Estuarine, Coastal and Shelf Science (1995) **41,** 225–248

Sediment Transport Processes in a West-central Florida Open Marine Marsh Tidal Creek; the Role of Tides and Extra-tropical Storms

Lynn A. Leonard[a,c], Albert C. Hine[a], Mark E. Luther[a] Richard P. Stumpf[b] and Eric E. Wright[a]

[a]Department of Marine Science, University of South Florida, 140 Seventh Avenue South, St Petersburg, FL 33701, U.S.A. and [b]Center for Coastal Geology and Regional Marine Studies, 600 Fourth Street South, St Petersburg, FL 33701, U.S.A.

Received 26 October 1992 and in revised form 28 July 1994

Keywords: salt marshes; sediments, transport; tidal cycles; Gulf of Mexico

The extensive open marine marshes on Florida's Gulf of Mexico coast constitute one of the largest continuous coastal marsh systems in the U.S.A. and are characterized by (1) the absence of an apparent modern or relict sediment supply, (2) a thin 1–2 m sediment veneer overlying highly karstified bedrock and (3) both low wave and low tidal energy regimes. More importantly, the Florida open marine marsh system appears to be keeping pace with current rates of sea-level rise in spite of a limited inorganic sediment supply and low tidal energies. Although the magnitudes and directions of suspended solid transport and the processes controlling these transports have been rigorously documented for other U.S.A. marsh systems, they have not been documented in the Florida marsh system. Total suspended solid (TSS) concentrations, current speeds and water levels were monitored in Cedar Creek, Florida, so that the TSS loads could be calculated and the processes exerting control over material exchange could be determined. Both TSS concentration and load are modulated by spring/neap variations and time-velocity asymmetries in the tidal currents. Concentrations at the creek mouth increase by as much as two orders of magnitude during strong wind events due to the presence of waves; however, large net sediment loads appear to be related to the coupled effects of waves and large tidal prisms. Waves initially mobilize sediments in the adjacent embayment but increased tidal prisms, and the associated higher velocities, are requisite for transport of this material further into the creek. Large tidal prisms may be the result of astronomically high tides or meteorologically forced tides. In Cedar Creek, the most important meteorological events affecting sedimentary processes are extra-tropical storms. This is because they occur at much higher frequencies than tropical storms and hurricanes, even though the latter are more potent and potentially could transport greater amounts of material. This study identifies the important processes controlling suspended solid transport in the broad expanses of *Juncus roemerianus*

[c]Present address: Department of Earth Science, University of North Carolina at Wilmington, 601 S. College Road, Wilmington, 28403, U.S.A.

0272–7714/95/020225+24 $12.00/0

dominated marsh adjacent to the large arcuate embayments prevalent along the west-central Florida marsh coast as described by Hine and Belknap (1988). The processes exerting control over sediment transport in the Cedar Creek drainage basin are similar to those documented in other marsh systems.

Introduction

Allochthonous sediment influx is one of the dominant processes in marsh accretion (Ranwell, 1964; Pestrong, 1972; Pethick, 1980) and, consequently, numerous studies have focused on direction and magnitude of total suspended material transport in tidal creeks (Boon, 1973; Settlemyre & Gardener, 1977; Ward, 1978; Ward, 1981; Reed *et al*., 1985; Reed, 1987; Roman & Daiber, 1989). The majority of flux studies, however, have been conducted within marsh systems located on the U.S. Atlantic coast, marshes along the Mississippi Delta of the Gulf of Mexico and some marshes along the coast of Great Britain. The 300 km stretch of microtidal marshes along the west-central Florida coast has received relatively little attention (Hine *et al*., 1988) as compared to other marshes despite an acknowledged absence of data from areas of low tidal energies (Stevenson *et al*., 1986).

The open marine marshes on Florida's Gulf of Mexico coast are considered to be unique due to a combination of low regional gradient and resultant low-wave energy, lack of modern or relict sand supply and relatively thin, generally 1–2 m, marsh sediment veneer overlying highly karstified limestone bedrock. Unlike most of the tidal marshes studied along the U.S. Atlantic coastal plain and Great Britain, the open marine marshes of Florida's Gulf coast are microtidal and, unlike microtidal marsh environments in the Gulf of Mexico (e.g. Mississippi Delta; DeLaune *et al*., 1983), these marshes are neither undergoing rapid subsidence nor receiving significant sediment input from riverine sources.

One general concept that seems to apply to microtidal coasts, such as the west-central marsh coast of Florida, is that low tidal energies limit the amount of inorganic sediment input available from seaward sources (Stevenson *et al*., 1986). Therefore, sedimentation during major storm events such as extra-tropical low-pressure systems or hurricanes, is believed to be a critical factor in the sediment budget of microtidal marshes (Harrison & Bloom, 1977; Settlemyre & Gardner, 1977; Stumpf, 1983; Baumann *et al*., 1984; Cahoon & Turner, 1987; Childers & Day, 1988; Rejmanek *et al*., 1988; Reed, 1989).

The aims of this study were (1) to identify (a) the directions and magnitudes of material transport and (b) the processes exerting control over this transport in a typical tidal creek in the west-central Florida open marine marsh system and (2) to compare these results to data gathered from similar studies in other coastal marsh systems. Suspended material concentrations, tides, currents, and meteorological events were monitored and total suspended solid loads were calculated. Particular attention was paid to the effects of wind-driven events in order to evaluate the role of storm-driven transport in the sediment budget of the study area marshes.

Study area

This investigation was conducted in one of the tidal creeks in the extensive open marine marsh system of west-central Florida's Gulf Coast (Hine *et al*., 1988). Cedar Creek, one

