SEDIMENTATION OF FINE-GRAINED PARTICLES IN LONG ISLAND SOUND: A REVIEW OF EVIDENCE PRIOR TO 1987

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ABSTRACT

A review of evidence, collected prior to 1987, reveals that the fine-grained sedimentary system of Long Island Sound has the following characteristics

1. The Sound has a trapping efficiency of 100%, that is, it is capable of retaining the entire annual supply of fine-grained sediment, or about 5.3×10^8 kg/year.
2. The total amount of fine-grained sediment held in suspension is about 2.5×10^8 kg or about one-half the annual supply. The residence time is, therefore, estimated to be 6 months.
3. Much, if not most, of the fine-grained sediment that accumulates in the navigation channels of the Sound's fringing harbors is supplied from the main body of the Sound. Dredges remove about 12×10^8 kg per year or about two and a half times the annual supply. The dredged sediment appears to be stored in permanent deposits at designated disposal sites on the Sound floor.
4. Resuspension and temporary redeposition occurs at a rate about 1000 times the rate of long term accumulation of fine-grained sediment in the Sound's surficial deposits.

Although the Sound effectively retains the fine-grained sediment supplied to it, within the Sound fine-grained sediment is widely dispersed by tidal resuspension and turbulent mixing.

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INTRODUCTION

More than a half million metric tons of fine-grained sediment are delivered to Long Island Sound every year. Deposition in the Sound seems to be able to accommodate the entire annual sediment supply, but the pathways by which sediment particles become incorporated into the permanent deposits on the Sound floor are tortuous. Every day an amount of sediment exceeding the total annual supply may be resuspended from the Sound floor by waves and tides and, at any one time, half of that material might be found in transport in the waters of the Sound. It is the purpose of this article to examine the sedimentary system of Long Island Sound in more detail in order to put the various components of this system into perspective.

Sediment budgets encompassing large areas of the coastal zone are usually subject to large uncertainties and the one discussed here is no exception. Estimates must be made of the rates of many different processes, all of which are extremely variable. Some of the site-specific data needed to do this will not be available and the available data is likely to vary both in quality and quantity. Nevertheless, sediment budgets may be useful for deciding the relative importance of various sediment sources and sinks and for identifying the most important fluxes of sediment. In this article, I will review the evidence collected prior to 1987 leading to the conclusion that Long Island Sound is a effective trap for fine-grained sediment and present some new information concerning the importance of resuspension in controlling the fate of particles in the Sound.

The data discussed here demonstrate the predominance of resuspension in controlling the vertical fluxes of particles in the Sound. In August, 1986, the U.S. Environmental Protection Agency (EPA) began field studies in the Sound as part of a nationwide Estuaries Program. One element of this program included investigations of suspended sediment distributions. Data continued to be collected and analyzed as this report was being written but I have not attempted to include any results of the EPA's ongoing program. This report, therefore, may be taken as a prelude to forthcoming conclusions of the National Estuaries Program's investigation of Long Island Sound.

Physical Oceanography

Long Island Sound is a large estuary between Connecticut on the north and Long Island, New York on the south (Figure 1). It is approximately 130 km long and 36 km wide at its widest point, covering an area of 3199.9 km^2 (Gordon, 1980). The median water depth is 20 m and 98% of the Sound floor is shallower than 47 m (Figure 2). The bathymetry in the eastern Sound is an irregular series of axial troughs and ridges with maximum water depths in excess of 100 m. The irregular bathymetry of the eastern Sound is separated from the central basin of the Sound by the Mattituck Sill (Figure 1). The low point along the sill is nearer the Connecticut shore where the water depth is about 25 m. West of the sill the thalweg of the Sound is oriented southwest across the central basin at a depth of about 30 m then approximately follows the north shore of Long Island west, passing to the south of Stratford Shoals. The deep trough then begins to diverge from

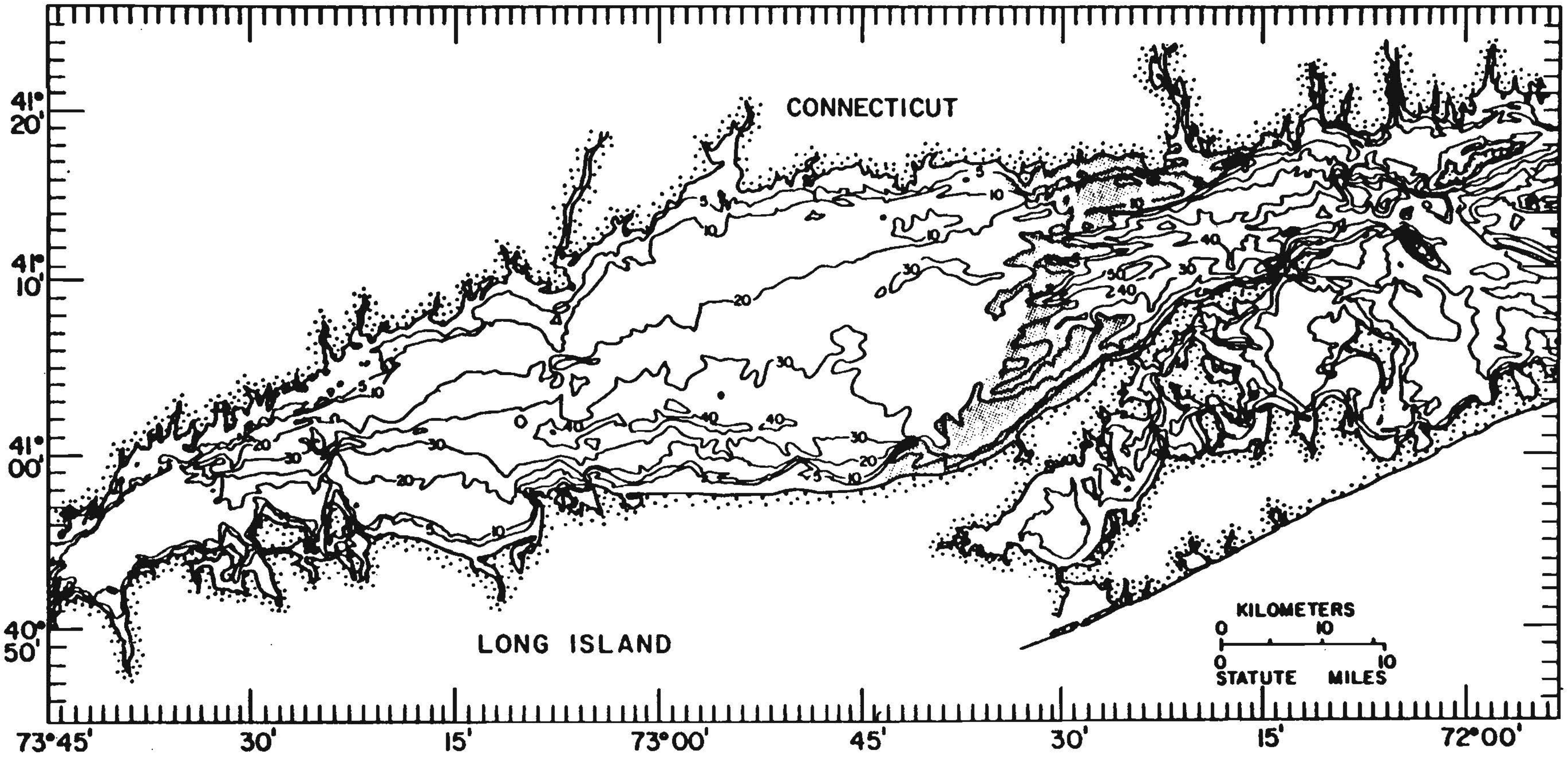


Figure 1. Bathymetric map of Long Island Sound. Bathymetric contours are in meters. The shaded area marks the location of Mattituck Sill.

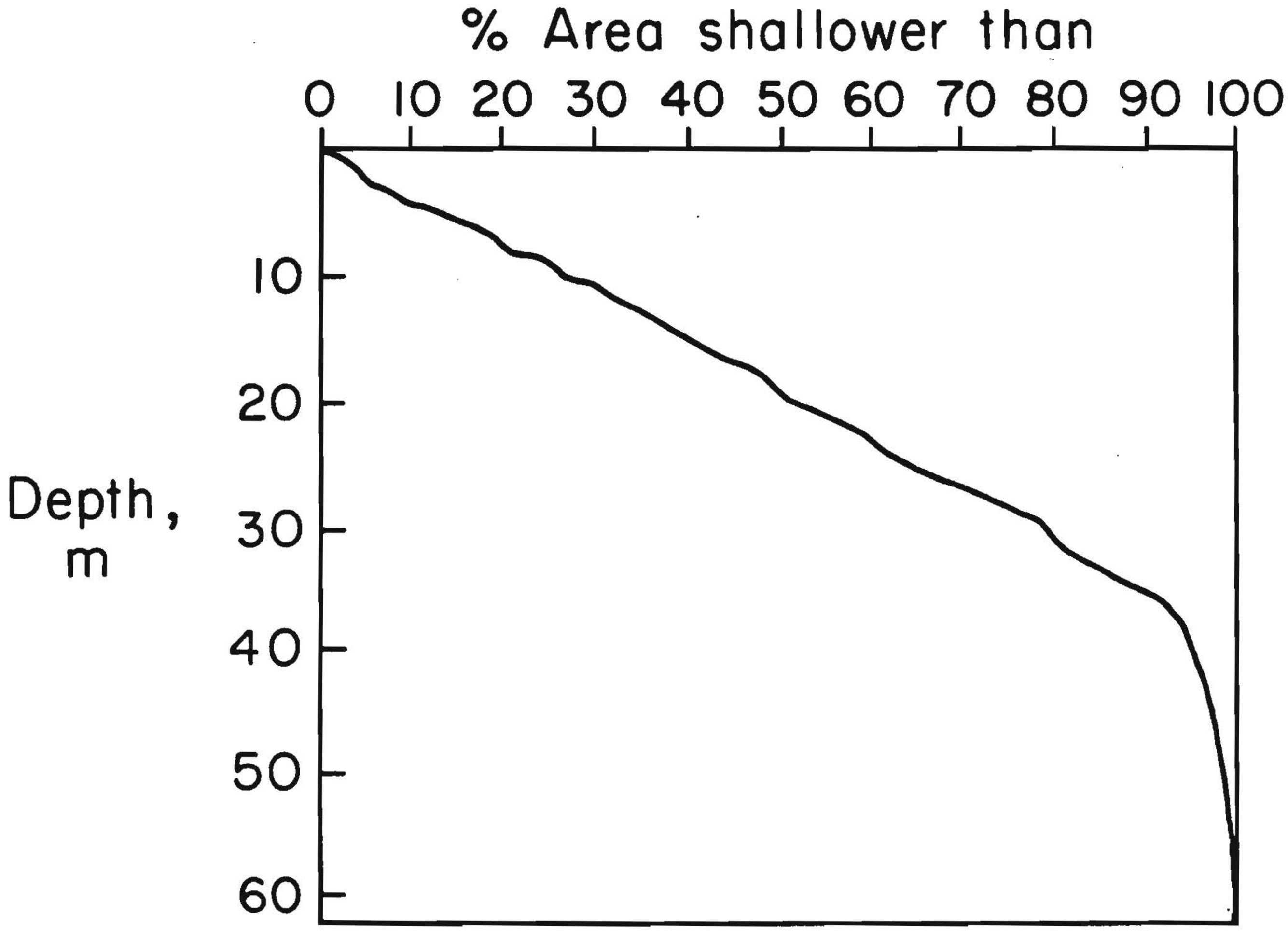


Figure 2. Hypsometric curve for the Sound basin calculated from a grid of 28,500 charted water depths, from mean low water, spaced at 0.3 nautical mile intervals.

the coast northward to Cable and Anchor Reef, and beyond towards the northern shore once again.

