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The Process of Sedimentation on the Surface of a Salt Marsh

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An unditched salt marsh-creek drainage basin (Holland Glade Marsh, Lewes, Delaware) has a sedimentation rate of 0·5 cm year^{-1}. During normal, storm-free conditions, the creek carries negligible amounts of sand and coarse silt. Of the material in the waters flooding the marsh surface, over 80% disappears from the floodwaters within 12 m of the creek. About one-half of the lost material is theoretically too fine to settle, even if flow were not turbulent; however, sediment found on *Spartina* stems can account for the loss.

The quantity of suspended sediment that does reach the back marsh during these normal tides is inadequate to maintain the marsh surface against local sea level rise. This suspended sediment is also much finer than the deposited sediments. Additionally, remote sections of low marsh, sections flooded by only the highest spring tides, have 15–30 cm of highly inorganic marsh muds.

This evidence indicates that normal tidal flooding does not produce sedimentation in Holland Glade. Study of the effects of two severe storms, of a frequency of once per year, suggests that such storms can deposit sufficient sediment to maintain the marsh.

The actual deposition of fine-grained sediments (fine silt and clay) appears to result primarily from biological trapping rather than from settling. In addition, this study proposes that the total sedimentation on mature marshes results from a balance between tidal and storm sedimentation. Storms will control sediment supply and movement on micro- and meso-tidal marshes, and will have less influence on macro-tidal marshes.

Introduction

Modern salt marshes generally have a high rate of sedimentation. In the marshes of eastern United States, this sedimentation seems ubiquitous, and continuous throughout the Holocene. Bloom (1964) determined a deposition of 10·7 m of sediment in a Connecticut salt marsh over the past 7000 years—a rate of 0·15 cm year^{-1} associated with the continual rise in sea level. Armentano & Woodwell (1975), using Pb-210, found a high rate of deposition of 0·64 cm year^{-1} in a Long Island marsh over the last 100 years. Comparable rates have been observed above marker beds emplaced in other areas such as Georgia (0·4 cm year^{-1}, Letzsch & Frey, 1980), Delaware (0·6 cm year^{-1}, Stearns & MacCreary, 1957) and also in England (0·5 cm year^{-1}, Richards, 1934). In many of these marshes this deposition results from the influx of inorganic sediments rather than from peat formation (Frey & Basan, 1978; Redfield, 1967; Harrison & Bloom, 1977).

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These studies have concluded that during a slow rise in sea level, the marsh surface accretes at a rate determined by sea level variation, with the level of the marsh surface relative to mean sea level determined by sediment supply and frequency of tidal flooding.

According to the resultant model, deposition occurs during tidal flooding. Tidal currents in the marsh creek resuspend sediment. When the creek waters flood the marsh surface, salt marsh vegetation acts as a baffle, calming the flood waters enough to allow sediment to settle. As the floodwaters cross the marsh, the sediments will then deposit per the settling lag theory of Postma (1961). This model explains the formation of levees along tidal creeks—where most material should settle, and it also explains the low sedimentation rates observed on the high marshes that are well removed from the creeks.

However, the tides are not necessarily the sole cause of sedimentation. Using marker layers of glitter in Connecticut marshes, Harrison & Bloom (1977) measured annual sedimentation rates each year for 12 years. Although they found that the areas of highest tidal range had the highest sedimentation rates, they also observed that the marshes having intermediate tidal ranges had negligible sedimentation during the one storm-free year. Niering *et al.* (1977) complemented these findings by identifying sand layers—probable storm deposits—in the subsurface of the areas affected by the storm-free year.

However, few, if any, studies have actually investigated the path of transport between the creeks and the marsh surface. At present one does not know the degree to which fine-grained suspended sediment concentrations depend on local tidal current velocities, whether suspended sediment physically settles on the marsh or is trapped by plants or filter feeders, and whether the sediment enters the marsh during normal conditions or during extreme events. A normal event will be considered one that is periodic and of fairly high frequency; such as a spring tide. An extreme event is one, such as a storm, that has severe flooding and winds, and occurs perhaps 1–2 times per year. This study considers these problems by investigating the movement of the suspended sediment in the creek and marsh surface waters and comparing the settling rates of the suspended sediment with those of the deposited sediments.

Study site

The Holland Glade Marsh near Lewes, Delaware, was chosen for the study (Figures 1 and 2). The study area lies about 5·5 km southeast of Lewes between the Lewes-Rehoboth Canal (the old Lewes Creek) and the Holland Glade Stream. The tides are semi-diurnal and slightly asymmetric. The mean tide range is about 80 cm.

