CHAPTER 118

HYDRODYNAMICS AND SEDIMENT TRANSPORT IN A SALT MARSH TIDAL CHANNEL

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ABSTRACT

Processes and sediment transport were investigated in a salt marsh drainage system at Kiawah Island, South Carolina. A general survey of the tidal current was done in the major tidal channel (Bass Creek) for a 10 tidal cycle period in August, 1977. Detailed determinations of current velocity, discharge, and suspended load were conducted during 15 tidal cycles in March, 1977 and again during 8 tidal cycles in July-August, 1977. For each of these periods, mass budget for the total suspended load were computed.

The tidal currents have a pronounced time velocity asymmetry with the maximum current velocity occurring nearer high slack water and the peak ebb velocity being 20 - 30% stronger than the flood. Suspended load transport is significantly affected by the time velocity asymmetry. Peak current occurring nearer high slack water causes a net displacement of suspended material in an ebb or seaward direction under normal conditions. This process is enhanced by the stronger ebb currents. Mass budgets reflect the ebb dominance of the system showing a net export of combustible (organic) material during the March sampling period and a net export of both noncombustible (inorganic) and combustible material during the July-August period. Also important to suspended load transport in marsh systems are stressed meteorological conditions. High winds or heavy rains increase suspended load concentration and can cause significant import or export of fine-grained material.

INTRODUCTION

The physical and sedimentological processes occurring in a salt marsh tidal channel system were studied at Kiawah Island, South Carolina (Fig. 1). The purpose of the investigation was to monitor hydrodynamic processes and determine their effect on suspended material transport. Therefore, the tides, currents, and suspended load were monitored within the tidal channel system, and mass budgets for the total suspended load computed.

Physical Setting

Study area. - The investigation was conducted in a small marsh system (5 km^2) on the northeastern end of Kiawah Island (Fig. 2). The marsh is enclosed on three sides by Holocene beach ridges (Hayes,

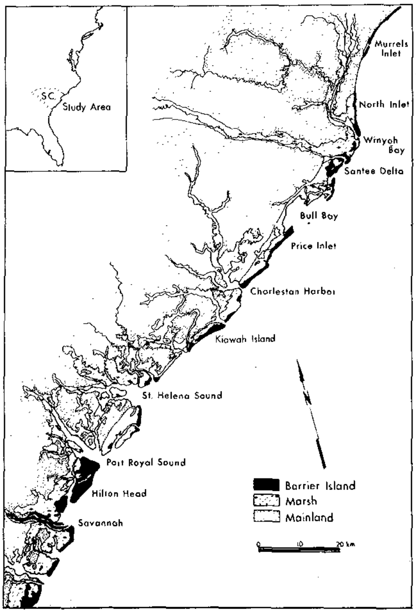

Figure 1. Location map of Kiawah Island, South Carolina.

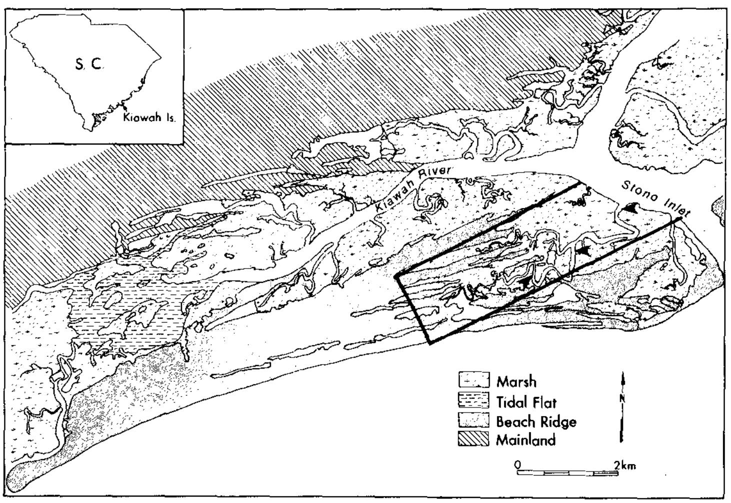

Figure 2. Map of Kiawah Island, South Carolina. The study was conducted in the Bass Creek marsh system outlined by the black line. Arrows point to locations where currents were monitored. Mass budgets for suspended material loads were done at the western-most station.

1975) which isolates it from any other major drainage system. One main tidal channel, Bass Creek, and its small tributaries, form the entire drainage network. The Bass Creek marsh system was chosen because it is unpolluted, essentially undisturbed by man, has no fresh water influx and has a simplified drainage system.