The tide enters the Sound through the eastern passage (the Race) as a progressive wave with a speed of about 0.6 m/sec along the Sound's axis (2.25 km/hr; Figure 3). The tidal range in the eastern Sound is about 0.7 m and the maximum tidal currents reach speeds of 5 knots. West of Mattituck Sill the progressive character of the tide changes to primarily a standing wave. The same phase of the tide occurs nearly simultaneously everywhere west of $70^{\circ}40'$W (Figure 3). The resonant co-oscillating tide produces maximum tidal ranges in the western Sound exceeding 2 m. Tidal currents in the central Sound are rotary and reach maximum speeds between 0.2 and 0.5 m/sec (Gordon, 1980).

The East River is a hydraulic tidal strait connecting western Long Island Sound to New York Harbor. The net flow of water through the East River is driven by the difference in water elevation between western Long Island Sound and the Upper Bay of New York Harbor. The difference in mean sea level between the two ends of the East River would produce a long-term net flow of water from the Sound at a rate between 4.7 and 9.4×10^6 m^3/tide (Jay and Bowman, 1975). The Stokes transport of water through the East River would be from the Sound to the Harbor at an additional rate of 5×10^6 m^3/tide, producing a total net average flow from the Sound at a rate between 217 and 434 m^3/sec (Jay and Bowman, 1975).

The East River also transports salt from the Sound to New York Harbor and there is an estuarine circulation in the East

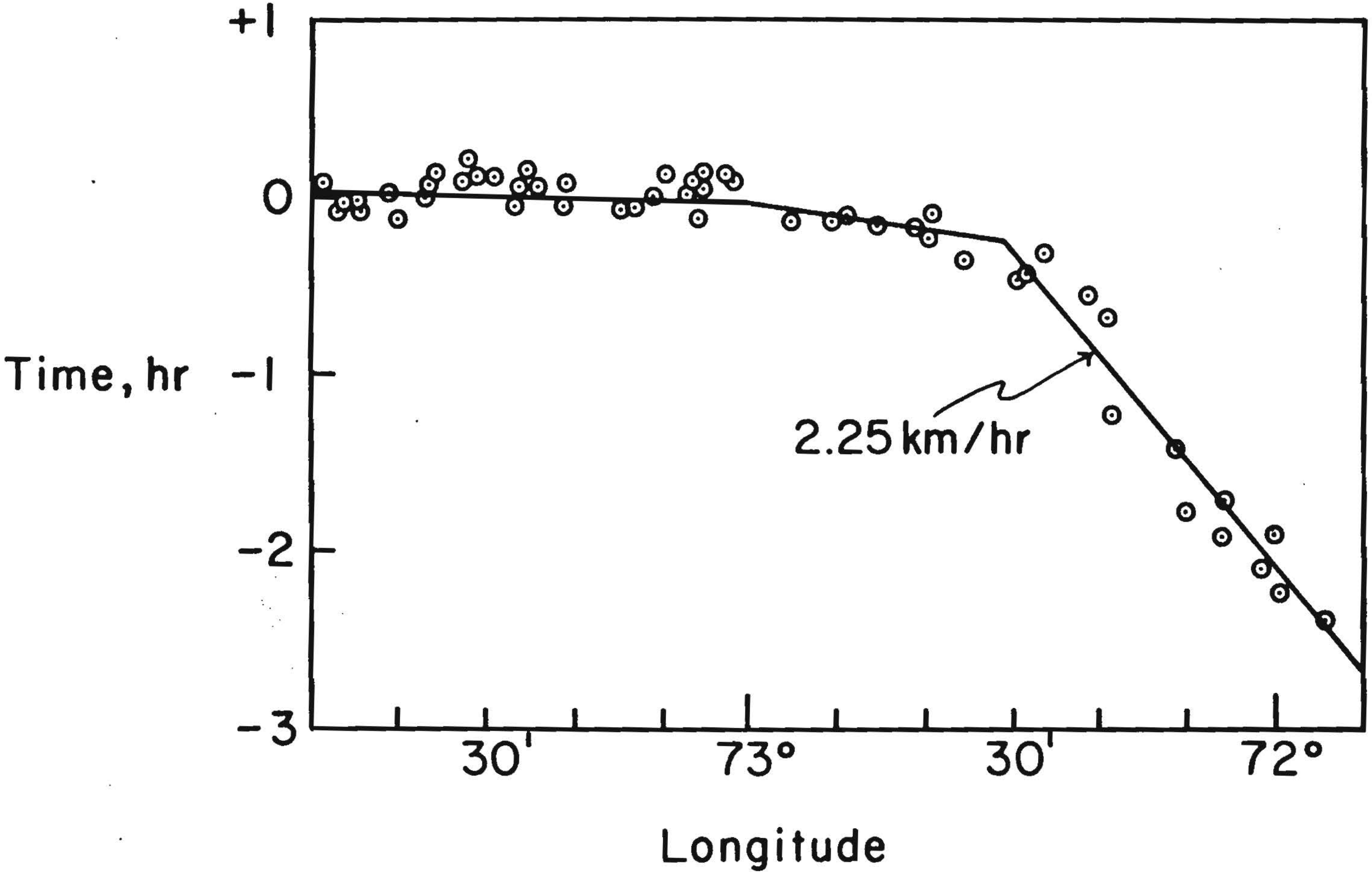


Figure 3. Time of high tide relative to Bridgeport, CT as a function of longitude. (From: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Survey, Tide Tables 1986, High and low water predictions East Coast of North and South America including Greenland: 288 p.).

River wherein fresher surface water flows eastwardly toward the Sound and more saline bottom water flows westwardly toward New York Harbor. This same pattern persists throughout the entire Sound (Gordon and Pilbeam, 1975; Wilson, 1976; Bokuniewicz et al., 1977); a well developed estuarine circulation exists even though the major source of fresh water to the Sound, the Connecticut River, enters the Sound near its mouth. The Connecticut River delivers freshwater to the Sound at an average rate of 465 m^3/sec and accounts for about 72% of the total freshwater supply. An additional 9% is supplied by the Thames River further to the east and 12% by the Housatonic River which empties directly into the central basin (Figure 4). The general freshening of the Sound to the west is due in part to the cumulative effects of the rivers of Connecticut and groundwater from Long Island entering into progressively narrower sections of the Sound to the west and in part to the net export of salt through the East River.

Sediment Distribution

The general character of the surficial sediment in the Sound is known from the published data of McCrone et al. (1961), Buzas (1965), McCrone (1966), Bokuniewicz, Gebert and Gordon (1976) and Bokuniewicz, Gordon and Kastens (1977) and the reports prepared by Donohue and Tucker (1970). Ali and Feldhausen (1975), Reid, Frame and Drexler (1974), Williams (1981), and Friedrich et al. (1986). In general, sand or coarser grain sizes are found on an east of Mattituck Sill and near both shores commonly where the water depth is less that about 10 m deep. Patches of coarse

