4 Sedimentary Processes in the Hudson River Estuary

Henry Bokuniewicz

ABSTRACT The Hudson River estuary is narrowly confined in its rocky valley. Unconsolidated sediments available to the estuary are primarily glacial till and glacial lake deposits. Estimates of sediment sources to the estuary range between 365,000 and 1.02 million metric tons (MT) y^{-1} at the head of tide with an additional amount to be added along the tidal estuary of between 80,000 and 390,000 MT y^{-1}. Tidal resuspension and transport is important throughout the estuary but fine-grained sediment transport associated with the recirculation of salt water is confined to the lower reaches. A substantial marine source of sediment is likely, but of uncertain magnitude. Two turbidity maxima appear to be generated by different mechanisms. One is formed near the head of salt and migrates down the estuary during times of high freshwater discharge. The other arises in mid-estuary. It is generated by tidally modulated and geomorphically controlled salinity fronts. A marine source of sediment is likely to be substantial.

Introduction

The Hudson River estuary, or the lower Hudson as it is sometimes called, begins where the tidal influence is first felt at Troy, New York, 240 kilometers (km) north of the Battery. From this point, the combined discharge of the upper Hudson and Mohawk rivers collects additional water from the drainage basins of twenty other, smaller tributaries. The intrusion of salt water is limited to the lower reaches and can extend 120 km above the Battery at times of low freshwater discharge.

The estuary acts as a machine for transporting sediment with two special, estuarine features. The first of these is the reversing tidal current. The Native American name for the Hudson is roughly translated as the "river that flows both ways." This tidal influence reaches all the way to the dam at Troy. Sediment introduced to the estuary is transported by tidal currents. Sand is usually moved near the estuary floor and sand transport can be recognized by the occurrence of ripples, or larger sand waves on the bottom. Because of the tidal conditions, sand is sometimes moved up the estuary and sometimes down.

The second distinguishing character of the estuarine sedimentary system is its relationship to the geochemical estuary, that is, the region of circulation of salty water. More dense, more saline water flows into the estuary at the sea floor while fresher, less dense surface water flows out to the sea. Within the geochemical estuary, fine-grained, suspended sediment is redistributed into turbidity maxima; that is, a region from which the concentration of suspended sediment decreases both upstream and downstream. Because of the landward circulation of bottom water, a marine source of sediment is likely. Fine-grained sediment is transported as suspended load in the estuary and deposited, resuspended, and redeposited many times before it is permanently buried in sediment deposits or exported to the sea. The deposition of fine-grained sediment is rapid in dredged navigation channels creating the need for continued maintenance.

The processes by which this transport occurs are extremely variable and cannot be predicted with certainty. Some measurements are available to document the general characterization of these processes, but there is little information concerning their variability in time and space. These processes are considered below.

Background

The Hudson and Mohawk Rivers transverse predominantly erosion-resistant uplands, although the valley itself occupies a terrain of erosion-susceptible shale. The lower Hudson crosses six geologic terrains. From Troy to Cornwall, the river runs through a valley in the Appalachian Ridge and Valley Province. This area is underlain by gently folded and tilted siltstones, shales, and carbonate rocks (Sanders, 1974). From Cornwall-on-Hudson southward to Peekskill, the river cuts through the Hudson Highlands, a band of resistant, Precambrian crystalline rocks. Below Peekskill, the west bank of the river skirts the rocks of the Newark Basin. These are predominantly Triassic and Jurassic Period sandstones, shales, and volcanic rocks (Sanders, 1974) and include the Palisades escarpment. The east bank is formed of high-grade metamorphic rocks of the Manhattan Prong of the New England Uplands: Precambrian and Lower Paleozoic Era schists, marble, quartzite, and gneiss. The Hudson discharges into the Upper and Lower bays on New York Harbor spilling out across the unconsolidated sediments of the Coastal Plain to the Atlantic Ocean.

All these rocks constrain the river in a resistant foundation wherein sediment sources are largely confined to a veneer of glacial deposits. Glacial tills, drift, and outwash sands blanket the entire drainage area. Most valleys of the tributaries are lined with unconsolidated silts and clays originally deposited in glacial lakes during the retreat of the Wisconsin glaciation. Ground moraine tends to be relatively resistant to erosion but can supply a wide range of grain sizes to the river. Sand enters the system from local concentrations of glacial sand bodies, while silt and clay can be provided from the reworking of glaciolacustrine deposits. In the lower reaches of the river, these sources are supplemented by a supply of sediment up-estuary from the sea. Sand from the Coastal Plain can migrate into the river under tidal influences and fine-grained, marine sediments are recycled into the Hudson by a characteristic, estuarine circulation.

Most of the lower Hudson drainage basin (57 percent) is forested, however anthropogenic influences permeate the entire estuary. Dredged areas comprise about 8 percent of the area of the estuary or some 23 km^2 out of a total surface area of 282 square kilometers above the Battery (Ellsworth, 1986). The banks of the estuary have been extensively stabilized by bulkheads and "rip-rap," or railroad beds, which run up the shore on both sides of the estuary. About 2 percent of the west shore and 21 percent of the east shore is stabilized by the railroad (Ellsworth, 1986). Rocky shoreline or stabilized shoreline accounts for approximately 43 percent of the total shoreline. The main stem of the estuary is dammed at Troy. Tributaries below Troy may be dammed or otherwise restricted by causeways supporting the railroads along the shores.

Important Processes

SEDIMENT INPUT

The amount of sediment delivered to the Hudson estuary is an important, but elusive number. The most direct measurements are made by periodically sampling the river water, determining the amount of suspended sediment per liter of water, and multiplying that by the discharge around the time of sampling. It can only be done easily above the tidal influence. Because it is an engaging task, it is not done all the time nor has it been done on every tributary. In addition, the sediment delivery is discontinuous; almost all the sediment supplied in a given year may be introduced over a few days during floods, exactly the time when measurements are most difficult to make. The sediment delivery can also vary widely from year to year. In the absence of direct measurements, sediment input may be calculated from estimates of the loss of soil from the land surface, but this isn't any easier or more certain.

