Rapp. P.-v. Réun. Cons. int. Explor. Mer, 186: 343–351. 1986

Consequences of sediment flux: escape or entrapment?

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Estuaries exhibit a full range of flux that extends from escape of sediment into the ocean to complete entrapment and storage within the system. The trapping efficiency of U.S. East Coast estuaries is compared with respect to long-term infilling and present-day flushing velocity, volumetric capacity, and circulatory mixing. It was found that entrapment prevails in many northern estuaries as a consequence of high volumetric capacity, low flushing velocity, and the nearly closed circulation. In many estuaries, channel deepening has reversed the "normal" trend of long-term infilling. Although dredging enhances circulatory entrapment, large-scale ocean dumping results in "escape" of sediment from estuaries. Consequently, man is changing the geologic role of many U.S. East Coast estuaries from a sink for fluvial and marine sediment to a source of sediment for the ocean.

Introduction

Estuaries and lagoons exhibit a full range of sediment flux that extends from: (1) escape of particulate contaminants, (2) entrapment and recycling, to (3) entrapment and storage within the system. Of the total amount of fluvial material supplied to an estuary, how much passes through to the ocean and how much is retained? What is the net effect of sediment flux into, or through the coastal zone? Answers to these questions are needed not only to determine the input of sediment and contaminants to the ocean but to predict whether a given contaminant will be retained close to its source, or become dispersed and thus have a regional impact.

Given the wide variations of flux and the great diversity of estuaries of varied size, shape, river inflow, tidal range, salinity, sediment infilling, and human activities in estuaries, it would seem difficult to discover any common consequences of flux. However, if we broadly compare many estuaries, examine their material balance, their hydrodynamic features, and human impacts, some common characteristics emerge.

Rationale

The escape–entrapment status of an estuarine system is mainly governed by its volumetric capacity to assimilate sediment in relation to the rate of sedimentation and the energy available to transport the sediment supplied. If supply and energy are not in balance, then transport processes act to establish equilibrium by either by-passing or trapping and depositing the sediment supply. Such changes are manifest in the elevation of the sediment surface or water depth, and in the net supply or loss of material from the system. Just as streams respond to changes in base level by eroding or aggrading and reshaping their channel geometry, so too can estuaries, in principle, respond to hydrodynamic forcing by adjusting their geometry and working towards a state of maximum stability. An estuarine channel must be neither too deep nor too shallow for the amount of river or tidal discharge or for the sediment load that passes through it. The interaction among sediment input, energy, and geometry produce an equilibrium surface, above which sediment cannot accumulate and below which deposition and accumulation are likely. When an estuary is dredged to depths greater than those dictated by the equilibrium regime, sediment rapidly accumulates to re-establish an equilibrium depth in accord with the hydrodynamics, as demonstrated in the Thames (Inglis and Allen, 1957). Similarly, broad shallow estuaries that are shoaled by sedimentation build up to an equilibrium level appropriate to the wave energy, fetch, and water depth (Price, 1947; Bokuniewicz and Gordon, 1980).

Although most modern estuaries formed at about the same time, ~6000 years ago, the stage of infilling and

INFILLING EFFECT

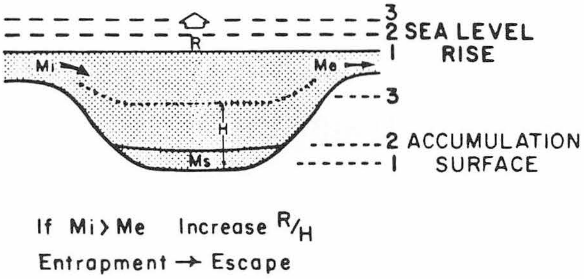

Figure 1. Schematic diagram of an estuary in longitudinal section showing effect of sediment infilling on the status of entrapment and escape. As the sediment influx, Mi, exceeds the export, Me, the accumulation rate, Ms, may increase at a faster rate than that of sea-level rise, R. This trend is reflected by diminished water depth, H, below equilibrium depth, in relation to sea-level rise, R, or increased R/H ratio.

hence the escape–entrapment status, varies widely among different estuaries. The geologic evolution and life span of an estuary depend on the balance between the sediment accumulation and the rise of sea level relative to the land. Sediment infilling opposes submergence. Where the pace of sea-level rise exceeds infilling, as in Chesapeake Bay and Long Island Sound, estuaries are relatively deep, and hence, have a large capacity to "assimilate" the sediment supply. That is, a greater proportion of the influx mass, Mi, is trapped than exported, Me. Consequently, the mass accumulation, Ms, increases and the ratio of sea-level rise, R, to depth below the equilibrium depth, H, increases (Fig. 1). As the volumetric capacity of an estuary below the equilibrium depth decreases, its trapping efficiency also decreases. If sea-level rise remains relatively constant, the capacity and life span of an estuary mainly depend on the sediment influx.