The primary marsh vegetation is Spartina alterniflora with Salicornia ambigua and Borrichia frutescens found at higher elevations. The marsh is composed of silt and clay-sized sediments (kaolinite and illite) except adjacent to abandoned beach ridges which have a high quartz sand content. Underlying the marsh sediments are fine-grained cohesive tidal flat sediments that have abundant oyster shell (Crassostrea virginica) deposits. The tidal channels normally have beds composed of fine sands, and the banks are composed of silts and clays. The channels are relatively unstable, showing numerous abandoned channels (cutoffs, oxbows, etc.). Channel migrations of up to 75 m in 24 years have occurred at locations where the channels have eroded into abandoned beach ridges (Ward and Domeracki, 1978).

Climate. - Kiawah Island has a marine subtropical climate modified by the Atlantic Ocean (Kjerfve, 1975). The monthly average temperatures for the period from 1935-1974 range from 10.2°C in January to 27.5°C in July with a mean of 18.9°C (Fig. 3). The average precipitation ranges from 6 cm in November to 18 cm in July, totaling 124 cm per year (data obtained from the National Weather Service).

Kiawah's climate is greatly influenced by frontal systems moving across the United States in an eastward direction (Kjerfve, 1975). During the winter months, when polar air masses traverse portions of the southeast, cold fronts produce west and northwest winds of considerable velocity. During the summer months, the Bermuda High creates anti-cyclonic circulation off the South Carolina coast causing southerly winds. The dominant winds are associated with the passage of low pressure systems or northeast storms.

The weather conditions that most affect marsh and tidal channel processes (observed in this study) are the occurrence of frequent afternoon and evening thundershowers. During the late spring and summer, severe thundershowers occur on a regular basis. During a single storm, several inches of rainfall and winds of over 50 km/hr may occur.

Tides. - The tides at Bass Creek are semi-diurnal with a strong diurnal component. The mean tidal range for 28 weeks of tidal data measured within Bass Creek is 1.75 meters. Two week averages vary from 1.54 to 1.92 meters. Individual tidal cycles have ranges from a maximum of 2.40 meters during spring tides to 0.84 meters during neap tides.

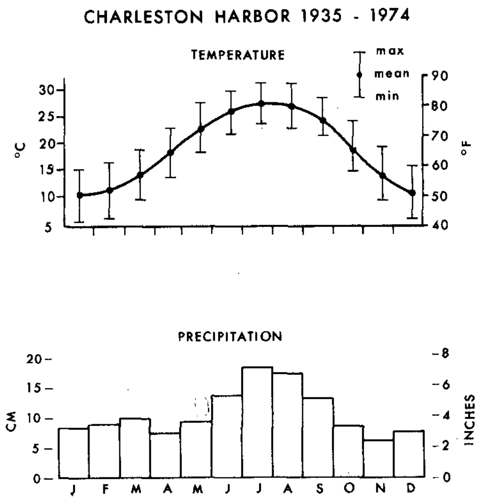

Figure 3. Average monthly temperatures and precipitation for Charleston Harbor, South Carolina, from 1935-1974.

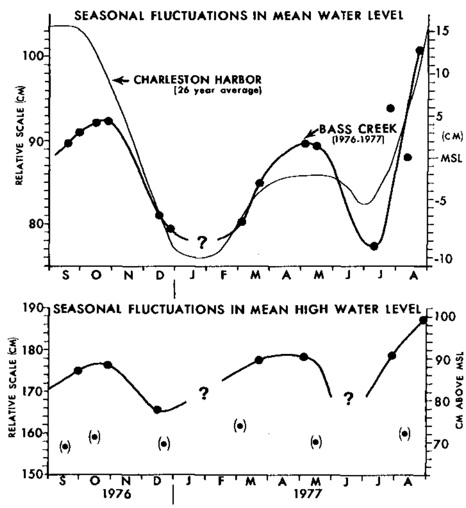

Figure 4. Seasonal fluctuations in water levels for Bass Creek and Charleston Harbor. Mean water levels for Bass Creek were determined by averaging hourly readings during two week periods. MSL is the mean water level at Bass Creek for 1976-1977. The curve for Charleston Harbor is from Hicks and Crosby (1974).

The mean water level, determined for 14 two-week periods by averaging ½ hour water level readings, shows a yearly variation of 22 cm (Fig. 4). The highest mean water level occurs during the late summer and early fall; while the minimum values occur during mid-winter. Similar trends have been reported by Humphries (1977) and Kjerfve, et al. (in press) for tidal creeks at North Inlet and by Hicks and Crosby (1974) for Charleston Harbor, South Carolina. The fluctuations in mean water level have been attributed to steric sea level changes (Patullo, et al., 1955).

