MAN'S IMPACT ON ESTUARINE SEDIMENTATION

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ABSTRACT

Estuaries are ephemeral features on a geological time scale being rapidly filled with sediments. Although most estuarine sedimentation rates are naturally high, man's activities have greatly accelerated the rates of filling of many estuaries, thus shortening their geological lifetimes. More importantly, the increased influxes of fine-grained sediments have degraded some estuaries, or segments of them, to the extent that their useful biological and recreational lifetimes have been cut drastically shorter than their geological lifetimes.

Much more effort should be directed at reducing the most manageable source of sediment to most estuaries—soil erosion. This would not only result in an improvement of water "quality," but would, within a few decades, result in significant reductions in the amounts of dredging required for channel maintenance. Dredging will, however, continue to be a persistent problem because the supply of sediments cannot be eliminated.

A new approach to dredging and spoil disposal is required. Regional plans must be developed to ensure that maintenance channel dredging can be carried out without prolonged delays. The present standards for characterization of dredged materials do not have a sound scientific basis, and should be reevaluated. While they were intended to be environmentally conservative, they may be unduly restrictive.

INTRODUCTION

Estuaries are the major sites for the accumulation of sediment along our coastline. Their positions at the mouths of rivers make them the ready recipients of sediment eroded from the land, and the characteristic circulation patterns produced by the mingling of fresh water from the land and salt water from the sea that takes place in estuaries makes them effective sediment traps. The rate of sediment accumulation in estuaries, which is already naturally high in many situations, has been increased by man's activities.

The primary purposes of this report are: (1) to review some of the characteristic estuarine sedimentation processes; (2) to look at some of the ways in which man has altered these processes; (3) to assess the significance of the effects of these changes on the estuarine milieu; and (4) to recommend the types of research needed for significant advances in our understanding of estuarine sedimentation processes.

For this discussion, we adopt the definition of an estuary most commonly used by physical oceanographers—an estuary is a semi-enclosed coastal body of water freely connected to the ocean within which seawater is measurably diluted by freshwater runoff from land.

SEA LEVEL, SEDIMENTATION, AND THE LIFE EXPECTANCY OF ESTUARIES

All present day estuaries were formed by the most recent rise in sea level which began approximately 15,000 to 18,000 years ago. During the last glacial stage (the Wisconsin) the level of the sea was about 125 m (410 ft) below its present level (Fig. 1) and most of the continental shelves of the world were exposed to the atmosphere. With the melting and retreat of the great ice sheets, sea level rose, rapidly at first, from about 15,000 years ago until about 9,000 years ago when it reached a position approximately 20 m (66 ft) below its present level. By 3,000 years ago the level of the sea was within 3 m (10 ft) of its present position, and since then the sea has risen even more slowly, averaging less than 1 m per 1,000 years.

The rising sea invaded numerous coastal embayments and produced estuaries in those that received enough fresh water to measurably dilute the encroaching seawater. Many of these coastal basins were former river valley systems. Examples are Chesapeake Bay, Delaware Bay, and the estuaries around the Mississippi Delta. Other basins, formed by glacial scour, were the fjords such as those found along the coasts of Alaska and British Columbia.

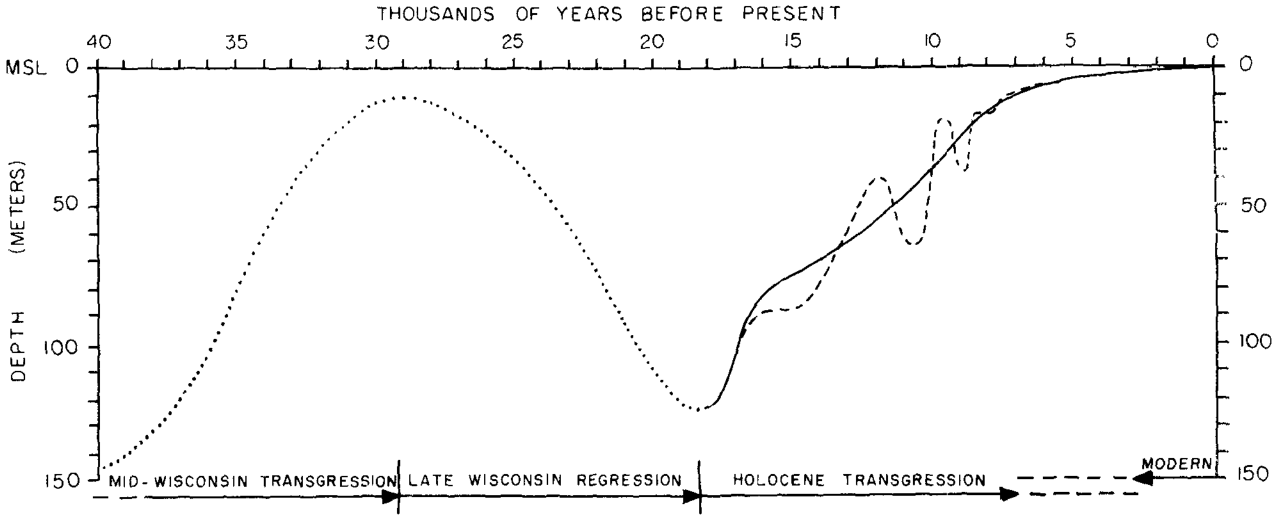

Figure 1.—Fluctuations of mean sea level from present to 40,000 before the present (B.P.). The curve was compiled from published and unpublished radiocarbon dates and other geologic evidence. Dotted curve estimated from minimal data. Solid curve shows approximate mean of dates computed. The dashed curve is slightly modified from Curray (1960, 1961). Probable fluctuations since 5,000 years B.P. are not shown (J. R. Curray, Late Quaternary History, Continental Shelves of the United States in the Quaternary of the United States, 1965).

Wave action and littoral drift formed bars off the mouths of some rivers thereby creating embayments which were later transformed into estuaries. Examples are Pamlico and Albemarle Sounds. Still other coastal basins that later became estuaries were formed by tectonic processes. San Francisco Bay is an example.

The rapidity of the rise of sea level was a major factor in the formation and maintenance of estuaries. Sedimentation could not keep pace with the rapidly rising sea that invaded numerous coastal basins. For the past few thousand years, however, the relative rate of infilling has been much greater than during the preceding several thousands of years. The rate of sea level rise has been slower, and within the past few hundred years the rate of sediment input has increased as a result of man's activities. It is, of course, the relative sea level rise—the rise relative to the sedimentation rate—that determines the geological lifetime of an estuary.

All modern estuaries then, are quite young geologically; certainly less than 15,000 years old. The relative youthfulness of many estuaries, particularly of drowned river valley estuaries like Chesapeake Bay, is indicated by their highly irregular, dendritic shorelines. As estuaries mature there is a progressive rectification or straightening of their shorelines; headlands are attacked by waves and current, and re-entrants in the coastline are filled by drifting sand. Once formed, estuaries are ephemeral features on a geologic time scale, being rapidly filled with sediments. Sediments are introduced not only by shore erosion, but also by rivers, by the wind, by the sea, and by biological activity. The sources are thus external, internal, and marginal. Typically, estuaries fill from their heads and their margins. An estuarine delta generally forms in the upper reaches of the estuary—near the new river mouth. The estuarine delta grows progressively seaward, extending the realm of the river and thereby expelling the intruding sea from the semi-enclosed coastal basin. Lateral accretion by marshes may also play a major role. As a result of these processes, the estuarine basin is converted back into a river valley. Finally, the river reaches the sea through a depositional plain and the transformation is complete.

While depositional rates in estuaries are naturally high, man's activities both within the estuarine zone itself, and throughout the drainage basin (sometimes hundreds of kilometers away) can greatly increase the sediment yields and the rates of filling, can alter the natural sedimentation patterns, and can shorten the geological lifetimes of estuaries—sometimes appreciably. More importantly, the indirect effects of increased inputs of sediments, particularly of fine-grained sediments, can degrade an estuary, or segments of it, to the extent that its useful biological and recreational lifetimes are cut drastically shorter than its geological lifetime—perhaps several orders of magnitude shorter.

