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Flux of Particulate Matter in the Tidal Marshes and Subtidal Shallows of the Rhode River Estuary

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ABSTRACT: **There was a net influx of suspended particulate matter to the uppermost part of the Rhode River estuary during the several years of this study. Most of the influx was due to episodic discharges of suspended sediment from the watershed during heavy rains. In contrast, tidal exchange of particulate matter was not related to rainstorms. Sediment composition data and historical records indicate that marsh accretion accounts for only 13% of the sediment trapping although marshes occupy 60% of the study area. Influx of particulate matter to the marshes is directly related to the amount of time they are submerged during tidal cycles.**

Introduction

Knowledge of the flux of suspended matter in estuaries is crucial to understanding turbidity, shoaling, and transport of nutrients and pollutants. Estuaries can filter most of the suspended matter they receive from rivers. This is especially true for partially mixed estuaries with outward flowing surface water and inward flowing bottom water (Schubel and Carter 1984). For example, Chesapeake Bay is such an effective sediment trap that it actually imports suspended matter from the ocean as well as from rivers (Schubel and Carter 1984). The efficiency of sediment trapping by an estuary may be determined in part by the ratio of its volume capacity to the annual freshwater inflow (Biggs and Howell 1984).

Tidal marshes are also considered sediment trapping environments (e.g., see review by Frey and Basan 1978), but little is known about their importance as sediment traps in estuaries. One study suggested that South Carolina marshes could trap 85% of the suspended matter in terrestrial runoff (Settlemyre and Gardner 1977). Another study suggested that the marshes of Chesapeake Bay could trap 15% of the annual influx of suspended matter, even though the total area of marshes is only 4% of the area of open water (Nixon 1980). However, Officer et al. (1984) found that sediment deposition in subtidal areas could more than account for the sediment influx to the upper Chesapeake Bay.

The sediment trapping ability of marshes is generally attributed to the presence of emergent macrophytes. Plant stems promote sedimentation by slowing current velocities and by providing surfaces for sediment adhesion, while plant roots tend to bind sediment against erosion (Redfield 1972; Frey and Basan 1978; Stumpf 1983). However, the amount of suspended matter that marshes receive may be limited by the amount of time they are submerged. This could partly explain why sediment accretion may decrease with increase in elevation in salt marshes (Richards 1934; Richard 1978). Even unvegetated mudflats have been found to accrete faster than nearby vegetated areas of slightly higher elevation (Richard 1978).

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Thus, subtidal environments might actually trap more sediment per unit area than marshes.

Episodic events can be very important to the flux of suspended matter in both estuaries and marshes. For example, 70% of the annual discharge of suspended matter from the Susquehanna River to Chesapeake Bay typically occurs during a few weeks in the spring (Gross et al. 1978). In marshes direct measurements of the flux of suspended matter are often confined to a few tidal cycles throughout the year (Nixon 1980), so relatively rare storm events are not often sampled. However, in instances when sampling coincided with storms, unusually high fluxes of suspended matter have been observed (Settlemyre and Gardner 1977; Stumpf 1983; Chalmers et al. 1985; Stevenson et al. 1985).

In the present study we used a network of automated samplers to measure the flux of suspended matter into and out of the uppermost section of the Rhode River estuary. The automated samplers provided a nearly continuous record of the flux of suspended matter and revealed the importance of storms. We also investigated the relative importance of tidal marshes and subtidal areas in sediment trapping.

The Study Site

The Rhode River is a subestuary on the western shore of Chesapeake Bay in Maryland (38°51′N, 75°36′W). Nontidal currents in most of the Rhode River are driven by salinity changes in Chesapeake Bay, but in the upper sections, circulation is strongly influenced by local runoff (Han 1974). The upper most section of the Rhode River, Muddy Creek, receives runoff from about 2,300 ha of watershed consisting of 62% forest, 23% croplands (corn and tobacco), 12% pasture and 3% freshwater swamp. Muddy Creek consists of 23 ha of shallow (less than 1 m deep) mudflat and creeks bordered by 22 ha of high marsh and 13 ha of low marsh (Fig. 1). The mudflat and creek areas are half exposed by 2% of low tides and almost fully exposed by 0.6% of low tides. Thus, they are essentially subtidal, although we have previously referred to the mudflat as intertidal (Jordan et al. 1983). The high marsh is 42 cm above mean low water, is flooded by 20% of high tides and is vegetated by *Spartina patens, Distichlis spicata, Iva frutescens, Spartina cynosuroides,* and *Scirpus olneyi.* The low marsh is 30 cm above mean low water, is flooded by 46% of high tides and is vegetated primarily by *Typha angustifolia.* Based on its vegetation and elevation, our low marsh would be called high marsh by many classification schemes (e.g., McCormick and Somes 1982; Tiner 1985), but we refer to it as low marsh since it is the lower of the two marsh types in our study site. The mean tidal amplitude in the Rhode River is 30 cm, but the water level can fluctuate considerably more due to weather conditions such as strong winds. The salinity in Muddy Creek ranges from 0 to 18‰.