During periods when the mean water level is at a maximum, the height and consequently the duration to which the marsh surface is flooded increases (as illustrated by the two-week averages for mean high water levels in Figure 4). Kjerfve, et al. (in press) found that due to higher autumn water levels at North Inlet, South Carolina, the marsh surface is inundated 42% of the time in October compared to 27% of the time in January. The length of time the marsh surface is covered is important to both depositional processes and nutrient exchanges. The marsh vegetation acts as a baffle, increasing sedimentation rates while it is covered with water. In addition, the marsh surface is the primary source of decaying vegetation. Increased flooding facilitates the removal of this material into the estuarine system where it can be utilized by the aquatic food chain.

Previous Studies

Physical and sedimentological processes in salt marsh tidal channels have been studied by a number of investigators trying to determine the flux of suspended material and dissolved substances. An excellent review of many of these articles is given by Frey and Basan (1978). Probably the most precise study was conducted by Boon (1973) in a marsh tidal creek in Virginia. The results of his work indicate that small low order tidal channels act as conduits, transporting both inorganic and organic particulate matter in a seaward (ebb) direction. His conclusions were based on sediment flux measurements done at a single channel cross section. Settlemyre and Gardner (1975) computed mass budgets for a larger tidal channel in an enclosed marsh in Charleston Harbor, South Carolina. Their results, contrary to Boon's, show an influx of inorganic particulate matter and an export of organic particulate matter. Hackney (1977), working in a marsh tidal channel in Mississippi, found an import of both organic and inorganic material during the summer and an export of both during the winter. Odum and de la Cruz (1967) computed mass budgets for organic detritus and found that it was exported from a Georgia salt marsh during all seasons.

A number of studies pertinent to understanding the processes in salt marsh tidal channels have been conducted on tidal flats. Some of the earlier investigations were done in the Dutch and German North Sea by Van Straaten and Kuenen (1957), Van Straaten (1961), Postma (1967) and Groen (1967). The results of these investigations indicate a landward increase in the fine-grained suspended material concentrations in tidal channels due to a "settling lag" and "scouring lag" effect. Coupled with this is a tidal current asymmetry, with the peak flood and ebb velocities occurring nearer low slack water. The effect of this asymmetry is that suspended material can be transported for a longer period on flood than ebb tides. Therefore, over a number of tidal cycles, there is a net landward displacement of the suspended load. They argued that, under normal conditions, this would cause a build-up of fine-grained material toward land with the North Sea being the source. Pestrong (1972a, 1972b) studied tidal flats and salt marshes in the San Francisco Bay area. His work suggests that tidal flats are overgrown by salt marshes by eroding sediment from the head of the marsh and flushing it seaward by ebb flow. Thus, the growth of the marsh onto the tidal flat is partially cannibalistic. Anderson (1972) has shown the importance of wave activity on the tidal flats in New Hampshire. At this location, it was illustrated that even small amplitude waves resuspend significant amounts of fine-grained sediment.

PROCESSES AND SEDIMENT TRANSPORT

Tidal Currents

Methods. - The current was monitored for a 10 tidal cycle period in August, 1977 at three locations within Bass Creek ranging from the mouth to a position 4 km in the flood direction (Fig. 2). At each location, a General Oceanics current meter was moored near the bottom (less than 1 meter) at mid-channel. Velocity and direction readings were taken at approximately 4 minute intervals for the 10 tidal cycle period.

Results. - The current velocity at all three locations has a pronounced time asymmetry (Fig. 5). Maximum current velocity normally occurs 1 to 3 hours before and 1 to 2 hours after high slack water. The current velocity at the two stations in Bass Creek away from the mouth also has a velocity asymmetry with the ebb current being much stronger than the flood. The average ratios of the maximum flood velocity (F max) to maximum ebb velocity (E max) at the two stations located 2 km and 4 km away from the mouth are 0.64 and 0.68 respectively for the 10 tidal cycles monitored. The station located in the mouth of Bass Creek shows no velocity asymmetry, having an average F max/E max ratio of 0.98.