As a result of such difficulties, estimates for the fluvially derived sediment input to the Lower Hudson Basin are scarce. Dole and Stabler (1909) put the total sediment discharge at Troy as 365,000 metric tons per year, (MT y^{-1}) while Panuzio (1965) places it at 750,000 MT y^{-1} at kilometer 120. For 1977, 1.02 million MT were supplied to the lower Hudson at Troy (Olsen, 1979), and 920,000 MT y^{-1}, on average, over thirty years (1947–77). Additional sediment is supplied by the tributaries entering the tidal portion of the river below the dam at Troy; these values must be added to the sediment load entering at Troy. Based on the relative areas of the drainage basin (Olsen, 1979), the river-borne sediment input from the lower Hudson provides 310,000 MT y^{-1} for 1977, and 280,000 MT y^{-1} for the thirty-year average. A different estimate can be made using the data from the United States Department of Agriculture, Soil Conservation Service to obtain a delivery ratio. In this way, the suspended sediment yield for each square kilometer was estimated to be between 25 MT km^{-2} y^{-1} and 32 MT km^{-2} y^{-1} (Ellsworth, 1986). Correspondingly, the calculation for the entire lower Hudson drainage basin, which has an area of 1.2 million hectares, is between 300,000 MT y^{-1} and 390,000 MT y^{-1}. A third estimate (Howarth, Fruci, and Sherman, 1991) was calculated by applying a generalized watershed loading model to the Hudson River drainage basin. The model result gave a three-year average (1983–86) fluvial sediment input for the lower Hudson of 260,000 MT y^{-1}.

Yet another model, the Hydrologic Simulation Program Fortran, was used for the quantification of the terrestrial source of sediment from the tributaries below Troy (Lodge, 1997). Twenty tributaries comprising the lower Hudson drainage basin were found to supply 80,000 and 100,000 MT y^{-1}, for 1992 and 1993, respectively. The combined discharge of the Catskill, Kinderhook, Normans Kill, and Wallkill creeks alone contributed 60 percent of the sediment load. New material was calculated to have a residence time of 22 days in the estuary (Lodge, 1997).

The sources of fine-grained sediment are diverse and distributed over 34,000 square kilometers. Little is supplied directly by erosion of the river banks (Ellsworth, 1986). The abundance of sand in the Hudson north of Kingston (Coch, 1986) is supplied by the local tributaries and, in part, by scouring of the channel floor.

MARINE SOURCES

The landward (i.e, up-estuary) transport of sediment seems common at the mouths of estuaries, and a marine supply can be substantial in some estuaries (Biggs, 1970; Bokuniewicz, Gebert, and Gordon, 1976; Meade, 1969; Hobbs et al., 1992; Turner, Millward, and Tyler, 1994). In Chesapeake Bay, for example, flood-dominated channels transport sand into the estuary mouth (Ludwick, 1974). This situation also seems to exist at the mouth of the Lower New York Bay (Swift and Ludwick, 1976). Large sandwaves have been found on the floor of the Ambrose Channel with asymmetry indicating landward transport. In the Hudson itself, the coarsening of sediments from the Hudson Highlands to the Battery has been attributed in part to the up-estuary transport of sand from the Coastal Plain (Coch, 1976).

Many estuaries are sinks for sediments (e.g., Nichols, 1977; Yarbo et al., 1983; Hobbs et al., 1992). The Hudson River Estuary also appears to be an effective trap for fine-grained sediment that is capable of absorbing not only fine-grained sediment supplied by its rivers but also a substantial ocean source (Bokuniewicz and Coch, 1986; Olsen et al., 1984; Ellsworth, 1986). Such behavior seems common, especially in partially mixed estuaries like the Hudson. It has been explained by the superposition of characteristic estuarine circulation on the suspended sediment distribution (Schubel and Carter, 1984) in conjunction with rapid particle settling speeds due to agglomeration. In general, the estuarine, density-driven circulation drives saline bottom water landward into the estuary while fresher surface water flows out. Higher concentrations of suspended sediment tend to be found near the estuary floor both because particles tend to sink to the bottom and because sediment on the seafloor can be resuspended by waves and tidal currents. Higher concentrations of suspended sediment in the bottom waters are, therefore, imported by the estuarine circulation.

The import of fine-grained, marine sediment into estuaries along the east coast has often been proposed. In the Hudson, the geochemical signature of silts and clays provided evidence that 30 percent of the fine-grained sediment being deposited in the estuary entered at its mouth (Olsen et al., 1984) and, an attempted sediment budget for the Hudson River estuary (Ellsworth, 1986) needed to invoke a marine source to balance the sources and sinks. At the Battery, the estimated input from the sea was between 139,000 and 734,000 MT y^{-1} (with a fluvial input at Troy estimated at 870,000 MT y^{-1}; Ellsworth, 1986). In addition, grain size analysis of bottom sediments suggests that the bottom sediments in the lower estuary are composed of one component of sand from the ocean and another of particles in flocs (Gibbs, Jha, and Chakrapani, 1994; Coch, 1976).

There is little information concerning the production of sediment particles (opal) in situ. Production rates have been estimated to correspond 135,000 MT y^{-1} over the entire area of the estuary (Ellsworth, 1986).

SUSPENDED SEDIMENT CONCENTRATION

Early measurements of the ambient suspended sediment concentrations in the upper reaches of the estuary report an average concentration of 17 mg L^{-1} (at kilometer 190; Dole and Stabler, 1909) and 33 mg L^{-1} (at kilometer 120; Panuzio, 1965). A