It has been reported that when John Adams, a Democrat, was President, he swam in the upper Potomac at Washington, D.C. Lincoln, a Republican, not only did not swim in the upper Potomac, but remarked that the stench from it was sometimes so bad that on warm summer evenings when the wind was off the Potomac he had to flee the White House. This indicates either that the quality of the upper Potomac had been seriously degraded by man's activities over this period·of about 60 years; or as a Republican friend of ours, H. H. Carter, points out, merely that "a Democrat will swim in anything."

ESTUARINE CIRCULATION AND SEDIMENTATION PATTERNS

Because of their characteristic circulation processes, estuaries are effective sediment traps. The tidal circulation is important in the formation of channels, tidal flats, and tidal deltas, but it is the net non-tidal circulation that is of primary importance in determining the rates and patterns of filling of most estuaries.

It is in the estuary where the mixing of fresh water from the land and salt water from the ocean produces dynamic conditions that lead to the eventual discharge of the river water to the ocean. The mixing may be due primarily to the action of the river, the wind, or the tide. There is a sequence of estuarine circulation types displaying different degrees of mixing of the fresh water and the sea water. The position that an estuary occupies in this sequence depends primarily upon the relative magnitudes of the riverflow and the tidal flow, and upon the geometry of the basin that contains the estuary. Changes in any of these factors may produce changes in the estuarine circulation pattern and may thereby alter the resulting sedimentation patterns. One end member of this sequence is the poorly mixed (highly stratified) salt-wedge estuary—that so-called Type A estuary. The other end member is the thoroughly mixed, sectionally homogeneous estuary—the Type D estuary. Two intermediate types which have been described are the partially mixed, Type B, estuary, and the vertically homogeneous, Type C, estuary.

Estuaries are actually continuously varying in their characteristics and may shift from type to type as conditions change. Also, at any given time, different circulation types may be observed within different segments of an estuary, depending on the relative magnitudes of the tidal flow and the freshwater flow, and upon the local geometry of the basin. The four types of estuarine circulation patterns are shown schematically in Fig. 2. In general, an estuary changes from Type A (Fig. 2A) to Type D (Fig. 2D) as the magnitude of the tidal flow increases relative to the riverflow and/or as the width of the basin increases relative to the depth.

The Salt-Wedge (Type A) Estuary

The Type A estuary, Fig. 2A. is a river-dominated estuary. It is also called a salt-wedge estuary because there is little mixing between the seawater and the fresh water, and the encroaching seawater is present as a wedge underlying the less dense, fresher river water. Salt-wedge estuaries occur where the ratio of width to depth is relatively small and the ratio of riverflow to tidal flow is relatively large. At locations upstream from the tip of the salt-wedge, the flow is downstream at all depths. Seaward of the tip of the wedge, the flow throughout the upper layer is still downstream at all times because of the dominance of the river over the tide. In the lower layer, the instantaneous flow may be upstream at all times, or it may reverse with the tide, but the net flow is upstream.

Fine suspended particles that are brought into the estuary by the river and settle into the lower layer are brought back upstream to the tip of the wedge by the slow net landward flow of the lower layer and accumulate in the vicinity of the tip of the wedge. This fluvial sediment may also be supplemented by fine particles from other sources. Heavier particles transported along the riverbed accumulate upstream of the wedge. The region surrounding the tip of the wedge, then, is a zone of rapid shoaling. The position of the tip of the salt-wedge is determined primarily by the freshwater discharge and the channel depth.

The Southwest Pass of the Mississippi River is a classic example of a salt-wedge estuary. The average flow through Southwest Pass is more than 5,100 m^3/sec (180,000 ft^3/sec), and peak flows may exceed 8,500 m^3/sec (300,000 ft^3/sec). The river completely dominates the circulation. The tidal range in the Gulf of Mexico is only about 36 cm (1.3 ft). The tip of the wedge migrates more than 235 km (126 n. miles) in response to changes in the discharge of the Mississippi. During periods of minimum flow, the tip may be about 40 km (22 n. miles) above New Orleans—nearly 235 km (126 n. miles) above the mouth of Southwest Pass. During periods of moderate flow, the tip of the wedge is located near the river's mouth, and the shoaling problem is so serious in this region that around-the-clock dredging is required to keep the navigation channel open.

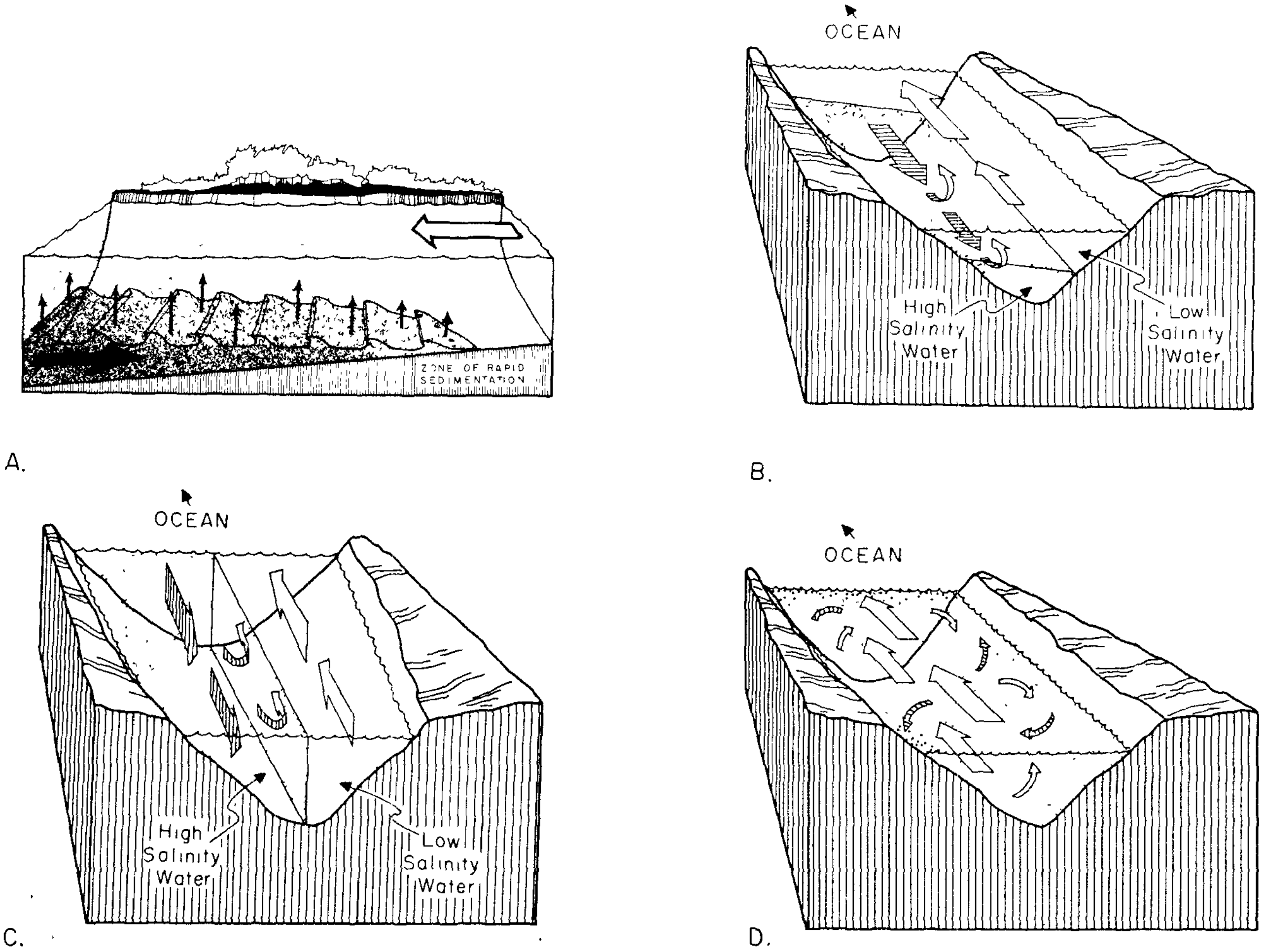

FIGURE 2.—*Four distinct examples in the sequence of estuarine types. A. Type A estuary. B. Looking seaward in Type B estuary in N. Hemisphere. C. Looking seaward in Type C estuary in N. Hemisphere. D. Looking seaward in Type D estuary in N. Hemisphere.*