In addition to the time velocity asymmetry of the currents, there is an asymmetry or difference in the duration of the flood and ebb flow. Inspection of Figure 5 shows that the flood currents normally occur for over 6½ hours, while the ebb currents flow for less than 6 hours. This

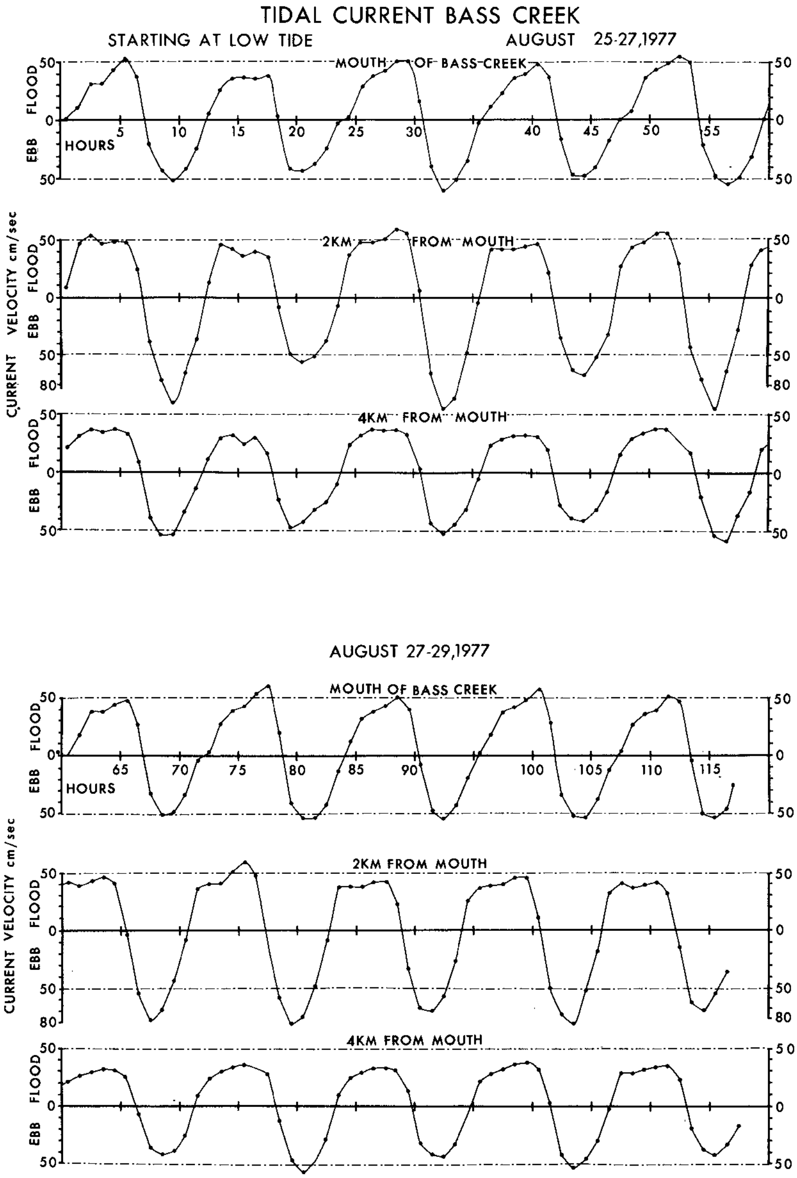

Figure 5. Time series profiles of the current during ten continuous tidal cycles in Bass Creek. The first five tidal cycles are shown on the upper half of the figure , and the last five are shown on the lower half. Each point on the curve is the average of 17 readings taken at approximately 4 minute intervals.

difference in duration is further verified in the 28 weeks of tide data analyzed in Bass Creek. The average duration of the flood component of the tide is 6.54 hours; while the average duration of the ebb is 5.69 hours. It should be pointed out that only half-hour readings were taken from the tidal records and used to compute these averages. Therefore, there may be some error. To determine the reliability of these figures, a number of tidal cycles were measured directly to obtain accurate flood and ebb durations. The results indicate that there is a large amount of variability in the duration of individual cycles, but the averages compare well to the 2-week averages (within 0.1 - 0.2 hours). Similar duration asymmetries in tidal inlets and marsh channels have been reported by Boon (1973), FitzGerald, et al., (1976), and Nummedal and Humphries (1978), and were attributed to distortion of the tidal wave and the formation of overtides. Nummedal further pointed out that if the flood and ebb discharges are similar, then because of the shorter duration, the ebb velocities would have to be higher than the flood to transport the same volume of water in a shorter period. This process contributes to the velocity asymmetry of the current.

Suspended Load Transport and Mass Budgets

Method. - The current, discharge, and suspended load were monitored during 23 tidal cycles in Bass Creek at a location that transmitted the entire tidal prism to an isolated area of the marsh (Fig. 2). The first sampling session was conducted in March, 1977, during which 15 out of 18 consecutive cycles were monitored. The other 8 tidal cycles were monitored during July-August, 1977. These two periods were chosen because March is representative of winter conditions in the southeastern United States, having minimum temperatures and precipitation (Fig. 3); while July-August represents summer conditions having maximum temperatures and precipitation.