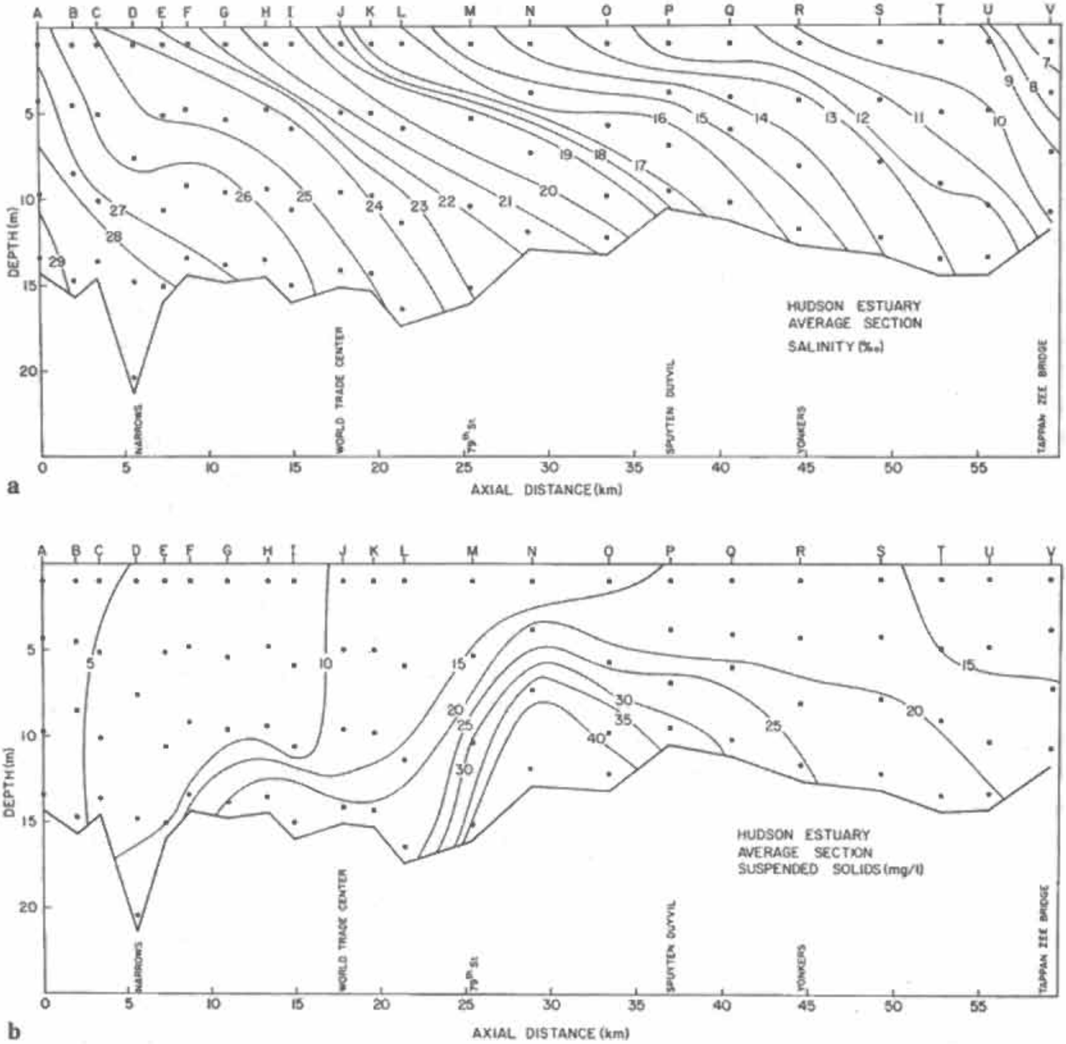


Figure 4.1. Average salinity (a) and average, suspended sediment concentrations (b) along the axis of the Hudson (from nine sections between November, 1980 and September, 1981; Hirschberg and Bokuniewicz, 1991).

value of 33 mg L^{-1} was also obtained from measurements at kilometer 30 over a tidal cycle (Olsen, 1979). Seasonal sampling along the axis of the estuary yielded an average concentration of 35 mg L^{-1} with mean values of 25 mg L^{-1} at the surface and 46 mg L^{-1} near the estuary floor (Arnold, 1982). Suspended particles appear in two dominant modes; those less than 4.65 μm in diameter and those greater than 22.1 μm (Menon, Gibbs, and Phillips, 1998).

Tidal cycle variations may range over a factor of 3 or 4 (at kilometer 30; Olsen, 1979) and seasonal variation from 17 to 45 mg L^{-1} in the upper reaches and 23 to 26 mg L^{-1} in the lower reaches (Arnold, 1982). In the upper reaches, the variation of suspended sediment load is expected to be due to changes in the delivery of sediment past Troy over the seasons, while in the lower reaches the variations seem to be controlled more by tidal resuspension (Arnold, 1982).

TURBIDITY MAXIMA

The Hudson River Estuary appears to have two turbidity maxima formed by different mechanisms. One is associated with the landward limit of sea salt. It is apparently formed by the estuarine circulation,

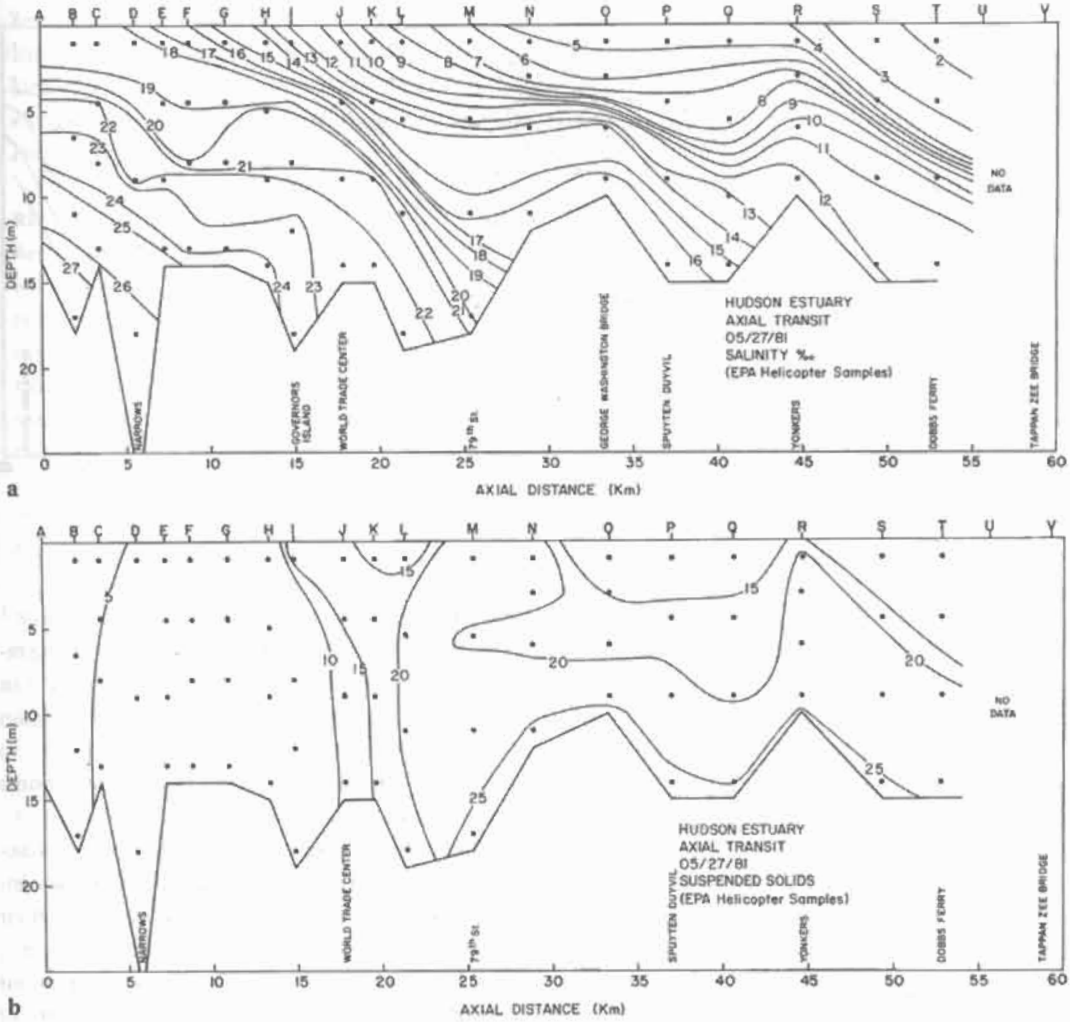


Figure 4.2. Near-synoptic, axial sections of salinity (a) and suspended sediment concentrations (b; 27 May, 1981).