The particular section of marsh studied does not have drainage ditches, making it a 'natural' marsh. The Holland Glade Marsh also does not have any direct headland runoff, eliminating runoff as a cause of sedimentation.

Figure 2 shows the various subenvironments contained in the marsh. The *Spartina alterniflora* low marsh varies in elevation between mean high water (MHW) and the level of the highest spring high tides (MHW + 15 cm). The highest points of low marsh lie along the creek (tall form *S. alterniflora*) and around the *Iva frutescens* and *S. patens* marsh (short form *S. alterniflora*). Only the highest spring tides flood the *S. patens* marshes and *Iva* marshes. The *S. patens* and *Iva* marshes overlie relict spits or dunes that had formed of beach sand about 3000 BP, when the Delaware Bay shoreline passed through the area (Stumpf, 1981; Kraft *et al.*, 1978). The creek (cross-section in Figure 2) has a muddy-sandy to sandy bottom and has a depth at high water of 60 cm at neap tide and 90 cm at spring tide. A small muddy-bottomed gut, about 0·3 m deep helps drain the back marsh behind the levee.

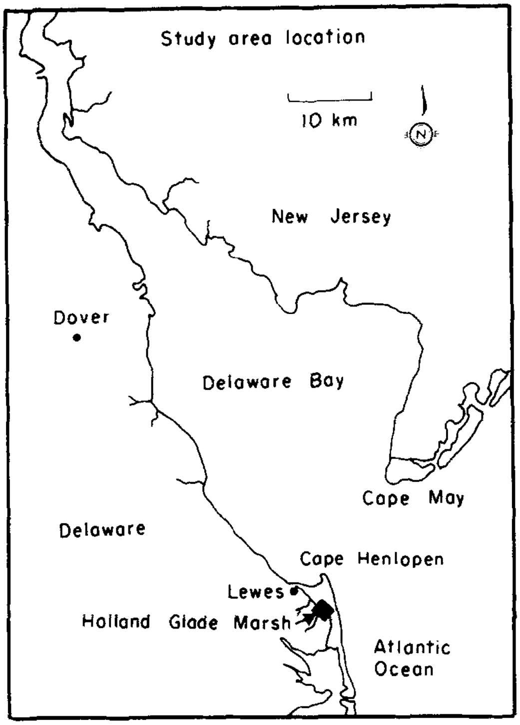

Figure 1. Study site location.

The marsh mud deposits that underlie the low marsh have a maximum thickness of 1·2 m and they overlie a late Holocene beach sand. Analyses of core peat stratigraphy indicate that the marsh has a sedimentation rate of 0·5 cm $year^{-1}$ since 1917 (Stumpf, 1981), a rate comparable to other Delaware salt marshes (Stearns & MacCreary, 1957; Brickman, 1978; Church *et al.*, 1981). Based on NOAA tidal records for Lewes, Delaware, local relative sea level has risen 0·3 cm $year^{-1}$ since 1919.

Methods and materials

Hydrography

Mean high water (MHW), mean low water (MLW), and flooding frequency were determined by calibrating tide staff readings obtained during each trip to the marsh with readings taken from a continuously recording tide gauge in Lewes. An electromagnetic current meter was used to measure water velocities. The mean velocity was taken at 6/10 of the creek depth, based on the standard logarithmic velocity profile (Graf, 1971). Water flow velocities and flow structure in the densely vegetated marsh were measured by injecting dyed filtered creek water with needle and syringe and then timing the movement of the dye. Vertical diffusion was estimated by determining the time the dye took to spread through the water column.

Water samples were taken with a hand-operated peristaltic pump. Samples collected simultaneously from the pump and from sample bottles dipped directly into the water had identical settling size distributions, indicating that the pump does not significantly alter