Prior to these sampling sessions, preliminary surveys were done to assess the accuracy at which the mean current, discharge, and suspended load could be determined. This information was then used to determine the experimental error involved in computing the instantaneous and total flux of suspended material over a flood or ebb portion of a tidal cycle. It was found that the mean current could be estimated within ± 4.2% to ± 8.5% and the suspended load within ± 6.3%, if measurements were made at 1/5, 1/2, and 4/5 the distance across the channel and at 0.2 and 0.8 the relative depth at each location (Figs. 6 and 7). The error involved in computing the instantaneous flux is the combined error for the current and suspended load or approximately ± 7.6 to ± 10.6% (Ward, 1978). The error for determining the total flux of suspended material over a flood or ebb portion of a tidal cycle is slightly less (Boon, 1973). Therefore, any net or residual flux of material

INSTRUMENT ARRAY

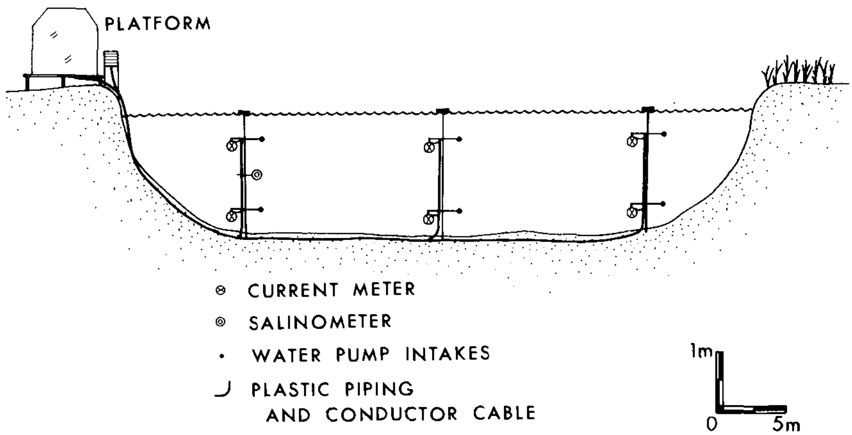

Figure 6. Schematic of the instrument array. The channel was approximately 50 meters wide, and the instrument frames were located 1/5, 1/2 and 4/5 the distance across the channel. The current meters and intakes for the water pumping system were able to rotate freely and were always aligned into the current. The current velocity, temperature, and salinity readings were taken inside a tent located on the platform. The water samples were taken at the outflow valves of the pumping system also located on the platform.

INSTRUMENT FRAME

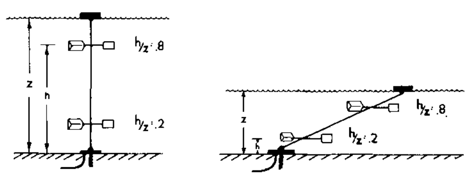

Figure 7. Schematic of the instrument frame. The base was augered into the channel and a float attached to the top. A hinge allowed the frame to raise and lower with changes in tidal height, keeping instruments at 0.2 and 0.8 of the total depth at all stages of the tide.

greater than ± 10% for the mass budget is considered to be significant and not the result of sampling errors.

Results. - The suspended load concentrations during the March sampling session are normally between 10 - 20 mg/l except during periods of high wind of heavy rain when concentration exceed 50 mg/l. During the July-August sampling session, the total suspended loads range from 20 - 200 mg/l, but are normally between 50 - 100 mg/l. The organic fractions range from 0 to 70% but have a mode at about 20%.

Time series data of the suspended load and current for the first two tidal cycles monitored during the July-August session illustrates the relationship between highest sediment transport and maximum current velocity (Fig. 8). During the first tidal cycle, highest suspended load concentrations during flood tide occur simultaneously with the strongest current. The suspended load concentration is over 160 mg/l, but drops to about 30 mg/l as high slack water approaches, and the coarser material settles out. After the ebb current reaches a maximum, the suspended load increases to 160 mg/l again.

Mass budgets of the suspended load for the tidal cycles monitored in March are shown in Figure 9. The first 6 cycles (TC1-6) are during spring tides, 7-10 during mean, and 13-18 during neap tides. In general, the spring tides are much more dynamic than neap tides in respect to sediment transport. Fluxes for the total suspended load are normally greater than 5 x 10^6 grams for any half cycles during the spring tides, while neap tide fluxes are normally closer to 1.0 x 10^6 grams. These higher transport rates result from greater discharges and stronger currents that occur during spring tides.