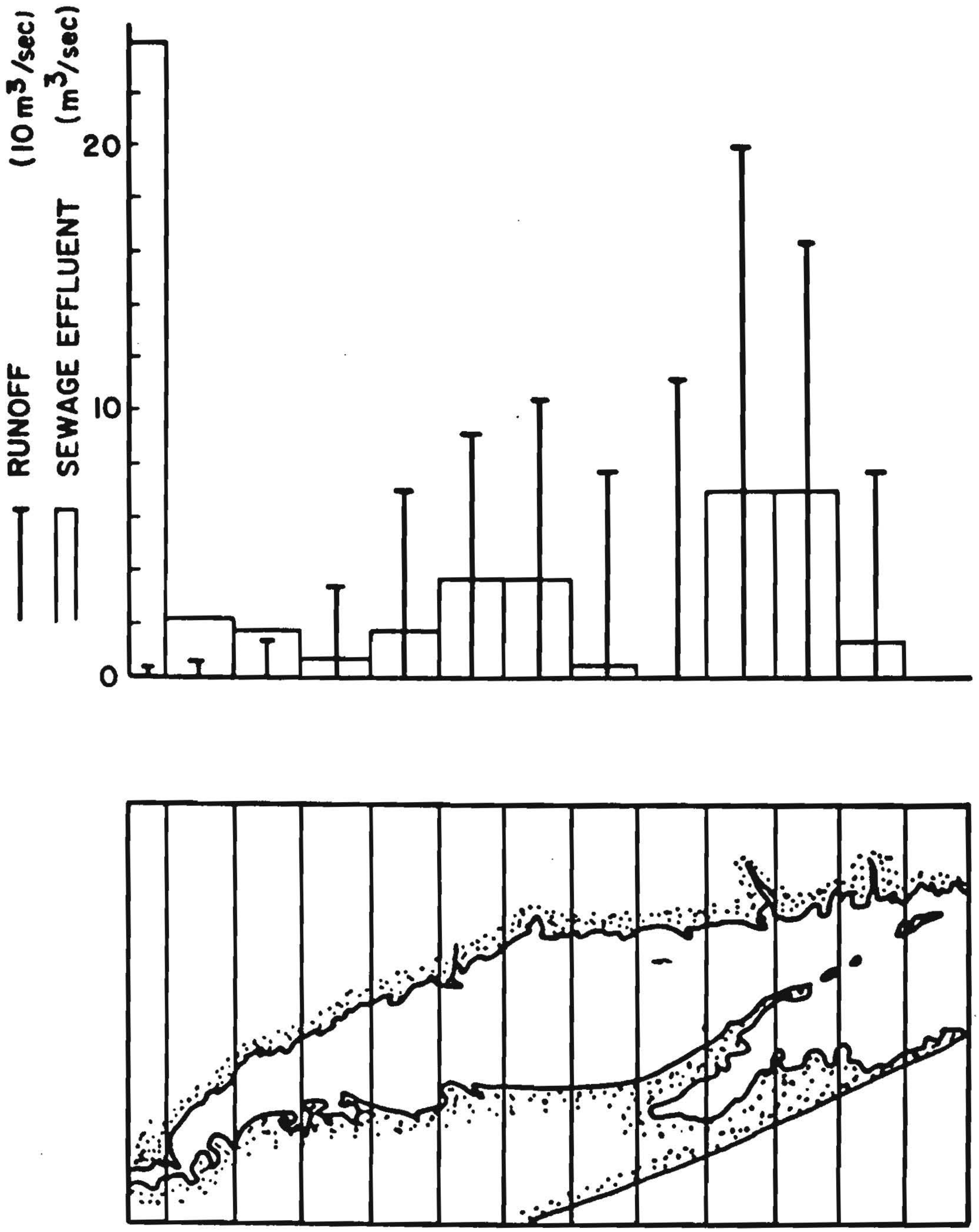


Figure 4. Supply of freshwater and sewage effluent entering Long Island Sound in arbitrary sections. (After Bowman 1975, as reported in Gordon, 1980).

sediment are also found on Stratford Shoal and Cable and Anchor Reef. Sand covers about 44% of the Sound floor and is the dominant component over about 75% (Figure 5). The central basin east of Mattituck Sill and west of Cable and Anchor Reef and the western basin (east of Cable and Anchor Reef) are blanketed with fine-grained sediment. This sediment is predominantly silt (McCrone, 1966; Ali and Feldhausen, 1975) with a minor clay component composed mostly of illite (McCrone, 1966; Sawhney and Frink, 1979). The onshore-offshore transitions from sand to mud are relatively sharp but from Mattituck Sill to the west the sand content of the bottom sediment decreases more gradually over a distance of about 20 km. Ali and Feldhausen (1975) define five environmentally significant facies-clayey silt, sandy-clayey silt, silty-clayey sand, silty sand and sand. Most of the variance among sediment samples, however, can be accounted for by a single parameter which is essentially the weight percent of sand in the sample (Bokuniewicz, 1980). As first suggested by Buzas (1965), the sediment of Long Island Sound is essentially a mixture of two sediment types - silt and sand.

Sedimentation Rate

There are three estimates of sedimentation rates in Long Island Sound. Two of these use naturally occurring radionuclides to obtain the sedimentation rate from cores taken at one site in the central basin ($41^{o}10.4'N; 72^{o}56.3'W$). The distribution of ^{210}Pb in the core yielded a sedimentation rate of less than 0.05 cm/yr after the application of a correction for bioturbation (Benninger et al., 1979). The sediment contains 9% organic

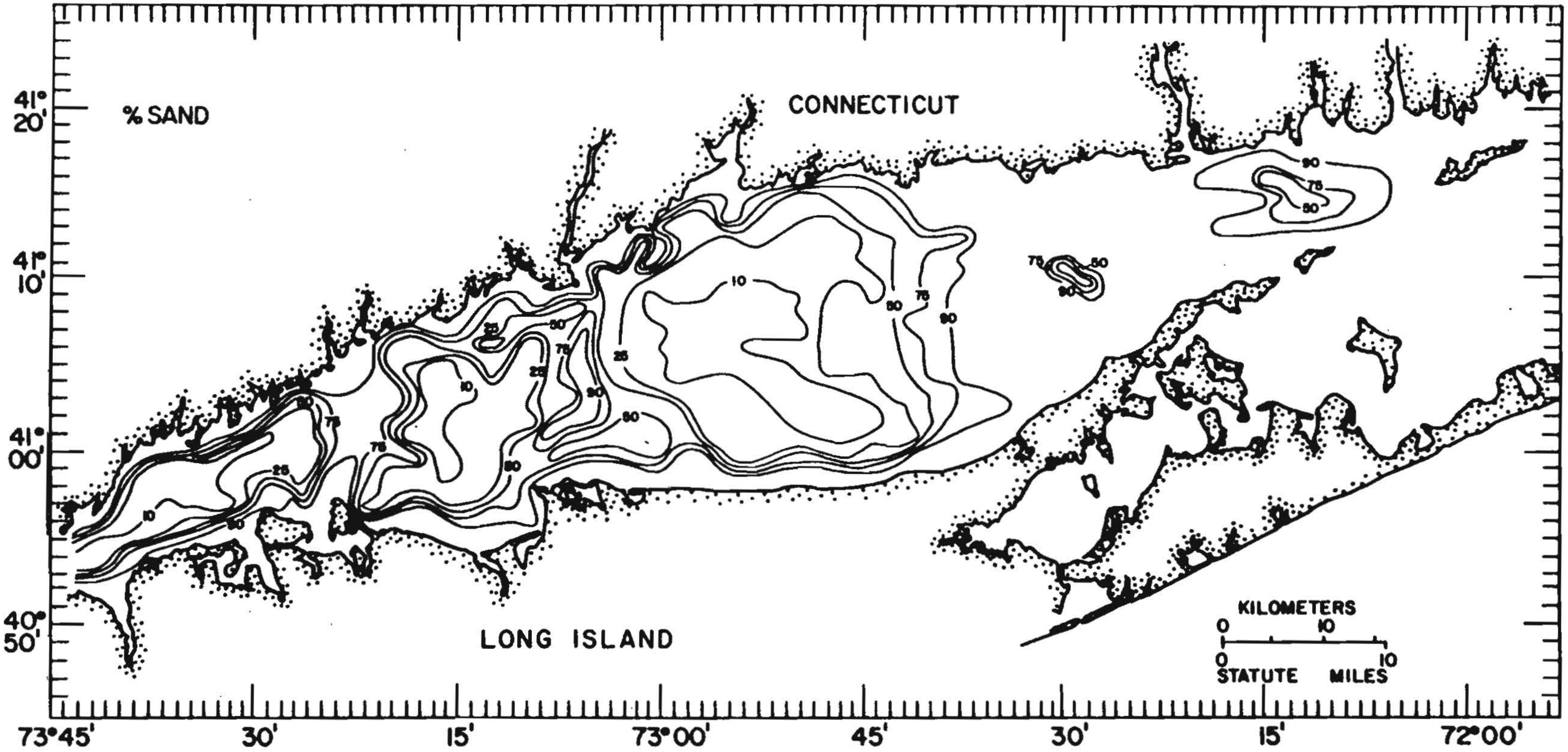


Figure 5. Contour map of the sand content of surficial sediment in Long Island Sound from published values.

material (Benoit et al., 1979) and if the average density of the inorganic particles is assumed to be 2.6 gms/cm^3 and the water content to be 55%, then the measured sedimentation rate would correspond to a flux of less than 0.05 gm/cm^2/yr. At the same site, radiocarbon dating yielded a mean deposition rate of 0.075 cm/yr over the past 1400 years (Benoit et al., 1979). This corresponds to an accumulation rate of 0.077 gms/cm^2/yr. A third estimate of the long-term sedimentation rate was made from isopach maps of marine sediments in the Sound that had been determined by a series of acoustic reflection profiles (Bokuniewicz, Gebert and Gordon, 1976). The Sound was assumed to have become an arm of the sea 8000 years ago and the sediment column was assumed to have compacted 35%. The average sedimentation rate for the central and western basins is 0.029 gms/cm^2/yr but this rate is not uniform. The greatest rates of accumulation are in excess of 0.1 gms/cm^2/yr to the west of Mattituck Sill and Stratford Shoal. Low rates are found in the deep trough that runs through the central basin. No explanation of this pattern is apparent in the hydrographic characteristics but it may be influenced by biologically mediated deposition in local areas (Bokuniewicz and Gordon, 1980). The average rate of accumulation was calculated to be 0.08 gms/cm^2/yr at the site where the cores were taken. This is the same value found by the radiometric techniques and may indicate long-term persistence of a uniform rate of deposition at any particular site.

Sediment Sources

There are two obvious sources of fine-grained sediment to the Sound. One of them is the rivers, primarily, the rivers of Connecticut and the other is shore erosion primarily along the Long Island shore. The rivers of Connecticut supply about 4.7×10^8 kg/year to the Sound (Gordon, 1979). Shoreline erosion of the high bluffs along the eastern half of the Long Island shore can supply an additional 0.5×10^8 kg/year (Bokuniewicz and Tanski, 1983) bringing the total annual supply to at least 5.2×10^8 kg of silt and clay. Additional areas of shoreline erosion and minor rivers on Long Island may increase this value by another 10% (Bokuniewicz and Gordon, 1980) but it also estimated that 0.2×10^8 kg/year are needed to supply the fringing marshes of the Long Island coast (Bokuniewicz and Tanski, 1983) and we might allow the same amount for deposition in the marshes of Connecticut. With these uncertain, but relatively minor, adjustments, the total supply of fine-grained sediment available for deposition in the main body of the Sound amounts to about 5.3×10^8 kg/year. The total area of the Sound is 3199.9 km^2 and 56% of this area is considered to be composed of fine-grained sediment (Bokuniewicz and Gordon, 1980). If fine-grained sediment was deposited on the muddy Sound floor the total supply of the specific sedimentation rate would be 0.03 $gms/cm^2/yr$. This is the same as the best estimate of the average sedimentation rate (0.029 $gms/cm^2/yr$) so that it appears that the Sound is 100% effective in trapping fine-grained sediment.

Dredging and Disposal of Dredged Mud

Over a 10-year period from 1970 to 1980 there have been some 362 dredging projects completed around the Sound (New England River Basin Commission, 1981). About 12 x 10^8 kg, or 1.3 million cubic meters, of fine-grained sediment are dredged from the fringing harbors of Long Island Sound annually. Most of this sediment has probably been supplied to the individual harbors from the main body of the Sound (Sawhney and Frink, 1979). The dredged sediment has been discharged at any of several designated disposal sites in the Sound. Disposal practices result in the creation of mounds of dredged sediment on the disposal site which apparently contain almost all of the sediment discharged (Science Application International Corporation, 1988). As a result, dredging and disposal processes remove mobile sediment to permanent deposits on the Sound floor.