although its location may be modified by bathymetric influence in the deepest parts of the estuary (the gorge). The second is formed at mid-estuary by the tidally modulated and geomorphically controlled formation and migration of salt fronts into the estuary. Secondary, mid-estuary turbidity maxima are sometimes seen, but these may be residuals from the previous tide.

Evidence for a turbidity maximum in a relatively limited reach of the estuary along the Manhattan shore below the George Washington Bridge was documented in a series of vertical distributions of water temperature, salinity, and suspended sediment concentrations measured along the axis of the Hudson River Estuary nine times between November 1980 and September 1981 (Hirschberg and Bokuniewicz, 1991). The average salinity section and the average section of suspended sediment concentration are shown in Figure 4.1. The observations did not extend to the limit of sea salt, but a strong turbidity maximum was found at the estuary floor between 79th Street and the Spuyten Duyvil (approximately at the position of Grant's Tomb at 122nd Street). Suspended sediment concentrations reached levels over 100 mg L^{-1} and the highest recorded value was 447 mg L^{-1}. This turbidity maximum, however, was not present in all the individual transects. On 27 May 1981, a nearly synoptic section was done from a helicopter (Fig. 4.2). Although there was well-developed

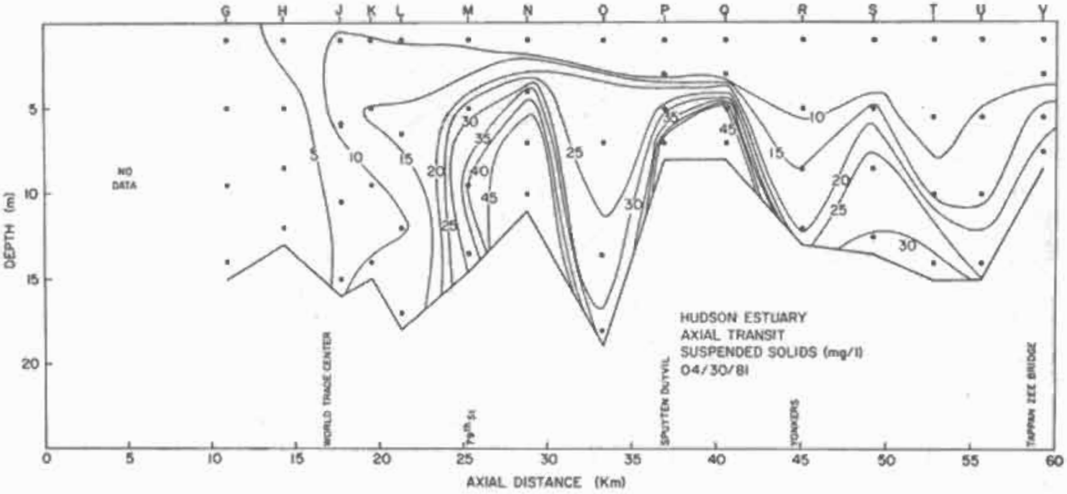


Figure 4.3. Axial section of the suspended sediment concentration showing two, mid-estuary turbidity maxima (30 April, 1981).

salinity stratification, no strong turbidity maximum was found. At another time (30 April 1981; Fig. 4.3), two turbidity maxima were found. This region of elevated turbidity was not associated with a local permanent or quasi-permanent salt front as one might expect in light of the conventional wisdom concerning the formation of estuarine turbidity maxima.

The turbidity maximum (Fig. 4.1) was located in the vicinity of the average position of the strong salinity gradients. Observations of this turbidity maximum showed near-bottom suspended sediment concentrations of 100 to 200 mg L^{-1} in the summer of 1992 increasing to between 100 to 400 mg L^{-1} during high discharge in 1993 (Geyer, 1995), although maximum concentrations reached 800 mg L^{-1} (Geyer, 1995). In the turbidity maximum, the concentration of the finest grained particles (less than 4.65 μm in diameter) increases about 50 percent over ambient levels to where it comprises 55 percent to 60 percent of the suspended load (Menon et al., 1998).

DEPOSITION

Fine-grained sediment may ultimately be deposited in wetlands, in dredged channels or in undredged areas of the estuary floors. Bridge borings disclosed a layer of estuarine sediment as much as 61 m thick in the Hudson (Newman et al., 1969). If we assume that estuarine conditions were established by 12,000 years B.P., the long-term accumulation rate is something less than 0.5 cm y^{-1} Direct measurements of deposition rates using radiometric techniques vary from 1 to 5 cm y^{-1} in undredged areas south of the George Washington Bridge, 1 to 3 cm y^{-1} in marginal zones and 0.1 to 0.3 cm y^{-1} on the estuary floor north of the George Washington Bridge (Olsen, 1979).

The conventional wisdom is that marshes accumulate to keep pace with sea level rise. Indeed they must if they are going to maintain their position over thousands of years. At the Battery, sea level is rising at an average rate of about 3 mm y^{-1}. Combining this with an estimate of marsh sediment composition, Ellsworth (1986) calculated a total deposition of 12,000 MT y^{-1} over the 22.8 km^2 of marshland. In the lower Hudson, measured rates are more rapid. Measurements of sedimentation rates at five marshes (Piermont, Iona, Tivoli Bay North, Tivoli Bay South, and Stockport Flats) yielded rates from 2 mm y^{-1} to greater than 11 mm y^{-1} (Peller, 1985; Robideau, 1997). With an average rate of 6 mm y^{-1} the rates tended to be slightly higher in the north and slightly lower in the south. On the average, this would raise the total marshland deposition to 24,000 MTy^{-1}.

The lower 18 kilometers of the estuary has been extensively dredged. Ninety-five percent of the total annual dredged sediment is removed from this area (Ellsworth, 1986). In the decade between 1966 and 1976, 705,990 m^3 of sediment were removed (Conner et al., 1979). Deposition rates in dredged areas, therefore, may average 14 cm y^{-1}. The deposition rate is not uniform. Recently in the estuary along the Manhattan shore, observations show that 15 cm or more could be deposited in a single freshet (Woodruff, 1999).

