at which the estuary moves to destroy itself.

The shoals in a typical estuary experiencing a natural regimen will not be composed of particles that are distinctively sized and located as described under the discussion of the "ideal" estuary that a laboratory regimen experiences. Instead, some coarse particles will be found in all the shoals, and the size, as defined by some criterion such as median diameter, will not decrease systematically as the mouth is approached. There will be errancies of considerable magnitude, due to the variable regimen, to the entry of tributaries, and also to departures of the physical characteristics from the ideal form. However, it is likely that a graph of median diameters will exhibit a trend from coarse to fine sizes as the mouth is approached. If the littoral material is typical beach sand, the bars at the entrance to the estuary will be composed of particles coarser than those found immediately upstream.

In summary, the hydraulic regimen of a typical estuary is extremely complicated and highly variable. Accurate quantitative observations of the sediment in transport at the various reaches of such an estuary are uncommon, and accordingly much less is known about the mechanics of the transportation and deposition than is the case for upland rivers. A study of a shoaling problem in an estuary therefore necessarily is based on a general knowledge of the hydraulic regimens of which the waterway is capable, the characteristics of the materials contained in the shoals, and spot sediment transport observations. The conclusion seems inescapable that most estuaries are doomed to destruction; they will become rivers meandering through mud flats or marshes and having dimensions adequate only to carry the upland discharges of water and sediment to sea.

DISCUSSION

Mr. Simmons complimented Mr. Wicker for his presentation and clear demonstration of the complexity of estuary sedimentation.

Charleston Harbor, which lies on the South Atlantic Coast and is formed by the confluence of the Cooper, Ashley, and Wando Riv-

ers, can be used to illustrate one of the complicated types of estuaries. The Cooper River discharges into Charleston Harbor almost all of the fresh water which enters it, and provides the controlling factor in this respect. The Wando River, on the other hand, has a much larger tidal prism than Cooper River, and is the controlling factor with respect to tidal flow. The Ashley River is somewhere between the other two, in that it has a smaller tidal prism than the Wando and a smaller fresh-water discharge than the Cooper.

To complicate further the hydraulics of Charleston Harbor, the flow of the Cooper River is regulated by the Santee-Cooper power project, so that the discharge frequently varies between 2,000 cfs. and 25,000 cfs. within a 24-hour period. Since the power plant operates on a demand basis, the cycle of fresh-water discharge is fairly uniform from day to day. However, since the tides follow a lunar cycle of approximately 24 hours 50 minutes, the relation between the tidal cycle and the fresh-water discharge cycle is constantly changing. If then is added to these factors the effects of the many divided channels and islands in Charleston Harbor, the complicated nature of the sedimentation processes that occur in this estuary can be realized.

Mr. Simmons also said that there is evidence which indicates that the sedimentation characteristics of estuaries vary in accordance with the phasing of the tides from neap to spring. The location and extent of shoals in estuary channels appear to be influenced greatly by the tidal range, so that comparison of hydrographic surveys of a given shoal following the neap portion of the tidal cycle with corresponding surveys made after the spring portion of the cycle may indicate only the effects of tidal range on the sedimentation characteristics of that particular reach of channel. Such surveys are often used to determine shoaling rates and dredging requirements, with the result that shoaling rates so determined vary widely from time to time and unnecessary dredging is sometimes undertaken.

Mr. Baines commented that for estuaries, in which the degrading process lasts for thousands of years, the external conditions change slowly but constantly. Consequently, if viewed from the aspect of geologic time, the estuary can never hope to be in equilibrium. However, in order to design and build structures to be installed in estuaries, studies should be made of the equilibrium conditions toward

which the estuary is striving. Once these have been determined in the laboratory, the principles can be adapted to the field.

Mr. Benedict asked how an estuary was produced.

Mr. Hershey, in partial answer to the question raised by Mr. Benedict, pointed out that along the east coast of the United States either the sea level is rising or the land sinking. Rivers that in the geologic past flowed to the sea in canyons now submerged, are entering estuaries. These have been formed by the change in the land-sea level relation, so that the sea is encroaching on the land, forming the large embayments herein described as estuaries.

Mr. Wicker, in answering Mr. Benedict's question, and in partial answer to Mr. Baines' comment on changes with geologic time, described the formation of the New Jersey-Delaware coast line by deposition from an enormous glacier 30 miles to the northward. He indicated also that drastically different climatic conditions prevailed at that time, some 60,000 years ago, primarily much heavier rainfall, which together with the melting ice, carried great quantities of sediment, resulting in the general land configuration, including estuaries, which is the present coast line.

Mr. Merkys inquired as to the manner of formation of bars at the mouth of an estuary from the movement of littoral currents.

In reply to Mr. Merkys' question, Mr. Wicker described the formation of bars at the mouth of an estuary as a result of the conflict between the inward and outward flowing water of the estuary and the along-shore flow of water and sediment. If the latter is large with respect to the former, bars rapidly form. If the estuary is very large, the littoral materials gradually encroach and bars gradually build up in the region of conflict.