Suspended Sediment Particles

There have been no comprehensive measurements of the suspended sediment distribution in Long Island Sound prior to 1987, but two types of observations of limited extent are available from which general conclusions concerning the suspended sediment concentrations may be drawn. High-frequency, long-term observations have been made 1 meter above the Sound floor at several locations (Bohlen, 1975; Bohlen and Winnick, 1985) using a transmissometer. At four other locations the vertical distribution of suspended sediment concentrations have been measured periodically by filtering water samples (Evjen, 1985; Paige, 1984; Dube, 1985 and Anders, 1986).

The distribution of suspended sediment concentrations from central Long Island Sound (41° 7.67'N, 72°52.35'W) is shown in Figure 6 (Paige, 1984). The average concentration near the sea floor was 7.9 mg/l or about 3 times greater than the surface concentrations. There was little vertical structure, however. At two other sites (40°55.96'N; 73°11.18'W and 40°57.28'N; 73°11.34'W) in Smithtown Bay, vertical profiles were measured at times of maximum and minimum tidal currents on six occasions (Dube, 1985; Figure 7). The concentrations ranged from 2 mg/l near the surface to over 44 mg/l at the sea floor. In general, concentrations near the sea floor were higher than concentrations at mid-depth or near the surface and concentrations were slightly higher at the station in 20 m of water than they were closer to shore in 10 m of water. There was no consistent pattern to the concentrations measured at different stages of the tide on the same day.

A final set of observations are available from a site near the Long Island shore of the central basin in 20 m of water (Anders, 1986). Observations of the suspended sediment levels were made on 26 occasions at various stages of the tide. The concentrations here were consistently larger 1 m above the sea floor than they were higher in the water column. The average near-bottom concentrations were about 6.6 mg/l or 2.5 times the concentrations near the surface.

Based on these observations we might expect that concentrations of suspended particles near the sea floor should be about 7 mg/l and values should be about 2 mg/l near the surface. A strong, persistent seasonal or tidal pattern of

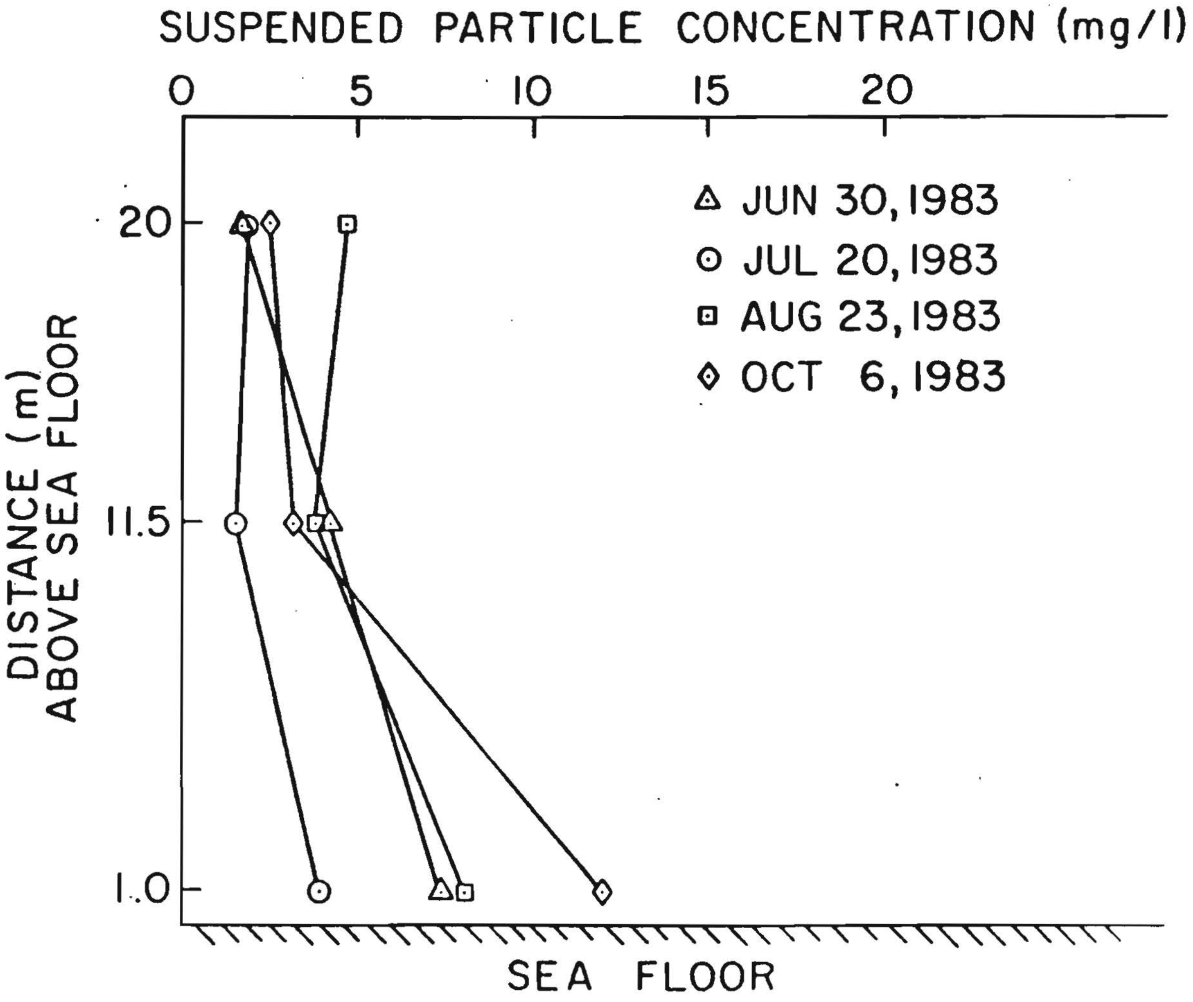
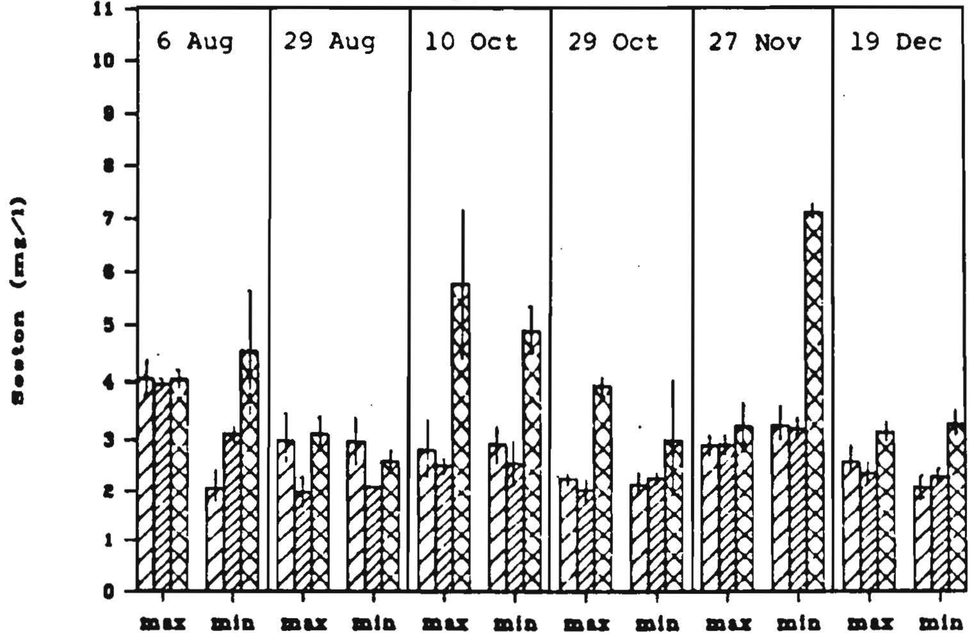
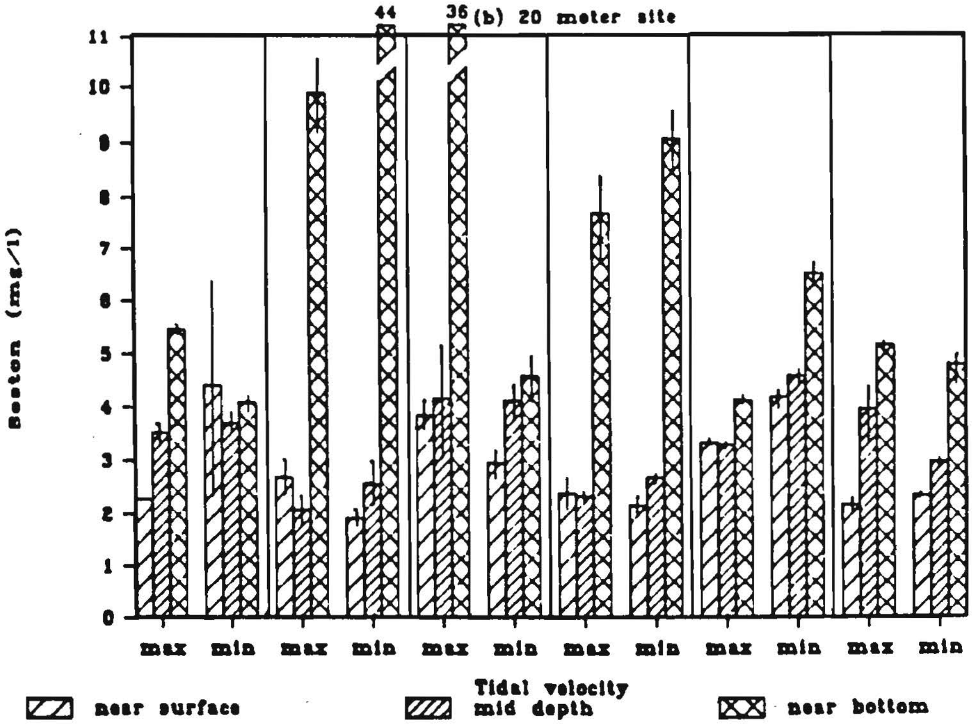


Figure 6. Suspended sediment concentration profiles in the central Sound (from Paige, 1984).