The Partially Mixed (Type B) Estuary

If the tidal flow is increased relative to the riverflow so that the tide is sufficiently strong to prevent the river from dominating the circulation, the added turbulence provides the mechanism for erasing the salt-wedge. This occurs when the volume rate of flow up the estuary on a flood tide is on the order of 10 times the volume rate of inflow of fresh water from the river. There is both advection and turbulent mixing across the freshwater-saltwater interface. The sharp interface which separated the fresh water of the upper layer from the sea water of the lower layer in the salt-wedge estuary is replaced by a region of more gradual change in salinity. Such an estuary is called a partially mixed, Type B, estuary. The difference in salinity between top and bottom remains nearly the same over much of the length of the estuary. The Coriolis force—an apparent deflecting force caused by the earth's rotation—produces a slight lateral salinity gradient across the estuary. The boundary between the seaward-flowing upper and landward-flowing lower layers is slightly tilted. In the Northern Hemisphere, the upper layer is deeper and the flow slightly stronger to the right of an observer facing seaward. The lower layer is nearer the surface and its flow is slightly stronger to the left of the seaward-facing observer.

Fine suspended particles that settle into the lower layer are carried upstream by its net landward flow, leading to an accumulation of sediment on the bottom between the upstream and downstream limits of salt intrusion. Because of the mixing which is more intense than in a salt-wedge estuary, there is generally an accumulation of fine suspended sediment in the landward reaches of the estuarine circulation regime. Such features, called "turbidity maxima," have been reported in the upper reaches of a large number of partially mixed estuaries throughout the world. These turbid zones characteristically begin in the estuary where a vertical gradient of salinity first appears and commonly extends downstream for 20–40 km (10–20 n. miles). Within a turbidity maximum the concentrations of suspended sediment and the turbidities are greater than either farther upstream in the source river or farther seaward in the estuary. Their formation has been attributed to the flocculation of the fluvial sediment, to the deflocculation of fluvial sediment, and to hydrodynamic processes. We believe that turbidity maxima are produced and maintained by physical processes—specifically the periodic resuspension of bottom sediments by tidal scour, and the estuarine circulation pattern—and that the importance ascribed to the role of flocculation in estuarine sedimentation is not supported by field evidence.

The most rapid shoaling in partially mixed estuaries normally is between the flood and ebb positions of the limit of sea salt intrusion. Rapid shoaling may also occur where the upstream flow of the lower layer is interrupted by entering tributaries, by abrupt changes in cross-sectional area, or by meandering or bifurcation of the channel. The Chesapeake Bay is a good example of a partially mixed estuary.

The Vertically Homogeneous (Type C) Estuary

If the role of the tide, relative to the river, is increased over that in the partially mixed estuary, the tidal mixing may be sufficiently intense to completely eradicate the vertical salinity gradient and produce a vertically homogeneous water column. The longitudinal salinity gradient still remains with the salinity increasing seaward. And, because of the Coriolis force, the lateral gradient in salinity also remains with the higher salinity water to the left of an observer facing seaward in the Northern Hemisphere. The boundary between the lower salinity water flowing seaward and the higher salinity water flowing up the estuary becomes more nearly vertical, and may intersect the water surface. In the Northern Hemisphere then, the net flow and sediment transport are generally upstream on the left side of the estuary facing seaward and downstream on the right side. Shoaling is generally most rapid near the upstream limit of sea salt, in regions of large cross-sectional area, adjacent to islands, and in channel bifurcations where the flow is interrupted. The wider reaches of the Delaware and Raritan (New Jersey) Bays are examples of vertically homogeneous estuaries.

The Sectionally Homogeneous (Type D) Estuary

If the tidal flow is increased even more so that it is very large relative to the riverflow, it may almost completely overwhelm the effect of the river. The tidal mixing may be so intense that not only is the vertical salinity gradient eradicated, but so also is the lateral gradient, producing a sectionally homogeneous estuary. The movement of water is essentially symmetrical about the main axis of the estuary with a slow net seaward flow at all depths. Truly sectionally homogeneous estuaries may not exist in nature. In estuaries that are approximately sectionally homogeneous, the most rapid sedimentation occurs in areas where the slow net seaward flow is interrupted by tributaries or obstacles. The Piscataqua estuary in New Hampshire appears to be nearly sectionally homogeneous, but observations in estuaries of this type are limited.

As pointed out previously, the position that an estuary occupies in this sequence of estuarine types depends primarily upon the relative magnitudes of the riverflow and the tidal flow, and upon the geometry of the basin. Relatively subtle changes in any of these factors may produce changes in the estuarine circulation pattern and thereby alter the resulting sedimentation patterns. In general, an estuary's sediment trapping efficiency is increased as the riverflow increases relative to the tidal flow, or as the depth increases. Most of the fluvial sediment is generally introduced into an estuary when the riverflow is high, when its trapping efficiency is greatest. When the riverflow subsides and the relative importance of the tidal flow increases, the estuary shifts in its circulation pattern toward one of greater mixing. During these more prolonged periods of low to moderate riverflow the sediment is redistributed.

ALTERATION OF PREVAILING SEDIMENTARY PROCESSES

Sources

Although sediment in estuaries comes from many sources—including the erosion of the margins of the estuarine basins, and the beaches and sea floor outside the estuary mouths—the sources most affected by the hand of man are the rivers that carry sediment from upland areas into the estuaries. Our discussion will focus mainly on the sediment loads of rivers, which are increased by such activities as farming, mining, and urbanization; and which are decreased by reservoirs and other protective works.

MAN'S ACTIVITIES THAT INCREASE RIVER SEDIMENT LOADS

Ever since the first European settlers landed, man has affected the amount of sediment in streams draining North America. The influence of man on sedimentation is especially well documented in the Chesapeake Bay region, where clearing of forests and wasteful farming practices (especially those used in raising tobacco) contributed enormous loads of sediment to the rivers. Clear streams became muddy and once relatively deep harbors at the heads of a number of the tributaries were filled with sediment. The Potomac River, whose waters were already somewhat turbid but which were still suitable for municipal use in 1853, had become so muddy by 1905 that the city of Washington had to install its first filtration plant. A comparison of the 1792 and 1947 shorelines of the upper Potomac (Fig. 3) shows that large areas of the Potomac near Washington have been filled with sediments stripped from farmland farther upstream. The Lincoln and Jefferson Memorials now stand on what was described in 1711 as a harbor suitable for great merchant vessels. Even today, an average of about 2 million m^3 (2.6 million yds^3) of sediment is deposited every year near the head of tide in the Potomac; not all of this sediment is the result of agriculture, as we shall see. There are other former seaport towns on the western shores of Chesapeake Bay where decaying docking facilities are now separated from navigable water by several miles of sediment-filled lowland.

Streams that drain modern day farmlands in many of the mid-Atlantic states carry about 10 times as much sediment as streams that drain equivalent areas of forest land. And this relation is by no means unique. In the Coastal Plain of northern Mississippi, sediment yields from cultivated lands are 10 to 100 times the yields from equivalent areas of forested lands. In two other areas where studies have been made—the Tobacco River Valley of Michigan and the Willamette Valley of Oregon—streams draining farmland carry two to four times as much sediment as streams draining equal areas of forested land.