RESUSPENSION

Resuspension rates may be determined directly by testing undisturbed sediment samples in a flume or by monitoring conditions at the sea floor closely over time. Flume tests have not been done on Hudson sediment but the importance of resuspension has been calculated from measurements of changes in the near-bottom suspended sediment concentration (Geyer, Woodruff, and Traykouski, 2001) at locations in the lower estuary along the Manhattan shoreline. Within the turbidity maximum, concentrations of suspended sediment were observed to decrease to low levels during slack tides from levels of several hundred milligrams per liter (Geyer, 1995). Although this tidally modulated deposition suggests that subsequent tidal resuspension is necessary to maintain the turbidity maximum, Geyer (1995) did not find a correlation between the suspended load and water velocity, suggesting that advection was the predominant control of concentrations.

Alternatively, resuspension rates may be estimated by assessing the vertical flux of settling sediment particles. The downward vertical flux of particles to the seafloor is often found to be much larger than the net, long-term deposition rate. As a result, the vertical flux to the seafloor is balanced to a first approximation by resuspension. One way to determine the vertical flux is from near-bottom sediment traps. These devices are designed to intercept the flux of sediment to the seafloor. Measurements of the vertical particle flux in the vicinity of the turbidity maximum ranged from 106 g cm^{-2} y^{-1} to 586 g cm^{-2} y^{-1} (Achman, Brownawell, and Zhang, 1996), which are three orders of magnitude greater than the long-term accumulation rate. Assuming that this is the rate at which sediment reaches the seafloor, this is also the resuspension rate.

Few measurements are available in the estuary and these were not taken for the purposes of determining the flux at the seafloor. Estimates can also be made from a combination of settling velocity and concentration. If 0.04 cm s^{-1} is taken as the settling velocity (Arnold, 1982) and 30 mg L^{-1} taken as a typical concentration away from the turbidity maximum, the vertical settling flux becomes 1.2×10^{-6} or 38 g cm^{-2} s^{-1}. This is lower than the sediment trap results but still much higher than the long term accumulation rate. As a result, it may be considered an estimate of resuspension.

SANDWAVES

Sandwaves are large ripples or underwater dunes that indicate the movement of sand along the estuary floor by currents. They may be active, with particles being moved continuously by the river flow or alternatively by the tides, or they may be relic, inactive fractures formed by unusual past events such as floods or exceptionally strong tides. They are often asymmetric in cross-sectional form with a steeper face in the direction of net transport. As has already been mentioned, asymmetric sandwaves in the mouth of New York Harbor indicate a net transport of sand up-estuary.

In the Hudson River Estuary, patches of asymmetric sandwaves are found as, for example, near Saugerties (Fig. 4.4; Bell et al., 2000). These usually show evidence of down-estuary transport of sand under the influence of the freshwater discharge and the ebbing tide. Where the estuary is divided into two channels, however, by a median shoal or island, one channel will show evidence of up-estuary transport under flooding tides while its partner will be dominated by down-estuary transport.

Discussion: Mechanism for a Mid-Estuary Turbidity Maximum

The reach of the estuary in the vicinity of the George Washington Bridge is characterized by large fractional changes in channel cross section area, in maximum channel depth, and in width. The channel cross-sectional area varies from approximately 11,000 m^2 to 177,000 m^2 (R. Wilson, 1999 Marine Sciences Research Center, personal communication). Preliminary observation in 1992, using a 200 KHZ echo sounder to visualize the halocline, and an AMS CTD showed the existence of large, quasi-stationary undulations in the halocline during maximum ebb as well as bottom salinity fronts situated in the vicinity of channel expansions. Hydraulically influenced, intratidal

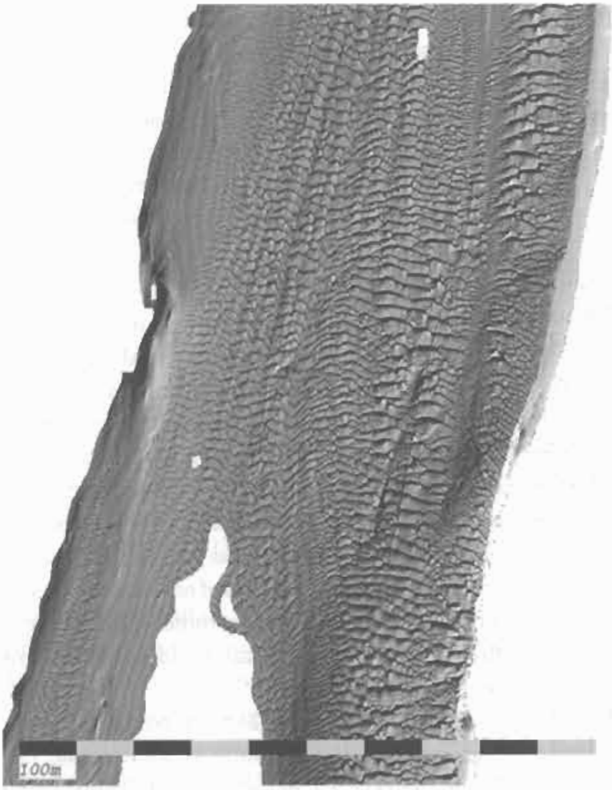
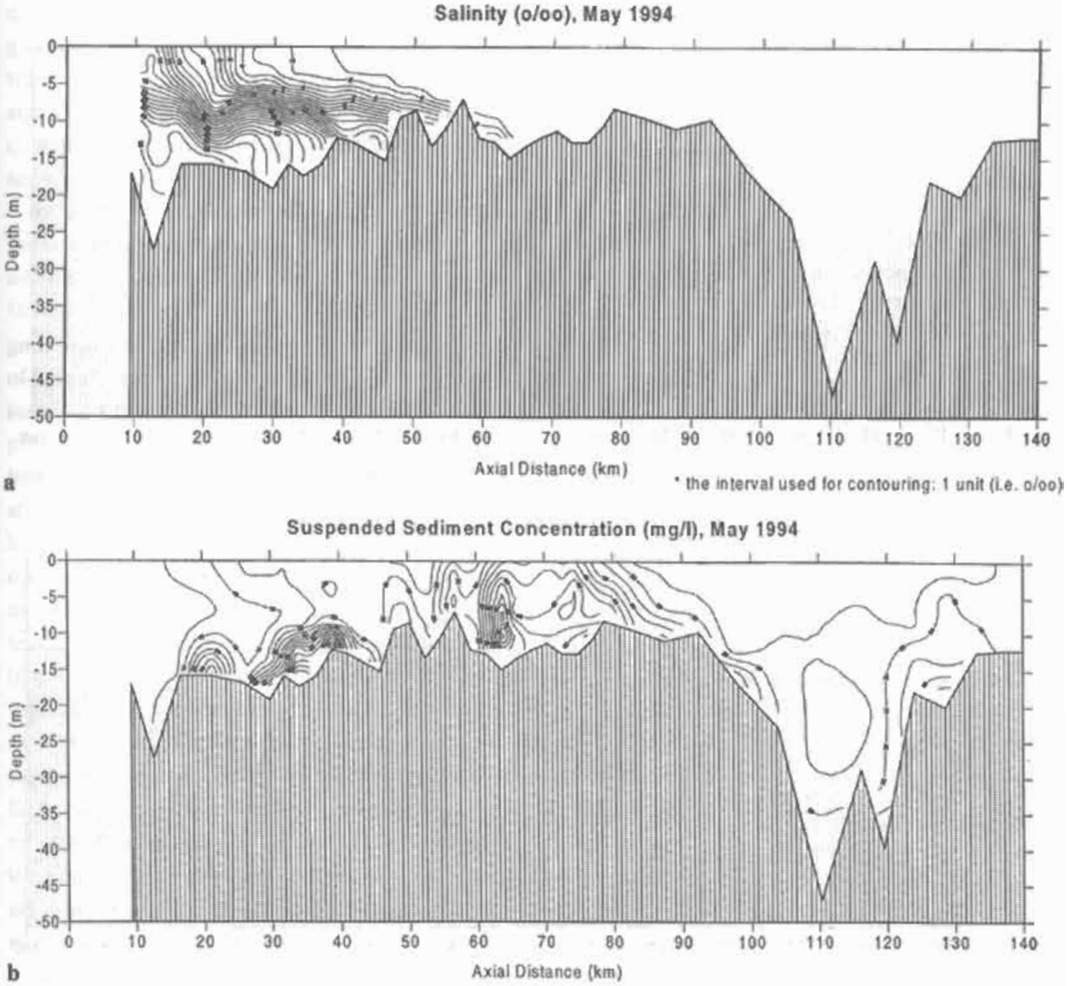