(a) 10 meter site



(b) 20 meter site

Figure 7. Suspended sediment concentrations at times of maximum and minimum tidal currents at selected dates in 1984. (From Dube, 1985).

variation should not be expected. The total volume of the Sound is 51.18 x $10^9 m^3$. If we assume that the average concentration is 5 mg/l then the total amount of material in suspension at any time is about 2.5 x 10^8 kg or about one-half of the annual supply of fine-grained material. During storms, however, the concentrations of suspended sediment may be 2 to 4 times higher than the usual values (Bohlen, 1975; Bokuniewicz et al., 1977).

The distribution of suspended sediment in the Sound is very poorly known. Lateral advection of suspended sediment from areas of high resuspension may exert a controlling influence on the suspended sediment distribution in such a large estuary. This has been shown to be the case in the St. Lawrence River estuarine, for example (d'Anglejan and Ingram, 1976). In the Sound where the water is less than 18 m deep, wave activity may sufficiently increase local resuspension to maintain lateral concentration gradients. There is little evidence to test this hypotheses however. A turbidity track made in Long Island Sound from deep to shallow water in an area where the bottom is mud and the tidal stream weak showed a substantial horizontal gradient in turbidity through the water column where the depth was about half the wave length of the waves present at the time of the track (Bokuniewicz and Gordon, 1980). Also box cores taken after a hurricane had passed showed evidence of resuspension shoreward of the 12 m isobath but no evidence of disturbance in deeper water (Aller, 1976 as reported in Bokuniewicz and Gordon, 1980).

The Sound's circulation may also exert an influence on the distribution of suspended sediment. The Sound has a typical estuarine circulation (Gordon and Pilbeam, 1975; Riley, 1952; Wilson, 1976). In principle such a circulation should generate a turbidity maximum (Festa and Hansen, 1978; Officer, 1980) and such maxima have been observed in many other estuaries (e.g. Schubel, 1972). It has never been sought in the Sound and, if it exists, its size, strength and location are not known. Since net near bottom currents are westward at least as far as Eatons Neck (Bokuniewicz et al., 1977), it is likely to be found in the western Sound if it exists.

Resuspension

The composition of a fraction of the suspended sediment population (> 32 micrometers) in the surface water was examined by Benninger (1976) (see also Turekian et al., 1980). The suspended material was a mixture of a biogenic component and a component of bottom sediment. Although more than 90% of the bottom material is terrestrially derived, no fresh terrestrial material was detectable in the suspended population indicating that newly introduced material is rapidly processed and diluted by sediment resuspended from the sea floor.

Although the high concentrations of suspended sediment observed under storm conditions can be accounted for by the resuspension of only 2 mm of the sea floor, the fluxes of particles across the sediment-water interface due to resuspension and redeposition greatly exceed the net, long-term sedimentation rate. At one site in the central basin, 1-liter wide-mouth jars were used to measure resuspension 15 cm above the silty-sand bottom of Long Island Sound, in a water depth of 14 m (McCall, 1977). Samples were taken from September 1972 through August 1973, measuring the amount of sediment that had accumulated in 1 to 3 month intervals. The longer sampling periods were in the winter, at which time the lowest vertical fluxes were observed: 3.6 gm/cm^2/month. Summer rates averaged 7.5 gm/cm^2/month. The 11/month mean corresponded to an annual rate of 55.8 gm/cm^2/yr (McCall, 1977). Since the long-term rate of accumulation in the Sound is about 0.03 gm/cm^2/yr less than 0.5% of the downward flux remains on the floor of the Sound or, in other words, over 99% appears to be held in suspension or continually resuspended. If the measured flux of 55.8 gm/cm^2/yr is representative of the resuspension of the muddy sound floor, then the total amount of resuspension corresponds to 10^{12}kg/yr or an average of 14 x 10^8 kg per tidal cycle.

Since McCall's study was completed additional work has been done to support the conclusion and to better define the character of the vertical flux of particles. The remainder of this article will be devoted to a consideration of these additional studies in more detail.

METHODS

Data on the vertical fluxes of particles in the Sound were obtained using sediment traps. These were cylinders with an internal diameter of 1.5 cm. They were 100 cm long; at one site, however, an additional mooring supporting sets of traps 25 cm long were used to measure fluxes within 30 cm of the sea floor. The traps were bound in clusters of 5 and suspended on a taut-wire mooring at three depths in the water column - one meter above the bottom, at mid-depth and one meter below the surface. At one site shorter traps were also set 30 cm above the bottom.

We have been experimenting with these types of traps for several years (e.g. Paige, 1984; Bokuniewicz and Hirschberg, 1982) and based on these test results we believe that (1) the fluxes are sufficiently large to be measured in this way; (2) the fluxes calculated from the traps have a precision of about 6%; (3) the measured fluxes are both reasonable and self-consistent; (4) for aspect ratios of 25 or greater, the results derived from traps in the Sound will be insensitive to either the aspect ratio or the diameter of the trap and (5) the flux calculated from the trap is, within uncertainties in the measurements, equal to the average product of the concentration and the settling velocity.

Sediment trap moorings were deployed at three sites at three different times. These were:

a. in the central sound (41°7.67'N; 72°52.35'W) between 2 June 1983 and 2 November 1983. The water depth here was 24 m and the tidal range was about 2.0 m. The sea floor is silt with an organic content of 9% (Benoit et al., 1979). Tidal excitation of bottom sediments dominates over wave disturbance of the sound floor here (Bokuniewicz and Gordon, 1980).

b. in Smithtown Bay (40°57.28'N; 73°11.34'W) between 29 August 1984 and 19 December 1984. The water here was 20 m deep with a 1.9 m tidal range. The bottom sediments were clayey silts.

c. near the south shore of central Long Island Sound (40°59.3'N, 72°53.6'W). The water depth here was 20 m with a tidal range of 1.8 m. The bottom sediment was sandy silt.

RESULTS

The measured fluxes for four periods between 2 June and 22 November 1983 at the first site in central Long Island Sound are shown in Figure 8. (The data for these deployments as well as the others are given in the Appendix I). The fluxes measured 1 m above the sound floor were always substantially higher than those measured 1 m below the surface or at mid-depth. The near bottom flux increased steadily from June through September to a maximum value of 53 mg/cm^2/day. In October the near bottom flux decreased while the surface fluxes increased. This change was accompanied by a decrease in the organic content of the material in suspension in the upper layers of the water column. The organic content of the material collected near the sea floor was near to that of the bottom sediments or about 9% while it was between 11 and 24% for the material collected near the surface. In October, the organic content of the surface material caught in the traps was reduced to 11%. Which may indicate more efficient admixing of bottom sediments into the surface waters after the breakdown of stratification in the fall.

All other factors being equal the decrease in the flux near the bottom between September and October may be largely the effect of decreasing water temperature. The temperature range in the Sound can exceed 20°C, as large a range as found anywhere in the world. For particles settling according to Stokes Law a change in water temperature from 20° to 5°C during the fall would decrease the settling velocity by about 60% by increasing the fluid viscosity.

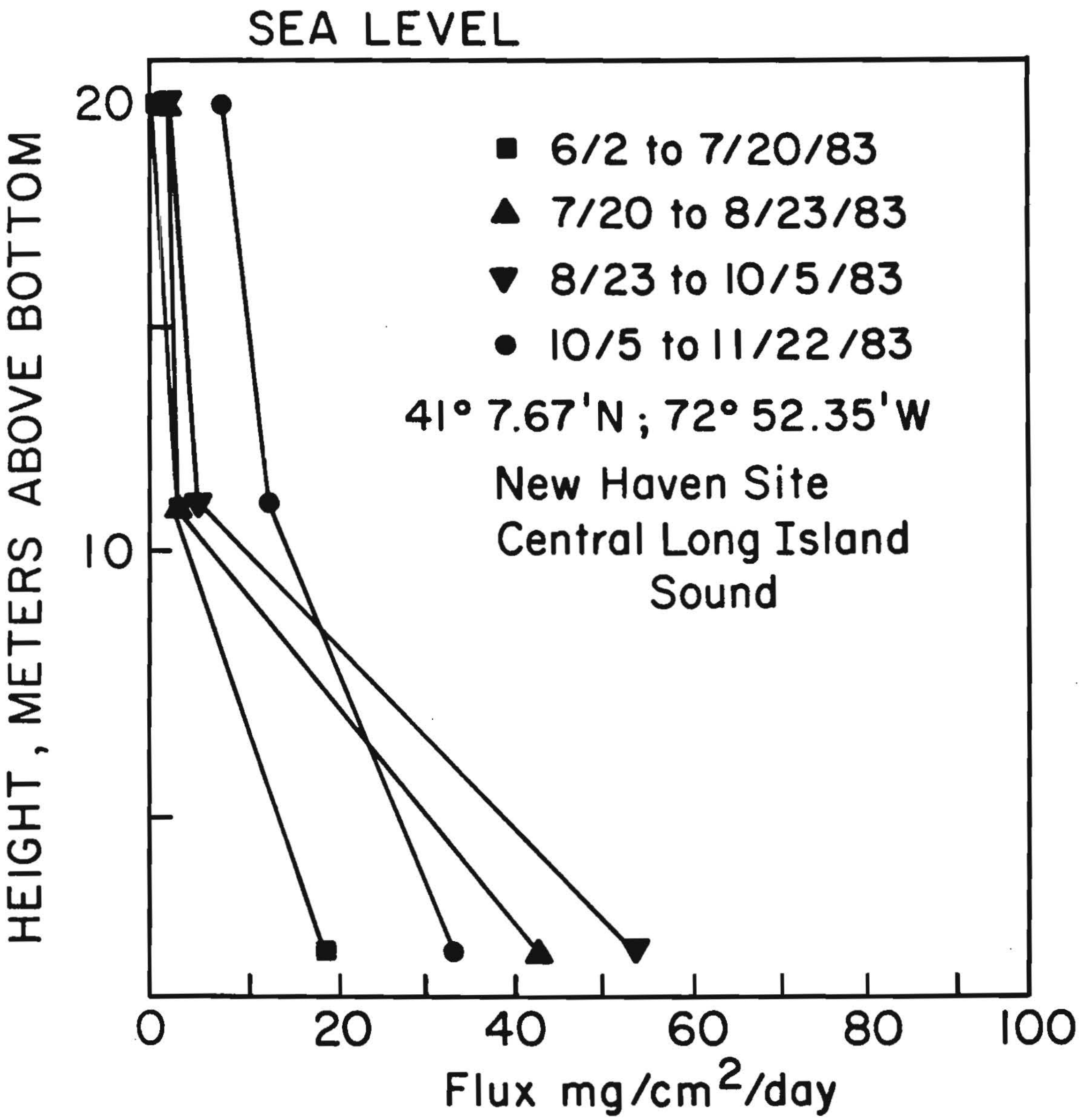


Figure 8. Sediment trap results from the central Sound.