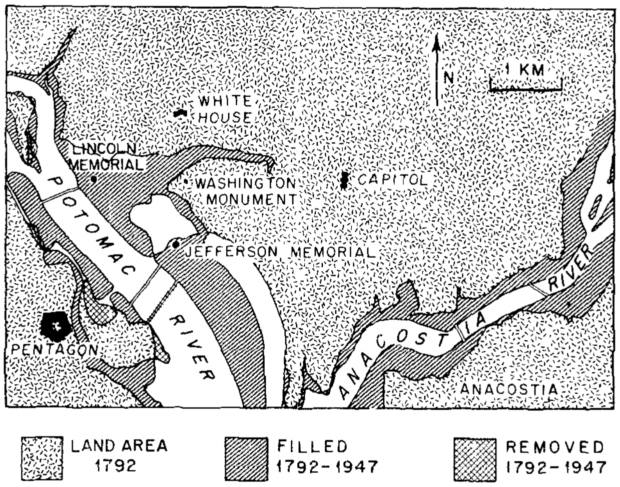

FIGURE 3.—Accumulation of sediment at Washington, D.C., near the head of tide in the Potomac and Anacostia Rivers, between 1792–1947.

Mining is another activity that has increased the sediment loads of rivers that flow into some estuaries. San Francisco Bay, for example, contains nearly a billion cubic meters of sediment washed from the Sierra Nevada during the 30-odd years of intensive hydraulic mining for gold. Even after the hydraulic processing was stopped in 1884, the mining debris continued to choke the valleys of the Sacramento River and some of its tributaries for many decades. Gradually, over the years, the debris has been moved downriver to be deposited more permanently in the marshes and shallower areas around San Francisco Bay. The mining debris that was released in only three decades is more than the total sediment from all other sources (including farmland) that the Sacramento River has carried in the twelve-and-a-half decades since 1850. It has been shown that this sediment had an important effect on the bay; the tidal prism was decreased, and the flushing regime significantly changed.

Urbanization is the most recent of man's activities to contribute large amounts of sediment to streams. Sediment loads derived from land being cleared or filled for the building of houses, roads, and other facilities are best documented in the area between Washington, D.C. and Baltimore, Md. During periods when housing developments, shopping centers, and highways are being built, the soil is disturbed and left exposed to wind and rain. The concentration of sediment in storm runoff from construction sites is a 100 to 1,000 times what it would be if the soil had been left in its natural vegetated state. Even though the soil is left exposed to erosion of this intensity for only a short time—a few years at most—the amount of land cleared for new housing and ancillary uses in the Washington-Baltimore area has been so great in recent years that the contribution of sediment is significantly large. Harold Guy of the U.S. Geological Survey has estimated that the Potomac River receives about a million tons of sediment per year from streams that drain the metropolitan Washington area. This is about the same amount of sediment that the Potomac River brings into the Washington area from all its other upland sources.

Another of man's activities that increases the sedimentation rates of estuaries is the disposal of dissolved phosphorus, nitrogen, and other plant nutrients into rivers and estuaries. Municipal sewage effluents, including effluents that have received secondary treatment—the highest degree of conventional treatment—contain high concentrations of nutrients. In some areas, agricultural runoff from fertilized croplands and animal feedlots also contributes nutrients to river waters and estuaries. These nutrients promote the growth of diatoms and other microscopic plants (phytoplankton) both in the rivers and in the estuaries that the rivers flow into. The mineral structures formed by many of these organisms persist after the organisms die and become part of the sediment loads of the rivers and the sedimentary deposits of the estuaries. The Army Corps of Engineers estimates, for example, that the diatom frustules produced in the Delaware River and Delaware Bay contribute about the same amount of sediment (a million-and-a-half tons per year) to the Delaware estuary as all other upland river sources. The effects of nutrient loading from municipal wastes on primary productivity are readily observable in the Potomac estuary, in Baltimore Harbor and the Back River estuary (Maryland), in Raritan Bay, in the Arthur Kill estuary, in the Hudson estuary, in the Delaware estuary, in San Francisco Bay, and in many other estuaries around the country. Stimulation of plant growth by nutrient-enriched runoff from agricultural areas is apparent in the upper Chesapeake Bay, the estuary of the Susquehanna River.

MAN'S ACTIVITIES THAT DECREASE RIVER SEDIMENT LOADS

Reservoirs probably cause the most significant interruptions in the natural movement of sediment to estuaries by rivers. Reservoirs are built on rivers for a number of purposes: for hydroelectric power, for flood control, for water supply, and for recreation. Regardless of their purpose, reservoirs share in common the ability to trap sediment. Even small reservoirs can trap significant proportions of river sediment. For example, a reservoir that can hold only one percent of the annual inflow of river water is capable of trapping nearly half the river's total sediment load. A reservoir whose capacity is 10 percent of the annual river water inflow can trap about 85 percent of the incoming sediment. Although a river will tend to erode its own bed downstream of a reservoir to partly compensate for the sediment it has lost, the net effect of the reservoir is to decrease the overall amount of sediment carried by the river. In the larger river basins of Georgia and the Carolinas, the sediment loads delivered to the estuaries are now something like one-third of what they were about 1910, mainly because of the large number of reservoirs that have been built since then for hydroelectric power and, to a lesser extent, for flood control.

On some rivers, settling basins and reservoirs have been built specifically as sediment traps to improve the quality of water farther downstream. In 1951, three desilting basins were constructed on the Schuylkill River of Pennsylvania to remove the excessive sediment that resulted from anthracite coal mining in the upper river basin. The basins are dredged every few years, and the dredged material is placed far enough from the river to be out of reach of floods. As a result of these basins, the sediment load carried by the Schuylkill into the Delaware estuary has been reduced from nearly a million tons per year to about 200,000 tons per year.

NET EFFECT OF MAN'S ACTIVITIES ON SOURCES OF SEDIMENT

The net effect of man's activities has no doubt been an increase in the sediment supplied to most of the estuaries of the United States, but we cannot say by how much. Although reservoirs and other controls have reduced the sediment in rivers in recent years, they have only partly offset the influences that caused the increases in the first place.

Added to this is the fact that sediment takes decades to move through a river system. Much of the sediments released by past mistakes—such as by poor mining practices and by poor soil conservation practices associated with agriculture—are still in the river valleys in transit storage between their sources and the estuaries. Even if the active supply of sediment to rivers were completely checked today, many decades would pass before the sediment loads would drop to their natural, pre-colonial, levels.

CONTROL OF RIVER SEDIMENT INPUT

The ultimate method of controlling the sediment that rivers contribute to estuaries is to control erosion at the source. The possibility of complete control, however, is remote. Erosion is basically a natural phenomenon. All land, whether in its natural state or altered by man's activities, yields a certain amount of sediment. Because the natural processes of erosion are less subject to control than are man's influences on these processes, perhaps the best that one can hope for is to keep erosion down to its natural level. But even this is probably a vain hope. In spite of the marked reduction that conservation measures have caused in soil erosion since they began to be applied in earnest over 30 years ago, cultivated farmland in the eastern United States, for example, continues to yield sediment at about 10 times the rate of equivalent areas of forested land. In places where former croplands and grazing lands have been replanted in forests and grasses, sediment yields have been considerably reduced. Although it is true that as long as men cultivate land, there seems to be little hope of reducing sediment yields to their natural rates—rates typical of heavily vegetated lands—much more effort should be directed at reducing sediment yields through appropriate soil conservation practices. If these controls are enforced not only for agriculture, but also for strip mining, urbanization, and highway construction, significant reductions in sediment inputs to estuaries will result. These reductions will, within a period of decades, be manifested in reductions in the dredging activity required to maintain many shipping channels; and may result in improvement in water quality of the estuarine zone, particularly if nutrient inputs are decreased.

ROUTES AND RATES OF TRANSPORT

Once sediment reaches an estuary, it may move directly to a site where it will remain permanently, but it is more likely to be deposited in a series of temporary storage areas or "parking lots" before coming to its final resting place. Although we have some idea of the kinds of places where sediment is most likely to eventually accumulate in estuaries, we are generally unable to predict the detailed route that sediment will follow between the point where it enters the estuary and the place where it finally comes to rest. Furthermore, we know little about how often sediment moves—whether it moves a short distance every day, or moves mainly during short but severe events such as storms and floods. We suspect that infrequent severe events are more important in delivering sediment to the estuary in the first place, but that the slower day-to-day processes are more important in redistributing sediment from one part of an estuary to another to determine the final depositional patterns. In upper San Francisco Bay, for example, the sediment brought in by the Sacramento River during the rainy winter months is initially deposited in broad shallow areas of the estuary. During the dry summer months the daily breezes that blow across the bay stir up the shallow waters and resuspend the sediments blanketing the shoal areas. The tidal currents transport this material to deeper areas, mostly farther up the bay. The deeper areas, in and near Mare Island Strait, are the location of the most intensive dredging of navigation channels in San Francisco Bay. About two million cubic meters, or about a third of all the sediment dredged in the entire San Francisco Bay system, are removed every year to maintain adequate channels into and within the Mare Island Naval Shipyard.