In late stages of infilling when estuary channels are shoaled, accumulation sites shift into marginal flats and marshes. When these zones are filled fluvial sediment can be conveyed directly to the sea. 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.

Trapping efficiency and mass balance

The status of escape or entrapment of sediment in a given estuary is mainly defined by the trapping efficiency. This is the fraction of the total mass of sediment input to an estuary that is retained. The trapping efficiency can be estimated in different ways:

(1) comparing the removal or sedimentation of a natural or artificial tracer with its input rate;
(2) calculation of the "detention" or "retention" time and the settling velocity of suspended sediment concentrations (O'Connor, 1981);
(3) comparing the water volume, or infilling capacity, with the total water inflow as for reservoir infilling (Brune, 1953; Biggs and Howell, 1984);
(4) comparing the input, Mi, and output, Me, of suspended sediment, utilizing box models in a mass-balance context (Officer, 1980; Officer and Nichols, 1980; Biggs, 1970);
(5) comparing the mass of sediment accumulated in an estuary with the mass input over a given time span (Ryan and Goodell, 1972).

A mass balance of sediment in an estuary is obtained by assessing the sediment to, and the losses from, an estuary. Assuming steady state and no net additions or losses, then the input, Mi, plus the sediment produced in the system, P, must equal the output, Me, plus the amount consumed in the estuary, C, and the flux to the bed, Ms, following the example of MacKenzie and Wollast (1977). Thus:

$$\underset{\text{(sources)}}{\mathrm{Mi} + \mathrm{P}} = \underset{\text{(losses or removal)}}{\mathrm{Me} + \mathrm{C} + \mathrm{Ms}}. \tag{1}$$

Then, the trapping efficiency (Ti), i.e. fraction retained, can be expressed as an index:

$$\mathrm{Ti} = \frac{\mathrm{Ms}}{\Sigma\mathrm{Mi} + \mathrm{P} - \mathrm{C}} \tag{2}$$

$$\mathrm{Ti} = 1 - \frac{\mathrm{Me}}{\Sigma\mathrm{Mi} + \mathrm{P} - \mathrm{C}}. \tag{3}$$

Usually, the trapping efficiency is expressed as a ratio, or percentage, of the accumulation mass to the input mass over a given time, or alternatively, one minus the ratio of the output flux to the input flux. The input mass or rate may be either the fluvial mass if this source accounts for all of the accumulated sediment, or the total mass from different sources (i.e. fluvial, marine, shore erosion, biological production). If production and consumption within the system are small, these terms can be neglected. The assumption of steady state is useful because it is then possible to estimate one of the unknown terms in Equation (1). In practice, however, steady state is only satisfactory when dealing with average properties of a system over long periods of time.

Uncertainties

It is clear that an estuary is an evolving system. It is uncertain, however, when equilibrium is attained between supply of sediment, hydrodynamic forces, and accumulation. We do not yet know the time scales of significant change. The circulation responds quickly to changes of sea level but cohesive sediments probably respond more slowly. Hence, the volumetric capacity may continue to change though sea level is stable. As the supply fluctuates with time, transport rates will readjust and, in turn, the deposition rates will readjust, with different types of sediments readjusting at different rates (Parker and Kirby, 1982). Thus, the rates and patterns deduced from geological or historical data may not be compatible with present-day rates. Therefore, budgets need to account for the time scale over which the budget is considered.

By measuring the change in estuary bathymetry over the interval between surveys, e.g. 30 to 100 years, the volume of sediment accumulated and its mass can be estimated. Although this method can provide good spatial coverage, the precision of measured changes is relatively poor, because the volumes are relatively large and thus, small changes deduced are equivocal (Parker and Kirby, 1982). The error term may be of the same magnitude as the expected sedimentation rate (Biggs and Howell, 1984).

