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STORAGE EFFICIENCY OF ESTUARIES

Maynard M. Nichols[1]

Estuaries of the U.S. Atlantic coast exhibit a range of storage efficiencies from complete storage to partial by-passing through the system. Efficiency, i.e. the ratio of sediment accumulation to river input rate, ranges 0.7 in the Altamaha River, Ga. to 7.6 in the Choptank River, Md. Northern estuaries trap and store the bulk of their river input in addition to large amounts of sediment supplied from other sources. Southern estuaries accumulate major sediment loads in marshes and allow partial escape through channels to the sea.

The storage efficiency of different estuaries is compared with respect to key factors that can be quantified and that vary within the region. It was found that storage efficiency in northern estuaries is encouraged by low flushing velocity and high volumetric capacity relative to river inflow. The long-term rise of sea level relative to the land tends to offset sediment accumulation and maintain or increase capacity. Within the range of estuaries considered, efficiency generally increases as the flow ratio decreases. This trend suggests the estuarine circulation in partially-mixed systems is important both in trapping fluvial sediment and in transporting sediment landward from the sea.

Introduction

Estuaries and lagoons exhibit a range of storage efficiencies that extend from complete storage to complete by-passing of fluvial sediment through the system. Although the efficiency varies widely with location, the principal questions to be asked in each case are the same. Of the total amount of fluvial material supplied to an estuary, how much is stored and how much passes through to the ocean? How efficient are estuaries in storing fluvial sediment? What physical factors determine the storage efficiency of an estuary? Storage efficiency is of fundamental interest because it determines whether or not fluvial sediment and river-borne contaminants are likely retained in an estuary. As a consequence of storage the kind and amount of suspended sediment discharged from an estuary may differ markedly from the sediment supplied. This paper aims to discuss physical factors affecting sediment storage and to show their relative importance in different estuaries along the U.S. Atlantic seaboard.

Comparison of estuaries is facilitated by new morphometric and hydrologic data compiled by NOAA (1985) in a National Estuarine Inventory data atlas. Additionally, accumulation rates are known from new measurements of seismic surveys, geochemical chronology and compilation of bathymetric changes.

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Definitions

Storage capacity is the amount of space or room, available to contain sediments. It is the fluid volume of an estuary basin at high tide. If eustatic sea-level and crustal movement are held constant, then sediment accumulation reduces storage capacity. The capacity lost annually, C_1, expressed in terms of percent, relates to the volume rate of sediment accumulation, Ra, ($m^3 yr^{-1}$) by:

$$C_1 = 100 \frac{Ra}{C} \qquad (1)$$

Where C is the capacity (m^3).

Additionally, the rate of sedimentation ($cm\ yr^{-1}$) is equal to the volume accumulation ($m^3\ yr^{-1}$) divided by the basin volume change ($m^3 cm^{-1}$).

Storage efficiency is the ability of an estuary to retain and hold sediment delivered to it. This can be expressed as a ratio or percentage of the accumulation mass to the input mass over a given time. Assuming a mass balance of sediment in an estuary and steady state on a geologic time scale, with no net additions or losses, then the input mass, Mi, plus the sediment produced in the system, P, must equal the accumulation mass on the bed, Ms, plus the amount consumed in the system, C, and the output mass, Me. Thus:

$$Mi + P = Ms + C + Me \qquad (2)$$

(sources) (losses or removal)

Then, the storage efficiency (Si), i.e. fraction retained over a given time, can be expressed as a ratio or percentage

$$S_1 = \frac{Ms}{\Sigma Mi + P - C} \qquad (3)$$

or

$$S_1 = 100 \frac{Ms}{\Sigma Mi + P - C} \qquad (4)$$

If production and consumption associated with organic activity within an estuary are small, these terms can be neglected. The input mass may be the fluvial mass, or volume, where the river supply accounts for all the accumulated sediment. Alternately, the input mass may be the total mass from different sources, e.g. fluvial, marine, shores or biological production. Since the source of material in the total accumulation mass usually is unknown, the storage efficiency ratio may be referred to the fluvial input mass which is often known. Therefore, a storage efficiency of 1 implies that the amount of sediment accumulated is equivalent to the amount supplied by rivers; however, the accumulated sediment may contain some sediment from marine or shore sources. An efficiency ratio greater than 1 implies that an estuary retains and stores more sediment than supplied by its rivers whereas a ratio less than 1 implies that the amount of sediment stored is less than the total fluvial input, a situation that develops when fluvial sediment by-passes an estuary.

Storage Zones and Scales

Sediment supplied to an estuary is not uniformly distributed throughout the system. Instead, accumulation is focused in certain zones or sites which are often manifest by morphological forms. The most common zone is a subtidal delta at the estuary head close to the main river, a major source of sediment in most estuaries (Fig. 1). Much sand accumulates at an estuary mouth in subtidal bars and shoals separated by interdigitating ebb and flood dominated channels. Intertidal flats and salt marshes around margins of an estuary are also prominent zones of storage particularly in macrotidal estuaries and in estuaries receiving relatively high loads of fine sediment. Within an estuary, sediment is stored in less energetic sites as reentrants, mouths of tributaries, secondary channels and deep basins.