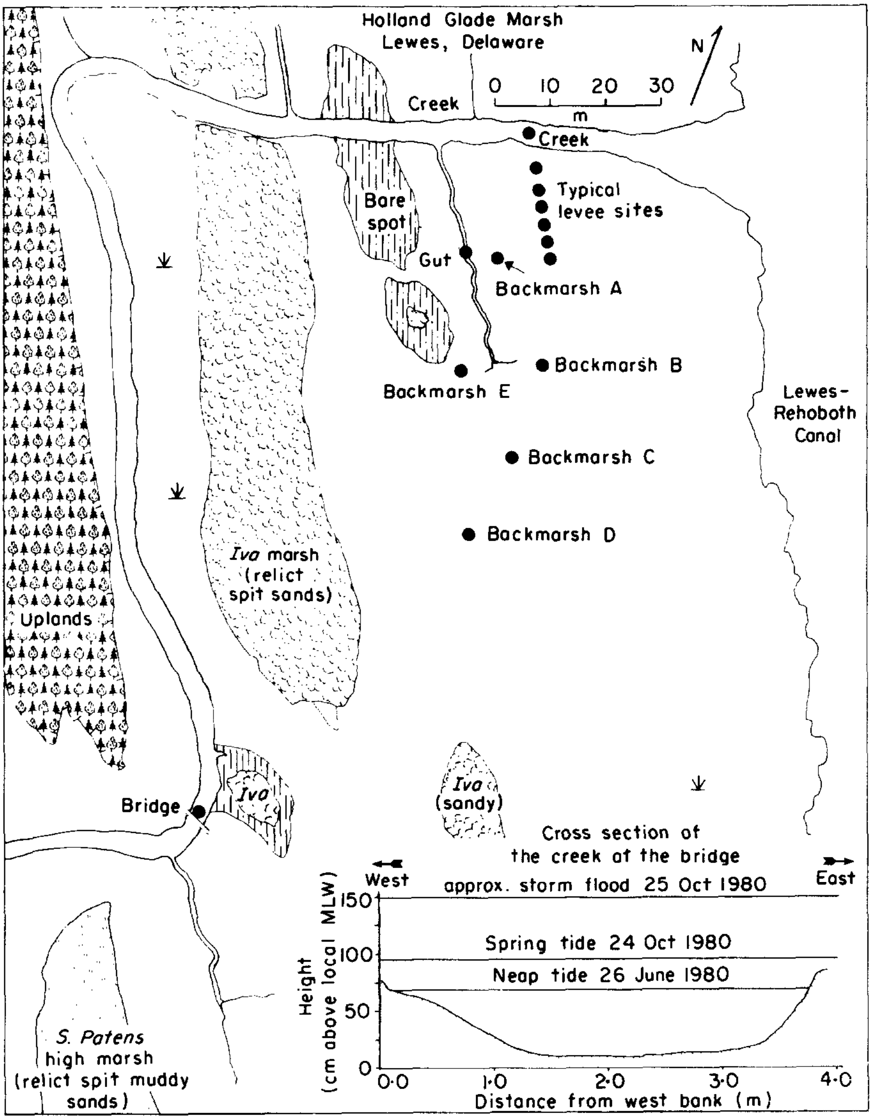

Figure 2. Sample location.

particle settling velocities. Samples were collected from 5 neap and 8 spring tides from April 1980 to February 1981. Although neap tides do not flood the marsh surface, the additional neap tide samples helped to indicate sediment variations with tidal current. One litre water samples were taken for total seston and total ash content, and 7·5 litre samples were taken for settling tube analyses (see below). Slackwater and maximum current sediment concentrations were compared using samples collected every hour from maximum flood to maximum ebb. Creek samples were taken about 10 cm below surface at spring tide high water to collect water most likely to flood the marsh surface. A few samples taken 10 cm above the bottom of the creek indicate that the suspended sediments have the same concentration through the water column.

Marsh water samples were taken from the sites shown in Figure 2, upcurrent from any disturbed grasses. Samples were taken about 5 cm below the surface, water depths were typically 10–15 cm. The water surface, the marsh surface, and the nearby grasses were not disturbed during sample collection. All samples were taken on the low marsh because the high marsh never flooded enough to take valid samples. Water temperatures were measured using a standard mercury thermometer. Salinities were measured using a refractometer.

All determination of total seston concentration an sediment size distributions used filtration through Whatman GFC glass fibre filters (effective pore size of 1 μm) per the procedure of Winneberger *et al.* (1963). Concentrations are accurate to 0·2 mg l^{-1}.

To determine the settling characteristics of the suspended sediments, raw water samples were analyzed by a settling tube technique similar to that of Postma (1961); (Stumpf, 1981). Raw water was placed in 70 cm high by 10 cm diameter plexiglas cylinders, and aliquots were drawn from tubing already inserted at the appropriate depths in the cylinders. To represent the *in situ* settling velocities as closely as possible, the raw samples were not diluted nor were any dispersants added, and all tests were run at the *in situ* water temperature within 2 h of sampling. Withdrawal times were chosen to produce size distributions in terms of set sizes, on the Wentworth scale, of quartz spheres. These effective diameters will be denoted by a subscript ' s ' (μm_s) to identify them as ' Stokes diameters ' rather than measured ones. The withdrawal times varied, because the Stokes settling velocities vary with changes in water temperature. The drawn samples were then filtered and weighed to give the size distribution. Size fraction concentrations have an error of 0·25 mg l^{-1}.