The mass of accumulated sediment estimated from bathymetric changes is often compared with fluxes determined from river gauging stations and field observations in estuarine cross-sections. The residuals computed from field observations usually represent only short-term fluxes and thus do not equate well with long-term averages calculated from gauging stations, or from bathymetric changes or other historical data. Furthermore, large sediment inputs from rivers occur during short periods of high runoff so that trapping efficiency based on normal inputs could be grossly overestimated. Likewise, the large temporal and spatial variance of currents and suspended sediment concentrations in estuarine cross-sections, and the technical difficulties of measuring bed-load, amplify the uncertainties.

Cycling modes

The fate of sediment in an estuary is partly determined by dispersal pathways. Three combinations are possible (Fig. 2): (1) the suspended sediment settles, and accumulates in low-energy zones, i.e. basins with restricted circulation such as deep river valleys or fjords, or where wave action is absent (Fig. 2C); (2) the sediment is partially entrapped in a nearly closed circulation system and recycled or resuspended from the bed, prior to accumulation (Fig. 2B); (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. 2A); alternatively, the sediment temporarily deposits and moves through in progressive steps, a step with each flood or storm (Fig. 2A).

The sequence from full entrapment to full escape 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

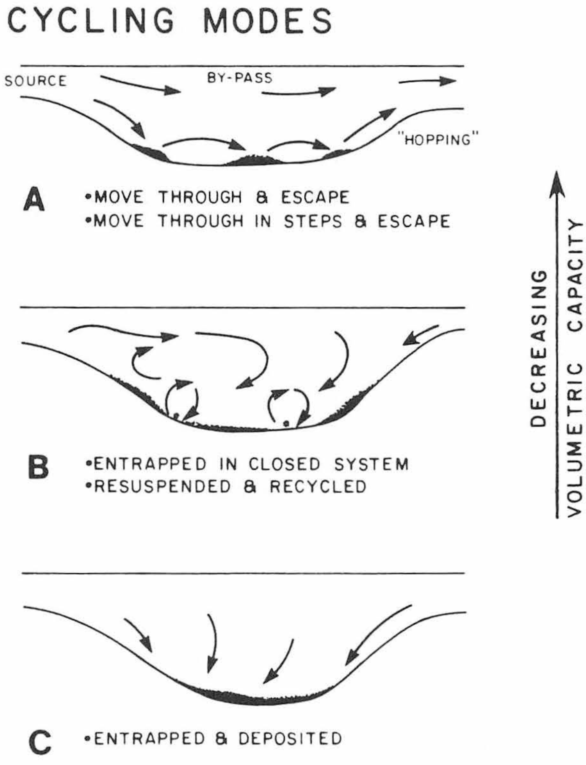

Figure 2. Cycling modes and fate of suspended sediment in an estuary. Arrows represent pathways of sediment dispersal; schematic.

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 A (salt wedge, Pritchard, 1955) towards type C (well-mixed) assuming inflow, tides, and width are constant. Additionally, mixing can be enhanced by wave stirring as shoals are built upwards into the wave regime. As an estuarine channel approaches or exceeds the equilibrium depth, sediment accumulation 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 (Allen, 1973). Long-continued entrapment and accumulation can convert an estuarine environment into a fluvial-dominated environment, whereby the river load escapes directly into the ocean, as exemplified by Alsea Bay, Oregon (Peterson *et al.*, 1984).

Circulation effects

Within estuaries of the same geometric type, there are differences in the circulation caused by differences in