The flux of material for tidal cycles 1-6 was summed in order to determine the net movement of material for that period. The net mass budget for the 6 cycle periods shows an export of 2.3 x 10^6 grams or about 5% of the total suspended load flux. Results of the error analysis indicate that fluxes this low are not reliable, as they may be accounted for by experimental error. Therefore, the budget is considered to be in balance. Inspection of the components of the total suspended load indicates there is also a balance of the non-combustibles (inorganic) fraction, but an export or ebb-directed net flux of 1.5 x 10^6 grams of combustibles (organics) fraction. The net export of combustibles accounts for a residual transport of approximately 16% which is considered reliable.

The effects of the meteorological conditions on suspended load transport become evident when individual tidal cycles are inspected. During cycles 1-4, when there were only light winds and no rainfall, the mass budgets reflect the movement of material due to the large tidal prisms associated with spring tides. As the tidal range and tidal

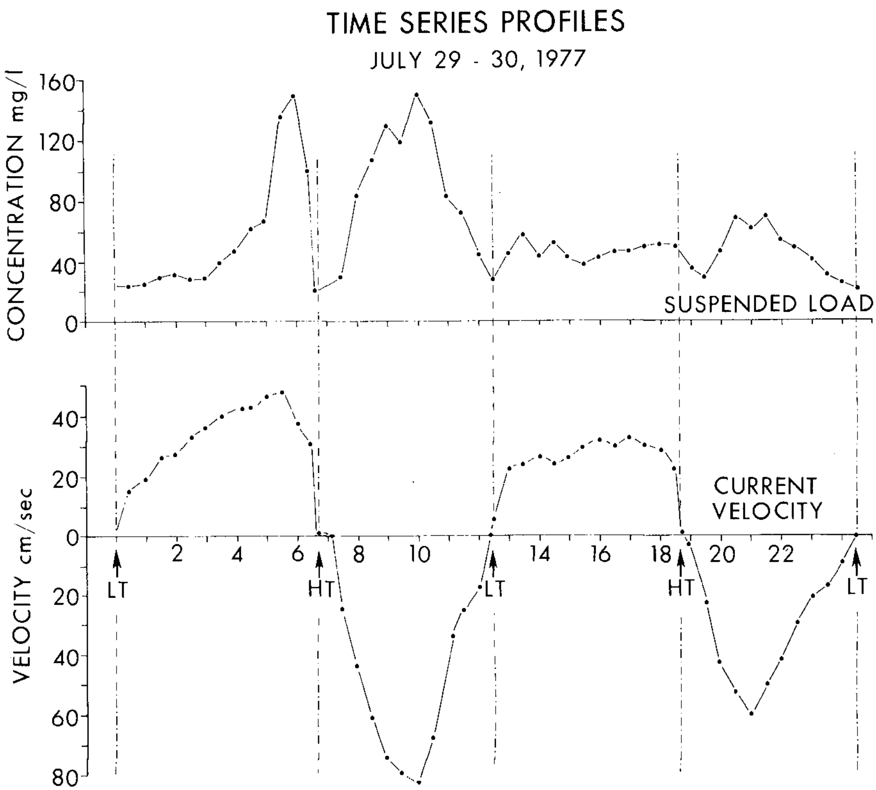

Figure 8. Time series profiles of the mean suspended load and current velocity in Bass Creek during the July, 1977 session. Note that the maximum suspended load concentrations occur with peak current velocity. Also note the time velocity asymmetry of the current.

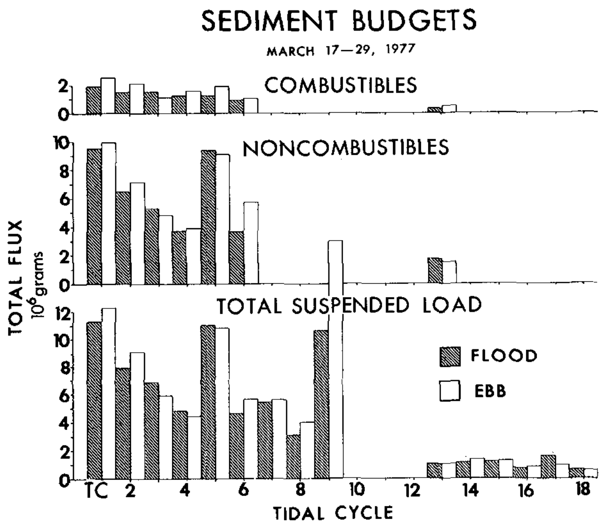

Figure 9. Mass budgets for the suspended load in Bass Creek during March, 1977. Tidal cycles 1-6 were during spring tides while 13-18 were during neap tides. Hatched columns represent the flood fluxes; open columns represent ebb fluxes.