Ash weights of all sediment samples are the weights of the sample that remained after 2 h in a 450°C muffle furnace. Replicates indicate an error of 5%. Subsurface samples were collected from cores taken with 5·7 cm diameter plastic pipe.

Marker layers were used to observe short-term sedimentation, sedimentation occurring over a period of months. Aluminum glitter was sprinkled onto 0·25 m^2 plots, one on the levee 2 m from the creekbank, the other in the high back marsh. Bioturbation is negligible at these sites. The amount of deposition on top of the glitter was measured along a cutaway surface. Stem density of *S. alterniflora* was also measured, using stem counts from 6 0·1 m^2 plots selected randomly on the levee.

Marsh elevations were determined using both a hand level set on a 1·50 m pole and a plane table and alidade (Lahee, 1952). Local MLW is used as datum. MHW lies 80 cm above MLW.

Results

Creek hydrography

The creek has a maximum current of 25–30 cm s^{-1} during both normal neap and spring tides. Ash comprises 75–90% of the total seston. For sampling times from spring to fall of 1980, the suspended sediment concentration varied from 40–70 mg l^{-1}. During the winter of 1980–81, concentration varied from 10–42 mg l^{-1}, 42 mg l^{-1} after a minor storm.

The suspended sediment size distribution changes only slightly between maximum flood current and high slackwater. The concentration of material $>15·6$ μm_s does not decrease more than 4 mg l^{-1}. This indicates that flood tidal resuspension in the adjacent creek does not contribute significantly to the sediment load (cf. Postma, 1961). The creek generally carries negligible amounts of material $>62·5$ μm_s and only 0–2 mg l^{-1}, 0–5% of the total

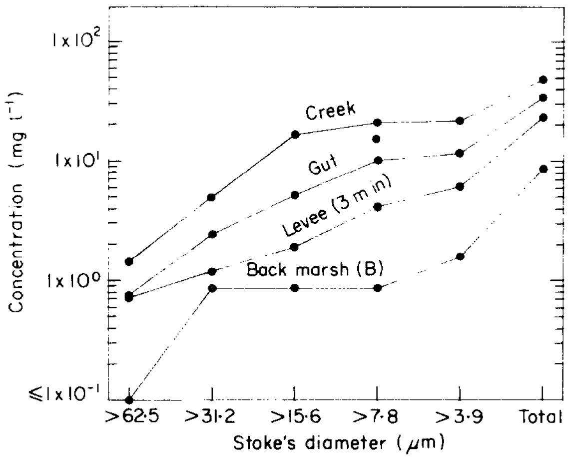

Figure 3. Size distribution of suspended solids.

load, during maximum flood current. A comparison of the creek shear stress with the Shield's resuspension criterion (Miller *et al.*, 1977) shows that the creek is competent to carry this material, (Stumpf, 1981); however, a permanent fluid mud layer on the creek bottom apparently helps prevent scour of the bed. This competence means that currents capable of removing the fluid mud could scour the bottom and produce a substantial load of suspended sand.

Marsh floodwater hydrography

In the hour preceding high water, floodwater surface speeds measured on the levee and near the gut typically vary from 2–1 cm s^{-1}. In the hour after, they often exceeded 3 cm s^{-1}. The associated Reynolds numbers were in the range 1000–3000 (10 cm depth, viscosity of 0·01 cP). The dye plumes consistently indicated turbulent flow; dye released within the water column mixed well through the water column. In addition, dye released within a few millimeters of the bottom remained at the bottom, with only slight horizontal flow, indicating the presence of a laminar sublayer during turbulent flow. This layer remains essentially stationary; a similar layer may encompass a larger portion of the water column around wrack deposits or extremely dense grass. The sublayer variations suggest the potential of thick vegetation to increase sedimentation by reducing flow and turbulence.

The approximate vertical diffusion coefficient, K_v, is 1 cm^2 s^{-1}. This compares with 9 cm^2 s^{-1} in the creek, a theoretical value based on the creek shear stress:

$$K_v = ku_* \frac{z}{d} (z-d)$$

(Graf, 1971) where von Karmen's constant $k=0\cdot4$; shear velocity $u_*=2\cdot5$ cm s^{-1}; sampling depth $z=10$ cm; water depth $d=90$ cm (Stumpf, 1981). Both the turbulence and the flow velocities of the floodwaters are one order of magnitude less than those of the creek.