If we have only a limited knowledge of the routes of transport within the estuary, we know even less about the rates of transport. We have some measurements of the rates at which sediment is supplied to the estuary from selected sources, mostly rivers. And, we have some knowledge of the rate at which some of the sediment accumulates in specific parts of estuaries, particularly in the dredged navigation channels. But we have only a limited picture of the rates of input from other sources and the rates of accumulation at other less obvious places, and a particularly limited picture of the rates at which a given particle of sediment might be expected to move from one part of the estuary to another on its way to a permanent resting place.

Patterns of Deposition

The pattern of deposition of sediment in an estuary is determined mainly by the non-tidal circulation patterns of the water. As pointed out previously, an estuary's net circulation pattern is determined primarily by the relative magnitudes of the river and tidal flows, and by the geometry of the estuarine basin. The circulation pattern can be altered, sometimes drastically, by changes in any of these factors.

TRAINING WORKS

Training works such as jetties and dikes are built for the expressed purpose of changing the pattern of flow and deposition in estuaries: specifically, to discourage the deposition of sediment where it is not wanted, or to facilitate its deposition in other places. The deposition of sediment is discouraged by channeling flows to increase their velocity and scouring potential. Deposition is encouraged by providing quiescent areas where suspended particles can settle to the bottom.

Although in theory training works should be an efficient means of controlling sediment, in practice their results are often difficult to predict. Works constructed in the early years of this century along the main shipping channel in Liverpool Bay in England, for example, were successful in increasing the velocities and the depths in the channel. However, they caused an unexpectedly rapid increase in sedimentation in the areas of the bay outside the channel as well as in the tributary estuary of the Mersey River.

DREDGING

Since problems associated with dredging are discussed at length in several other papers in this volume, our comments will be limited. Dredging of navigation channels is the most pervasive of man's activities in estuaries that affect the circulation of water, and consequently, the pattern of deposition of sediment. In many estuaries, dredging seriously disrupts the natural equilibrium that formerly existed between river inflow, tidal exchange, sediment supply, and the configuration of the estuary floor. The response to dredging is frequently to "heal" the disruption by filling the dredged channel with sediment.

If left to itself, the healing might proceed in the following way. Suppose we have an estuary where the sediment inflow and the bottom geometry are in some kind of steady-state balance with respect to each other. This might be a large estuary, such as Delaware Bay, that is slowly and steadily being filled with sediment, mainly in its upper reaches, or it may be a narrow estuary, such as the Savannah River between Georgia and South Carolina, that flows in a river-size channel through sediment-filled lowlands to the sea. When a deep channel is dredged in such an estuary, it allows salt water to penetrate farther inland than formerly and it shifts the nodal point of the upstream flowing seawater farther up the estuary. This nodal point becomes the locus of most rapid sedimentation and remains so until the channel at that point is filled with sediment. When that part of the channel is filled and the salt water can no longer penetrate that far inland, the nodal point is progressively shifted seaward and another part of the channel is filled. This process continues until the entire navigation channel is healed—provided that enough sediment and time are available. If the navigation channel is dredged repeatedly, as are most channels where the supply of sediment is heavy, the sediment continues to accumulate at or near the first nodal point which continues to be the location of maximum dredging effort in the estuary. The maintenance of navigation channels in many estuaries, therefore, is a battle between man's efforts to disrupt a pre-existing state of equilibrium, and the estuary's tendency to restore that equilibrium.

A major problem in dredging is the disposal of the dredged material (spoil). In many cases, spoil is dumped in places where sediment of that texture would not have accumulated naturally, or at least not nearly as rapidly in the natural course of events as in spoiling. This applies to disposal sites both inside and outside of estuaries.

Spoil is commonly dumped inside the estuary, sometimes directly alongside the channel. The spoil may remain where it is dumped, especially if it is dumped in deep spots out of reach of strong currents. Often, however, dredge spoil returns to the channel. In recent years, according to estimates made by the U.S. Army Corps of Engineers, about half the sediment dredged from the navigation channels in Charleston Harbor and San Francisco Bay is material that has already been dredged at least once before and has made its way back into the channels from the place where it was dumped.

In some estuaries, spoil is dumped on fringing land areas. A principal advantage is that these areas can be diked to prevent the return of the spoil to the estuary. The main disadvantage is that the marginal areas are often salt marshes that are valued for their role in the protection and production of fish and other forms of estuarine life. Dumping spoil on these areas usually destroys their original plant and animal communities.

Spoil is also taken by barge or hopper dredge and dumped in the ocean outside estuaries. In 1968, for example, about 50 million tons of dredged spoil was dumped in ocean waters off the coast of the United States. In many ocean areas, such as off New York city where some 7 million tons of spoil are dumped every year, the spoil is a markedly different type of sediment from the natural bottom material and it is introduced at a rate many times greater than the natural rate of local sediment input to the ocean. This is perhaps man's greatest alteration of the pattern of deposition—taking material that was destined by nature to be deposited in estuaries and dumping it at sea.

Modification of Prevailing Sedimentation Processes By Engineering Projects: A Mistake and A "Success"

CHARLESTON HARBOR

Charleston Harbor, one of the finest natural harbors on the Atlantic seaboard, has served the needs of the region since the town was settled in 1670. It is an interesting example of an estuary whose circulation and sedimentation were markedly altered by changing the freshwater input to the estuary. The Charleston Harbor estuary receives freshwater inflow from the Ashley, Cooper, and Wando Rivers. The mouth of the estuary is restricted, and entrance from the Atlantic Ocean is gained through a single, jettied-channel. Prior to 1942, the freshwater input was very small, averaging less than 20 m^3/sec (700 ft^3/sec), and the harbor was somewhere between a vertically homogeneous and sectionally homogeneous estuary. Fine-grained sediment was moved slowly through the estuary to the ocean, and little dredging was required. Maintenance dredging to keep the main channel at a depth of 9 m was only about 60,000 m^3/yr (80,000 yds^3/yr) at a cost of about $11,600/yr.

In late 1941, a hydroelectric dam was completed which diverted most of the flow of the nearby Santee River, the largest river on the south Atlantic seaboard, into the upper Cooper River which flows into Charleston Harbor. The average freshwater input to the harbor rose from less than 20 m^3/sec (700 ft^3/sec) to more than 400 m^3/sec (14,000 ft^3/sec). The inflow of fluvial sediment was increased by about a factor of four. More importantly, the marked increase in the freshwater discharge shifted the circulation pattern in the harbor from a well-mixed estuary to a two-layered circulation pattern characteristic of a partially-mixed (Type B) estuary. Fine sedimentary particles which would previously have been carried completely through the estuary to the ocean were now entrapped in the estuary by the net upstream flow of the lower layer and accumulated in the inner harbor—in the upper reaches of the non-tidal estuarine circulation regime. Shoaling became a serious problem. Dredging required to maintain the inner harbor channel jumped to an average of 1.8 million m^3/yr (2.3 million yds^3/yr) at an average cost of about $380,000/yr during the 9 year period from 1944 to 1952. More recently, dredging has averaged about 7.5 million m^3/yr (10 million yds^3/yr).

Nearly half of the currently dredged material represents older dredged spoil that has returned to the channel. Another 10 percent or so of the new spoil is due to the deepening of the main navigation channel from 9.1 to 10.7 m (30 to 35 ft) between 1941 and 1943. The major factor in the increased shoaling rate was the change in estuarine circulation produced by the diversion of water from the Santee River into the harbor. This was conclusively demonstrated by hydraulic model studies.

The shoaling problem has become so difficult and expensive to control that plans are well underway for rediversion of the Santee back to its original channel.