The increase in the measured flux during the early winter at high elevations in the water column was contrary to the change expected due to changing water temperature. Such an increase may be due either to increases in the settling velocity of the suspended population or to increases in the particle concentration. The reduction in organic content during this period may indicate a change in the particles toward higher bulk densities and, therefore higher settling velocities. Alternatively, if the breakdown of stratification allowed more resuspended material to be mixed into the surface waters higher average concentrations could result. The data were not adequate to resolve the relative importance of these two alternatives. In any event, there has been some change in the suspended population in the surficial waters and it is likely that the near bottom population has also changed so that the observed decrease in the near-bottom flux was not due only to the effect of decreasing water temperature.

The measured fluxes at the second site, in Smithtown Bay, were similar both in magnitude and in the observed patterns (Figure 9). Fluxes near the sea floor were always higher than those higher in the water column. The magnitude of the fluxes measured at mid-depth and near the surface in Smithtown Bay were comparable to those measured in the same relative positions in the central Sound. The near bottom flux at this shallower station, however, were significantly lower. The near-bottom fluxes decreased after September, 1984, as it did in the central Sound in 1983, and continued to decrease into December, 1984. The direction and magnitude of this decrease was as expected for

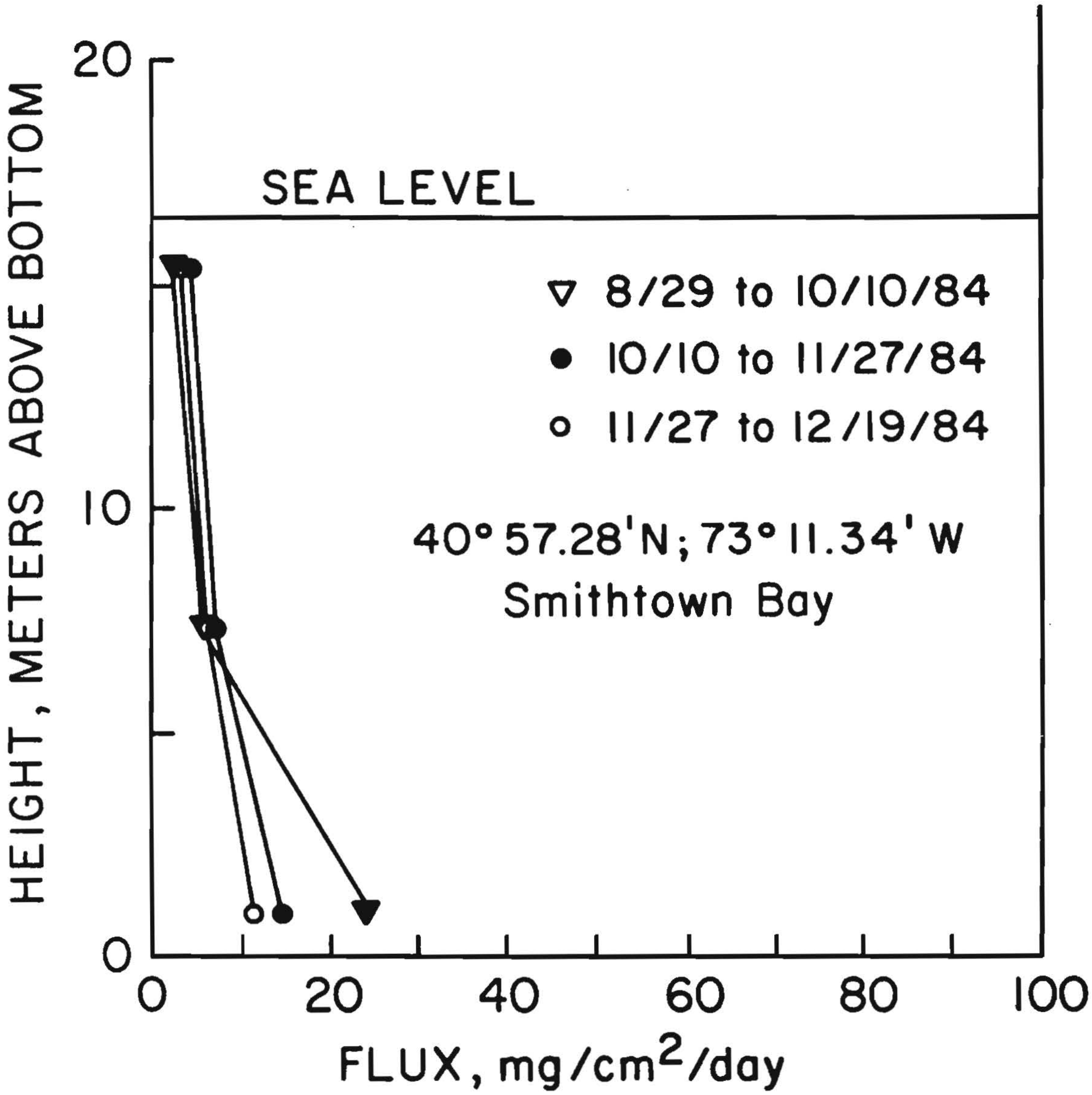


Figure 9. Sediment trap results from Smithtown Bay.

an observed decrease in the water temperature from 23° to 6°C. The fluxes higher in the water column, however, did not show this effect but rather increased slightly as the water cooled. This increase was also accompanied by a slight decrease in the organic content of the material collected at mid-depth and near the surface from about 15% to 13%.

The deployment at the site near the southern shore of the central sound included additional moorings holding sediment traps 25 cm long and an additional set of these traps positioned 30 cm above the bottom. This was done not only to compare the results of traps of different aspect ratios at this location but also to attempt to measure the flux nearer to the Sound floor.

There were five deployments with traps of both 100 cm length and 25 cm length at each of 3 depths. During one deployment period the mooring with traps 100 cm long was lost. As a result, there were 12 pairs of data to compare the relative effectiveness of the two sizes of traps. During the first deployment of the summer the shorter traps at all depths collected significantly less material than the longer traps. The difference in the mean absolute fluxes calculated from each of these sizes of traps ranged from 0.04 to 0.07 $mg/cm^2/day$ with the differences amounting to about 100% of the low measured fluxes near the surface and about 9% for the higher measured fluxes near the sea floor. For the other 6 pairs of data there were no significant differences between the two sizes of traps. (Such inconsistent results have been observed on other trials; about 30% of the time the shorter traps will collect significantly less material than the longer ones. Although the reason for this is not apparent it may be that some material is episodically resuspended out of the smaller traps depending upon the prevailing conditions).

The fluxes measured by the shorter traps are shown in Figure 10 and those by the longer traps in Figure 11. These fluxes were comparable in magnitude those measured during the same season at the same relative depth at the other stations. The patterns were also the same. Consistently higher fluxes were measured near the bottom and, in the early winter, the magnitude of the near-bottom flux decreased an amount that might be expected due primarily to a change in the water temperature while the fluxes in the surface water increased. The measured fluxes at 30 cm were about twice as high as those at 1 m for the same period and these values approached the high values that were measured by McCall (1977) 15 cm above the Sound floor at another site.

At this site also, periodic measurements of the suspended sediment concentrations were made. These are, of course, not true average values of the concentration at the level of the sediment traps during the deployment period, but if we assume that they are typical values and that the traps were measuring the average value of the product of the concentration and the settling speed, then the settling speed can be estimated (Appendix II). A reasonable settling speed appeared to be about 0.05 cm/sec, or 43 m/day but the estimates ranged from 2 to 112 m/day with an average value for particles near the sea floor of about 30 m/day.

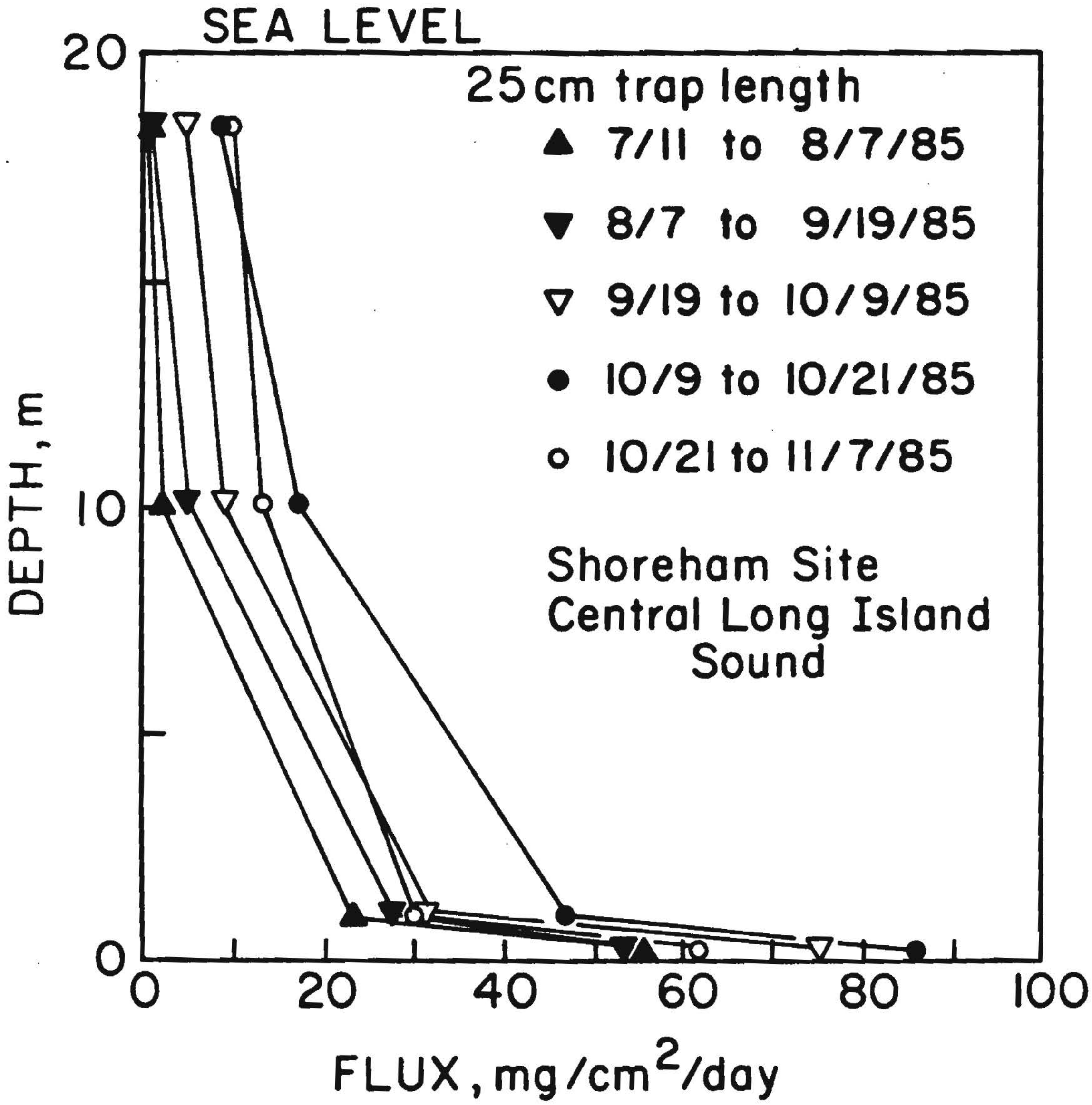


Figure 10. Sediment trap results from near the south shore of the central Sound using short traps 25 cm in length.