Sediment that goes into storage in an estuary is not permanently lost from the transport system. Most sites are in a state of remobilization in response to fluctuations of waves and currents. The sediment may undergo repeated cycles of resuspension and deposition prior to semi-permanent storage. It may move from zone to zone down an energy gradient before it finds a resting place in a less energetic zone.

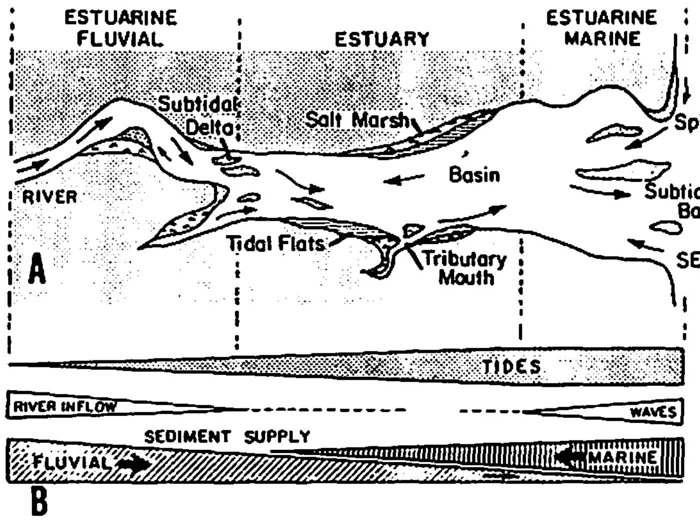

Figure 1. (A) Conceptual model of different types of sediment storage zones in a hypothetical estuary: arrows represent direction of net sediment movement: (B) Relative intensity of dominant dispersal agents, tides, river inflow and waves, in relation to dominant sediment input, either fluvial or marine, along the estuary length.

Storage and remobilization of sediment proceed over a wide range of time scales following the scales of motion or energy supply. The time intervals either are random or regular and periodic. As shown in figure 2A, remobilization can vary from seconds, a scale of turbulent energy, to semi-diurnal, diurnal or biweekly rhythms of the tide as well as long-term frequencies (10^3 to 10^{10}secs) associated with infrequent episodic events as storms or, with sea level fluctuations. On a time scale of 0.1 to 10^5 secs, sediment is stored and remobilized on entrance bars and shoals in response to turbulence, wind waves or semi-diurnal tidal currents (Fig. 2B). By contrast, sediment stored in marshes, may require time periods of 10^8 to 10^{10} secs or longer to remobilize as a result of storms or lateral channel migration.

Evidence for episodes of storage and remobilization at scales of about 10^7 to 10^{10} secs (i.e. one-half to one hundred years), is expressed in estuarine deposits by: 1) differences between short-term deposition and long-term total accumulation rates. These rates can be determined by variations of activity of different radionuclides with depth in deposits. Such differences represent sediment released from storage and transported elsewhere, 2) minor structures in bed deposits that display discontinuities and erosional activity (Nichols, 1986). Such structures are exhibited by X-ray radiographs of sediment cores and marked by changes of sediment density with depth.

In many estuaries the internal storage and release of sediment may exceed the supply from external sources. The turbidity maximum of the Gironde Estuary, France stores on the average 4.4 tons of suspended sediment, an amount equal to about two years supply from the river. In years when river input is low, the turbidity maximum can be depleted by 1.0 million tons of suspended sediment and the deficit released to the ocean (Jouanneau and LaTouche, 1981).

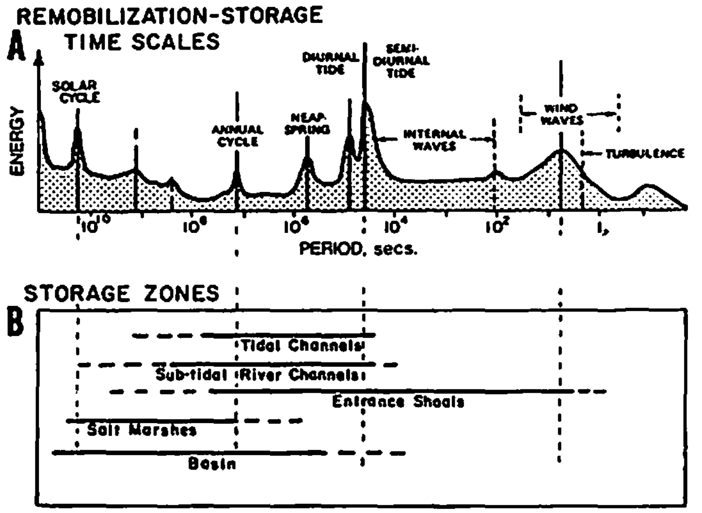

Figure 2. (A) Schematic representation of remobilization time scales contained in different types of energy input in estuaries. Energy scale is in arbitrary units, from Nichols (1986). (B) Corresponding distribution of time scales in different types of estuary storage zones, schematic.