TABLE 1. Inorganic sediment of different subenvironments

	Deposits		Suspended sediment	
	Levee (86%)[a]	Back marsh (80%)[a]	Levee (83%)[a]	Back marsh (<63%)[a]
Inorganic, $>16\ \mu m_s$	32%	25%	$2\ mg\ l^{-1}$	$<0\cdot4\ mg\ l^{-1}$
$<4\ \mu m_s$	42%	47%	$13\ mg\ l^{-1}$	$3\cdot6\ mg\ l^{-1}$

[a]Percent inorganic.

Floodwater sediments

The composition of the suspended sediments changes dramatically over the levee. As creekwaters move across the levee, the coarse material drops out, and the overall suspended sediment concentration decreases over 80% (Figure 3). As expected, the gut and levee suspended sediments have size distributions intermediate to those of the creek and those of the back marsh. Occassionally, the back marsh samples had more material $>31\ \mu m_s$ than the creek and levee samples (stations B, C, D). Inspection of those back marsh filters showed large particles (100–1000 μm) of organic material; particles that are absent on the filters bearing $<31\ \mu m_s$ material. A study of ash weights from some back marsh samples indicates that 47% of the material in the fraction $>4\ \mu m_s$ is inorganic, as compared with 63% of that $<4\ \mu m_s$. The large material appears to have been organic detritus derived from the grasses.

Sedimentary deposits

Most of the levee and back marsh deposits consist of inorganic silts and clays, with only a very small percentage of sand. For this reason the size analyses concentrated on the percentages of coarse silt ($>16\ \mu m_s$), fine silt ($16–4\ \mu m_s$), and clay ($<4\ \mu m_s$).

Occasional laminae of sand appear in the cores, sand with a modal sieve size of 80–125 μm. One layer at 20 cm appeared in several cores.

Comparison of the deposits and suspended sediments of the back marsh shows an inconsistency (Table 1); the deposits have much coarse silt and the water contains none. The back marsh and levee deposits have virtually the same percentage (25%) of coarse silt (confirmed by Students t-test, with $p=0\cdot05$), yet on a normal tide, $6–8\ mgl^{-1}$ of coarse silt drop on the creek bank and on the levee, and negligible amounts reach the back marsh. Also, the creek normally does not carry 100 μm sand, such as that found in the cores. The inorganic sediments normally in transit are much finer than those forming the deposits.

One can readily discount bioturbation from carrying sand and coarse silt up from underlying sand deposits. The marsh muds range from 0–1·2 m in thickness. In general, the $>16\ \mu m_s$ fraction does not increase with depth, and core radiography showed horizontal layering of both fine and coarse grained deposits; a feature common to salt marshes and contrary to bioturbation (Bouma, 1963; Evans, 1965; Pestrong, 1972; van Straaten, 1954).

It appears, then, that normal tidal flooding does not supply the size of material needed to build the marsh.

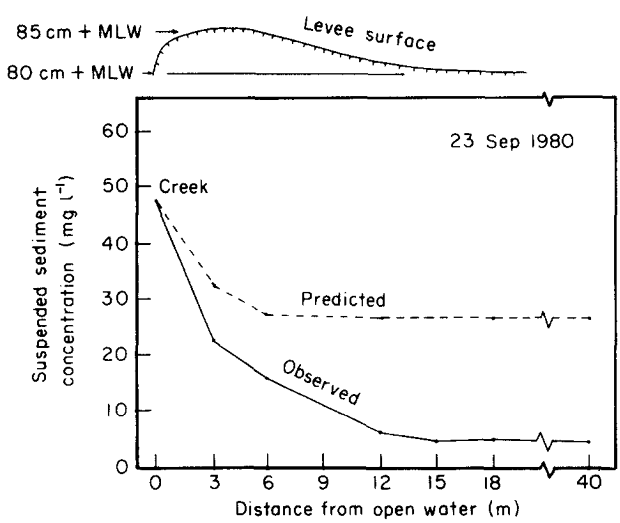

Figure 4. Floodwater sediment concentrations over the marsh surface.

Discussion—Tidal sedimentation

Sediment loss

Looking at the change in total concentration along transects perpendicular to the creek, one observes what first appears to be the expected sediment loss (Figure 3). The concentration does decrease rapidly over the levee; however, the loss of material is much too large to be caused by settling. This can be confirmed by a simple model that predicts the sediment concentration produced by settling at any distance from the creek. By neglected particle suspension by turbulence, particles with a settling velocity of w will travel a minimum distance

$$L = v\frac{h}{w}$$

where L = distance from open water; v = floodwater velocity, an average of $1 \cdot 5\ \text{cm s}^{-1}$ during late flood tide; h = distance of settling, the distance from the water surface to the level of the intake tube, 4–5 cm. This model overestimates the loss caused by settling, and underestimates the concentrations, because it neglects turbulent suspension.