Methods

The watershed is separated into several sub-watersheds by natural drainage divides. Discharges of water and suspended matter from five of these sub-watersheds, which total 2,050 ha, were monitored with automated samplers (Fig. 1; Correll 1977, 1981; Correll and Dixon 1980). Discharge of suspended matter from the 229 ha of unmonitored watershed was estimated from data on the monitored watersheds. Occasionally, discharge from an additional 376 ha (watersheds 101 and 108, Fig. 1) also needed to be estimated due to failure of the samplers.

The automated samplers of four of the watersheds employed sharp-crested 120° V-notch weirs to measure water flow. Depth of water behind the weirs was measured with float-actuated gauges and recorded every 15 min. Flow rates were calculated from these depth measurements. The samplers automatically pumped aliquots of stream water every time 154 m^3 had been discharged since the previous sample. These aliquots were combined to produce flow-weighted composite samples that were collected for analysis every week.

The sampler of the fifth watershed (121, Fig. 1) was located in a tidally influenced area. Therefore, water flow was measured in a 4.8 m wide tidal flume using a tide gauge interfaced with an electromagnetic current meter (Marsh-McBirney Model 711). Every 30 min, flow was recorded and a volume of

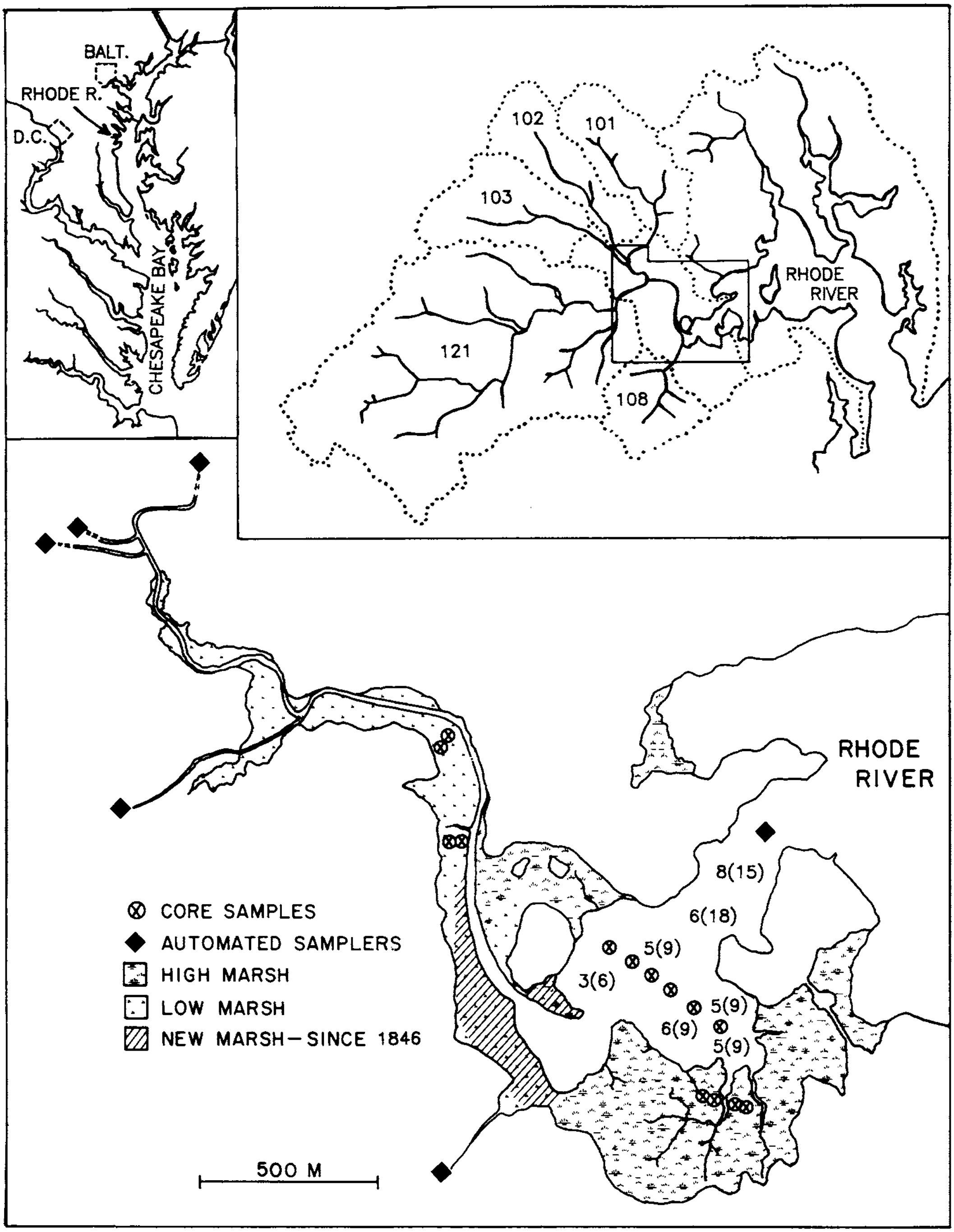

Fig. 1. Upper left: location of the Rhode River on the Chesapeake Bay near Washington, D.C. and Baltimore. Upper right: the Rhode River with its watershed outlined in dotted lines. The monitored sub-watersheds are numbered. Bottom: Muddy Creek and its bordering marshes. Dashed outlines of tributaries indicate reduced scale. Depths in subtidal area are given in dm below mean low water. Depths measured in 1846 are given in parentheses.

water proportional to the flow was sampled. Samples of incoming and outgoing tidal water were combined into separate flow-weighted composite samples that were collected for analysis each week. Tidal exchanges in and out of Muddy Creek were measured with a sampler similar to the one described above. However, instead of using a tidal flume, the sampler was located in a naturally constricted channel at the mouth of Muddy Creek (Fig. 1).