Regional Status

More than 24 major river estuaries indent the U.S. Atlantic coast between Cape Cod and Cape Canaveral (Fig. 4). The mid-Atlantic estuaries occupy river valleys cut in coastal plain strata when sea level was much lower (~100m) than at present. The size of nine of these estuaries relates to mean annual river discharge (Fig. 3). This probably reflects the erosional ability of rivers during glacial times of low sea level (Emery and Uchupi, 1972). The Hudson and Penobscot estuaries however, which occupy glaciated valleys cut in crystalline rock, have relatively low volumetric capacity in comparison to their river discharge. In contrast, Long Island Sound, which is overdeepened by glacier erosion (Gordon, 1980), has a relatively high capacity (65 km^3) in comparison to its river discharge (30 km^3/yr).

The northern estuaries receive a much larger freshwater discharge than the southern estuaries (Fig. 4A). Despite the relatively high river discharge the sediment influx, prior to extensive intervention of man (1909), is lower in the northern estuaries than in the southern estuaries (Fig 4B). This is a consequence of the erosion-resistant character of glaciated terrain in the north (Meade, 1969). In contrast, rivers of relatively low discharge in the south drain weathered and erodable Piedmont terrain. Although reservoirs have been constructed and upland land use has changed since 1900, according to Meade and Trimble (1974) sediment loads have not been reduced markedly (Fig 4C).

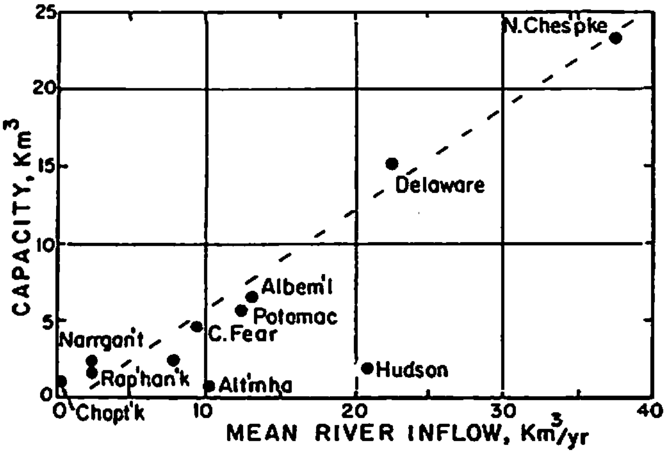

Figure 3. Volumetric capacity of major U.S. East Coast estuaries as a function of mean annual river discharge. Modified from Emery and Uchupi (1972).

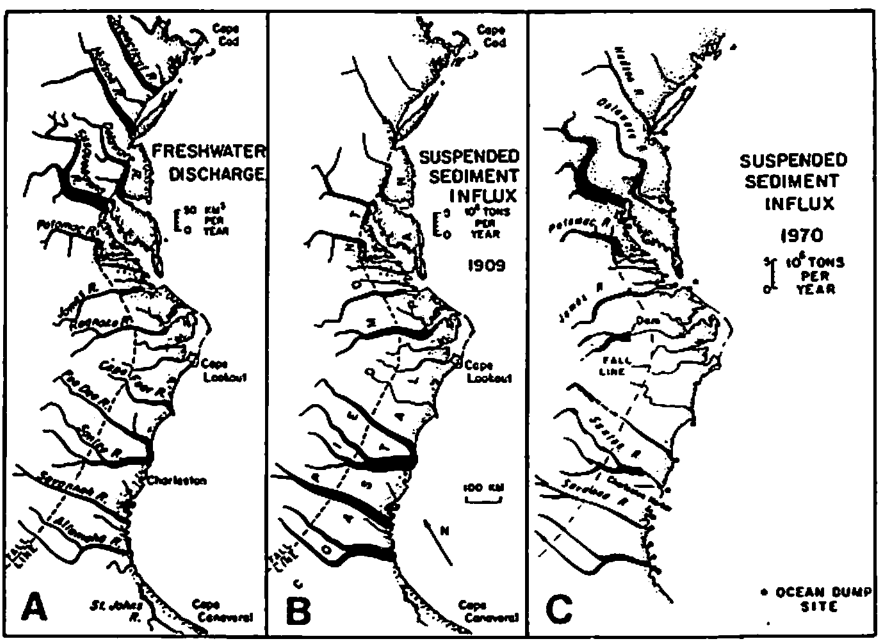

Figure 4. Major rivers and estuaries of the Atlantic seaboard showing, by the width of black forms: (A) Freshwater discharge mainly from U.S.G.S. stream records, 1931-1960; (B) Suspended sediment discharge based on Dole and Stabler (1909); (C) Suspended sediment influx affected by dams, about 1970. From Meade (1969), Meade and Trimble (1974).

Accumulation rates in the selected Atlantic coast estuaries range from about 0.07 million metric tons/yr in marshes of the Altamaha River estuary to 6.8 million tons/yr in Delaware Bay (Table 1). In general, estuaries with substantial or high volumetric capacity have relatively high accumulation rates except for Long Island Sound. The Savannah River estuary has relatively high accumulation, an estimated 2.7 million tons/yr, despite its small capacity. This is likely encouraged by channel dredging. The accumulation rates include material supplied from rivers as well as from other sources.