As Figure 4 shows, particle settling does not explain the loss of fine-grained material from the water. (With concentrations $< 50\ \text{mg l}^{-1}$ and time intervals of 15–20 min additional flocculation will be insignificant; Krone, 1962). October samples shows that the creek seston contains $11 \cdot 5\ \text{mg l}^{-1}$ of size $< 1\ \mu\text{m}_s$, which is material that will not settle in still water. Yet, most of the corresponding back marsh water samples (stations A, B, C, D) had concentrations less than this.

Clearly, a mechanism other than settling must remove sediment from the water column. Biological trapping may offer the best explanation. One possibility is the ribbed mussel, *Geukensia demissa* (Dill.), a filter feeder that lives along the levee and gut. Kraeuter (1976) found that a mussel could deposit $0 \cdot 12$ g per tide of both organic and inorganic material.

TABLE 2. Sediment capture by *S. alterniflora*

Floodwater sediment loss:	
Slow-settling sediment loss ($<8\ \mu m_s$), C	20 mg l^{-1}
total discharge per meter of levee, Q	2700 l m^{-1}
Total sediment loss per meter of creek bank, $Q_s = C \times Q$	55 g m^{-1}
Amount of sediment found on *S. alterniflora* (3–12 cm from surface):	
S. alterniflora density across levee, N	470 stems m^{-2}[a]
inorganic sediment per stem, C_g	5 mg l^{-1}
levee width, Y	12 m
Sequestered sediment per meter of levee $Q_g = N \times C_g \times Y$	28 g m^{-1}
Percent of total loss	50%

[a]$\sigma = 114$.

TABLE 3. Predicted sedimentation rates based on normal (storm-free) tides

	Levee MLW+85 cm		Low back marsh MLW+80 cm		High back marsh MLW+85 cm	
	probable	maximum	probable	maximum	probable	maximum
Average sediment supply per tide (Q_s—g m^{-2})	$0 \cdot 9 \times 10^{-3}$	$1 \cdot 1 \times 10^{-3}$	50×10^{-6}	100×10^{-6}	25×10^{-6}	25×10^{-6}
Flooding frequency (F—times $year^{-1}$)	150	200	300	350	150	200
Conversion: soil volume per weight of ashed sediment (A)	4 ml g^{-1}					
Sedimentation rate ($Q_s \times F \times A$—cm $year^{-1}$)	0·5[a]	0·9[a]	0·06[b]	0·14[b]	0·02[b]	0·02[b]
Sea level rise (Breakwater Harbor, Lewes, Delaware)	0·3 cm $year^{-1}$					
Real sedimentation rate (since 1917)	0·5 cm $year^{-1}$					

[a]Q_s on levee $= Q \times C_L / Y$, where
$Q = h \times T \times v$, the mean overlevee discharge during flood tide; for 1/2 maximum spring tide: flooding depth $h = 5$ cm, flow duration $T = 3 \cdot 6 \times 10^3$ s, flow velocity $v = 1 \cdot 5$ cm s^{-1} ($Q = 27$ cm^{-1} of creek bank);
C_L = sediment dropped ($40\text{–}50 \times 10^{-3}$ g l^{-1});
Y = levee width (1200 cm).
[b]Q_s on back marsh $= C_B \times h$, where
C_B = concentration of sediment over back marsh (5×10^{-3} g l^{-1} on high back marsh; $5\text{–}10 \times 10^{-3}$ g l^{-1} on low back marsh)
h = average depth of flooding (using 90 cm above MLW, calculated from tide data)

The mussel density in Holland Glade is less than $2\,m^{-2}$ across the 12 m wide levee, so they would deposit <3 g per metre of bank, about 5% of the lost material (cf. Table 2).

The plants offer another alternative. Schubel (1973) and Ginsberg & Lowenstan (1958) found that seagrasses can sequester muds. This suggests that material might adhere to the stems and leaves of the *Spartina* in the water column. This hypothesis was tested by collecting 30 live *S. alterniflora* stems at low water on 3 occasions and washing off the sediment that adhered to the section of stem standing 3–12 cm above the marsh surface. The bottom 3 cm were not sampled because one cannot cleanly define the location of the marsh surface on the base of the stems. The thick coatings of mud on the bottom few centimetres may, in effect, belong to the marsh surface. However, if all or part of the coating came from the water—which is likely—then the estimate of sediment sequestering is conservative.