Using data from the automated samplers, we calculated weekly budgets of suspended matter entering and leaving Muddy Creek. The study covered three main time periods: May 1977 to July 1978, January 1980 to October 1982, and July 1984 to August 1985. Within these time periods, gaps in the data occurred due to a variety of electrical and mechanical problems unrelated to storm events. In all, 156 weeks were sampled.

The concentration of total suspended matter in the weekly samples was measured by filtering through prewashed, preweighed Millipore 0.45-μm filters (or equivalent), rinsing with distilled water to remove salts, drying at 60 °C and reweighing. Mineral suspended matter was determined by ashing these filters at 1,000 °C and weighing the residue. A temperature of 1,000 °C was used to insure complete combustion of the organic matter, and complete volatilization of the interlayer and bound water associated with clays (Millipore Corp. 1966; Carroll 1970). Water associated with clays can compromise 5–20% of their weight depending on the type of clay (Brown 1961; Carroll 1970).

We took core samples of the top 25 cm of sediment at the locations shown in Fig. 1. Each core was taken by slowly pressing a 6-cm diameter plastic tube into the sediment, stoppering the end, and withdrawing the tube. The cores were cut into 5-cm sections and the sections were dried at 60 °C and weighed. The dried sections were ground and samples of the ground sediment were ashed at 1,000 °C to determine mineral content.

A tide gauge at the Smithsonian pier 0.5 km from Muddy Creek provided data used as references for depth measurements and for calculations of frequency distributions of tide heights and of the average time the marshes were submerged per day. Tide gauge records from the pier agreed with measurements by the automated sampler at the mouth of Muddy Creek and with measurements made in the marshes by Jordan et al. (1983). The bathymetry of the mudflat was surveyed by measuring depths with a meter stick at regular intervals along several transects between distinct landmarks. The depths at which the marshes flooded were determined from unreported data on tidal flows collected in the study of Jordan et al. (1983).

Precipitation was monitored with a manual rain gauge and a Stevens tipping bucket rain gauge located 0.5 km from Muddy Creek. The tipping bucket gauge recorded the amount of precipitation during 5-min intervals. From these data the weekly maximum precipitation rates were determined.