Storage efficiency which is expressed as a ratio of sediment accumulation to river input rate, ranges 0.7 in the Altamaha River estuary, Ga. to 7.6 in the Choptank River estuary, Md. (Table 1). The data available are mainly for the northern estuaries and vary widely with location. The variability can result from changes in either mass accumulation or river input. All the northern estuaries have efficiency ratios greater than 1 indicating that they trap and store an amount of sediment equivalent to the input of suspended sediment from their rivers in addition to sediment from other sources as the ocean. Of note are the large ratios in Narragansett Bay, Delaware Bay, the Rappahannock and Choptank river estuaries.

The Altamaha river and Mobile Bay have ratios of 0.7 indicating that they trap and store an amount equivalent to about 70 percent of their river input whereas about 30 percent escapes to the ocean. In comparison the Gironde, France exports on amount equivalent to 70 percent of its river input but this may include some sediment derived from sources within the estuary as well as the river.

Rationale

Many physical factors combine to determine the storage efficiency of an estuary. A simple deduction is that the storage quantity, Ms, varies as a function of multiple factors: the supply or input, Mi, the storage capacity, C, the character of the sediment, G, and the removal or loss through the entrance, Me, the energy input and circulation, E, expressed in a simple general form as:

$$Ms = f(Mi, C, G, Me, E) \qquad (5)$$

The variables are all a function of time and represent volumes per unit time (L^3/T), except for G. Storage therefore, results from the interaction of variables that tend to add or remove sediment with a resultant net accumulation. The expression is the basis for more elaborate models and in itself is useful for sorting out prospective relationships.

The Input Factor

A supply of sediment is a prerequisite for sediment storage; it is a key term for estimating storage efficiency. In the simplest case, the storage rates respond directly to input variations. In real estuaries however, sediment is focused in storage sites. As an estuary fills, the size of the sites as well as the size of an entire estuary basin, can change. Thus, younger sediment may be spread over a larger area of the estuary floor than the older sediments, hence accumulating in thinner layers. A constant input therefore, can be expressed in a single core of stored sediment as a changing input.

Although mass balance calculations assume steady state input, this condition obtains only at very long time scales, 10^{11} secs or longer. At these scales the input can be the original source such as eroded upland soil. Most measurements of input however, span short time scales, years and decades, and record substantial fluctuations, e.g. as a result of varying river discharge and sediment concentrations. At short time scales the bulk of the input likely is derived from proximate sources as estuary shores, banks and fluvial floodplains that are, themselves, intermediate or transient storage sites. Estimates of storage efficiency therefore, are tempered by multiple sources with different time histories and by lack of common data in which input and storage terms are measured over the same time periods.

The Capacity Factor

For an estuary to store sediment there must be room to contain the sediment. If other factors are constant, the larger the estuary basin, the greater the estuarys' ability to retain and hold sediment. For example, the Delaware estuary and Northern Chesapeake Bay with capacities greater than 10 km^3 have accumulation rates exceeding 3 million tons/yr. In contrast the Altamaha and Choptank estuaries with capacities less than 1.5 km^3 have accumulation rates less than 0.5 million tons/yr (Table 1). Capacity decreases the sediment-transport capacity because the cross-sectional area for freshwater flow usually increases seaward through an estuary resulting in a reduction in velocity. Furthermore, capacity increases retention of sediments by increasing the residence time of the water for a given inflow, and thus favors settling of suspended sediment to the bed.

A rise of sea level relative to the land increases estuary capacity if the rate of rise exceeds the rate of sediment infilling. Sea level rise opposes infilling. Where the relative rise of sea level is large compared to accumulation rates, the storage capacity is likely large and increasing with time. This is the case for most estuaries between Cape Cod and Cape Lookout except for the Hudson (Fig. 5A; Table 1). Where sea level rise is small compared to accumulation rates, the storage capacity is small or likely exceeded by infilling. This is the case for estuaries bordered by extensive marshland between Cape Lookout and Cape Canaveral (Fig. 5A, Table 1). These estuaries are likely filled nearly to capacity during the postglacial rise of sea level by high sediment influx of their rivers (Meade, 1982).

In an evaluation of sediment trap efficiency of freshwater reservoirs, Brune (1953) used the ratio of volumetric capacity to annual river inflow to develop a curve for predicting the life of a reservoir. Biggs and Howell (1984) use Brune's curve to predict the sediment trapping ability of estuaries. The present set of data do not fall within the envelope of Brune's curve except for Mobile Bay. Within the range of estuaries considered there is no trend of trapping efficiency to increase with an increase of in the capacity-inflow ratio. All the northern estuaries as a group, except the Hudson, exhibit relatively high capacity-inflow ratios compared to the southern estuaries except Savanna.

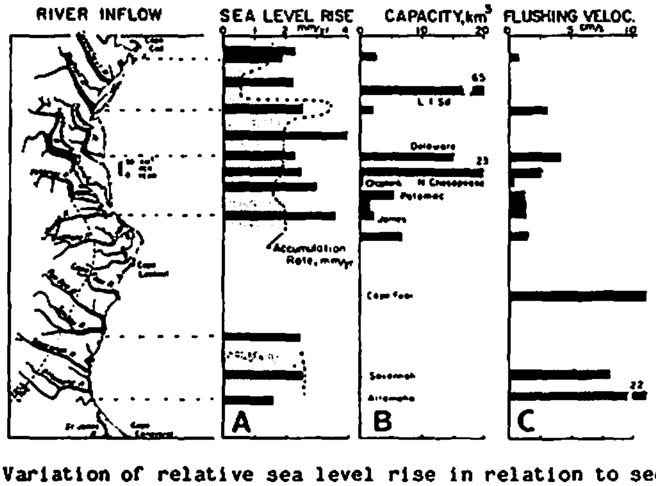

Figure 5. (A) Variation of relative sea level rise in relation to sediment accumulation rates in estuaries of the Atlantic seaboard. Data from tide gages between 1940-1980 (Hicks et al., 1983) and accumulation rates from various sources (Table 1); (B) Distribution of estuary capacity; (C) Variation of flushing velocity in estuaries along the Atlantic Seaboard.