Figure 4.4. Sandwaves as shown by a multibeam survey in the vicinity of Saugerties. Bedforms in the left-hand (west) side appear to be migrating up-estuary while those in the right hand (east) side are migrating down-estuary (courtesy of R. Flood and V. Ferrini, Marine Sciences Research Center, Stony Brook University, Stony Brook, NY).

halocline behavior could lead to advection of bottom fronts, which would influence particles trapping the area.

Evidence suggests the following mechanism for the formation of the mid-estuarine turbidity maximum (Bokuniewicz and Ullman, 1995). During an ebbing tide, a salt front is found downstream of the George Washington Bridge as a result of the downstream expansion of the channel below the construction at the Bridge. This front is characterized by strong salinity gradients that intersect the bottom and a strong halocline. Suspended particles settling through the halocline become trapped in the lower water layer. As the ebb tide wanes and the flood begins, the salt wedge moves northward into the estuary gravitationally. Additional sediment is resuspended as it transgresses and this sediment is trapped behind the front under the halocline. The front's progress seems to be arrested on the bathymetry south of the George Washington Bridge even as the flood continues as evidenced by a rise in the halocline. During the flood, suspended sediment apparently is also transported laterally to the west side of the river (Geyer, 1995). As the flood tide ends and the ebb begins, the salinity gradients become unstable and the front breaks down. This event apparently can strand turbid water near the northernmost position of penetration of the salt wedge while a new front is generated further downstream to begin the process again. I would suggest that the second mid-estuary turbidity maximum, which is sometimes seen north of the first, may be turbid water formed on the previous tide and stranded as the next ebb began.

The occurrence of these turbidity maxima are influenced, as expected, by the freshwater discharge. The mid-estuary maximum tends to remain fixed in the vicinity of Grant's Tomb and seems to be found as long as the freshwater discharge allows saltwater penetration to that location. The maximum at the head of salt migrates down the estuary at times of high discharge and up-estuary at low. The freshwater discharge to the estuary averages 550 m^3 s^{-1} (Olsen, 1979). Figure 4.5 shows the axial distribution of salt and suspended sediment in May 1994, when the discharge was 2,690 m^3 s^{-1}.


Salinity (o/oo), May 1994

* the interval used for contouring: 1 unit (i.e. o/oo)

Suspended Sediment Concentration (mg/l), May 1994

Figure 4.5. Axial distribution of salt (a) and suspended sediment (b) under high discharge (May, 1994). The salinity contour interval is one part per thousand; the suspended sediment concentration contour interval is 10 mg L^{-1}. The Battery is at kilometer 31 on this scale.

Three turbidity maxima were seen. One at the limit of sea salt, a second south of its expected position near Grant's Tomb and a third south of the Battery. By contrast, the summer of 1995 was a drought. The discharge in September 1995 was 255 $m^3 s^{-1}$ and the axial distribution of salinity and suspended sediment is shown in Figure 4.6. The estuary is well mixed and two distinct turbidity maxima are seen; one at the head of salt, and one near Grant's Tomb.

Important Unsolved Problems

Available observations provide us with information about all the major processes occurring in the estuary. The Hudson, however, is both spatially diverse and temporally variable so without adequate spatial and temporal observations, the integrated behavior of sediment in the estuary remains elusive. As a result, managers often find answers to their questions unsatisfying and inadequate. For example, a sediment budget for the estuary requires deposition rates in the various substrates on the estuary floor. These facies have not been mapped in detail, although a current effort by the New York State Department of Environmental Conservation is moving in that direction (see chapter by Bell et al., this volume). Even when they are, deposition rates have been determined in only a few locations, so large uncertainties will remain in the amount of sediment deposited.