Results and Discussion

Discharge of suspended matter from the watershed was highly episodic (Fig. 2). Discharge rates ranged up to 220 metric tons per week (t wk^{-1}), but rates higher than 40 t wk^{-1} were only observed during weeks when more than 2 cm of precipitation occurred. High precipitation is a prerequisite for high discharge, but low discharges were also observed during weeks with more than 2 cm of precipitation. Both the discharge of water and the average concentration of suspended matter in water from the watershed are significantly correlated with the volume of precipitation (Table 1). However, the concentration of suspended matter is more highly correlated with the weekly maximum rate of precipitation ($r^2 = 0.28$) than with the volume of precipitation ($r^2 = 0.16$, Table 1). The high proportion of unexplained variance indicates that other factors have important effects on the discharges of suspended matter and water. For example, water discharge is strongly influenced by evapotranspiration as well as by the volume of precipitation (Chirlin and Schaffner 1977). Also, precipitation rate alone may not control concentrations of suspended matter since storms occurring when the soil is saturated with water will produce greater proportions of above ground runoff than storms occurring when the soil is dry. However, storms occurring in rapid succession

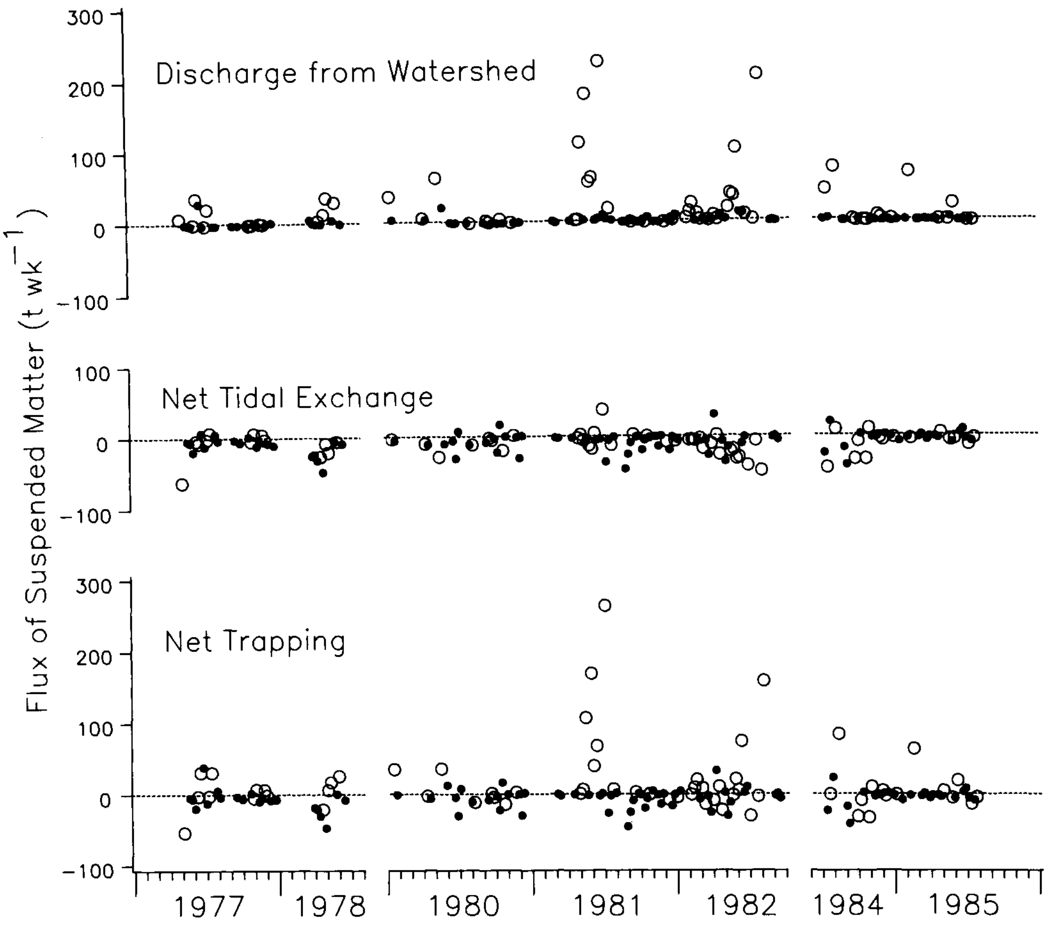

Fig. 2. Weekly average flux of suspended matter (t wk^{-1}): discharge from the watershed, tidal exchange between Muddy Creek and the Rhode River, net trapping in marshes and subtidal area. A positive flux is a net influx to the marshes and the subtidal area; a negative flux is a net output. Open circles indicate weeks with more than 2 cm of precipitation.