Sediment Character

Sediment storage is encouraged by rapid particle settling from suspension to the bed, i.e. for a given residence time and average water depth. In estuaries, settling velocity of fine sediment not only depends on particle size but on the state of aggregation. Composite particles like flocs, aggregates or agglomerates settle many times faster than their dispersed component particles and hence, go into storage more readily than dispersed particles. Whether or not physicochemical flocculation plays an important role in estuaries is an open question. Estuaries however, are often very productive and contain large numbers of suspension feeding animals that filter, ingest and void sediment, thus forming fecal pellets or agglomerates bound by sticky organic matter. In a study of biological processing in Delaware Bay, Biggs and Howell (1984) found that organisms are capable of depositing 200 times the annual fluvial input of suspended sediments. Because settling rates change with state of aggregation and with the degree of organic processing which are largely unknown, it is beyond the present scope to calculate settling rates and resultant accumulation rates as a function of storage efficiency.

Once cohesive sediment is deposited on the bed, its fate is determined by its yield strength or force required to break bonds between aggregates and by the shear velocity for erosion. Sediment can remain in temporary storage if its shear strength exceeds the critical shear velocity. The relation between yield strength and critical shear velocity is known from experimental results of Migniot (1968) and Krone (1963). Data on both the properties and excitation of sediment are not, as yet, adequate to compare estuaries. However, Migniot's relationship can provide an evaluation of the long-term balance of erosion or accumulation in an estuary and thus, indicate whether the bed is a source or sink for sediment.

Entrance Morphology and Output

Storage in estuaries is relatively low if more sediment is removed and exported through the entrance than is added by all sources. Output is affected by the morphology and size of the entrance that in turn, has a direct effect on the estuary residence time. Morphology varies from semi-enclosed to open or unrestricted. These types depend on the relative magnitude and effectiveness of wave-induced onshore and longshore drift in building bars, spits or sills that obstruct flow through the entrance. This action is opposed to the flushing ability of tidal and freshwater discharge that tend to keep the entrance open. In macrotidal estuaries like the Gironde, France, discharge through the entrance is augmented by intense tidal mixing, sediment resuspension and coastal currents that carry resuspended sediment down the coast.

Estuary entrances tend to attain dynamic equilibrium whereby the tidal and freshwater discharge coadjusts to the cross-sectional geometry through erosion and deposition. The discharge, Q, is a function of mean velocity, V, and cross-sectional area, A, so that in any section x:

$$Q_x = V_x A_x \tag{6}$$

Most entrances exhibit equilibrium and follow a linear relationship between flow area and tidal prism (Fig. 5). Therefore, morphology has little effect on storage. Disequilibrium occurs however, when longshore and onshore drift carry sand into the entrance faster than it can be removed by flow in and out. The entrance itself not only stores sediment but it reduces exchange between the estuary and ocean thus encouraging storage of sediment supplied by rivers or shores. Similar disequilibra can arise if the tidal prism is reduced, for a given entrance flow area, by intertidal filling. Changes in entrance morphology and resulting storage often occur seasonally linked to shifting wind and wave regimes or fluctuating river inflow. The entrance therefore, acts like a dynamic "valve" to regulate the export of sediment.

As the sediment storage capacity of an estuary is reduced by infilling, a greater proportion of the river input likely will be exported than stored.

The Energy and Circulation Factor

For an estuary to store sediment delivered to it, the energy input must be sufficiently low to allow sediment to deposit and accumulate. The chief sources of energy are the river flow, waves and tides. Sediment carried by river flow tends to go into storage because the flow usually looses its transport capacity as it flows seaward through enlarged cross sections of an estuary. River flow is most important near the estuary head but during floods, inflow may dominate throughout. As a result river-borne sediment, together with sediment scoured from the estuary, can pass directly into the sea.

The degree to which sediment is thrust through an estuary is determined by the river's flushing velocity (Gibbs, 1977). This parameter is derived from mean annual river discharge divided by the cross-sectional area at the landward limit of salt water, 1 ppt, a key chemical boundary. The flushing velocity dictates the seaward position where suspended sediment is dispersed by estuarine mixing and by the transport of tides and density currents.

As shown by data from selected estuaries on the Atlantic seaboard, the flushing velocity for the northern estuaries ranges 0.2 to 3.6 cm/s whereas for the southern estuaries it ranges 8 to 22 cm/s (Fig. 5C). The southern estuaries also have a relatively small volumetric capacity and a large seasonal range (Fig. 6). In contrast, large rivers like the Amazon and Mississippi thrust most of their water and sediment seaward into the ocean. Consequently, their storage efficiency may be expected to be very low, or nil, compared to northern estuaries of the Atlantic seaboard.