DELAWARE BAY

Delaware Bay has also served maritime commerce since colonial times, providing access between the sea and such cities as Philadelphia and Trenton. In recent years some fairly successful measures have been taken to control sediment, both in the inflowing rivers and in the bay itself. The desilting works in the Schuylkill River need no further discussion here except to point out that they have resulted in a fivefold decrease in the sediment brought by the Schuylkill to the upper estuary at Philadelphia.

Within the Delaware estuary, the Corps of Engineers has been able to decrease the amount of dredge spoil that has returned to the navigation channels. Before 1954, when spoil was dumped overboard in the Delaware estuary 15 to 20 million m^3 (20 to 26 million yds^3) of sediment were dredged in an average year, and the navigation channel could not always be maintained at its specified depth. Beginning in 1954, all dredge spoil was placed in diked areas to prevent its return to the channels. Since then, only about 6 million m^3 (8 million yds^3) of sediment are dredged every year, and the navigation channels are consistently deeper. Although this is one of the more successful instances of coping with estuarine sedimentation, it is only a temporary expedient in the long run. Peripheral lands for spoil disposal are becoming scarcer and more costly because of competing demands such as development or conservation, and the end of available land for spoil disposal around the fringes of the Delaware estuary is already in sight

The Effects of Sediments on the Biota and on the Aesthetics of the Estuarine Environment

Clearly, man has affected the input of sediments to estuaries by land-use practices throughout their drainage basins, by the construction of dams and reservoirs on tributary rivers, by diversion of rivers, and by engineering projects to control shore erosion of the margins of estuaries. He has also affected the distribution patterns of sediments within estuaries, both in the water column (suspended sediments) and on the bottom (deposited sediments), by changing the estuarine circulation patterns either through alteration of the freshwater inputs, or through modification of their geometry by dredging or by other engineering projects. Man's impact on depositional patterns has already been described briefly in the previous section. In addition to the obvious effects of shoalings on basin geometry and therefore on circulation, and on the geological lifetimes of estuaries, changes of the rate of sedimentation and of the character of the sedimentary material can have significant effects on organisms, particularly the animals that live on the bottom. Fine-grained sediments may also affect the chemical character of the interstitial water and, when resuspended by waves and currents, that of the overlying waters.

EFFECTS ON THE BIOTA

Dredging and the disposal of dredged materials have generated a great deal of concern, discussion, and speculation about the impacts of such activities on the quality of the estuarine environment. During active dredging and spoiling there are increases in the concentrations of suspended sediment. Substantial increases—increases of more than a 100 mg/l—are generally local, restricted to an area within a few hundred meters of the activity, and any biological or aesthetic effects of these increased turbidities are not persistent.

Dredging can, of course, alter the estuarine circulation pattern and, in doing so, also change both the general sediment distribution patterns and the concentrations of suspended sediment. Changes in these factors can persist after dredging and spoiling have been completed.

Increases in the concentrations of suspended sediment above some threshold level that result from any activity can have significant environmental effects—on aesthetics, on water quality, and on the biota. The available literature indicates, however, that direct effects of suspended sediment on most estuarine organisms of the higher trophic levels occur only at relatively high concentrations, concentrations greater than 500 mg/l, and generally greater than 1,000 mg/l. Such concentrations are rare in most estuaries, even during dredging and spoiling activities except at, or very near, the source. Even in the immediate vicinity of dredging activity, the increased suspended sediment concentrations may not be lethal to important organisms of the higher trophic levels. Studies of caged fish and crustaceans placed within 8 to 15 meters of active dredges and overboard spoil discharges failed to produce any evidence of increased mortality or damage to gill epithelium compared to control organisms.

It has also been reported that there was no increase in the mortality of oysters adjacent to dredging operations in the intercoastal waterway near Charleston, S.C. The same investigators also found that oysters could survive even when suspended directly in the turbid discharge, and that the organisms died only when they were actually buried. Other investigations indicated that oysters decrease their pumping rates when subjected to relatively high concentrations of suspended sediment. It has been reported that a concentration of suspended silt of only 100 mg/l reduces the pumping rate of adult oysters by about 50 percent. If the pumping rate were reduced below some critical threshold for an extended period, the oyster would obviously die from starvation. It is unlikely that this would happen as a result of dredging activity. Furthermore, concentrations greater than 100 mg/l occur naturally over many productive oyster bars whenever bottom sediments are resuspended by normal tidal currents. These periodic increases of suspended sediment do not appear to seriously affect growth rates.

Sublethal effects of chronic exposure to moderate excess concentrations of suspended sediment—concentrations above those that would occur naturally—have not been convincingly documented for any estuarine species. Such effects will be difficult to establish unequivocally. One would anticipate that sensitivity to suspended sediment would be a function not only of species, but of life stage, and of other environmental stresses.

Increases in the concentration of suspended sediment that are large enough to markedly change the visibility of the waters of segments of an estuary can produce shifts in the fish population. Since game fish feed by sight, some minimum visibility is required for successful feeding. If visibility falls below this threshold, fish such as carp which feed in a vacuum-cleaner fashion are favored. This probably occurs only when concentrations of fine suspended sediment exceed several hundreds of mg/l. Visibility is a function not only of the concentration of total suspended solids, but also of their size distribution and composition.

The disposal of dredged materials generally results in the initial destruction of many, perhaps most, of the bottom dwelling organisms (benthos) at the disposal site through burial and smothering. It has been documented in a number of estuaries, however, that the spoil is recolonized relatively rapidly by organisms from surrounding areas except when the spoil differs markedly in texture from the host sediments. Studies of overboard disposal sites in the upper and lower Chesapeake Bay showed that within one-and-one-half years the population density and species diversity of the spoil areas could not be distinguished from those of surrounding areas. In the upper Chesapeake Bay recovery of the channel—the dredged area—was not complete, but in the lower bay complete recovery of both the dredged and spoil areas was documented. Where marked textural changes result from the dredging or spoiling activity, recolonization may be limited. The dredged canals of Boca Ciega Bay, Fla., are examples.

If dredging or spoiling produce substantial changes in the depth distribution of an estuary, or segments of it, significant changes may occur in habitat space and therefore in the distribution of organisms. Areas of the bottom can be removed from the euphotic zone by dredging, and areas can be built-up by spoiling from a relatively deep position into the surface layer where they are subjected to stirring by currents and waves. Clearly such alterations are not necessary consequences of dredging and spoiling.

The magnitude of the impact of dredging and spoiling is also a function of the time of year they are done. These activities should be scheduled when there will be the least probable impact on the most "important" indigenous species. Generally, for any given species the early life history stages are more sensitive to environmental stresses than later stages.

Studies indicate that substantial dredging and spoiling projects can be carried out in estuaries without any gross biological effects or any persistent aesthetic degradation. Any chronic biological effects that might arise either from exposure of organisms to spoil and associated contaminants for long periods, or from exposure to relatively subtle, but persistent, changes of the physico-chemico milieu have not been documented. Much of the research that has been done and is still being done to determine the effects of dredging and spoil disposal is ill conceived and will not provide answers to the pertinent questions.

EFFECTS ON WATER QUALITY AND AESTHETICS

Fine-grained suspended sediment can affect the distribution of dissolved oxygen in estuarine waters both directly and indirectly. The oxygen demand of organic-rich sediments may produce a sag in the oxygen distribution. It has been reported that in the Arthur Kill, for example, when dredged spoil was resuspended oxygen levels were reduced from 16 to 83 percent below their average levels. Other investigators reported that when surface sediments from Wassaw Sound, Ga., were suspended in the estuarine water, they were capable of removing "533 times their own volume of oxygen from the water." No such effect was observed in the upper Chesapeake Bay, and studies of Louisiana marshes did not demonstrate any significant oxygen depletion as a result of dredging activities. Since the concentration of suspended sediment affects the transparency of water, increases in suspended sediment levels decrease the depth of the euphotic zone and therefore the production of oxygen by phytoplankton.