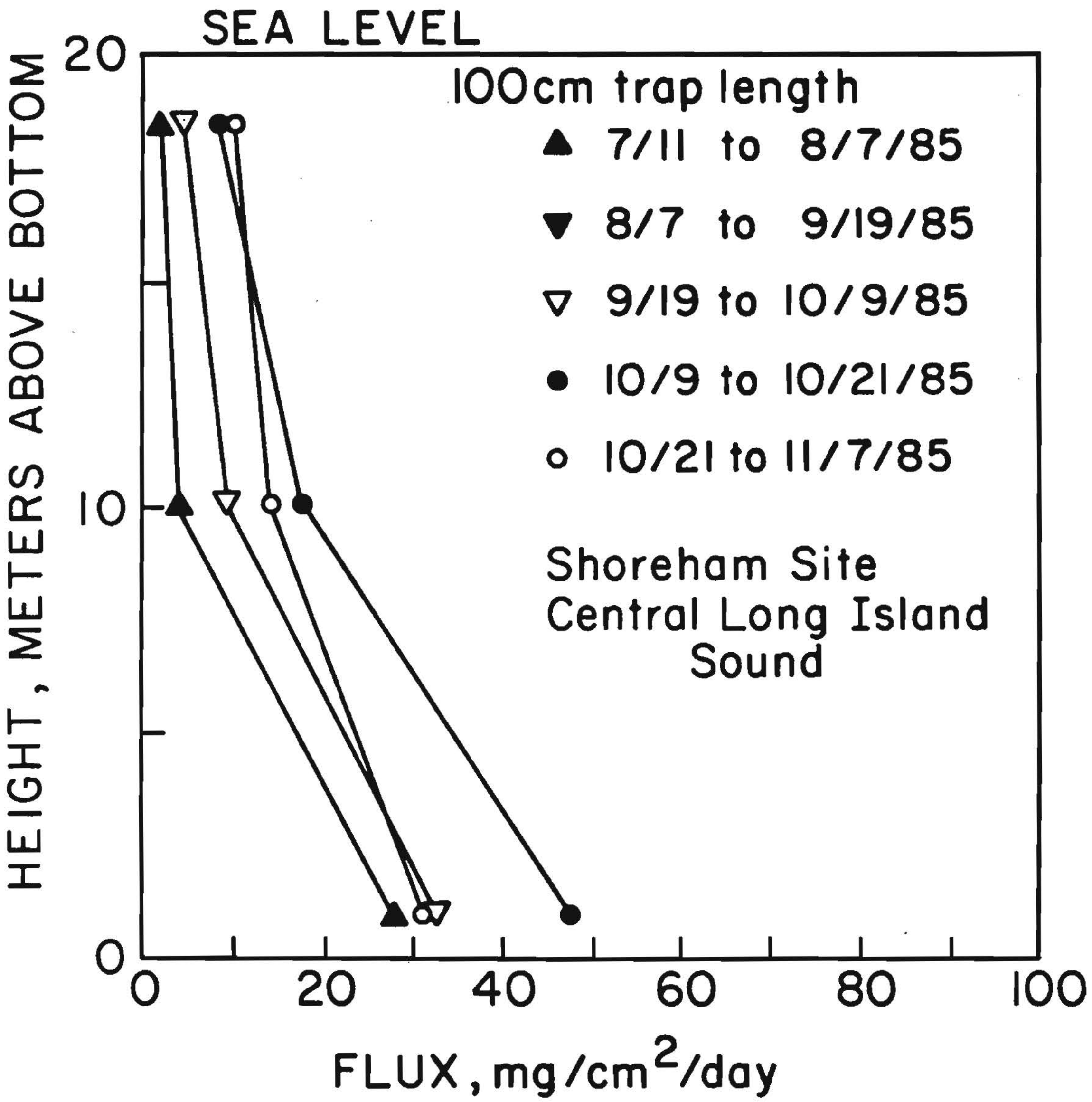


Figure 11. Sediment trap results from near the south shore of the central Sound using long traps 100 cm in length.

DISCUSSION

Based on these few observations we might expect that, in general, the settling flux near the surface of the sound should be about 5 mg/cm^2/day, lower in the summer (1 or 2 mg/cm^2/day) and increasing during the fall. One meter above the sound floor the flux should be expected to be about 30 mg/cm^2/day and to decrease by about 60% over the fall season due primarily to the decrease in water temperature. The ratio of the rate of long-term sediment deposition and the flux of sediment particles settling to the bottom might be used to describe the short-term retention efficiency of the sea floor. The fluxes measured at one meter, however, are not necessarily equal to the flux of particles into the laminar sublayer which would be deposited, if only temporarily. In fact the results at the site near the south shore of the central Sound indicate that the flux increases substantially within one meter of the sea floor. Nevertheless, for the purpose of comparing the behavior of different estuaries we might use the flux measured at one meter as a standard for the comparison when this valve is available. The calculated, relative retention efficiencies will be overestimates, however.

Based on the measured fluxes at a height of 1 m, the relative, short-term retention efficiency for the floor of Long Island Sound is 0.1%. Some data are available to calculate similar values from at least five other estuaries - Narragansett Bay, Puget Sound, Buzzards Bay, Chesapeake Bay and San Francisco Bay.

Narragansett Bay has been estimated to trap between 90 and 100% of the fine-grained sediment supplied to it (Biggs and

Howell, 1984) and sediment traps have been used to assess the mobilization of this sediment by resuspension (Oviatt and Nixon, 1975). The sediment traps used here were funnels with a 16 cm diameter attached to a bouyant frame. The traps were sampled every month between October 1972 and November 1973. The trap frames were deployed 1, 2, 3 and 4 m above the sea floor at 3 stations in the bay - the mouth of the bay, mid-bay and the head of the bay. The water depth at all stations was about 7 m. The measured fluxes were generally 2 to 3 times higher near the bottom than they were near the surface. No strong seasonal patterns were found and the flux 1 m above the bottom was greatest near the bay mouth at a rate of 5.01 $mg/cm^2/day$ compared to rates of 3.01 $mg/cm^2/day$ in the mid-bay and 2.03 $mg/cm^2/day$ in the upper bay (Oviatt and Nixon, 1975). The average long-term deposition rate is 0.13 $mg/cm^2/day$ (Farrington, 1971 as cited in Oviatt and Nixon, 1975) so the short-term retention efficiency of the bay floor is then between 2.5 and 6.2 %.

Cylindrical sediment traps 20 cm wide and 1 m long were used in Puget Sound (Feely et al., 1986). These were positioned at depths of 20, 50, 100, 160 and 200 m at one station and sampled bi-monthly throughout 1981. The nominal water depth here was apparently 200 m so that the lowermost trap would have been about 1 m above the bottom. During the winter average fluxes near the sea floor were 8.92 $mg/cm^2/day$. The winter flux decreased rapidly to a level of 1.65 $mg/cm^2/day$ at a depth of 100 m. During the summer, the flux remained below 9.77 $mg/cm^2/day$ to a depth of 150 m then increased rapidly to 91.60 $mg/cm^2/day$ near the bottom. The long-term deposition rate in the underlying sediments was 31.50 mg/cm^2/day (Feely et al., 1986) so that the short-term retention efficiency of the sea floor here is about 35%.

In Buzzards Bay, Massachusetts, resuspension rates as high as 1.3 mg/cm^2/day were calculated (Roman and Tenore, 1978) from data obtained with sediment traps (Young, 1971 as reported by Roman and Tenore, 1978). The authors concluded that a maximum of 2% of the sediment falling through the water column remained on the bay floor and 98% was resuspended.

The settling flux of suspended sediment may also be calculated from simultaneous observations of the concentration of particles and their settling velocity. These were measured at one station in Chesapeake Bay (Schubel, 1972) at six depths, including 0.5 and 1.5 m above the bay floor over a 30-hour period. The flux is calculated as the product of these two measurements and was found to be about 290 mg/cm/day at 0.5 m and 0.8 mg/cm^2/day at 1.5 m. Averaging these values in order to estimate the flux at 1 m, we find an average value of about 190 mg/cm^2/day. The average long-term sedimentation rate in the upper Chesapeake Bay is 3.5 mm/yr (Hirschberg and Schubel, 1979) or about 1.24 mg/cm^2/day. The short-term retention efficiency is then about 0.6%.

In San Francisco's South Bay and its San Pablo Bay, geochemical evidence has been used to calculate long-term deposition rates of 0.08 and 0.30 gm/cm^2/day, respectively, and to estimate the resuspension rates to be about 2.7 and 1.9 mg/cm^2/yr, respectively (Hammond and Fuller, 1982; Fuller and Hammond, 1982). If we assume that the sedimentation flux is the sum of the resuspension and the long-term deposition, then the retention efficiencies are about 3% for South Bay and 14% for San Pablo Bay. A similar approach that was applied to the fine-grained sediment deposits of the Yangtze River continental shelf yielded a short-term retention efficiency of about 10% (McKee et al., 1983).