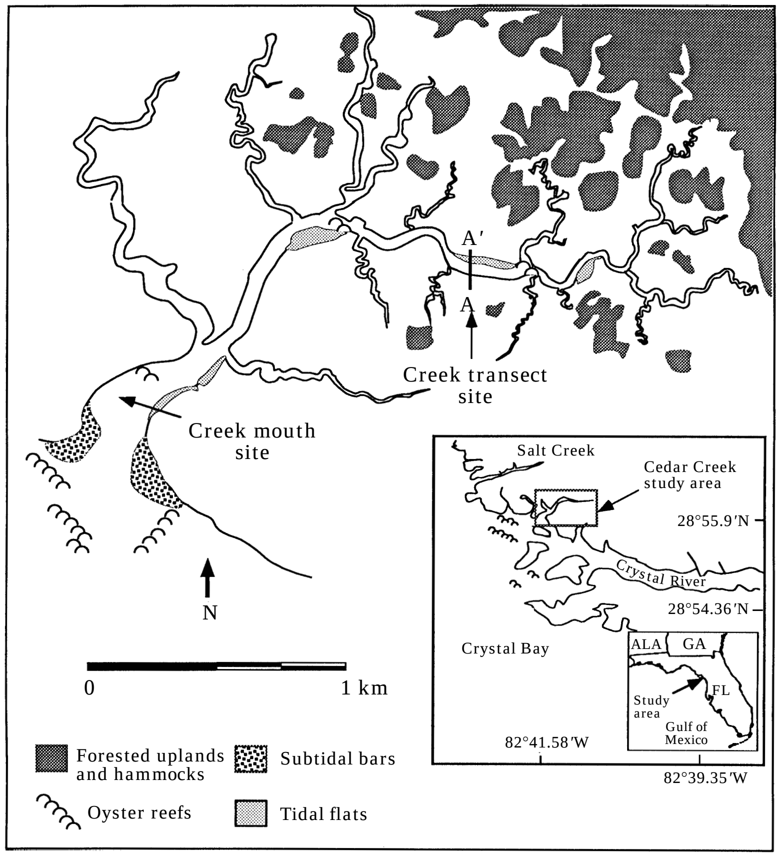

Figure 1. Location map of the Cedar Creek drainage basin near Crystal River Florida. The creek mouth is located at 28°55·9′, 82°41·58′. Creek transect A–A′ is shown in Figure 3.

of the major tidal channels adjacent to the Crystal River Embayment, a shelf embayment as defined by Hine *et al.* (1988) (Figure 1), was chosen for this study because it has only one opening to the sea, contains little development in the drainage basin, has minimal upland freshwater influx and was easily accessible.

Cedar Creek drains a marsh basin approximately 5 km^2 in area and discharges into a small shallow embayment rimmed by extensive sand flats and oyster (*Crassostrea virginica*) reefs. *Juncus roemerianus* Scheele is the dominant vegetation in the basin with *Spartina alterniflora* Loisel in low areas and along creeks. *Cladium jamaicensis* Crantz occurs locally and becomes particularly prevalent near the upland fringe. Forested uplands and the Gulf of Mexico delineate the boundaries of the marsh. The marsh surface is essentially planar except for where the topography is controlled by the highly karstified underlying Eocene limestone. Forested hammocks exist on bedrock highs, whereas tidal creeks and their tributaries develop in bedrock lows. In general, the tidal creek channels are floored by exposed bedrock, however, sandy point bar deposits, intertidal flats and oyster bars also occur. The abundance of sand and oyster bars increases with proximity to the creek mouth.

The mean tidal range on this coast is 0·8 m (microtidal) with the maximum spring tidal range recorded at Cedar Creek being 1·2 m during the study period. Astronomical tides at Cedar Creek are semi-diurnal with a strong diurnal inequality. Tides are strongly influenced by wind events, specifically, the passage of extra-tropical low-pressure systems in winter (Hine & Belknap, 1986).

Methods

Although measurements accounting for both spatial and temporal variations in velocity and suspended load concentration are preferable when attempting to quantify sediment exchanges through a tidal creek (Boon, 1973, 1978; Bayliss-Smith *et al.*, 1979; Ward, 1981; Reed *et al.*, 1985; Reed, 1987), our sediment load calculations depended on monitoring of a single station at hourly intervals over numerous consecutive tidal cycles. Therefore, it was necessary to establish the validity of these measurements in representing the total transport in the creek at that location. Preliminary experiments were conducted to determine the spatial and temporal variability of total suspended solid (TSS) loads across the creek.

Spatial variations

A permanent transect site was established across a 30-m wide straight segment of the creek (see Figure 1 for location). The resulting cross-section (A–A′) was divided into three subregions on the basis of creek bottom morphology (channel, tidal flat and an intermediate transitional area) and the proposed single monitoring location was chosen at 50 cm above the bottom in the creek channel. A hand-held Marsh McBirney electromagnetic current meter was used to obtain vertical velocity profiles in the water columns above each of the three morphological regions. One-minute velocity means were computed from measurements taken at 10, 25, 50, 75, 100, 110 and 125 cm above the bottom once per hour over three separate and complete tidal cycles; one spring cycle (13 April 1991), one mid-spring/neap cycle (15 April 1991) and one neap cycle (6 May 1991).

The shape of the velocity profiles indicate that, except during periods of extremely low velocities associated with slack water, the water column consists of two regions. The lower region, within 50–30 cm of the bed, is characterized by decreasing current velocities as the bed is approached. Within the upper region, current velocities are relatively uniform (Figure 2). Except for the region very close to the creek wall on the tidal flat, lateral variations in velocity are within instrument precision when measured at a constant height above the bottom along transect A–A′.

Vertical integrated averages above each of the three morphological regions (Figure 3) were computed and compared to velocities measured at 50 cm above the bottom in the creek channel. Error estimates for vertical profiles indicate that single point estimates were found to approximate the vertically integrated means for each of the subregions normally within $\pm$ 13% error. Percent error was computed by subtracting the integrated average from the point estimate, dividing by the integrated average and multiplying by 100. Larger errors were associated with lower velocities such as those existing in very shallow water and during neap tides or slack water.

Lateral and vertical variations in concentration were identified by collecting 1-l water samples (with replicates) in each of the three morphological regions. Each area was

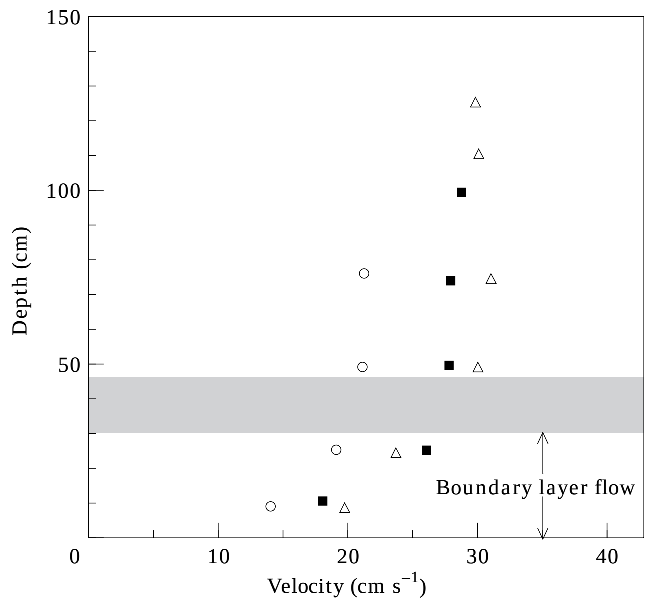

Figure 2. Example of a typical velocity profile collected in Cedar Creek showing the region of boundary layer flow within each of the morphological regions defined in the text. Stippled area represents the variable height above the bottom (30–50 cm) at which the boundary between the upper and lower flow regimes may occur. △, channel; ■, transition; ○, tidal flat.

sampled at heights of 30, 50, or 75 cm above the creek bed for the channel and transitional regions. Tidal flat samples were collected at 30 cm above the bottom. Sampling occurred over one complete spring tidal cycle (13 April) at 1-h intervals. Water samples were collected using a hand-operated pump and stored on ice. Within several hours of collection, water samples were filtered through 1-µm, precombusted, glass-fibre filters. Filters were washed with deionized water to remove salts, dried at 80 °C and weighed on an analytical balance. Total suspended solid (TSS) concentrations were calculated in terms of mg l^{-1}.