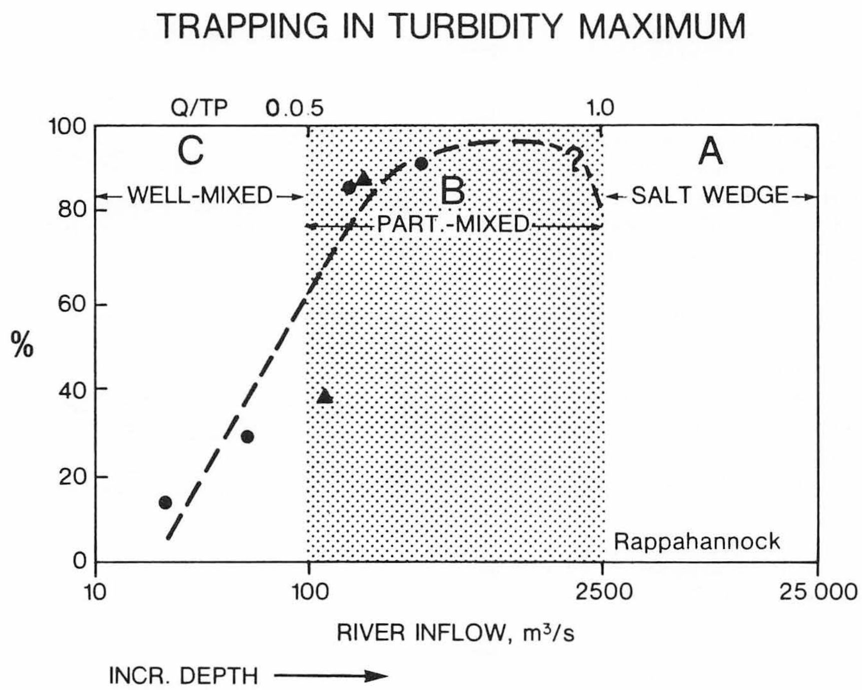

Figure 3. Trend of trapping efficiency with increasing river inflow in the turbidity maximum of the Rappahannock estuary, Virginia; expressed as percentage of fluvial input. Triangle data based on box model of Officer and Nichols (1980); solid dots based on field observations of currents and suspended sediments (Nichols, 1974, 1977). Mixing regimes, A, B, C, according to Pritchard's (1955) classification based on ratio of mean river discharge, Q, to intertidal volume, TP. If upper threshold is reached in salt wedge regime, sediment would pass through the mouth.

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. Field measurements of flow, salinity, and suspended sediment were made for 4 to 10 days landward and seaward of the turbidity maximum in the Rappahannock estuary, Virginia (Nichols, 1974, 1977). The resulting flux calculations of input (Mi) and output (Me) in a box model of the turbidity maximum zone, revealed a trend for trapping efficiency to increase at higher inflow levels while the estuary changed from well-mixed to partially mixed (Fig. 3). Since this estuary retains its salt intrusion through all stages of river flooding, the flushing velocity is not high enough, i.e. to reach a threshold or to force the salt wedge and fluvial sediment load through the mouth. Box models of estuarine-wide input and output indicate that the estuary not only traps the bulk of its fluvial load but also gains a substantial supply of sediment through the lower layer from the Chesapeake Bay or farther seaward (Officer and Nichols, 1980).

Equilibrium and contaminants

Contaminant distributions in a given estuary can vary with location as a consequence of different sediment accumulation rates that are a response to flow equilibrium. For example, Kepone, a chlorinated hydrocarbon, escaped from a point source into freshwater and tidal reaches of the James estuary, Virginia, for more than nine years (Fig. 4) (Nichols and Cutshall, 1981). This contaminant makes a good sediment tracer because it strongly adsorbs to fine particles ($Kd > 10^6$). Its concentration in the surface sediments does not decrease with distance downstream from the source but instead follows the sediment dispersal and accumulation regime (Fig. 4A). Concentrations are higher in the middle estuary than towards the river or farther seaward. As shown in Figure 4B, sedimentation rates are relatively low just seaward of the source where they slightly exceed erosion. Most accumulation occurs within localized "sinks" of the middle estuary. Consequently, contamination is greatest in zones of relatively fast sedimentation. These "far-field" zones hold the greatest mass and thickness of contaminated sediment. They were the first to be contaminated, except for the immediate "near-field" area, and they were the first to recover when the Kepone source was stabilized. It is believed that most contaminated suspended sediment is swept through the landward zone where sedimentation is low and accumulation of contaminant is negligible. This is partly confirmed by the limited thickness of con-