These tests indicate that the sediment on this part of the live plants can account for 50% of the suspended sediment lost during a spring tide (Table 2). The sediment collected may have accumulated over several tidal cycles. However, the bottom 3 cm of stem, together with dead and fallen stems, may collect a substantial amount of material and make up for this error. Live stems taken from the back marsh bore an average load of 0·25 mg per stem, whereas creek bank plants carried 5 mg per stem. The small load of the back marsh plants is consistent with the negligible changes in seston concentration in the back marsh.

Sediment trapped by *Spartina* may reach the marsh surface through several pathways: as fecal pellets during daily grazing by gastropods (*Melampus* sp.), which are abundant on the *Spartina* in Holland Glade; by rainwater washing the sediment to the base of the stems, perhaps every week (also observed); or by the death and collapse of the stem at the end of the season. These observations of live stems indicate that sequestering by grass can reasonably explain the loss of clay-sized sediment from the water column and its deposition on the marsh surface, whereas settling cannot.

Sedimentation rate

Table 3 shows the sedimentation rates predicted using the sediment supplied to the marsh during normal conditions. The rate for the levee assumes that all the material lost from the water flowing over the levee will deposit on the surface, this includes both settling and adhesion to the plants. The sedimentation rate for the back marsh is based on the assumption that all sediment in the water column at high water deposits on the surface. The calculation also assumes that no erosion occurs. These assumptions will lead to overestimates.

The rates indicate that the levee can potentially maintain itself against rising sea level. Problems arise, however, in the back marsh predictions. At best, the low sections can accrete at 1/2 the rate of sea level rise, and only 1/4 of the actual sedimentation rate. Furthermore, the lowest marsh should accrete more rapidly than the higher and more remote sections. Yet, the high back marsh lies on an inorganic (85% ash *vs.* 80% ash on the low back marsh) mud substrate at least 20 cm thick. In several places, the back marsh has built to an elevation of 90 cm above MLW, a level that only the highest spring tides can flood. Evidently, an assumption of sedimentation during normal tides has some severe contradictions.

Storm deposition

On 5–6 March 1981, a small northeaster struck the Delaware coast. The winds blew consistently at $12–15\,m\,s^{-1}$ (25–30 knots) for over 30 h. The storm surge, superimposed on a spring tide, produced substantial flooding in Holland Glade. On the morning of 6 March, the highwater level lie at MLW + 105 cm— higher than the level of the 24 October spring tide, the highest astronomical tide of the year.

The creek had a suspended sediment concentration of 42 mg l^{-1}, much higher than the 15 mg l^{-1} measured two weeks earlier (19 February). In addition, back marsh floodwaters had concentrations of about 15 mg l^{-1}, 5–10 mg l^{-1} higher than previously observed.

Although the floodwater surface was still below grass canopy level (25 cm water depth *vs.* 40 cm for the grass), the high winds clearly affected the movement of the floodwaters. A 1–2 cm thick surface boundary layer formed, which had a mean flow speed of 5–6 cm s^{-1} as compared with 2 cm s^{-1} for the main body of the floodwaters.

These observations give evidence of what will happen during a major storm. The storm may increase the suspended sediment concentration. With sufficiently deep floodwaters, wind stress will greatly increase the suspended load transport into the marsh. Quite likely, with over-canopy flow, wind waves will form, further augmenting the depth and amount of turbulence in the floodwaters. This can increase sediment transport into the back marsh.

Bayliss-Smith *et al.* (1979) studied flow in a similar creek in England. They found a normal creek velocity of 20 cm s^{-1}. During one severe storm, which covered their marsh to a depth of 80 cm, they recorded creek velocities in excess of 70 cm s^{-1} just before high water. If velocities like that occur in Holland Glade, the flow may scour the fluid mud and sand from the bottom. From the suspension, the sand laminae may form on the marsh surface (Bayliss-Smith *et al.*, 1979; Evans, 1965).

On 25 October 1980, a '25-year' storm hit the Delaware coast. The combination of spring tides and wind-induced storm surge produced extensive flooding. Over 70 cm of water covered the marsh surface; 50 cm higher than the 24 October spring tide (Figure 2; cross-section). The *S. patens* and *Distichlis* on the relict spit and around the uplands were flattened away from the creek, indicating the presence of some substantial overmarsh flows. Substantial wrack deposits were found only where these currents met the upland woods.