Replicate 1-l water samples collected hourly for each of the three morphological subregions throughout complete tidal cycles on 14 April (spring) and 6 May (neap) were used to determine the error associated with estimating TSS concentration. Analysis of three replicate pairs having a mean concentration of 24·2 mg l^{-1} indicated that a 3% analytical error is associated with measured TSS concentrations. Lateral variations in concentration measured simultaneously were well within the concentration ranges for replicate samples and therefore considered minimal. In addition, suspended load concentrations measured at 30 and 70 cm within each subregion were usually highly and significantly correlated with one another (Table 1). Several neap tide values, however, were less highly correlated and non-significant due, in part, to small sample size and a narrow range of current velocities. Comparisons of concentrations measured at 50 cm above the bottom in the creek channel to vertically integrated means indicate that a percent error of less than 9 is usually associated with usage of the 50-cm measurement as an estimate of the mean concentration for the entire creek cross-section.

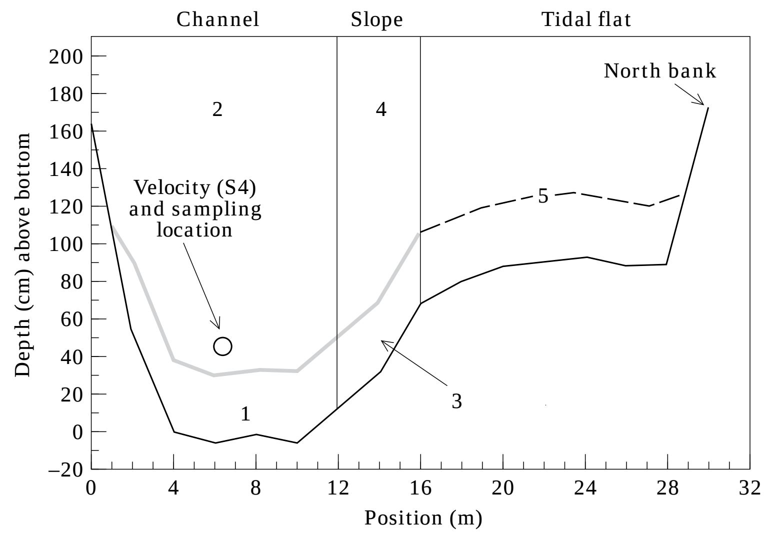

Figure 3. Cedar Creek cross-section at transect A–A′. Numbers 1–5 indicate sampling compartments. Shaded line indicates the region separating boundary layer flow from the overlying region of uniform flow as defined in Figure 2. Dashed line indicates the uppermost extent of the boundary layer region on the tidal flat. For sampling purposes, the latter two areas were treated as one compartment (5).

TABLE 1. Correlation coefficients for suspended load concentrations among five compartments in the Cedar Creek transect

	Compartment				
Compartment	1	2	3	4	5
1	—	0·91	0·84	0·94	0·99
		0·95*	0·40*	0·32*	0·39*
2		—	0·71	0·86	0·93
			0·24	0·53*	− 0·45
3			—	0·93	0·81
				0·16	− 0·48
4				—	0·91
					0·04

Upper values from spring tides; lower values from neap tides.
*Non-significant correlations ($P>0{\cdot}05$).

Total suspended solid loads were determined using the expression:

$$Q_s = \int_0^T q_s \, dt$$

where Q_s is the TSS transport through a cross-section of a tidal creek during the interval 0–T, q_s is the instantaneous estimate of TSS transport, and t is time (Boon, 1978). The total error for determining q_s is the combined errors of estimating velocity and concentration (Boon, 1978; Ward, 1978):

$$E_{q_i} = \sqrt{(\mathrm{E}_{c_i})^2 + (\mathrm{E}_{s_i})^2}$$

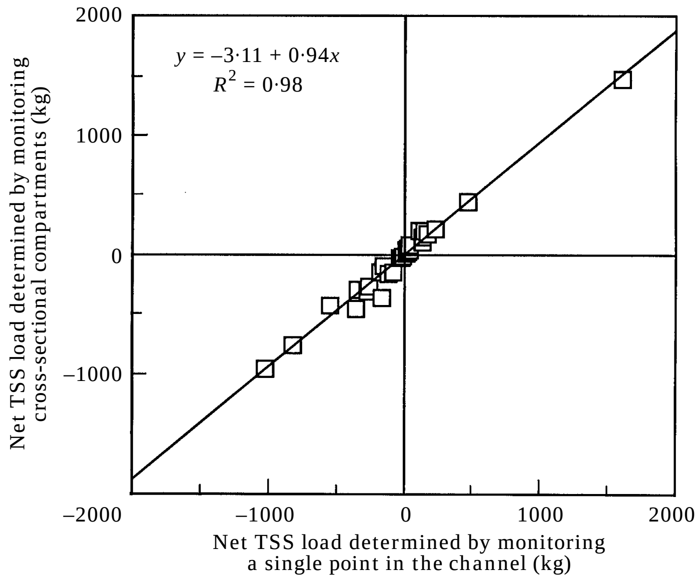

Figure 4. Regressions of TSS load calculated by monitoring within each of the cross-section compartments against load calculated by monitoring at one location within the creek channel.

where E_{q_i} is the error in determining the suspended material load within a channel subsection (for our purposes we treated the entire channel as one section), E_{c_i} is the error in determining mean current velocity within a channel subsection, and E_{s_i} is the error in determining mean suspended material concentration within a channel subsection. Percent error values associated with the use of point measurements of velocity and concentration were used to compute the total error (E_{q_i}) associated with TSS load estimates. The total error associated with our TSS loads computed from single site monitoring is 16%. This value should not be exceeded when net loads are expressed as a percentage of the mean flood and ebb loads if the measurement is to be considered real and not simply the result of experimental error.