Increased suspended sediment concentrations may also affect the production of oxygen by rooted aquatic plants. Areas of the bottom formerly within the euphotic zone can be removed from it as a result of man's activities. Prior to about 1920 much of the bottom of the upper Potomac outside of the channel was covered with a dense growth of rooted plants. During the 1920's this vegetation almost completely disappeared and lower oxygen levels were reported in this area. The effects of the disappearance of these plants on the distribution of dissolved oxygen were confounded by the effects of other significant environmental changes on oxygen levels.

Fine sedimentary particles can act as both a source and a sink for nutrients and other constituents. Nutrients may be sorbed onto fine-grained particles, or desorbed from them depending upon a variety of physico-chemico conditions. These include salinity, pH, temperature, the chemical composition of the particles, and the concentrations of nutrients in the water. The mechanisms that control these exchange processes are poorly understood, and should be investigated.

It is well known that fine-grained particles concentrate a variety of pollutants, including: petroleum byproducts, heavy metals, pesticides, and some radionuclides. In the water column the bulk of each of these contaminants is usually associated with fine suspended particles, and therefore the distribution, transportation and accumulation of these substances are determined primarily by the suspended sediment dispersal systems. Filter-feeding organisms which ingest these particles and associated contaminants agglomerate the smaller particles into larger composite particles in their feces and pseudofeces thereby providing the contaminants in a more concentrated form to deposit feeders. Laboratory experiments have demonstrated the ability of oysters to concentrate DDT in their pseudo-feces. Increases in the concentration of DDT and other pesticides in detritus particles of fine-grained bottom sediment of estuaries of up to 100,000 times those in the overlying waters have been reported. These residues can sometimes be transferred to detritus feeding organisms. Increases in the concentration of contaminants at each trophic level are well documented for radioactive isotopes and some pesticides. This phenomenon has been referred to as "biological magnification."

Fine sediments can also serve as a temporary sink for radioactive contaminants. It has been shown, for example, that ^{65}Zn may be held by fine-grained sediments for months with a continual low level release to the interstitial and overlying waters.

The effects of fine-grained particles and their associated contaminants on the composition of both the interstitial and overlying waters, and on the biota are poorly understood. This is an area that should receive considerable attention. From the standpoint of dredging, it is particularly important. Appropriate standards for permissible levels of contaminants in spoil should be based, not on the total concentration of each contaminant, but on the concentration that is available for biological uptake—the concentration of the reactive fraction. While standards based on totals are safe they place undue restrictions on the disposal of dredged materials. It is becoming clear that fine-grained particles play a significant role in determining the quality of the estuarine environment, and the composition of its biota.

Increases in the levels of suspended particulate matter can also have a significant aesthetic effect. Above some threshold level, suspended matter is aesthetically displeasing and inhibits recreational use. This level is a function not only of the total concentration, but also of the size distribution and the composition of the suspended material. A concentration of 100 mg/l of fine quartz sand does not have the same effect on water color and transparency as does the same concentration of organic-rich silt and clay. Individuals also have different aesthetic thresholds.

SOME RECOMMENDATIONS FOR FURTHER STUDY

Some of the types of studies we feel must be done if we are to understand how estuaries operate sedimentologically; if we are to be able to predict the consequences of manmade alterations of the prevailing sedimentary processes; and if we are to manage estuaries for the greatest use of man, are described below.

Sources of Sediment to Estuaries

One of our principal needs in understanding the sources of sediment brought to estuaries is for more complete data on the sediment loads carried by rivers—the principal source of sediments to most estuaries. In less than half of the estuaries of the country do we have any kind of regular measurement of the input of river sediment. Furthermore, the records we do have are mostly too short. Only a few river sediment stations have been in operation long enough to have documented the extreme events that are so important in the introduction of sediment: events such as the hurricane flood of August 1955 when the Delaware River carried more sediment past Trenton in two days than in all five years combined in the mid-1960's drought; or the three days in December 1964 when the Eel River in northern California transported more sediment than in the preceding eight years; or the week following Tropical Storm Agnes in June 1972 when the Susquehanna discharged 20–25 times as much sediment as during the previous year. Events of this magnitude occur only rarely—a few times a century at most—but their importance to estuarine sedimentation is so great that programs should be designed to record their effects when and where they do occur.

Daily sampling stations should be established on the lower reaches of all major rivers—upstream from the landward limit of measurable sea salt intrusion—to measure the inputs to estuaries of water, sediment, nutrients, and other substances. These stations should be permanently maintained to catch the large events, and permit an assessment of their relative importance. In addition, a funding mechanism should be developed to support research of the effects of events on the estuarine environment.

We also need to further our understanding of sources of estuarine sediments other than rivers. In a recent study of the sources of shoaling material in the navigation channels of the Delaware estuary, for example, the U.S. Army Corps of Engineers estimated that only one-fourth of the shoaling material could be accounted for by present day river sources. The remaining three-fourths was attributed to erosion of the bed and banks of the estuary, diatoms produced in the estuary in response to an excess supply of nutrients, and other sources (some of which could not be identified). It has been suggested that shore erosion is the principal source of sediment to the middle and lower reaches of the Chesapeake

Bay estuary. These sources deserve more of our attention so that we can identify them more accurately, assess the rates at which they add sediment to the estuaries, and find out to what degree they are subject to manipulation and control by man.

Routes and Rates of Sediment Transport

Tracers offer a promising approach to studying the routes and rates of sediment movement. Tracers such as fluorescent particles can be added to the sediment, and the sediment can be sampled repeatedly to determine the routes and rates of sediment movement; or one can make opportunistic use of distinctive contaminants, such as radioactive isotopes or heavy metals, that are dumped into estuaries either intentionally or inadvertently. These compounds sometimes can be used as labels to follow sediments from known sources to sites of deposition. Releases from nuclear power plants should be investigated as possible tracers. An attempt should be made to assess the impact of man on the prevailing sedimentary processes. Such an assessment would have to come primarily from an examination of the sedimentary record.

Patterns of Sediment Accumulation

In the past we have relied mainly on dredging records as a measure of sediment accumulation, but they tell us little about how sediments accumulate in the large areas of estuaries that lie outside the dredged channels. For some estuaries, modern day navigation charts have been compared with older ones (some dating back to the mid-1800's) to estimate the accumulation of sediment. Because the charts are already available, a systematic comparison of old and recent survey sheets could be made for most estuaries of the country at relatively little expense. Some newer techniques can also be applied—particularly those techniques that use the decay rate of naturally radioactive material to measure the age of sediment and how long ago or how rapidly it may have accumulated. An effort should be made to refine those radiometric dating techniques that are particularly applicable to estuarine deposits, and to apply the techniques to a variety of estuarine systems. The two methods that have the greatest promise are Pb^{210} which has a useful range of 10 to 100 years and C^{14} which can be used to date events that occurred in the past 1,000 to 10,000 years.

Another difficult aspect of the sediment budget of most estuaries is the question: on a net basis, does more sediment move out of the estuary into the sea than moves into the estuary from the sea? We know that sediment escapes from estuaries on outgoing tides, and we know that sediment is moved into estuaries from the sea floor on incoming tides; but we do not know enough about the quantity or kind of sediment that moves either way to be able to say whether, on balance, more moves out than in. Here again, well-designed tracer studies might be useful.

An estuary's sedimentary deposits contain the history of that environment, and it is only through the examination of this sedimentary record that one can assess the impact of man on the distributions of both naturally occurring substances and of man-made pollutants, such as PBCs (polychlorinated biphenyls) and pesticides. Naturally occurring substances include not only innocuous sedimentary particles, but also some pollutants; pollutants such as heavy metals which are present in the earth's crust and are carried into the estuarine environment both in solution and adsorbed to fine suspended particles by rivers and streams. Heavy metals are, of course, also introduced into the environment as a result of man's activities.

The sedimentary record also contains the most reliable information of the frequency of natural catastrophic events such as floods, droughts, and hurricanes that have occurred during the past several thousand years. The importance of episodes in the development of estuaries has not been well documented because of the infrequency of such events and the difficulty of sampling during most storms and floods.