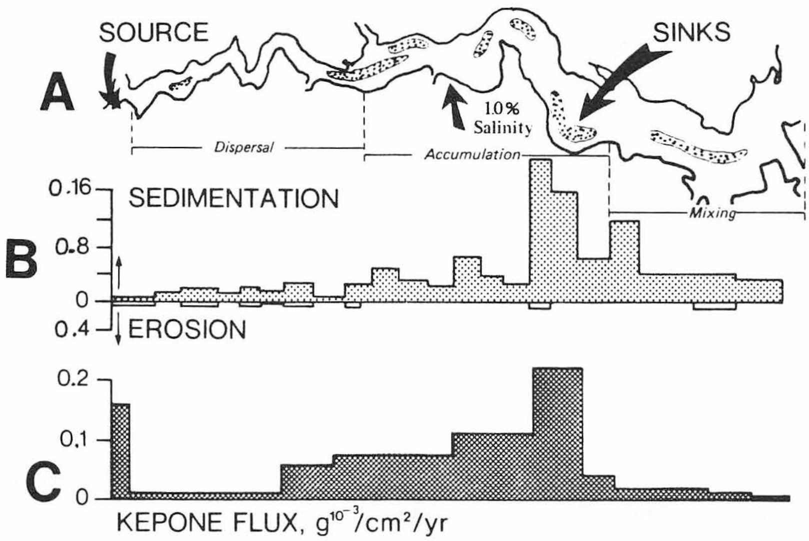

Figure 4. A. Distribution of localized, sediment Kepone sinks in relation to contaminant source in the James estuary, Virginia, and to sediment regimes: dispersal, accumulation, and haline mixing. Inner limit of salty water at 1·0 ppt salinity at average inflow. B. Longitudinal distribution of sedimentation rates in sections of the James estuary, based on bathymetric changes over 35 years, in million tonnes per year. C. Longitudinal distribution of Kepone flux to bed sediments averaged over 12-year span, 1966–1978.

taminated sediment (Nichols and Cutshall, 1981). The sediment surface is likely in near-equilibrium with the river flow, tidal currents, and sea-level rise. In contrast, the load of contaminants is mainly deposited in the turbidity maximum zone of the middle estuary, particularly in dredged channels that are out of equilibrium. In the middle estuary sedimentation exceeds erosion as well as the rise of sea level.

Flushing velocity

To compare the status of escape and entrapment of sediment in a broad range of estuaries, it is useful to consider the flushing velocity. This parameter is derived from mean annual river discharge divided by the cross-sectional area at the landward limit of salt water, 1 ppt salinity (Gibbs, 1977). According to Gibbs (1977), the flushing velocity is a measure of the river's ability to thrust fresh water and sediment into the ocean. It dictates the seaward position where suspended sediment is dispersed by estuarine mixing, the transport by tides, waves, and density currents. As shown by data from selected U.S. East Coast river estuaries (Fig. 5), the flushing velocity of northern U.S. estuaries is relatively low and the seasonal change limited. These estuaries also have a relatively large volumetric capacity, low sediment influx, and low infilling rates. Of the southern U.S. estuaries, the Savannah, which has been deepened by dredging, also has a relatively low flushing velocity. However, the Altamaha, which is relatively shallow and not dredged, has a much larger seasonal range and a higher flushing velocity. The Seine and Gironde in France occupy intermediate positions between southern and northern U.S. estuaries (Fig. 5).

Regional status

More than 24 major river estuaries indent the U.S. Atlantic seaboard between Cape Cod and Cape Canaveral (Fig. 6A). Including adjacent marshland and lesser estuaries, they have a total open-water area of 40 000 km^2. The northern estuaries receive a much larger freshwater discharge than the southern estuaries (Fig. 6A) (Meade, 1969). Volumetric capacity of the northern estuaries is quite high, in part because their river valleys were over-deepened by glacial discharge during the most recent glaciation, a time when sea level was lower than at present. In contrast, the capacity of the southern estuaries, prior to extensive intervention by man, was relatively low despite a smaller river discharge, because of the high sediment influx from their rivers and the consequent infilling (Fig. 6B). The northern rivers drain a glacier-scoured terrain which yields little sediment, while the southern rivers drain a deeply weathered terrain which yields much sediment. These contrasts are likely to be part of a broad global, latitudinal, change from glaciated subarctic to humid subtropical zones.