Boon (1978) and Ward (1978) suggested that the error for determining sediment flux may be reduced by increasing the number of sampling subsections. To determine whether an increase in sampling subsections along the Cedar Creek transect would result in significantly different load values for this study, two analyses were conducted. First, the creek cross-section was further subdivided into five compartments on the basis of creek bottom morphology and the velocity profile data (Figure 3). Instantaneous TSS loads were then calculated by determining discharge, suspended material concentration and the suspended solid load for each of the five compartments in Figure 3 and summing the values. The second method calculated the instantaneous TSS load using concentrations and velocities measured at a single site located approximately 50 cm above the creek bottom. Values calculated from the compartmental sampling technique were linearly regressed on the values obtained from the single site method. The two methods were highly positively correlated with an r^2 value of 0·98. The slope and y-intercept of the regression, 0·94 and $-3{\cdot}11$, respectively (Figure 4), and the high r^2 value indicate that concentrations and velocities measured at 50 cm above the bottom in the creek

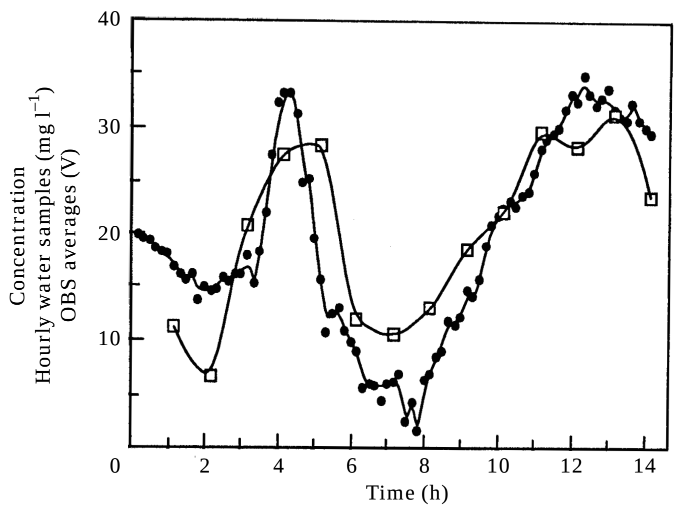

Figure 5. Total suspended solid concentrations measured by OBS at frequencies greater than 1 h and from 1-l water samples collected at frequencies equal to 1 h on 7 August 1991. Optical back scatter (OBS) samples (●) are 10-min mean values, whereas hourly samples (□) are instantaneous.

channel may be used to obtain estimates of instantaneous TSS through the entire cross-section of the creek. Regression values were not used to estimate sediment loads, but are merely provided to demonstrate that an increase of sampling compartments from 1 to 5 does not substantially change TSS load estimates.

Temporal variations

To ensure that significant suspended sediment concentration variations did not occur at periodicities of less than 1 h, the anticipated long-term sampling interval, instantaneous hourly measurements of concentration were compared with 10-min mean optical back-scatter (OBS) measurements of TSS concentration (expressed in mV) measured over a 12-h period (Figure 5). These data indicate that concentrations do not vary appreciably at periodicities under 1 h and that hourly sampling is an adequate measure of concentration on the order of a tidal cycle.

Velocity pulses, which may be an important factor when estimating the transport of suspended sediments, have also been documented in tidal creek flows (Bayliss-Smith *et al.*, 1979; Reed, 1987). Both Bayliss-Smith *et al.* (1979) and Reed (1987) identified tidal current velocity pulses when sampling at time intervals of at least 10 min. In the present study, short-term velocity variations were always monitored by storing 10-min averages of measurements taken at 0·5-s intervals with an InterOcean S4 electromagnetic current meter in order to account for potential velocity pulses.

Lower frequency temporal variations in suspended load, discharge, and current velocity were measured during two ‘long-term’ deployments. The first, conducted over 10 continuous tidal cycles on 6–11 August 1991 was designed to represent summer ‘fair weather’ conditions and the second, representative of winter ‘storm’ conditions, was conducted over 27 continuous tidal cycles on 12–27 February 1992. For both of these deployments, water level, and current speeds (Marsh McBirney meters) were collected and automatically recorded at the transect site, at a site located 300 m landward of the mouth of Cedar Creek and in the embayment adjacent to the creek mouth (Figure 1).

ISCO 3700 automated water samplers were utilized at the creek transect site for the August deployment and at both the transect and creek mouth sites during the February deployment. One-litre water samples were collected automatically every hour at an approximate height of 50 cm above the creek bed. Water level, current velocities and salinity were independently measured at the inner creek sites with an S4 current meter. Meteorologic data (wind speed and direction, air temperature and barometric pressure) were measured at the creek transect site and recorded on an NRG 9200 data logger during the February 1992 deployment.

For both long-term deployments, water samples were filtered through 1-μm precombusted, glass-fibre filters within several hours of collection. Samples were dried, weighed and concentrations determined. Estimates of sediment load were determined for individual tidal cycles using the relationship cited above (Boon, 1978).

Sedimentology

Surficial grab samples of both marsh soils and subtidal bar deposits were collected for sedimentological analyses. For grain-size analyses, organic matter was digested in a 30% hydrogen peroxide solution and then grain size was determined according to a modified Folk (1980) method. Selected sediment and filter samples were analysed separately for percent organic carbon either on a Carlo-Erba 1106 elemental analyser or by combustion for 10 min in an evacuated furnace at 900 °C (volume of CO_2 produced). CO_2 gases produced during the combustion process were collected and analysed on a Finnigan MAT 250 mass spectrometer against a NORIT sample equilibrated to standard PDB to determine stable carbon signatures. Mineralogies were determined using a Scintag 2000 X-ray diffractometer.

Results

Time–velocity asymmetry

Velocity data collected (Figure 6) indicate that peak flooding currents are, on average, 10–20% stronger than ebbing currents, but that the peak ebb velocities are maintained for a longer period of time. The data also indicate that maximum flood velocities occur near maximum high water, usually within 1–2 h, whereas maximum ebb velocities occur mid-cycle. Suspended-material concentrations typically reach a maximum soon after peak velocities (Figure 6). In general, maximum flooding concentrations are slightly greater than maximum ebb concentrations. Maximum TSS concentrations, however, are maintained for a longer period of time during ebb events.