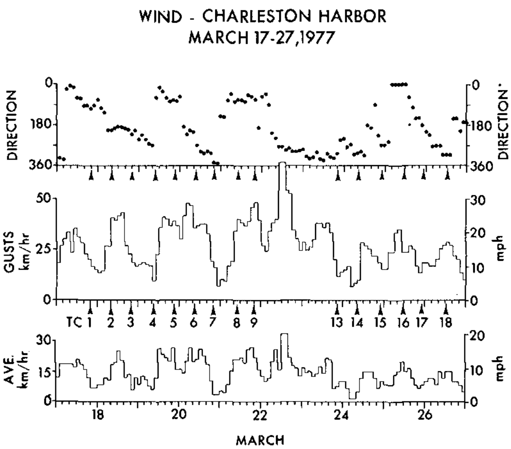

Figure 10. Wind velocity and directions for Charleston Harbor, South Carolina. The times that correspond to the tidal cycles monitored are labelled TC1-18. Note the strong gusting winds from the northeast during TC-9.

prism decrease, sediment transport reduces. During tidal cycle 5, winds gusting to 40 km/hr from the northeast and east (Fig. 10) caused a slight set-up in the tidal height and an increase in wave activity within the tidal channels. The wave activity eroded material from the channel margin, increasing the total suspended load and the mass budgets. During the following tidal cycle, the winds remained strong, but began blowing from the south. The marsh system is orientated such that winds from the northeast are most effective in increasing the wave activity and causing a set-up in the tides. Winds from other directions seem to have only a minor effect on marsh processes; therefore, the sediment flux for tidal cycle 6 is markedly reduced.

The relationship between meteorological conditions and sedimentary processes is again demonstrated during tidal cycle 9. During the ebb portion of tidal cycle 8, the wind began to blow consistently from the northeast at about 25 km/h. During the flood portion of tidal cycle 9, the winds remained from the northeast, but increased in velocity reaching nearly 50 km/h. This caused a water level nearly 40 cm higher than would normally be expected and a flood duration of over 7 hours. These increases resulted in the water elevation being abnormally higher than the ocean level which produced an abnormally steep hydraulic slope. When the tide turned, the increase in the hydraulic slope created currents of over 75 cm/sec which were greater than those measured during maximum spring tides. Due to the set-up, wave activity, and high ebb currents resulting from the northeast winds, much more material was transported than in any of the previous cycles. Over 10.6×10^6 grams and 16.9×10^6 grams were transported on the flood and ebb respectively.

Mass budgets for the summer show similar trends as the March budgets except for the quantity of material being transported (Fig. 11). During the winter sampling period, the maximum amount of material transported over any ½ tidal cycle past the channel cross-section is 20×10^6 grams. During the summer sampling period, the maximum value reaches 87×10^6 grams. This dramatic increase may be attributed to three factors. Steric sea level is at a maximum which would conceivably increase the tidal prisms (Fig. 4). Second, the warmer water temperatures may reduce the cohesiveness of the fine-grained material, making it more erodable. Finally, there is an increase in biologic activity during the summer. Observations in the field show that the activity of the fiddler crab (<u>Uca pugnax</u>) and other organisms is greatly increased. This, in addition to the increase in the floral growth, increases the turbidity and suspended load and, consequently, the mass budgets. In all probability, it is a combination of these factors.

The net flux of material for the five tidal cycles monitored during the spring tides (TC1-5; Fig. 11) indicate that there is an export of both the combustible and noncombustible fractions of the suspended load. A residual of approximately 40.7×10^6 grams (35%) of noncombustible and 2.9×10^6 grams (10%) of combustible material was exported.