By constructing dams, diverting rivers, and dredging

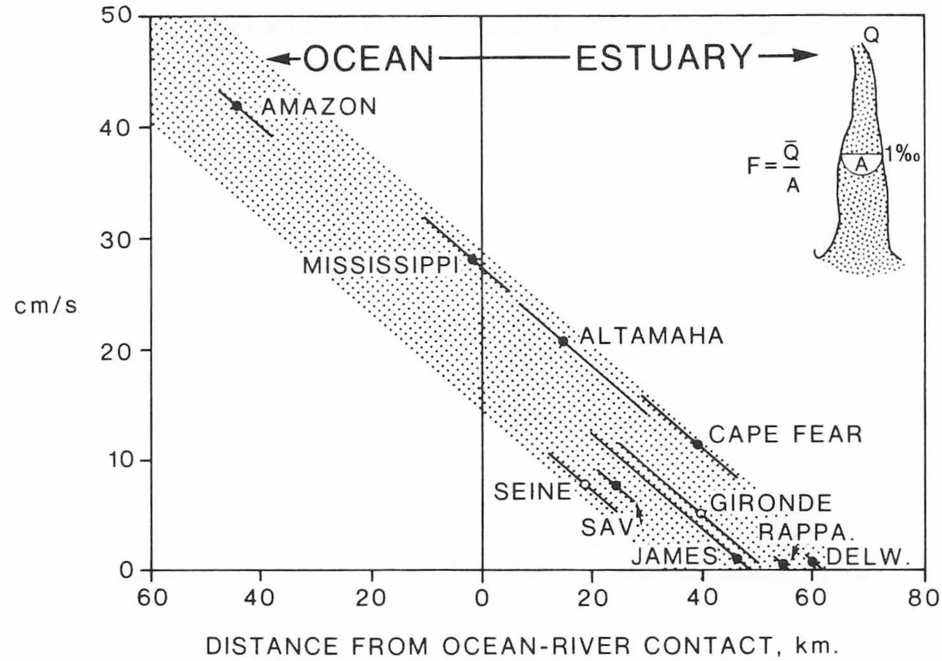

Figure 5. Position of the inner limit of salty water at 1 ppt salinity in relation to flushing velocity for various river estuaries. Length of line represents seasonal range in position; dots and circles indicate position at average river inflow. Sav. is Savannah; Rappa. is Rappahannock estuary; Delw. is Delaware estuary. Inset: F is flushing velocity; $\bar{Q}$ is average river discharge; and A is cross-sectional area at landward limit of salty water. Adapted from Gibbs (1977).

estuaries, man has markedly changed the natural trends of sediment flux and infilling (Fig. 6c) during the last 70 years. The total annual suspended sediment discharge recorded at U.S.G.S. gauging stations in 1906–1907 was 25 million tonnes per year (Dole and Stabler, 1909) while in 1967–1970 it was 13 million tonnes per year (Meade, 1969), a reduction of about one half. However, the amount of fluvial sediment input actually received by estuaries is variable. Some reservoirs may trap and store sediment for awhile, whereas "new" sediment can be mobilized downstream of the dams. And large amounts of sediment can be flushed out of reservoirs by extreme floods (Meade, 1982).

Although U.S. East Coast estuaries have widely variant sediment influx, storage capacities, and hydrodynamic characteristics, the net effect of these features is

Table 1. Trapping efficiency in selected U.S. East Coast estuaries, and Mobile Bay, U.S. Gulf Coast. For notations Ms, Mi, Me, see text.

Estuary	Volume (km^3)	Mean depth (m)	River influx (10^6 t/yr)	Trapping efficiency (%)	Method	Reference
Narragansett Bay	2·4	9	0·09	90	Box model; Me/Mi	Morton (1972)
				69–>100 %	Mass accumulated; Ms/Mi	Santschi *et al.* (1984)
Long Island Sound	51	10	0.5	>100	Geol. infill; Ms/Mi	Bokuniewicz *et al.* (1976)
Hudson, Inner Harbor	0.4	13	1.0	70–>100 %	Geol. infill; Ms/Mi	Olsen (1979)
Delaware Bay	19	10	1.3	>100	Mass accumulated; Ms/Mi	Neiheisel (1973)
Northern Chesapeake	19	6	0·6	90	Box model; Me/Mi	Biggs (1970)
Entire Chesapeake	80	7	1.0	100	Box model; Me/Mi	Schubel and Carter (1976)
Rappahannock	1.8	4.5	0.3	90	Box model; Me/Mi	Nichols (1977)
				>100	Mass accumulated; Ms/Mi	Lukin (1983)
Potomac	7.3	6	1.4	96	Geol. infill; Ms/Mi	Knebel *et al.* (1981)
Choptank	1.5	5.4	0.05	90–97	Box model and mass accumulated; Ms/Mi/Me	Yarbro *et al.* (1984)
James	2.5	3.8	1.7	100	Mass accumulated; Ms/Mi	Nichols, unpub.
				70	Box model; Me/Mi (flood)	Officer and Nichols (1980)
Savannah	0.1	10	0.8	>100	Mass accumulated; Ms/Mi	Meade (1982)
Mobile	3.2	3	4.3	70	Mass accumulated; Ms/Mi	Ryan and Goodell (1972)