may produce successively lower discharges of suspended matter (Wood 1977). Whatever factors may influence the discharge of suspended matter, it is clear that large discharges are very sporadic and are produced by precipitation events. Furthermore, a few large discharges may make up a large proportion of the yearly discharge. For example, discharge during only 3 wk out of the 156 studied, accounted for 32% of the total discharge of suspended matter.

Net tidal exchange of suspended matter, measured with the sampler at the mouth of Muddy Creek, was not related to precipitation events, but appeared to fluctuate randomly with an average export of 6.8 t wk^{-1} from Muddy Creek to the rest of the Rhode River (Fig. 2). This suggests that most of the suspended matter discharged from the watershed during storms is trapped within Muddy Creek or its bordering marshes. The net trapping of suspended matter, calculated as the difference between the input from the watershed into Muddy Creek and the net tidal output from Muddy Creek, generally reflects the sporadic inputs from the watershed (Fig. 2). Our data are consistent with observations that after heavy rains Muddy Creek turns brown for a few days due to high concentrations of suspended matter.

During weeks with less than 2 cm of precipitation, more than two-thirds of the weeks studied, the average tidal export of sus-

TABLE 1. Coefficients of determination of regressions based on 156 weekly measurements. Sediment concentration is the mean concentration observed in water from the sub-watersheds weighted by the volume of water discharged from each sub-watershed. The slopes of all regressions are significantly different from zero ($p < 0.0001$).

Dependent Variable	Independent Variable	r^2
Suspended matter discharge	Precipitation volume	0.31
Water discharge	Precipitation volume	0.11
Suspended matter concentration	Precipitation volume	0.16
Suspended matter concentration	Peak precipitation rate	0.28

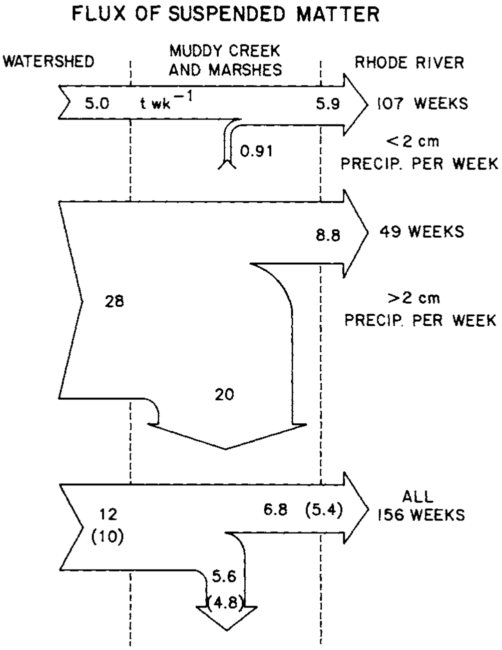

Fig. 3. Average flux of suspended matter (t wk^{-1}) during weeks with less than or more than 2 cm precipitation, and during all weeks combined. Numbers in parentheses are for mineral matter. Downward arrows represent net trapping.

pended matter was slightly, but not significantly, higher than the average input from the watershed (Fig. 3). However, during weeks with more than 2 cm of rain, 69% of the influx of suspended matter from the watershed was trapped in Muddy Creek or the marshes. On the average, tidal export was higher in weeks with more than 2 cm precipitation, but this trend was not consistent among individual weeks. For example, the largest discharge of suspended matter from the watershed, in early July 1981, coincided with a period of net tidal import of suspended matter to Muddy Creek (Fig. 2).

On the average, 45% of the influx of suspended matter from the watershed was trapped in Muddy Creek or the marshes. Biggs and Howell (1984) suggest that the sediment trapping efficiency of an estuary can be roughly predicted from the ratio of its volume to the annual freshwater inflow. The mean volume of Muddy Creek is 0.15×10^6 m^3 and the annual inflow was 1.7×10^6 m^3 (average of weeks sampled × 52). From these values Biggs' and Howell's (1984) model predicts a trapping efficiency of 75 to 95%, much higher than we measured. Actually, the trapping efficiency of our study site varies greatly from week to week, with the highest efficiencies during weeks with the highest discharges of suspended matter. It seems likely that high precipitation leads to the discharge of rapidly settling suspended matter.