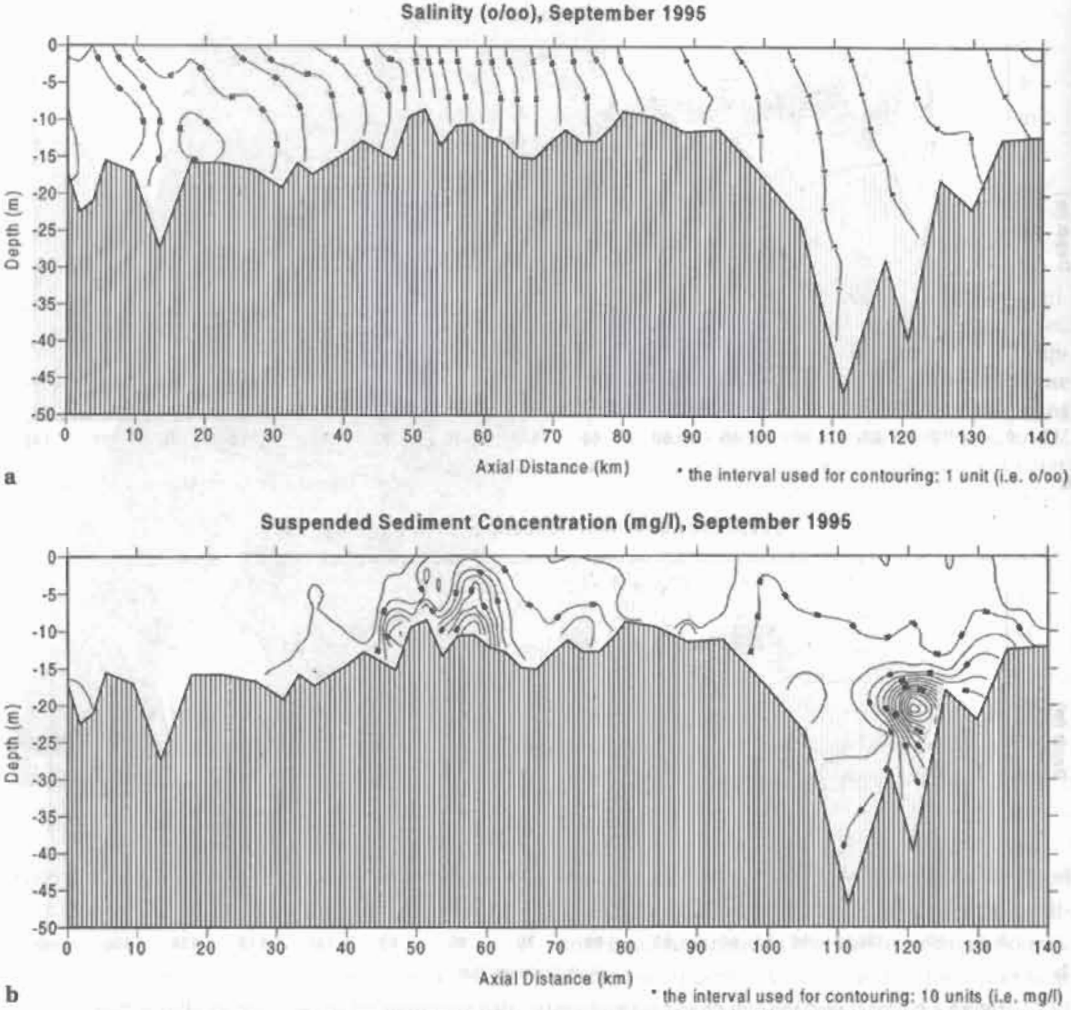


Figure 4.6. Axial distribution of salt (a) and suspended sediment (b) under low discharge (September, 1995). The salinity contour interval is one part per thousand; the suspended sediment concentration contour interval is 10 mg L^{-1}. The Battery is at kilometer 31 on this scale.

As we have seen, even straightforward questions, like how much sediment is brought into the estuary by rivers, are answered only within fairly broad ranges. Monitoring has not been continuous. Storm events are hostile to any measurement program and easy to miss. Most of the tributaries are not monitored, forcing reliance on indirect calculations.

The amount of resuspension poses similar diffi- made to measure spatial or temporal variability. As a result, resuspension can only be quantified in the most general terms. An oceanic source also seems likely, but what is its magnitude? How does it vary with changes in discharge? Could it be that the oceanic source buffers the system? Even without increases in the fluvial sources, increased dredging may result in an increased deposition of sediments of marine origin.

question on the road to these answers are the degree and mechanism of lateral transport in the estuary. Some work has been done on this issue but its significance remains to be integrated into a more comprehensive conceptual model of the estuarine sedimentary system.

In the future of estuarine research, in general, there needs to be attention given to comparisons between estuaries. Thirty years ago, Emery and Uchupi (1972) pointed out that far more effort has gone into making detailed studies of sediments of individual estuaries than into either comparing results from a variety of estuaries with similar physical or geological characteristics, or into critical evaluation of processes. Their observation still holds true today. Schemes for classifying the hydraulic regimes of estuaries have been developed and widely used but little effort has been devoted to comparing estuarine sedimentary systems. Holistic comparative studies are needed to better understand those sedimentary processes that characterize estuaries. The Hudson-Raritan estuarine system invites comparisons with a wide variety of other local systems such as Narragansett Bay, Long Island Sound, Peconic Bay, and the Connecticut River estuary. Of these, the Hudson system is probably the most heavily impacted by human activities. Anthropogenic effects add an additional complicating factor that is not present in less urbanized estuaries.

REFERENCES

Achman, D. R., Brownawell, B. J., and Zhang, L. 1996. Exchange of Polychlorinated Biphenyls between Sediment and Water in the Hudson River Estuary, *Estuaries* **19**: 950–65.

Arnold, C. A. 1982. "Modes of Fine-grained Suspended Sediment Occurrences in the Hudson River Estuary." Marine Sciences Research Center, State University of New York at Stony Brook, Stony Brook, NY. Master's Thesis: 102 pp.

Bell, R. E., Flood, R. D., Carbotte, S. M., Ryan, W. B. F., McHugh, C., Cornier, M., Versteeg, R., Chayes, D., Bokuniewicz, H., Ferrini, V., and Thissen, J. 2000. Hudson River Estuary Program Benthic Mapping Project Final Report. NY State Department of Environmental Conservation, Albany, NY.

Biggs, R. B. 1970. Sources and distribution of suspended sediment in Northern Chesapeake Bay, *Marine Geology* **9**: 187–201.

Bokuniewicz, H. J. 1996. *Building the Turbidity Maximum in the Hudson River Estuary*. Marine Sciences Research Center, State University of New York at Stony Brook, Stony Brook, NY. Special Report 115. 35 pp.

Bokuniewicz, H. J., and Coch, N. K. 1986. Some management implications of sedimentation in the Hudson-Raritan estuarine system. *Northeastern Geology and Environmental Sciences* **8**: 165–70.