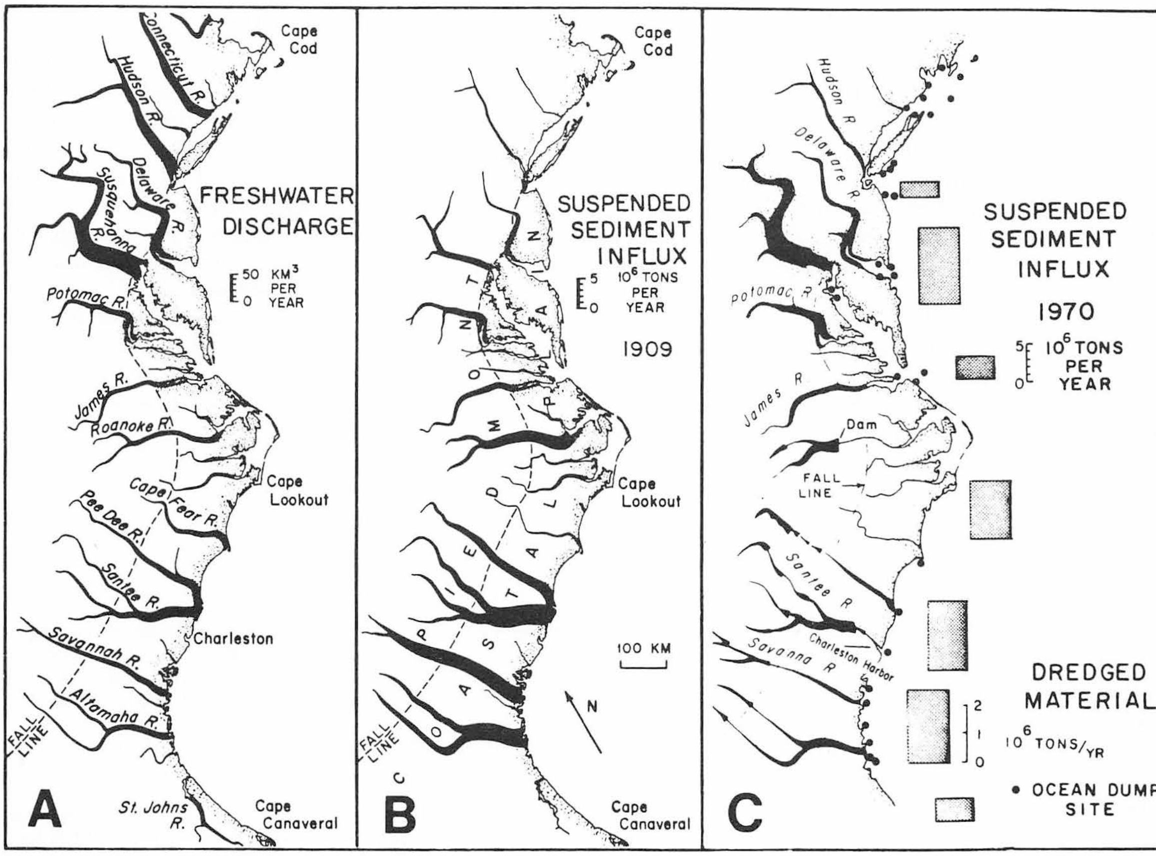

Figure 6. Water and sediment discharge by major rivers of the U.S. East Coast between Cape Cod and Cape Canaveral. (A) Freshwater discharge, based mainly on 1931–1960 U.S.G.S. stream records; (B) suspended sediment discharge based on Dole and Stabler (1909); (C) suspended sediment influx affected by dams in about 1970 and average annual quantities of dredged material taken from major estuaries. Figure and data modified from Meade (1969), Meade and Trimble (1974), and Nichols (1978); dredge data from U.S. Army Corps of Engineers annual reports 1970–1974, and ocean disposal from Gross (1975) and CEQ (1970).

indicated by the trapping efficiency (Table 1). Calculations are mainly derived from box models of input–output, (Mi/Me) or from comparisons of the mass accumulation on the estuary floor (Ms) with the fluvial influx (Mi). All the northern U.S. East Coast estuaries have trapping efficiencies greater than 70 %. Several estuaries, such as northern Chesapeake Bay and Long Island Sound, not only trap the bulk of the fluvial load but also receive a supply from the ocean. Their volumetric capacity is maintained or increased by rising sea level. Sediment budget calculations for southern estuaries are scarce; however, in the Savannah, 2·7 million tonnes reportedly are dredged annually while less than 0·7 million tonnes of suspended sediment are supplied from the river (Meade, 1976). It is inferred that the remaining 2·0 million tonnes move into the estuary from offshore. It seems likely some of the material has been previously dredged.