CONCLUSIONS

Like many estuaries, the Sound appears to be an effective sediment trap capable of containing all the sediment that is delivered to it from throughout the drainage basins of its rivers. The residence time for sediment particles in the water column is about six months, because of resuspension and bioturbation any particular particle, with its contaminant burden, may be mobile in the Sound for a century. The particle will be resuspended and redeposited many times before it is finally incorporated into the permanent sediment deposit. During the time that particles are mobile, they should be widely dispersed throughout the estuary by the tides.

How well the Sound actually conforms to this conceptual model depends not only on the strength of the local variations in sources or sinks of sediment but also upon inhomogeneities in the vertical flux and horizontal distribution of particles. Inhomogeneities can arise, for example, as a result of local resuspension or as a result of differences in the erodability of bottom sediments. Little information was available, however, to estimate the influence of these mechanisms.

New particles are introduced to the Sound by the rivers of Connecticut, predominantly the Connecticut River and by erosion of Long Island's shore. Because of potentially high resuspension rates, however, the amount of unbound, mobile sediment is many times larger than the annual supply of new material (Bokuniewicz and Gordon, 1980). As a result, temporary storage in and episodic release of resuspended sediment from the Sound's border harbors and marshes may be important local sources and sinks. The clay mineralogy of sediments in small estuaries bordering Long Island Sound and the accumulation rates in salt marshes indicate that these features are typically sinks for suspended sediment in the Sound (Sawhney and Frink, 1978; Richard, 1978; Bokuniewicz and Tanski, 1983; Harrison and Bloom, 1977). Under storm conditions increased resuspension and erosion in shallow coastal waters may make these same features strong temporary sources of sediment to the main body of the Sound (Richard, 1978; Bokuniewicz et al., 1977). To illustrate the potential importance of this effect, a simple model may be developed to estimate the amount of harbor sediment which is dispersed throughout the Sound. During a storm a layer of bottom sediment of thickness l_H is resuspended in the harbor and a thickness l_S is resuspended in the deeper, main body of the Sound. If the average water depth in the harbor is D_H, then the typical concentration of suspended sediment in the harbor waters as a result of the storm is $C_H = l_H\rho/D_H$, where ρ is the dry bulk sediment density at the sediment-water interface. Likewise, in the Sound the average suspended sediment concentration is $C_S = l_S\rho/D_S$ where D_S is the water depth. As the tide ebbs from the harbor a volume of water, W, and its suspended material is transferred from the harbor to the main body of the Sound. If the mixing is very rapid, as it will be during an intense storm, the harbor sediment will be mixed into the waters of the Sound until a uniform concentration of C_S is everywhere attained. The amount of sediment removed from the harbor on ebb tide is

$$\rho W\ 1_H/D_H$$

On the flood tide an amount, $\rho W\ 1_S/D_S$, is returned to the harbor, so that the net flux of material to the Sound per tidal cycle is

$$\rho W \frac{1_H - 1_S}{D_H - D_S}$$

Because the water is shallower in the harbor and more storm energy can reach the bottom, 1_H is probably greater than 1_S; however, to minimize the flux estimate, 1_H can be assumed to be equal to 1_S with a value of 2 mm. The typical water depth in the harbor is about one-fifth the depth in the main body of the Sound so that the net volume flux of material, at the bed density, carried soundward per tidal cycle is

$$4W1_S/5D_H$$

In New Haven Harbor, as an example, the tidal prism is 50 million cubic meters and the depth is 3 m, so that the net soundward flux per tidal cycle is about 25,000 cubic meters of sediment, at the bed density, during a storm.

Even under the same hydrodynamic conditions, the magnitude of resuspension may change from place to place. Some of the factors that influence the magnitude of resuspension are fairly well known but others are not. The sediment distribution has been determined and the energy available for resuspension can be estimated from predictions of the waves and tidal action. There is not comprehensive data, however, on the distribution of water content, cation exchange capacity, sodium absorption ration, or bed structure. In addition, variable biological influences may exert a significant influence. Intense bioturbation by bivalves such as _Yoldia limatula_ and _Nucula annulata_ has been shown to decrease the critical erosion velocity of Long Island Sound sediment (Rhoads et al., 1978; Yingst and Rhoads, 1978) and laboratory flume studies have shown that the presence of _Nucula_ may increase the amount of resuspended sediment by a factor of two (Tsai and Lick, 1985). The impact of these agents on the suspended sediment field in the Sound, however, may not be straightforward and the relative resuspension potential in different areas cannot be forecast except, in a general way, from the grain size, tidal currents, and water depth as an indicator of wave disturbances. The effects of persistent areas of high resuspension may be disclosed as regions of high suspended concentrations during regional surveys being done by the EPA's National Estuary Program.

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APPENDIX I

Table I of IV

New Haven Site: Central Sound
Site: 41°7.67'N 72°52.35'W
Water depth: 21 m

Trap Length: 100 cm

Period 1983	No. of Days	FLUX mg/cm²/day[1] (Organic Content)		
		1 m above bottom	11 m above bottom	20 m above bottom
06/02 to 07/20	49	19.00 ± 6% (10%)	2.30 ± 4% (17%)	1.73 ± 10% (24%)
07/20 to 08/23	34	42.67 ± 7% (10%)	2.87 ± 15% (16%)	1.60 ± 19% (18%)
08/23 to 10/05	43	53.00 ± 5% (9%)	4.53 ± 5% (16%)	2.73 ± 12% (19%)
10/05 to 11/22	49	33.67 ± 2% (10%)	12.97 ± 5% (11%)	8.33 ± 4% (19%)

[1] Mean and standard deviation based on 5 replicates

Table II of IV

Smithtown Bay
Site: 40°57.28′N 73°11.34′W
Water depth: 16.5 m

Trap Length: 100 cm

Period 1984	No. of Days	FLUX mg/cm²/day[1] (Organic Content)		
		1 m above bottom	7.6 m above bottom	15.5 m above bottom
08/29 to 10/10	42	23.7 ± 1.00[2] (12.7%)	5.8 ± 0.19 (15.0%)	3.1 ± 0.11 (15.7%)
10/10 to 11/27	48	14.8 ± 0.25 (12.2%)	6.6 ± 0.22 (13.6%)	4.5 ± 0.21 (13.6%)
11/27 to 12/19	23	11.5 ± 0.22 (13.2%)	6.4 ± 0.22 (13.7%)	4.2 ± 0.13 (12.4%)

[1] Mean and standard deviation based on 5 replicates
[2] 1.5 m above bottom

Table III of IV

New Haven Site: Central Sound
Site: 41°7.67'N 72°52.35'W
Water depth: 20 m

Trap Length: 25 cm

Period 1985	No. of Days	FLUX mg/cm²/day[1] (Organic Content) 0.3 m above bottom	1 m above bottom	10 m above bottom	18.5 m above bottom
07/11 to 08/07	27	56.69 ± 3.40 (10.7%)	23.39 ± 0.73 (15.7%)	2.13 ± 0.21 (19.5%)	0.67 ± 0.08 (25.5%)
07/08 to 09/19	43	54.37 ± 1.88 (11.1%)	27.67 ± 0.76 (12.7%)	4.23 ± 0.28 (18.1%)	1.58 ± 0.12 (20.6%)
09/20 to 09/10	19	75.59 ± 11.33 (6.7%)	31.52 ± 0.94 (11.7%)	9.04 ± 0.30 (12.6%)	4.46 ± 0.27 (13.4%)
09/10 to 10/21	12	85.97 ± 1.90 (7.3%)	46.52 ± 1.64 (10.3%)	16.95 ± 0.00 (12.9%)	8.76 ± 0.23 (14.0%)
10/21 to 11/07	17	61.22 ± 1.32 (8.3%)	31.57 ± 1.86 (12.6%)	13.23 ± 0.74 (13.4%)	9.64 ± 0.33 (13.4%)

[1] Mean and standard deviation based on 5 replicates

Table IV of IV

Shoreham Site: Central Sound
Site: 40°59.3′N 72°53.6′W
Water depth: 20 m

Trap Length: 100 cm

Period 1985	No. of Days	FLUX mg/cm^2/day[1] (Organic Content)[2]		
		1 m above bottom	10 m above bottom	18.5 m above bottom
07/11 to 08/07	27	27.79 ± 1.2 (15.7%)	3.39 ± 0.21 (19.5%)	2.13 ± 0.4 (25.5%)
08/07 to 09/19	43	LOST	LOST	LOST
09/20 to 09/10	19	31.88 ± 1.0 (11.7%)	9.63 ± 0.81 (12.6%)	4.88 ± 0.2 (13.4%)
09/10 to 10/21	12	47.55 ± 0.6 (10.3%)	17.42 ± 0.67 (12.9%)	8.76 ± 0.2 (14.0%)
10/21 to 07/11	17	32.10 ± 0.5 (12.6%)	14.76 ± 0.75 (13.4%)	9.77 ± 0.4 (13.4%)

[1] Mean and standard deviation of 5 replicates
[2] From analysis of material collected simultaneously in traps 25 cm long

APPENDIX II

The deployments of sediment traps offshore of Shoreham were associated with the water column sampling described in Anders (1986) which included total suspended solids. We have calculated the settling velocity from this data using, when possible, the maximum, minimum and average value of all the measured suspended sediment concentrations at the depth of the traps over the deployment period. These are the results:

Deployment Period	Trap Position	Sediment Trap flux mg/cm^2/day	Total Suspended Solids (min.,ave.,max.) mg/e	Settling Velocity* (max.,ave.,min.) x 10^{-2}cm/sec
7/11-8/7	Surface	0.67	0.5, 1.4, 3.4	1.5, 0.6, 0.2
	Mid-depth	2.13	1.1, 2.3, 3.9	2.2, 1.1, 0.6
	Bottom	23.39	3.1, 6.6, 9.3	8.7, 4.1, 2.9
8/7-9/19	Surface	1.58	1.8	1.0
	Mid-depth	4.23	1.9	2.6
	Bottom	27.67	7.1	4.5
9/20-10/9	Surface	4.46	2.0	2.6
	Mid-depth	9.04	2.7	4.0
	Bottom	31.52	5.5	6.6
10/9-10/21	Surface	8.76	3.5	2.9
	Mid-depth	16.95	4.5	4.4
	Bottom	46.52	9.0	6.0
9/20-11/7	Surface	6.26	1.2, 2.6, 5.1	6.0, 2.8, 1.4
	Mid-depth	9.62	1.8, 3.4, 6.8	6.2, 3.3, 1.6
	Bottom	30.39	2.7, 6.6,16.3	13.0 5.3, 2.2

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*1 x 10^{-2}cm/sec = 8.64 m/day