The back marsh surface showed no striking evidence of sedimentation. However, a 1–2 mm thick layer of sand-free silty mud lay on top of the bare spot. The mud layer had size percentages (sand: coarse silt: fine silt: clay) of 5:30:30:35. Previous surface samples of the same area had distributions of 20:27:24:29, respectively. A layer like this has otherwise never been observed there. Additionally, the layer had essentially the same size composition as the mud found in the back marsh substrate.

Observations of a marker layer of glitter provide evidence for storm-dominated sedimentation. On 20 June 1981, layers were placed on the levee and at station D. Thirteen weeks later (23 October) much of the glitter remained visible; the rest lay within a millimetre of the surface. This time interval had no storms. On 18–20 November, a northeaster—combined with spring tides—struck the Delaware coast. Three consecutive high tides produced up to 60 cm of flooding on the marsh. On 24 November, the glitter was checked again. During this four-week interval, 2–5 mm of mud had buried the levee glitter. Some of the back marsh glitter remained visible, most of it lay 0–2 mm below the surface. Significantly, the lack of deposition on the levee during the 13-week interval suggests that the tidal rates of Table 3 are, in fact, overestimated, and that levee sedimentation might not result simply from tidal deposition. The levee observations also provide strong support for the dominance of storm deposition over normal deposition; the back marsh observations are supportive, albeit somewhat equivocal.

Based on 26 major storms over a 21-year period of record, the average high water during a storm can clear the grass canopy (about 40–60 cm in the back marsh). The duration, the period in which high tides during the storm exceed normal astronomical spring high tides, averages 40 h. The October and November storms discussed above were average by these standards. Each of these storms left about 2 mm of sediment. Hence, 1–2 extreme storms per year can mobilize enough sediment to produce a sedimentation rate of 2–4 mm $year^{-1}$, a rate comparable to the mean sedimentation rate of 5 mm $year^{-1}$. Annual sedimentation depends directly on storm frequency and available sediment, rather than on short-term sea level rise.

Conclusions

The data and interpretations of this study point out problems with the sedimentation models now in use. Existing models tend to emphasize sedimentation during normal tides; but this study has found that these tides do not supply adequate amounts of the proper size of sediment. Additionally, settling cannot explain the deposition of clay and most silt in the back marsh. Settling lag can account for deposition of sand and coarse silt on the back marsh, but the short slackwater period and turbulence on the marsh would prevent the deposition of fine-grained material by settling—a point neglected by Pestrong (1972), although considered in the summary of Frey & Basan (1978).

Another contradiction may lie in an area beyond the scope of this study: the relative importance of tide range and storm frequency. In a micro-tidal area, most storms could produce extensive canopy flow. In a macro-tidal marsh, a storm during low tide would hardly flood the marsh, and only the most severe storm could produce substantially more flooding than a spring tide. Yet, most detailed studies on sedimentation rates have been made in meso- to macro-tidal areas. In a macro-tidal salt marsh, the high tides may regularly produce near-canopy flow, thereby bringing substantial quantities of sediment to the back marsh. The transported sediment would gradually leave the water column as the floodwaters move landward, leading to results such as those predicted by Table 3—lower sedimentation rates on the high back marsh—and as observed in some meso- to macro-tidal areas (Ranwell, 1964; Richards, 1934; Chapman, 1974).

Storm floods, on the other hand, may be more democratic in their distribution of sediment. The winds and turbulence could supply all sites equally. Storms may also produce such strong currents over the marsh that erosion and intramarsh transport ensues. In either case, deposition in the back marsh would depend primarily on the number of storms capable of producing canopy flow and strong currents in the marsh.

This concept of tides versus storms may extend beyond marshes. The geomorphology of meso-tidal barrier islands of the U.S. middle Atlantic is considered to be storm-dominated, but that of Georgia and New England macro-tidal barriers is controlled by more regular processes, such as tidal and eolian transport (Hayes, 1979).

Further study

This study identifies two factors that have often been neglected in previous research: storms and biologic sediment trapping. Sediment collection by grasses was simply tested in this study, and apparently it has not otherwise been analyzed in marshes. The implications are most important. By trapping sediment, the *Spartina* grasses partially control the geologic process that maintains their environment against a rise in sea level.

Finally, research is critically needed on the effects of storms on marshes. Storm deposition can be partially independent of sea level rise; thus, a marsh may remain stable only when storms can supply enough sediment for sedimentation to equal sea level rise. Future studies should investigate what kinds of marshes have storm-dominated deposition and resolve how floodwaters, transported sediments, and the marsh surface behave during storms.

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