The energy input of waves is largely determined by water depth, fetch and intensity of winds. Generally, in broad estuaries, sediment goes into storage below a critical depth, or base level, for the deepest penetration of storm waves. In Long Island Sound this level is about 18m (Bokuniewicz and Gordon, 1980). The level for sediment accumulation is not constant however, but can vary within limits depending on the effectiveness of orbital wave motion on the bed sediment character, boundary roughness, suspended sediment concentrations and morphology. In broad shallow bays of Texas, sediment builds up to a level of equilibrium appropriate to the ratio between average wind fetch and water depth (Price, 1947).

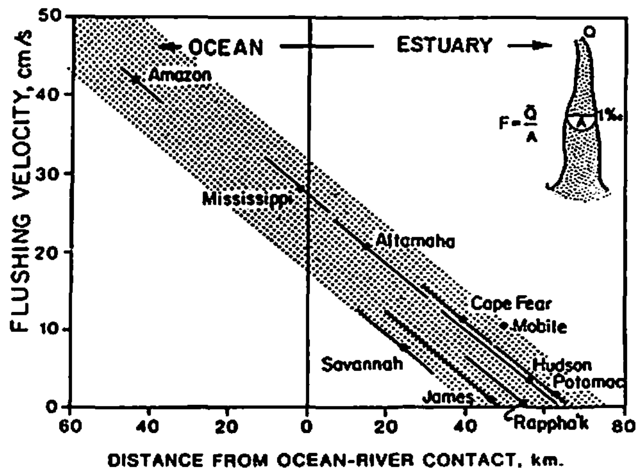

Figure 6. Position of the landward limit of saltwater expressed as distance from the mouth, in relation to flushing velocity for various river estuaries. Length of line represents seasonal range and the dot is the position at average river inflow (after Gibbs, 1977).

Where the tide is the main energy input sediment storage is mediated by the behavior of the tide wave as it interacts with the channel geometry to develop toward maximum stability. Depth and width convergence rates with distance landward tend to balance frictional dissipation of the tide wave (Wright et al. 1973). To attain dynamic equilibrium, an estuary co-adjusts its tidal discharge and its channel geometry by changing its tidal characteristics including tidal wave length, amplitude and the longitudinal gradient of tidal discharge which is determined by the tidal prism as in equation (6). Coadjustments are also made by erosion and deposition. An estuary channel must be neither too deep nor too shallow for the amount of discharge and for the load of sediment it transports. If the supply of sediment and energy input are not in balance, then transport processes act to establish equilibrium by either trapping or bypassing the sediment supply. When a natural estuary is dredged to depths greater than those dictated by the equilibrium regime, sediments go into storage to reestablish an equilibrium level in accord with the tidal regime (Inglis and Allen, 1957). This is exemplified by changes in cross-sectional areas along the Delaware Estuary, (Fig. A) and along the Gironde (Fig. B). A regular exponential increase of cross-sectional area with distance seaward suggests near-equilibrium between geometry and tidal flow.

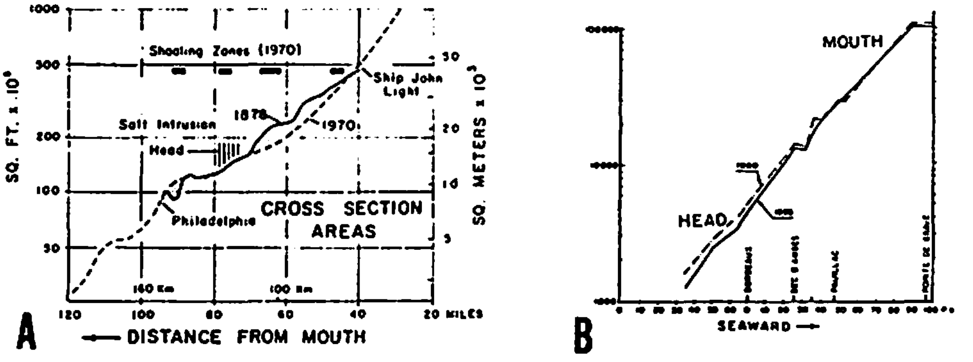

Figure 7. (A) Changes in cross-sectional area along the Delaware Estuary between 1878 and 1970 in relation to shoaling zones in 1970. Zone of reduced cross section, shaded, from Nichols (1978). Reproduced with permission of Dowden, Hutchinson and Ross; (B) Distribution of cross-sectional areas along the Gironde estuary between 1893 and 1960. Zone of reduced cross section shaded. Reproduced by permission of E. Schweizerbart'sche Verlagsbuchhandlung.