How much of the trapped material is deposited on the creek and mudflat bottoms and how much is trapped within the marshes? To answer these questions we examined the rate of sediment accretion and the sediment composition of the marshes and the subtidal area. Hydrographic and topographic maps made in 1846 by the U.S. Coast and Geodetic Survey (National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce) suggest that the subtidal area has accreted more than the marshes. The hydrographic map from 1846 indicates that the mudflat, which comprises most of the subtidal area of Muddy Creek, was about 0.5 m deeper in 1846 than it is today (Fig. 1). In addition, local relative sea level, measured at Annapolis from 1929 to 1980, has been rising at a rate of 3.7 mm y^{-1} (Hicks et al. 1983). This relative rise in sea level is due both to eustatic rise in sea level and subsidence of the land in the Chesapeake Bay region (Hicks et al. 1983). By extrapolation, we estimate that local relative sea level has risen a total of 0.5 m since 1846. This means that the rate of sediment accretion in the subtidal area has been about 7 mm y^{-1} since 1846. This roughly agrees with core dating results for the same area of the Rhode River, which indicated accretion

TABLE 2. Density (dry g cm^{-3} of whole sediment) and mineral content (percent of dry weight) of sediments from six core samples from the subtidal area (± standard error).

Depth (cm)	Density (g cm^{-3})	Mineral (%)
0–5	0.332 ± 0.024	87.0 ± 0.4
5–10	0.391 ± 0.024	—
10–15	0.406 ± 0.027	—
15–20	0.457 ± 0.041	88.5 ± 0.5
20–25	0.455 ± 0.020	—

rates of 3.5–4.8 mm y^{-1} based on ^{14}C dating and 10–16 mm y^{-1} based on ^{210}Pb dating (Donoghue 1981). The topographic map from 1846 indicates that marshes covered all of the area presently covered by the high marsh and two-thirds of the area presently covered by the low marsh (Fig. 1). This suggests that the high marsh has accreted at about the same rate as sea level rise while the low marsh has accreted slightly faster. Other measurements of marsh accretion, reviewed by Hatton et al. (1983), seldom differ from the rate of sea level rise by more than a factor of two, despite differences in the rate of sea level rise among the marshes investigated. Studies of marshes on the eastern shore of Chesapeake Bay have distinguished two types of marshes: those like ours that form by accretion of sediment at rates faster than sea level rise, and those that form by submergence of uplands and accrete slower than sea level rise (Stevenson et al. 1985; Kearney and Ward 1986). Marshes which are accreting faster than sea level rise have also been described as "immature" marshes, which are generally at low elevation and in a state of expansion (Frey and Basan 1978). By comparison, "mature" marshes are at relatively high elevation and have stable boundaries. These descriptions seem to fit our low and high marshes, respectively.

Sediment density (dry weight per original bulk volume) and mineral content differ among the subtidal area and marshes. Sediment density increases with depth in the subtidal sediment until a depth of 15–20 cm (Table 2). This probably reflects the fact that the surface sediment is less consolidated and contains more interstitial water than the deep sediment. In the marshes, there are no consistent trends of mineral content and density with depth down to the depth we sampled. In general, the sediment of the subtidal area is the most dense and has the highest mineral concentration, the sediment of the high marsh is the least dense and has the lowest mineral concentration, and the sediment of the low marsh is intermediate (Table 3).

Assuming that the marshes accrete at the rate of sea level rise and the subtidal area accretes at about 7 mm y^{-1}, as inferred from the 1846 maps, we can calculate the amount of mineral sediment accreted (Table 3). For this calculation we also assume that sediment deposited in the subtidal area ultimately attains the density and mineral content of sediment at 15–20 cm. Based on this estimate, about 760 t y^{-1} mineral sediment is trapped in the subtidal area and the marshes combined. In contrast, our measurements of flux of suspended mineral matter (Fig. 3) indicate that only 248 t y^{-1} were trapped. This discrepancy apparently does not reflect unusually low precipitation,

TABLE 3. Density and mineral content of sediments and estimation of mineral deposition rates in the marshes and subtidal area. Mineral content and density in subtidal area are from Table 2. Data for marshes are based on means of two depths (0–5 cm and 15–20 cm) and four cores ± standard error.