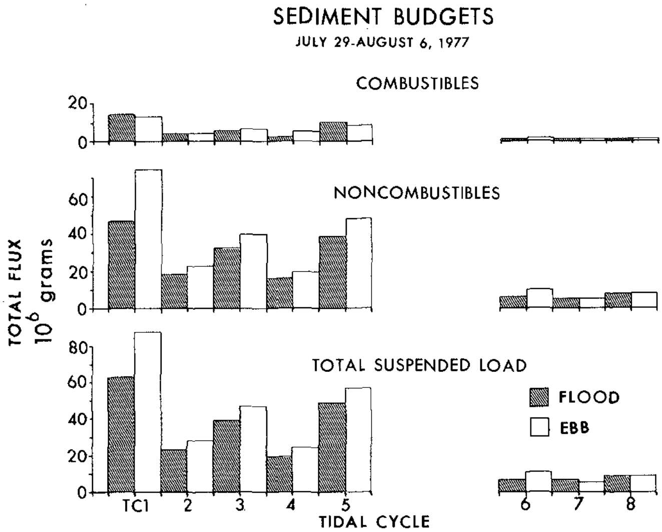

Figure 11. Mass budgets for the suspended load in Bass Creek during July-August, 1977. Tidal cycles 1-5 were during spring tides while 6-8 were during neap tides. Hatched columns represent flood fluxes; open columns represent ebb fluxes.

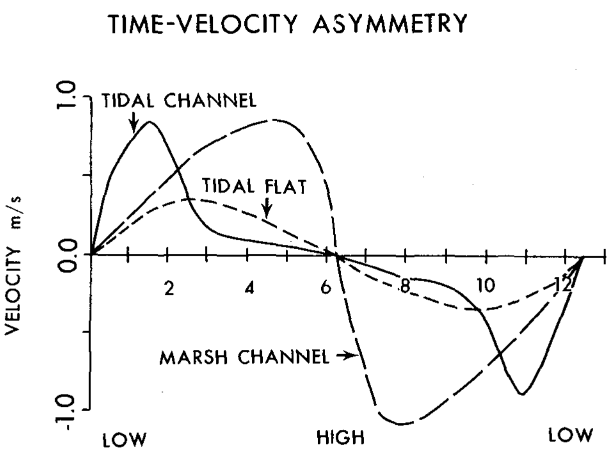

Figure 12. Representative current profiles from tidal channels and tidal flats in the Wadden Sea (Postma, 1967) and the marsh channel at Bass Creek, South Carolina. Note the shifting of peak current velocity from being asymmetric toward low slack water in the Wadden Sea to high slack water in Bass Creek.

Discussion

The time velocity asymmetry strongly affects the movement of sediment within tidal channels and ultimately controls the flux of particulate matter under normal meteorological conditions. As illustrated in Figure 8, the strongest current occurs 1-2 hours before and 2-3 hours after high slack water, and the maximum ebb current velocity can be between 50 to 100% stronger than the flood. The net effect of the time asymmetry is that a parcel of water can be transported at maximum velocity only 1-2 hours during the flood. Conversely, the same parcel of water can be transported up to 3-4 hours on the ebb tide. Consequently, even without the maximum currents being unequal, the water parcel undergoes a net seaward or ebb-directed displacement. This effect is further enhanced by the stronger ebb currents. The suspended load reaches a peak simultaneously with the current and therefore would be displaced in a similar manner as a water parcel. Thus, the time velocity asymmetry causes a net movement of material seaward. This same relationship, but, in reverse, is used along with "settling and scouring lag" to explain a net landward transport of suspended material in the Wadden Sea (Van Straaten and Kuenen, 1957; Postma, 1967; Groen, 1967). Data published by Postma (1967) shown in Figure 12 illustrates the time velocity asymmetry measured in the Wadden Sea. The maximum current velocity occurs near low slack water causing a net displacement of water and suspended material landward. If the period of maximum current is shifted toward high slack water as in the southeastern United States, then there is a seaward flux of material.

CONCLUSIONS

This study of the physical and sedimentological processes in the Bass Creek salt marsh tidal channel system illustrates the complex relationship between the tidal regime and, consequently the tidal currents, the meteorological conditions, the biologic activity, and the transport and deposition of sediment. The major findings of this study based on the two extended sampling periods and the general monitoring of the tides and currents at Bass Creek, S. C. are:

1. Sediment transport varies nearly an order of magnitude from the high transport period of the summer to the low transport period of the winter. This variation is primarily attributed to steric sea level fluctuation and changes in biologic activity.

2. Sediment transport varies a great deal from tidal cycle to tidal cycle under normal conditions due to changes in tidal prisms or discharge.

3. There is a net export of combustible (organic) suspended material during both the summer and winter in the marsh tidal channel.

4. There is an export of noncombustible (inorganic) suspended material during the summer and a balance during the winter.

5. The net export of material under normal conditions can be attributed to the time velocity asymmetry of the currents.

6. Stressed meteorological events (such as heavy rains or strong winds) increase sediment transport in marshes dramatically.

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