Spring–neap variations

Peak suspended load concentrations correspond to episodes of maximum velocity associated with larger tidal prisms (i.e. spring tides) and therefore reflect spring/neap variations in velocity. Spring tide total suspended solid concentrations range from about 5 to 40 mg l^{-1}, whereas during neap tides, typical concentrations range from 5 to 10 mg l^{-1} [Figure 7(a,b)]. Replicate samples indicate that concentrations measured simultaneously may vary by as much as 18 mg l^{-1} during spring tide and 10 mg l^{-1} during

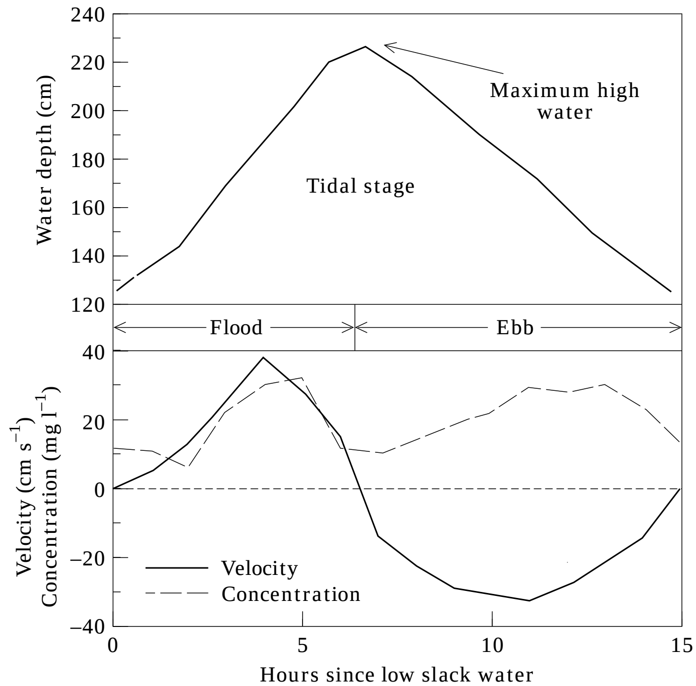

Figure 6. Example of water level, velocity and concentration curves at the transect location in Cedar Creek during 15 h of a spring tide (9 August 1991).

neap tides. Maximum tidal current velocities measured were approximately 40 cm s^{-1} during spring tides and 10 cm s^{-1} during neap tides. Data collected in the creek mouth and adjacent embayment suggest that during non-storm conditions, concentrations for these areas are the same as the TSS concentrations measured at the transect site.

Seasonal variations

Total suspended solid concentrations ranged from 5 to 40 mg l^{-1} during August 1991 and 4 to 670 mg l^{-1} during February 1992. While the variability in TSS was larger due to storm activity, in general, TSS concentrations were slightly lower in the winter (Figure 8). This may be attributed to increased biological activity in the summer. Field observations indicate that the activity of the fiddler crab, *Uca pugnax*, and other organisms is increased during the summer, thus leading to increases in bioturbation of the surface and creek wall sediments and deposition of faecal material. Although unquantified by this study, the increased biological activity may be one mechanism for increasing turbidity and suspended load (Settlemyre & Gardner, 1977; Ward, 1981). Exceptions to this general trend during non-wind driven tides were primarily due to periodic increases in disaggregated *Cladophora delicatula* in the water column during the winter.

Winter TSS values exceeded summer values during high-energy wind events and associated wave activity at the creek mouth. Hine and Belknap (1986) have shown that the tides in the Crystal River Embayment are strongly wind-driven. Two high-energy wind-driven events were documented in February 1992 [Figure 9(a)]. The first event occurred late on 17 February (hours 90–100) and early into 18 February and coincided

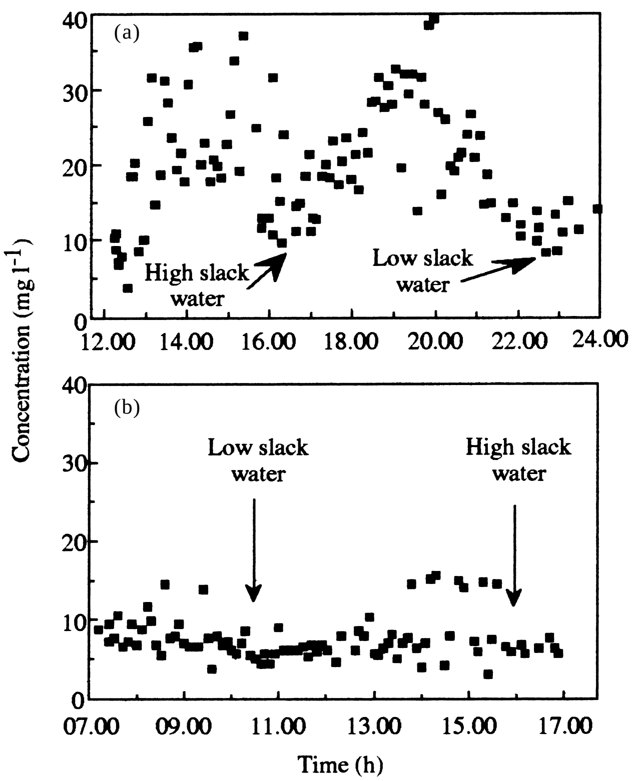

Figure 7. Total suspended solid concentrations over (a) a spring tidal cycle and (b) a neap tidal cycle (6 May 1991). Data were collected at the S4 location on transect A–A′. Scatter in the data is the result of replicate sampling and shows the inherent variability in TSS concentration even when measured simultaneously.

with the passage of the leading edge of a cold front. South-westerly sustained winds yielded maximum hourly averages of 23 km h^{-1} during this event. The latter event, consisting of 19–31 km h^{-1} sustained westerly winds, began on the morning of 26 February (hour 320) and continued until very early on 27 February. Both wind events resulted in significant wave activity at the creek mouth, as demonstrated by the standard deviation of the pressure data [Figure 9(b)]. Although the duration of the second event exceeded the first by almost 12 h, it exerted little influence on water levels [Figure 9(c)], and neither event appeared to be strong enough to exert more than a minor influence on tidal current velocities [Figure 9(d)].

Both wind events correspond well with measured increases in suspended load concentration at both the creek transect and the creek mouth site [Figure 9(e)]. The wind event on 17–18 February yielded the most dramatic changes in suspended load concentration. The peak of this event coincided with maximum spring tide and resulted in TSS concentrations as high as 668 mg l^{-1} at the creek transect site and 1171 mg l^{-1} at the creek mouth site. These concentrations are one and two orders of magnitude greater than concentrations measured at these locations during fair weather. Maximum concentrations of 140 mg l^{-1} at the mouth and 50 mg l^{-1} at the creek transect site occurred during the second wind event on 26–27 February.