Bokuniewicz, H. J., Gebert, J., and Gordon, R. B. 1976. Sediment mass balance of a large estuary: Long Island Sound. *Estuarine, Coastal and Shelf Science*, **4**: 523–36.

Bokuniewicz, H., McTiernan, L., and Davis, W. 1991. Measurement of sediment resuspension rates in Long Island Sound. *Geo-Marine Letters* **11**: 159–61.

Bokuniewicz, H. J., and Ullman, D. 1995. *Turbidity Distribution in the Hudson River Estuary*. Marine Sciences Research Center, State University of New York at Stony Brook, Stony Brook, NY. Special Report 109. 12 pp.

Coch, N. K. 1976. Temporal and aerial variations in same Hudson River Estuary sediments, March – October, 1974: Geological Society of America, Northeastern Section, Abstract with Programs 8: 153, Boulder, CO.

1986. Sediment characteristics and facies distribution in the Hudson System. *Northeastern Geology and Environmental Sciences* **8**: 109–29.

Conner, W. G., Aurand, D., Leslie, M., Slaughter, J., Amr, A., and Ravenscroft, F. I. 1979. Disposal of dredged material within the NY District Vol. 1 – Present Practices and Candidate Alternatives, MITRE Corporation, McLean, VA: 362 pp.

Dole, R. B., and Stabler, H. 1909. Denudation. U.S. Geological Survey. Water Supply Paper No. 234: 78–93.

Ellsworth, J. M. 1986. Sources and Sinks for fine-grained sediment in the Lower Hudson River, *Northeastern Geology and Environmental Sciences* **8**: 141–55.

Emery, K. A., and Uchupi, E. 1972. Western Atlantic Ocean: Topography, rocks, structure, water, life and sediments. Amer. Assoc. of Petrol. Geol. Mem., 17. 532 pp.

Geyer, W. R. 1995. *Final Report: Particle Trapping in the Lower Hudson Estuary*. Hudson River Foundation, New York. 30 pp.

Geyer, W. R., Woodruff, J. P., and Traykouski, P. 2001. Sediment Transport and Trapping in the Hudson Estuary. *Estuaries* **24**: 670–79.

Gibbs, R. J., Jha, P. K., and Chakrapani, G. J. 1994. Sediment Particle Size in the Hudson River Estuary, *Sedimentology* **41**: 1063–68.

Hirschberg, D., and Bokuniewicz, H. J. 1991. Measurements of water temperature, salinity and suspended sediment concentrations along the axis of the Hudson River estuary 1980–1981. Marine Sciences Research Center, State University of New York at Stony Brook, Stony Brook, NY. Special Data Report No. 11: 30.

Hobbs, C. H., Halka, J. P., Kerkin, P. T., and Carron, M. J. 1992. Chesapeake Bay sediment budget. *Journal of Coastal Research* **8**: 292–300.

Howarth, R. W., Fruci, J. R., and Sherman, D. 1991. Inputs of sediment and carbon to an estuarine ecosystem: Influence of land use. *Ecological Applications* **1**: 27–39.

Lodge, J. M. 1997. "A model of tributary sediment input to the tidal Hudson River." Marine Sciences Research Center, State University of New York at Stony Brook, Stony Brook, NY. Master's thesis. 143 pp.

Ludwick, J. C. 1974. Tidal currents and zig-zag shoals in a wide estuary entrance. Boulder, CO: Geological Society of America, Bulletin 85: 717–26.

Meade, R. H. 1969. Landward transport of bottom sediments in estuaries of the Atlantic Coastal Plain. *Journal of Sedimentary Petrology* **14**: 22–34.

Menon, M. G., Gibbs, R. J., and Phillips, A. 1998. Accumulation of muds and metals in the Hudson River estuary turbidity maximum. *Environmental Geology* **34**: 214–22.

Newman, W. S., Thurber, D. H., Zeiss, H. S., Rokach, A., and Musich, L. 1969. Late Quarternary geology of the Hudson River estuary: A preliminary report. *Transactions of the New York Academy of Sciences: Series II*. **31**: 548–70.

Nichols, M. M. 1977. Response and recovery of an estuary following a river flood. *Journal of Sedimentary Petrology* **47**: 1171–86.

Olsen, C. R. 1979. Radionuclides, sedimentation and accumulation of pollutants in the Hudson Estuary. Columbia University, New York, NY. Ph.D. Thesis, 343 pp.

Olsen, C. R., Larsen, I. L., Brewster, R. H., Cutshall, N. H., Bopp, R. F., and Simpson, H. J. 1984. A geochemical assessment of sedimentation and contaminant distribution in the Hudson-Raritan Estuary. NOAA. Technical. Report. NOS OMS 2: 101p.

Panuzio, F. L. 1965. Lower Hudson siltation. In *Proceedings of the Federal Inter-Agency Sedimentation Conference*, 1963. Miscellaneous Publication No. 970. Agriculture Research Service: 512–50.

Peller, P. 1985. Recent sediment and pollutant accumulation in the Hudson River National Estuary Sanctuary. In Cooper, J. C. (ed) Polgar Fellowship Reports, Hudson River Foundation, New York, NY.

Robideau, R. M. 1997. "Sedimentation rates in Hudson River marshes determined by radionuclide dating techniques." Rensselaer Polytechnic Institute, Troy, NY. Master's thesis, 115 p.

Sanders, J. E. 1974. Geomorphology of the Hudson Estuary. *Annals of the New York Academy of Science* **250**: 5–38.

Schubel, J. R., and Carter, H. H. 1984. Suspended sediment budget for Chesapeake Bay. In M. L. Wiley (ed). *Estuarine Processes*, New York: Academic Press, pp. 48–62.

Swift, D. J. P., and Ludwick, J. 1976. Substrate response to hydraulic processes. Grain size frequency distributions and bedforms. In Stanley, D. J. and D. J. P. Swift (eds.). *Marine Sediment Transport and Environmental Management*, New York: John Wiley and Sons. pp. 159–96.

Turner, A., Millward, G. E., and Tyler, A. O. 1994. The distribution and chemical composition of particles in a macrotidal estuary. *Estuarine, Coastal and Shelf Science* **38**: 1–17.

Woodruff, J. D. 1999. Sediment deposition in the Lower Hudson River estuary. Masters Thesis, Massachusetts Institute of Technology Woods Hole Oceanographic Institution.

Yarbo, L. A., Carlson, P. R., Fisher, T. R., Chanton, J. P., and Kemp, W. M. 1983. A sediment budget for the Choptank River estuary in Maryland USA. *Estuarine, Coastal and Shelf Science* **17**: 555–70.