	Subtidal	Low Marsh	High Marsh
Density (g cm^{-3})	0.457 ± 0.041	0.198 ± 0.008	0.137 ± 0.013
Percent mineral	88.5 ± 0.5	60.5 ± 1.8	36.1 ± 4.7
g Mineral per cm^3	0.406 ± 0.039	0.120 ± 0.008	0.054 ± 0.011
Area (ha)	23	13	22
Submergence (h d^{-1})	24	7	2
Accretion (mm y^{-1})	7	3.7	3.7
Mineral deposition (g m^{-2} y^{-1})	2,800	440	200
Mineral deposition (g m^{-2} h^{-1})	0.32	0.18	0.27
Mineral deposition (t y^{-1})	650	58	44

because the precipitation rate during our study was 105 cm y^{-1} which is about equal to the long-term average (Fassig 1907). It is possible that some of the deposited sediment originated from shoreline erosion, but data from other studies on the mineralogy and magnetic susceptibility of sediments in Muddy Creek suggests that the sediments originated from soil eroded from the watershed (Donoghue 1981; Oldfield 1983; Oldfield et al. 1985). Also, the marshes along Muddy Creek tend to protect the shore from erosion. It is most likely that the long-term sediment deposition rate is influenced by events that are too infrequent to have been adequately sampled during the period of our measurements. This is consistent with Donoghue's (1981) observation that one severe storm, tropical storm David in 1979, caused the deposition of up to 2.4 cm of sediment in Muddy Creek. Similarly, Hirschberg and Schubel (1979) found that half of the sediment deposition in northern Chesapeake Bay since 1900 was caused by two large floods, one in 1936 and one in 1972.

In a previous study we measured tidal exchanges of suspended matter in representative sections of the high and low marshes during 11 tidal cycles throughout the year (Jordan et al. 1983). Converting these measurements to fluxes of suspended mineral matter (using unpublished data on mineral content), we estimate that the low marsh trapped 329 g m^{-2} y^{-1} and the high marsh trapped 107 g m^{-2} y^{-1} mineral sediment. These rates are less than those based on the accretion estimate, 440 g m^{-2} y^{-1} in the low marsh and 200 g m^{-2} y^{-1} in the high marsh (Table 3), but this discrepancy could be attributed to the importance of episodic events which would be missed in a sampling of only 11 tidal cycles per year. Episodic events could also produce yearly variations in accretion. For example, Harrison and Bloom (1977) found that marshes accrete more in years with many storms than in years with few storms.

The measurements of tidal exchange of suspended matter by the marshes (Jordan et al. 1983) and the estimates of sediment accretion (Table 3) suggest that differences in sediment trapping rates among the subtidal area and marshes are related to the amount of time the areas are submerged. Even if the subtidal area and marshes accreted at the same rates in terms of depth, the rate of deposition of mineral sediment would still be related to the duration of submergence, because the mineral content of the sediment increases with increasing submergence. Accretion of marsh sediment is due both to sediment trapping and to accumulation of plant detritus (Redfield 1972; Frey and Basan 1978). Thus, as the elevation of a marsh increases, accretion becomes more a result of accumulation of organic matter and less a result of sediment trapping.

The mechanism by which marsh accretion keeps pace with sea level rise is not known. In marshes having predominately mineral sediment, the direct connection between sediment influx and the time spent submerged could provide a feedback mechanism forcing accretion to match the rise of sea level. However, in marshes where accretion is mainly due to organic matter accumulation, the time spent submerged may control accretion by affecting plant productivity (McCaffrey and Thompson 1980) or decomposition rates. The accumulation of organic matter may be limited ultimately by the tendency of very thick peat deposits to compress under their own weight (Kaye and Barghoorn 1964).

Inability to keep up with sea level rise may ultimately lead to the deterioration of a marsh (Baumann et al. 1984; Stevenson et al. 1985). Thus, preservation of marshes depends on maintenance of their ability to accrete sufficiently. Our marshes accrete in pace with sea level rise, but do not function as important sediment traps. Marshes occupy 60% of our study area, but we estimate that they account for only 13% of the sediment trapping. The rest of the sediment is trapped in the subtidal area especially during brief episodes of high discharge from the local watershed. The marshes of the Rhode River are primarily the end result rather than the cause of sediment trapping.

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