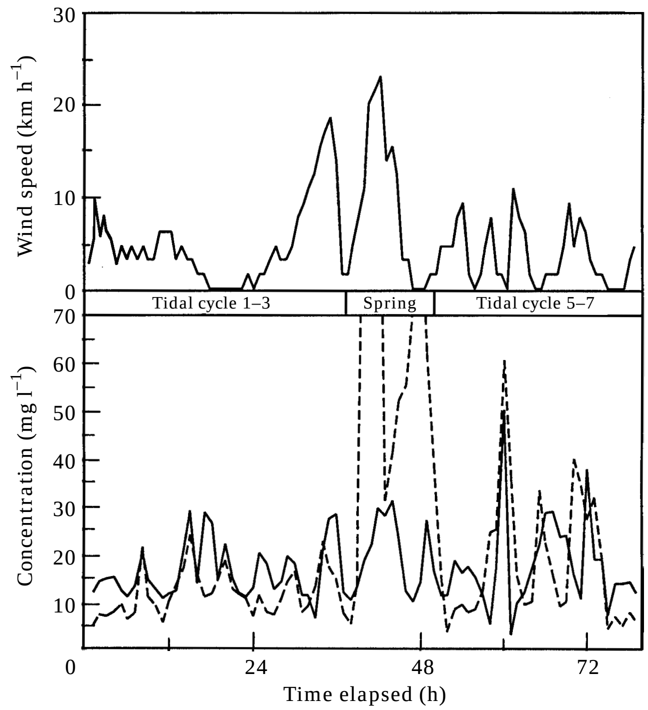

Figure 8. Total suspended solid concentrations measured over seven consecutive tidal cycles during both the summer (– – –: 6–9 August 1991) and the winter (– – –: 16–19 February 1992). In both cases, tidal cycles 1–3 precede maximum spring tide, tidal cycle 4 is maximum spring tide and tidal cycles 5–7 follow spring tides. Maximum concentrations exceeding axis scale for winter tidal cycle 4 are 668 and 151 mg l^{-1}, respectively. Wind speed data collected during the winter deployment are shown in the upper panel (00.00h 16 February to 23.00h 19 February 1992).

Suspended sediment transport

Net TSS transports were calculated for a 5-day period during the August deployment and a 14-day period during the February deployment (Table 2). The sediment load data indicate that a great deal of variability exists, although smaller net TSS loads are generally associated with smaller tidal prisms (e.g. neap tides) and larger net loads with larger tidal prisms (e.g. spring tides).

The summer data set shows that the TSS transport in the seaward direction is roughly equal to the landward transport through the creek cross-section. Over six consecutive, non-wind-driven tidal cycles measured in August 1991, a net export of 566 kg occurred. For the tidal cycles measured in February 1992, non-wind-driven net TSS loads were similar to those measured in the summer. Higher TSS loads, however, coincided with wind/wave events and exceeded fair weather values by as much as three orders of magnitude (Figure 10). The maximum net tidal transport measured, an import of 26 400 kg, occurred on a spring tide during a south-westerly wind event. Sustained westerly winds blowing for almost 24 h during neap tides elevated TSS concentrations considerably over those for a ‘ normal ’ neap cycle [Figure 9(f)], but did not result in comparable suspended solid loads.

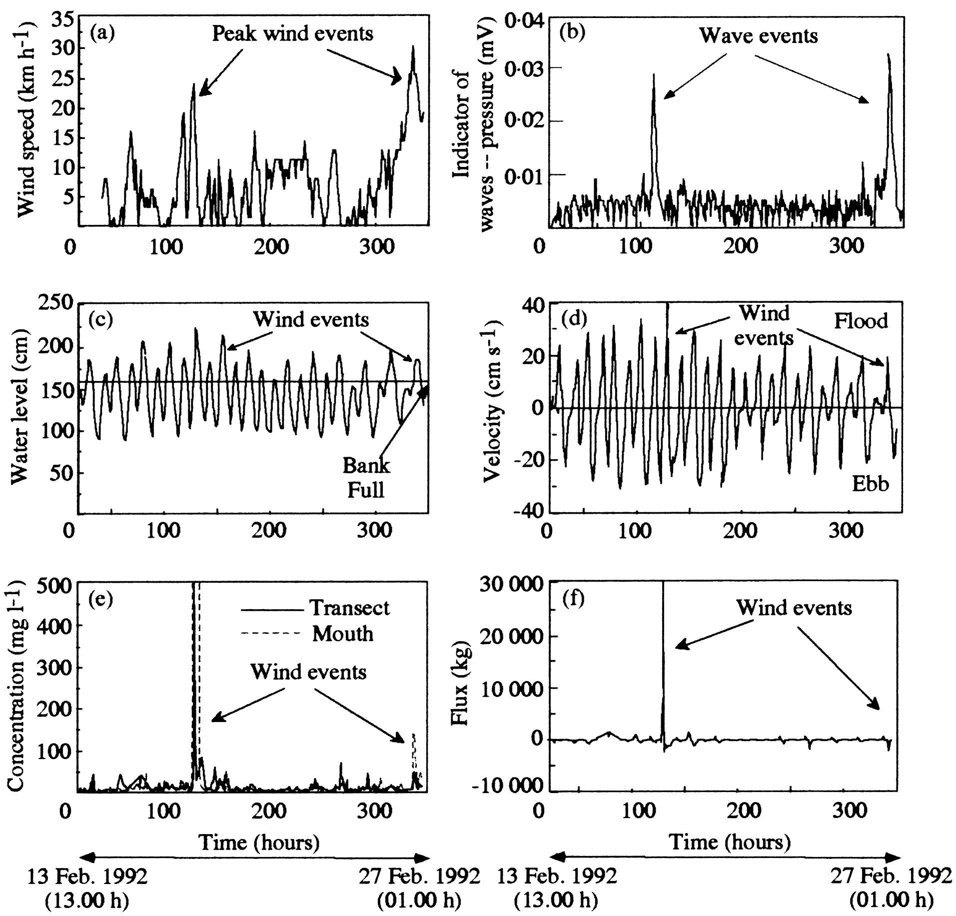

Figure 9. (a) Wind speed, (b) standard deviations of pressure (waves), (c) water level, (d) current velocity, (e) total suspended solid concentrations, and (f) total suspended solid loads for the February deployment. 0=13 February (13.00h), 325=27 February (01.00h).

Material composition

Material transported by creek flow is typified by a predominantly inorganic (percent organic C ranging from 3 to 22%; Table 3) assemblage composed of fine sands and silts ranging in size from 0·05 to 0·24 mm, fine clays and organic aggregates. Faecal pellets are occasionally observed in suspended load. Microscopic investigation of filtered samples indicate that the inorganic component consists primarily of quartz in the sand and silt size fractions. X-ray diffraction of selected filters indicates that the clay fraction consists of smectite, sepiolite and kaolinite. Diatoms are also a common component of the suspended solids in the tidal creek waters.