Model Studies

Physical and mathematical models can provide valuable insight into a variety of sedimentary processes. They are not, however, a panacea for all estuarine sedimentation problems, and are only as good as the prototype data and theoretical assumptions on which they are based. Perhaps the greatest need is for more attention to be directed at the formulation of conceptual models of estuarine sedimentation. Conceptual models should, in any case, precede the construction of mathematical or physical models.

Characterization of Fine-Grained Sediments

Appropriate field and laboratory studies should be conducted to characterize the chemical and mineralogic nature, and the reactivity of the fine-grained, carbon-rich particles. It is clear that fine-grained particles can play a major role in determining the quality of coastal waters, and the distribution of organisms. These studies should also include investigations that would lead to the establishment of meaningful diagnostic standards for the disposal of dredged materials. While the present standards used by the EPA to characterize dredged materials were intended to be environmentally conservative they may be unduly restrictive with respect to the designated parameters, while they ignore a large number of important contaminants such as PCBs, pesticides, and others. In any event, they are clearly not based on sound scientific evidence. Standards for dredged materials should not be based on the total concentrations of contaminants, but rather they should reflect the total masses of contaminants that are available for biological uptake. These masses are the concentrations of the reactive fractions of these contaminants—the fractions available for biological uptake—times the total mass of dredged material. Even with such standards, decisions on dredging and spoil disposal should be based on the physical, chemical, biological, and geological characteristics of the particular estuary. The uniform application of Federal standards has little merit other than simplicity of enforcement.

We know far too little about the effects of sediment-borne contaminants on estuarine life. We need an extensive series of laboratory experiments to test the effects of a variety of contaminants on different organisms. It is particularly important that these experiments simulate field conditions; too many of the experimental results we already have cannot be extrapolated beyond the laboratory. Only after such a series of experiments can we establish diagnostic standards and criteria for such things as dredged materials. Increased emphasis should be directed at studies to determine the chronic effects of exposure to moderate excess concentrations of a variety of contaminants.

The new Dredged Materials Research Program (DMRP) of the U.S. Army Corps of Engineers is an important step in the right direction. The DMRP should provide a great deal of valuable information for the more effective mangement of estuarine dredging and spoil disposal.

Alternatives to Present Practices

Even if we succeed in reducing sediment inputs to estuaries through enforcement of strict soil conservation measures, dredging will continue to be a persistent estuarine activity. Not only are estuaries naturally areas of relatively rapid sedimentation, but much of the material dredged from navigation channels is material previously introduced, and redistributed by prevailing estuarine circulation processes. Further, the increasing use of deeper draft vessels, and the increasing demand for pleasure boat marinas and facilities will require additional dredging.

Estuary-wide dredging and spoil disposal plans should be developed to ensure that maintenance channel dredging can be carried out without undue delays. Such plans should include the designation of a variety of types of sites (overboard, diked, et cetera) for disposal of different types of spoil. Certain kinds of spoil may have a greater environmental impact if disposed of in aerobic (oxygenated) diked areas, than if disposed of by conventional overboard methods within oxygen-deficient areas of an estuary. If regional plans are not developed promptly, the activities of a number of major ports will be seriously affected and will result in serious economic perturbations. These dredging and spoil disposal plans should be significantly flexible to provide a mechanism for decision making on requests for other types of dredging permits. The suggestion that a number of our major ports are "poorly located" is to some extent correct, but the suggestion that they should be moved is naive at best. Major ports could not be moved without serious economic upheaval, and the lead time to implement any such proposals would have to be decades. The growth of some ports located near the heads of estuaries should perhaps be controlled.

We should also direct more attention to more productive means of disposing of spoil. An example is the process developed by Professor Donald Rhoads of Yale University to make construction bricks from estuarine mud. Or we might consider taking railroad cars that haul coal to seaports and filling them on the return trip with dredge spoil that can be used to fill or reclaim lands that have been strip mined. Formation or nourishment of islands for recreational use is another possibility. Surely there must be other more ingenious ways of disposing of dredged material than dumping in estuaries or transporting it out to sea.

SOME CLOSING OBSERVATIONS

The great value of the estuarine zone is in the multiplicity of uses it serves, but herein also lies its vulnerability. Estuaries can support certain levels of shipping and transportation without a loss of commercial and recreational fish landings. Estuaries can tolerate some dredging and disposal activities without persistent damage to the biota or aesthetic degradation. Estuaries also have a capacity to tolerate some human, industrial, and municipal wastes; and to assimilate some waste heat without suffering persistent and significant ecological damage. And, the biological resources of estuaries can be harvested at certain levels without seriously affecting future yields. Estuaries can serve all of these uses and still remain aesthetically pleasing environments for man's recreation—for his re-creation. But an estuary's capacities to support these varied activities are finite. The ability of an estuary to tolerate each "environmental insult" before suffering significant ecological or aesthetic damage not only varies from estuary to estuary but varies in different parts of a given estuary as well. And, within any segment of an estuary it varies temporally. Uniform, invariant regulations and standards for the disposal of wastes, whether they are heat, nutrients, or dredged spoil, are environmentally naive. The only justification for their enactment is that it simplifies enforcement. A uniform speed limit of 25 mph is as irrational as one of 100 mph is irresponsible. Uniform estuarine regulations are wasteful of valuable natural resources—resources that should be used, and used responsibly. The philosophy of those crusaders who espouse cessation as the solution to all environmental problems is not viable. People live. They eat, they defecate, they procreate, and yes, they also need to recreate. This is not to imply that we should not insist on good waste treatment, on carefully supervised methods of dredging and spoil disposal, and on controlled mining of bottom and subbottom mineral resources. We should. We should insist on more.

Estuaries should be zoned. To date, formal zonation of the estuarine environment has been restricted primarily to that associated with military activities. Man zones his terrestrial environment into residential and industrial areas, and he sets aside portions of it for parks and forests for recreation. He identifies other segments of it for the disposal of his waste products. He does not make it an official policy to spread his garbage and trash uniformly over the landscape. He neither demands nor expects all parts of his terrestrial environment to be of equal quality.

Should he expect to be able to swim and harvest seafood in every part of every estuary? Segments of some estuaries should be identified as spoil disposal areas, other segments as the receiving waters for municipal and industrial wastes, others as sinks for the heated effluents from power plants, others as spawning and nursery areas, others for military activities, and others as fishing and recreational areas; still others should be preserved, or at least conserved in a wild state. These segments are not all mutually exclusive; there would be considerable overlap. And the spatial boundaries of the various zones should be defined as a function of time.

Because the primary reasons for the management of estuaries are to protect their biological resources and to conserve their aesthetic and recreational values, certain activities should be restricted more severely in some areas than in others and also during those periods when organisms are most vulnerable. During these vulnerable periods—generally the egg and larval stages—temperature standards should perhaps be more stringent, and dredging and spoil disposals should perhaps be restricted or prohibited in the important spawning and nursery zones. The zonation of estuaries would be much more difficult than zoning man's terrestrial environment, and some of these suggestions may not be applicable to small estuaries. The establishment and enforcement of an estuarine zoning system would require more than simple policing. It would require careful and intelligent planning and management. But planning and management by whom?

The establishment of a zoning system is contingent upon the assignment of priorities to the various uses. These decisions require not only scientific inputs but social and economic inputs as well. Decisions as to which activities are "most important" and what water quality standards are "good" or "acceptable" are largely value judgments—important to whom? . . . good or acceptable for what purpose? Natural scientists have no peculiar talents for making value judgments. Scientists can incontestably determine neither what uses of an estuary are most important nor even which are most desirable. In terms of gross monetary return, the most important uses of the estuarine zone are, according to the "National Estuarine Pollution Study," for military activities, for shipping, and for industry. But the monetary values of commercial and recreational fisheries are also very high although they are more difficult to estimate. And, if indeed, communication with nature is one of man's ultimate sources of happiness as Dubos and others have suggested, then the true worth of the recreational value of estuaries cannot be measured in dollars and cents.

Through science, we can learn to understand estuaries and even to control them in part, but scientists cannot unequivocally and decisively determine the ways in which we should control them. These decisions should be made by the citizens who are affected—by all of them.

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