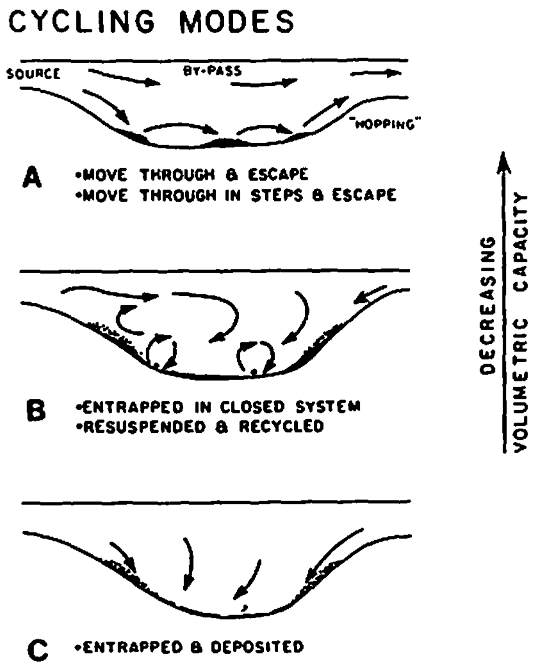

Figure 8. Cycling modes and fate of suspended sediment in an estuary. Arrows represent pathways of sediment dispersal; schematic. From Nichols and Biggs (1985).

The fate of sediment in an estuary is partly determined by cycling pathways. Three modes are possible: 1) the suspended sediment settles and accumulates in low energy zones, i.e. off river mouths or in basins with restricted circulation (Fig. 8C). Narragansett Bay is an example of this mode of transport but with a superimposed estuarine circulation (McMaster, 1984). 2) the sediment is partially entrapped in a nearly-closed circulation system and recycled or resuspended from the bed, prior to accumulation (Fig. 8B). Northern Chesapeake Bay, the Potomac and Rappahannock exemplify this transport mode. 3) the sediment moves directly through the estuary and escapes, either by the force of river floods, or by intense wave and tidal mixing (Fig. 8A); alternatively, the sediment temporarily deposits and moves through in progressive steps, a step with each flood or storm (Fig. 8A). The Mississippi River entrance and the Gironde River estuary in time of flood, are examples of this transport mode.

Within estuaries of the same geometric type, there are differences in the net circulation caused by differences in river inflow and tidal range. Pritchard (1955) shows that when width and depth are held constant, the circulation changes from a well-mixed or partially-mixed (Type B) system to a salt wedge (Type A) system as the ratio of inflow to tidal current increases.

The ratio of mean annual river discharge entering an estuary during a tidal cycle, to the mean tidal prism provides an index to the degree of haline mixing and type of estuarine circulation. Flow ratios in estuaries of the Atlantic seaboard range from 0.005 in the Penobscot to 0.283 in the Altamaha (Fig. 5D). By comparison ratios reach 0.45 in Mobile Bay and 0.50 in the Gironde Estuary, France. This indicates that the river flow is sufficiently large to overwhelm the tidal flow and tends to flush out fine sediment. Storage efficiency therefore, is likely reduced. A graph of storage efficiency as a function of flow ratios for the Atlantic coast estuaries evaluated (Fig. 9), shows a broad trend of efficiency to be lower in

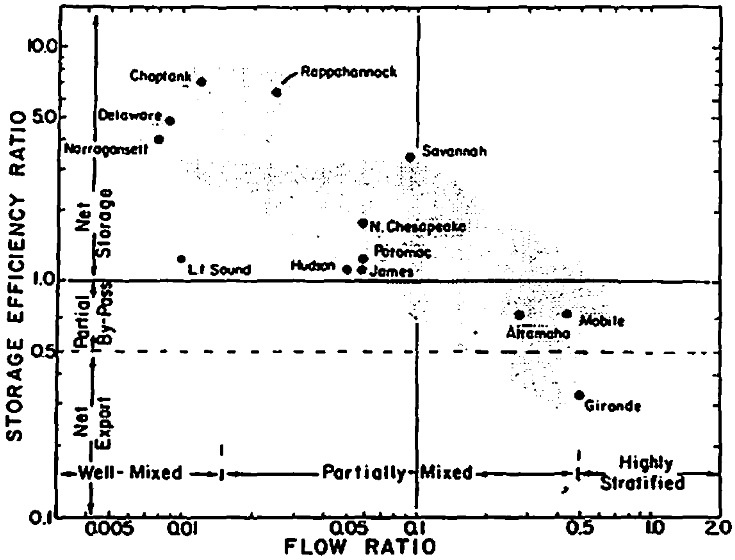

Figure 9. Graph of storage efficiency ratio as a function of flow ratio for selected Atlantic coast estuaries. Flow ratios from NOAA (1985).

estuaries with high flow ratios and higher in estuaries with low flow ratios. Most of the systems are partially-mixed with ratios in the range of 0.015 to 0.5, Mobile Bay and the Gironde River are highly stratified during floods whereas Narragansett Bay, Long Island Sound and Delaware Bay are essentially well-mixed systems. Within the range of partially-mixed estuaries the trend of the flow ratios suggests that the estuarine circulation is important both in trapping fluvial sediment input and in transporting sediment landward from the sea. The relatively low storage efficiency of estuaries with low flow ratios that approach a highly stratified regime, suggests that the river flow can overwhelm tidal currents and periodically flush out part of the river load. In well-mixed systems with low flow ratios, other factors as high capacity relative to inflow, rapid particle settling and biological processing may have a greater influence than the estuarine circulation in promoting storage.