In contrast, subtidal bar deposits are coarser than the suspended solids, typically muddy sands (Figure 11) with a shell hash component and lower in organic content (usually 3% organic C or less; Table 3). Mineralogically, the fine fraction consists

TABLE 2. Suspended sediment loads at transect A–A′ for selected flood/ebb cycles during August 1991 (S) and February 1992 (W)

Flood/ ebb event		TSS load (kg)	Net load (kg FE^{-1})	% Average of flood and ebb	Tidal range (cm)	Max current velocity (cm s^{-1})	Creek discharge (m^3 FE^{-1})	Net discharge (m^3 FE^{-1})
S-1	F	952	40	4·3	60	20·6	67 690	
	E	912				20·1	59 652	8038
S-2	F	3339	780	26·5	103	38·1	174 676	
	E	2559				28·8	120 215	54 460
S-3	**F**	**1333**	**65**	**2·5**	**58**	**23·6**	**85 540**	
	E	**1268**				**23·7**	**79 550**	**5990**
S-4	**F**	**3956**	**− 707**	**16·4**	**105**	**38·1**	**179 275**	
	E	**4663**				**32·3**	**216 405**	**− 37 130**
S-5	F	1857	93	5·2	72	29·6	95 442	
	E	1764				26·7	113 490	− 18 049
S-6	F	3647	− 839	20·6	98	36·0	153 551	
	E	4486				31·4	219 493	− 65 942
S-7[a]	F	2278	1032	58·6	72	27·2	99 755	
	E	1246				27·6	98 021	1734
W-1	F	64	− 31	39·5	—	—	19 071	
	E	95					12 709	6362
W-2	F	585	− 1376	108·1	96	23·9	98 700	
	E	1961				22·5	86 367	1233
W-3[a]	F	167	− 151	62·4	78	17·9	55 664	
	E	318				14·1	40 603	1506
W-7	**F**	**488**	**21**	**4·3**	**85**	**17·7**	**5941**	
	E	**467**				**15·0**	**3465**	**2476**
W-8	**F**	**2413**	**839**	**42·0**	**112**	**33·6**	**133 401**	
	E	**1574**				**28·5**	**111 883**	**21 518**
W-9	**F**[c]	**1190**	**− 261**	**19·7**	**85**	**26·8**	**91 212**	
	E	**1451**				**28·5**	**102 135**	**− 10 923**
W-10	**F**[c]	**36 701**	**26 397**	**112·3**	**108**	**39·2**	**140 824**	
	E[c]	**10 304**				**25·9**	**173 422**	**− 32 598**
W-11	F	561	− 555	66·2	77	19·5	65 514	
	E	1116				22·0	74 176	− 8662
W-12	F	2806	− 1268	36·9	104	29·2	130 470	
	E	4074				29·4	170 223	− 39 753
W-13	F	375	− 245	49·1	83	18·8	56 747	
	E	620				23·6	63 456	− 6709
W-14	F	1022	− 488	38·6	95	25·7	97 648	
	E	1510				29·5	106 187	− 8539

Continued

TABLE 2. *Continued*

Flood/ ebb event		TSS load (kg)	Net load (kg FE^{-1})	% Average of flood and ebb	Tidal range (cm)	Max current velocity (cm s^{-1})	Creek discharge (m^3 FE^{-1})	Net discharge (m^3 FE^{-1})
W-15	F	264	68	29·6	75	15·1	43 457	
	E	196				15·9	35 273	8184
W-16	F	131	65	66·7	63	13·0	26 012	
	E[b]	66				6·9	19 651	6361
W-17	F	476	18	4·0	89	19·6	66 739	
	E	458				20·0	53 563	13 176
W-18	F[b]	306	222	113·7	65	12·3	34 879	
	E[b]	84				6·4	22 245	12 634
W-19	F[b]	1145	− 338	25·7	102	24·4	97 456	
	E[b]	1483				24·9	87 793	9663
W-20	F[b]	348	188	73·7	76	12·7	41 891	
	E[b]	160				12·8	26 358	15 533
W-21	F	964	− 2675	116·3	98	23·1	90 964	
	E	3639				25·5	97 474	− 6510
W-22	F	126	24	20·9	61	8·0	19 995	
	E	103				4·7	16 108	3887
W-23	F[b]	685	− 356	41·2	93	18·8	73 378	
	E[b]	1041				23·1	66 950	6428
W-24	F[b]	216	164	122·1	66	9·3	27 246	
	E[b]	52				3·4	8146	19 100
W-25	*F*	*1032*	*− 399*	*277·5*	*88*	*19·2*	*106 754*	
	E[c]	*1431*				*21·2*	*112 055*	*− 5301*
W-26	*F*[c]	*66*	*23*	*42·2*	*43*	*3·5*	*11 749*	
	E[c]	*43*				*2·4*	*6046*	*5703*
W-27[a]	*F*[c]	*3658*	*790*	*24·2*	*56*	*18·8*	*57 076*	
	E[c]	*2868*				*19·3*	*77 475*	*− 20 399*

Negative net loads indicate seaward transport and positive loads indicate landward transport. F, Flood tide; E, Ebb tide. Flood/ebb events (FE) are divided into complete tidal cycles by dashed lines. Spring tides are in bold face type and neap tides are in italics.
[a]Incomplete tidal cycles. [b]Winds 8–15 km h^{-1}. [c]Winds >15 km h^{-1}.

primarily of quartzose and carbonate silts whereas the coarser fraction is composed of shell fragments and carbonate granules eroded from the underlying limestone.

Surficial marsh sediment is finer than the materials found in the subtidal bars (Figure 11) and are higher in organic carbon (approximately 7–13%). The inorganic component consists mainly of quartzose fine sands and silts and the clays, smectite, sepiolite and kaolinite. Calcite and dolomite occur as minor constituents.

During fair weather conditions, organic carbon accounts for between 5 and 26% of the total suspended solid load (by weight) depending on spring/neap tidal and seasonal variations (Table 3). The fair weather mineralogy of the TSS inorganic fraction is similar

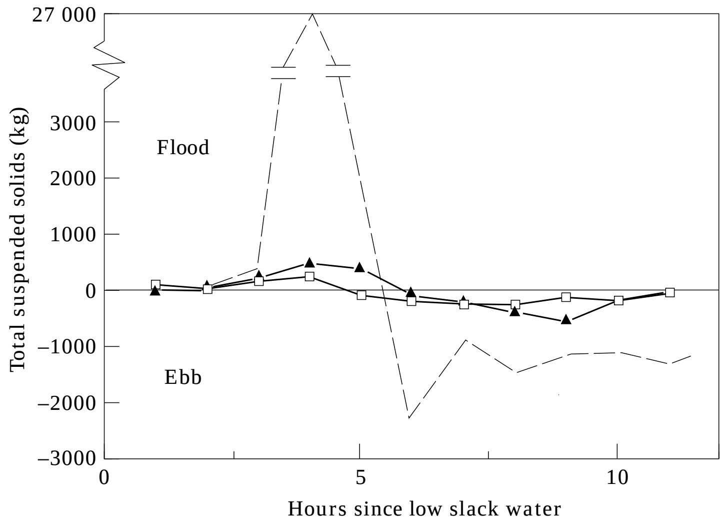

Figure 10. Hourly TSS loads for the three tidal cycles preceding (▲—▲), during (– – –) and following (□—□) the extra-tropical frontal passage on 17 and 18 February 1992 wind tide.