Dredging and disposal of sediment are major geologic processes in U.S. East Coast estuaries. Every year an estimated 9 to 19 million tonnes are dredged from the estuaries to maintain and deepen shipping channels (EPA, 1974; Gross, 1975). There has been active dredging and disposal along this coast for about 100 years. And more dredged material is generated with time in recent decades because sedimentation rates increase as channels are cut deeper (Nichols, 1978). Dredged material is disposed either on land and behind dikes, or in open water near channels. Additionally, an estimated 7 to 12 million tonnes per year are dumped in various coastal ocean sites (Fig. 6C). Part of this load may be redistributed back into the estuaries, as Meade (1972) inferred for the Savannah. Also, several mineralogical studies indicate landward movement of sediment from the shelf into different estuaries (e.g. Pevear, 1972; Hathaway, 1972; Pinet and Morgan, 1979). However, the amount of material re-entering estuaries from dump sites as opposed to natural sources, e.g. via longshore drift, is unknown. The proportions of sand and mud from different sources are largely unknown except for Charleston Harbor (Van Nieuwenhuise *et al.*, 1978), and the proportions of natural mud to contaminated mud need to be determined.

Dredging of estuaries and harbors improves conditions for entrapment of sediment; e.g. it increases water depth, reduces current velocities, causes more salty water to penetrate landward, and shifts the null zone and site of maximum shoaling landwards. Thus, deepening can accelerate the return of dredged material placed in seaward reaches. Estuary dredging combined with ocean disposal therefore can be self-perpetuating. Nonetheless, as channels of U.S. East Coast estuaries are dredged deeper with time, and substantial amounts of material are dumped offshore, there must be a net seaward sediment flux from the estuaries. Over the long-term, man is changing the geologic role of the estuaries from a sink for fluvial and marine sediment to a source of sediment for the ocean.

Consequences for contaminant flux

The removal of dredged material from estuaries and disposal on the shelf is clearly an important pathway by which contaminants can be transported through the coastal zone. This is documented by Olsen *et al.* (1984) for the Hudson River–Raritan estuarine system, New York, one of the few comprehensive estimates available for the U.S. East Coast. The annual discharge of metals and the synthetic organic compounds PCB and chlordane (Table 2) has been estimated from mass-balance calculations using the amounts accumulated in estuarine sediments (M_s) and the total input of contaminants from rivers and anthropogenic discharges (M_i). As shown in Table 2, dredge disposal can account for 11 to 62 % of the total net contaminant flux to the shelf.

Table 2. Net contaminant fluxes from the Hudson–Raritan estuary to coastal waters; from Olsen *et al.* (1984).

Contaminant	Advected seawards[a] (t/yr)	Dredge disposal[b] (t/yr)	Total (t/yr)
Copper	870	275	1 145
Zinc	2 900	375	3 275
Lead	460	325	785
PHCs	4 200	2 100	6 300
PCBs	1·4	1·7	3
DDD	No data	0·1	>0·1
Chlordane	0·06	0·1	0·16

[a]The advected metal, PCB, and chlordane fluxes were calculated using the accumulation data by Olsen *et al.* (1984) and total inputs determined by Mueller *et al.* (1982).
[b]Dredge disposal fluxes were calculated from records of sediment removal and average contaminant concentrations in the dredged material.

Concluding commentary

The northern U.S. East Coast estuaries are effective traps for sediment and, hence, for particle-reactive contaminants. The removal and redistribution of particulate material in estuaries, and in the coastal zone in general, are important processes that need to be accounted for in global budgets of fluvial flux into the ocean. Calculation of these fluxes is not a simple task. Accounting for materials requires more data than now exist, in particular, the natural and anthropogenic exchanges at seaward boundaries, identification of steady state over a certain time span, accounting for large temporal variations of inputs and outputs and biologically mediated fluxes, and the determination of uncertainties.

This is contribution number 1324 of the Virginia Institute of Marine Science.

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