Effect of Evolution

The sequence from full storage to partially by-passing can proceed with long-term infilling and decreasing volumetric capacity which is manifest in decreasing water depth below the equilibrium depth. The effect of depth on salinity, circulation and mixing has been demonstrated in hydraulic and numerical models (Nichols, 1972; Simmons, 1965; 1972; Festa and Hansen, 1976). As an estuary shoals, near-bottom flow from the ocean is reduced, vertical velocity increases and the two-layered circulation weakens, i.e. the circulation type shifts from Type B (partially mixed, Pritchard, 1955) toward Type C (well-mixed) assuming inflow, tides and width are constant. As an estuarine channel approaches or exceeds the equilibrium depth, sediment storage shifts into littoral zones and sediment patterns become complicated because inflow, tides and waves alternately dominate. The Gironde estuary, France is a good example of this stage (Jouanneau and Latouche, 1981). Long-continued entrapment and storage can convert an estuarine environment into a fluvial dominated regime whereby river sediment passes directly into the ocean, as exemplified by Alsea Bay, Oregon (Peterson et al., 1984). Thus, with progressive infilling, the geologic function of an estuary can change from a sink for fluvial and marine sediment to a source of fluvial sediment for the ocean.

Uncertainties and Constraints

Calculation of storage efficiency and comparison of characteristics of estuaries is tempered by a lack of input and accumulation data from the southern estuaries. Most data comes from individual studies and different sources. Consequently there is a lack of common sampling methods, a lack of common time scales and lack of input and accumulation measurements over the same time periods. Most rates are measured during normal conditions and steady state is assumed in sediment budgets. In contrast, much sediment likely goes into storage after storms. The problems are amplified because errors and uncertainties of mass balance budgets are seldom reported. The lack of information contributes to the variability of data (e.g. Table 1) and lack of statistically significant relationships between storage efficiency and causal factors. Despite these limitations, the results document regional trends and they can assist in further elaboration and sorting out prospective relationships.

Conclusions

1. Estuaries of the U.S. Atlantic coast exhibit a range of storage efficiency. The northern estuaries have much larger storage efficiency ratios than the southern estuaries. They not only store an amount equivalent to their river input but also store large amounts of sediment supplied from other sources as the sea.

2. Many factors combine to regulate storage efficiency. In the northern estuaries storage is encouraged by low flushing velocity and high volumetric capacity relative to river inflow. Within the range of partially-mixed systems, flow ratios suggest that the estuarine circulation is important in trapping fluvial sediment and in transporting sediment landward from the sea.
3. As a result of the moderate to high storage efficiency, most particle-reactive contaminants supplied by rivers are likely retained in estuaries and the regional impact of contamination on the ocean is minimized.

This is a contribution of the Virginia Institute of Marine Science.

Table 1. Morphometric and hydrodynamic characteristics of selected U.S. Atlantic coast estuaries and corresponding sediment input from rivers, mass accumulation and storage efficiency. Sediment data from various sources; data for Mobile Bay, AL, and the Gironde estuary, France, included for comparison. For definition of parameters, see text.

Estuary	Volume Capacity	Mean River Discharge	Mean Flushing Velocity	Mean Flow Ratio	Accumulation Rate	River Input	Storage Efficiency	Reference
	km^3	km^3/yr	cm/s		10^6 metric t/y	10^6 metric t/y	ratio	
Penobscot Bay, ME	46.7	15	0.2	0.007	--	--	--	
Narragansett Bay, RI	2.6	2	0.7	0.008	0.46	0.11	4.2	McMaster, 1984
Long Island Sound, NY	65.0	30	--	0.010	0.58	0.52	1.1	Bokuniewicz & Gordon, 1980
Hudson & Inner Harbor, NY	2.3	21	3.1	0.050	1.20	1.10	1.1	Olsen, 1984
Delaware Bay	15.0	22	3.6	0.009	6.8	1.40	4.8	Neiheisel, 1973
Northern Chesapeake Bay, MD	23.0	36	2.6	0.059	3.10	2.00	1.6	Officer et al., 1984
Potomac River, VA, MD	5.6	12	1.3	0.059	1.54	1.40	1.1	Knebel et al., 1981
Rappahannock River, VA	1.8	3	1.4	0.030	1.90	0.30	6.3	Lukin, 1983
James River, VA	2.5	8	1.5	0.060	1.80	1.70	1.1	Nichols (unpub.)
Choptank River, MD	1.1	0.1	0.3	0.012	0.38	0.05	7.6	Yarbro et al., 1984
Albemarle Sound, NC	7.0	13	1.5	0.220	--	--	--	NOAA, 1985
Cape Fear River, NC	0.4	10	11.3	0.120	--	--	--	NOAA, 1985
Savannah River, GA	0.3	11	8.0	0.092	2.70	0.80	3.4	Meade, 1976; Meade & Trimble, 1974
Altamaha River, GA	0.12	10	22.0	0.283	0.07	0.10	0.7	Unpub.; Meade & Trimble, 1974
Mobile Bay, AL	2.8	61	11.0	0.450	3.00	4.30	0.7	Ryan & Goodell, 1972
Gironde River, France	2.2	33	5.0	0.500	0.70	2.20	0.3	Jouanneau & Latouche, 1981

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