TABLE 3. Organic carbon percentages (by weight) for marsh sediments and suspended sediments in Cedar Creek

Source	% Organic carbon				No. of samples	Method
	Range		Mean (SD)			
Subtidal bar	1·03–3·2		2·26 (0·7)		10	C-H-N
Marsh hammock	5·4–6·6		5·2 (0·31)		10	C-H-N
	6·87					CO_2 produced
Marsh soils	9·5–13·0		10·02 (1·29)		10	C-H-N
	6·96–11·03					CO_2 produced
Suspended sediments						
Neap	Flood	Ebb	Flood	Ebb		
May	14·7–19·5	8·9–26·1	16·8 (2·1)	18·9 (7·4)	4 each	CO_2 produced
Feb.	2·4–4·7	21·2–21·7	3·4 (1·0)	21·4 (0·25)	4 each	CO_2 produced
Spring						
May	13·2–15·1	15·9–17·3	14·1 (0·74)	16·8 (0·62)	4 each	CO_2 produced
Aug.	8·7–18·9	13·4–14·9	13·5 (4·8)	14 (0·67)	4 each	CO_2 produced
Feb.	7·8–12·9	11·0–10·8	9·7 (2·3)	10·8 (0·09)	4 each	CO_2 produced
Storm event	2·0–2·4		2·2 (0·16)		4	CO_2 produced

to that of the marsh soils. Following storm events, however, microscopic inspection of the filters suggests an increase in the abundance of quartzose sands, calcitic material (in the form of granules eroded from the underlying limestones and shell fragments) in the suspended load. The percentage of organic material decreases to 2 to 3% during storms; a percent organic carbon value typical of the subtidal bar sediments. This is probably in response to the increased contribution of the inorganic fraction (i.e. shell fragments, sands and limestone granules).

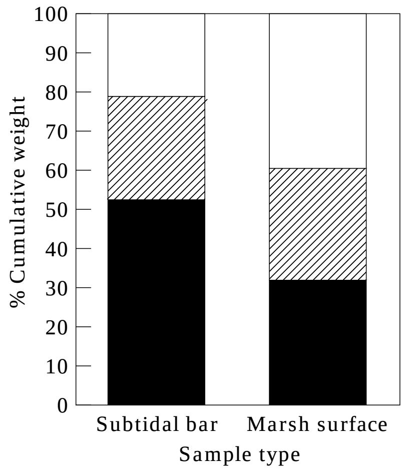

Figure 11. Graphical representation of the grain-size characteristics of bulk sediment samples collected on a subtidal bar and on the marsh surface. Each column represents mean characteristics of five replicate samples. ■, % Sand; ▨, % silt; □, % clay.

Percent organic carbon values measured by CHN analyses are also shown in Table 3 for sediments collected from subtidal bars in the creek, the marsh substrate and on a marsh hammock. Organic carbon content is less than 15% in all areas, and is especially low in subtidal bar sediments (3·2–1%) which consist mainly of muddy sands with shell fragments.

The stable carbon isotope signatures of the sediments in the study area are shown in Table 4. The δ^{13}C values for suspended materials do not appear to vary with spring/neap, flood/ebb or seasonal cycles. The δ^{13}C values of both the suspended material and the marsh sediments reflect a predominantly *J. roemerianus* signature (approximately $-25{\cdot}5$; Hutton, 1986) altered slightly, perhaps, by the introduction of marine materials.

Discussion

Fair weather processes

The open marine marshes on Florida's Gulf of Mexico coast are different from other highly studied marsh systems by mean tidal ranges of less than 1 m, very low wave energies due to a low regional gradient and a lack of modern or relict inorganic sediment supply (Hine & Belknap, 1986). When compared with other marsh systems, however, the data presented here indicate that the processes exerting control over TSS transport in Cedar Creek (and other similar creek systems in the west-central Florida marsh system) are consistent with those documented elsewhere.

Time–velocity asymmetries have frequently been invoked, particularly in south-eastern U.S.A. marshes, to account for net imports or exports of suspended material through tidal creeks (Boon, 1973; Settlemyre & Gardner, 1977; Ward, 1978; Roman, 1981; Stevenson *et al.*, 1985). These studies have shown that both maximum ebb and flood current velocities for most tidal cycles occur within 1–2 h of high slack water, that peak ebb currents are on average 20–30% stronger than the peak flood (Stevenson *et al.*, 1988) and that the resulting sediment budgets exhibit net exports (Settlemyre & Gardner, 1977; Roman, 1981; Ward, 1981).

TABLE 4. $\delta^{13}C$ values for marsh sediments and suspended sediments from Cedar Creek

	$\delta^{13}C$	
Surficial sediments		
Creek bottom	− 25·36, − 24·71, − 24·68	
Hammock	− 24·68	
Marsh soils		
Surface	− 24·75	
6 cm below surface	− 24·72	
10 cm below surface	− 24·81	
14 cm below surface	− 24·80	
18 cm below surface	− 24·75	
Suspended sediments	Flood	Ebb
Neap tides		
May	− 25·35	− 27·6
Aug.	—	—
Feb.	− 25·7	− 27·0
Spring tides		
May	− 25	− 25·35
Aug.	− 25·3	− 25·1
Feb.	− 24·85	− 25·3
Storm tides	− 24·55	

Data collected between 7 and 11 August 1991 (Table 2) in Cedar Creek indicate that sediment loads are greatest during the flood cycle when maximum current velocities are stronger and coincide with higher water levels. During the ebb portion of the cycle, lower instantaneous TSS load estimates occur due to lower maximum velocities and the occurrence of maximum velocity at lower water levels. For net TSS transports measured within our error limits, the seaward direction of transport (i.e. export) is favoured. This results from the prolonged duration of maximum current velocities during ebb tide as suggested by Ward (1981).

As documented for other marsh systems (Boon, 1978; Ward, 1978; Reed, 1987), TSS transports in Cedar Creek are also strongly affected by tidal current speed fluctuations due to spring/neap variability. In Cedar Creek, concentrations of total suspended solids are quite low (<15 mg l^{-1}) during neap tides. Low current speeds during these tides are incapable of maintaining elevated TSS concentrations and therefore result in minimal net transports or balances between ebb and flood transport (Table 2). Maximum suspended sediment concentrations (as much as 40 mg l^{-1}) and net sediment loads occur primarily during spring tides when current velocities and tidal prisms are at a maximum. This observation is consistent with those by Ward (1981) who observed that sediment loads declined as tidal range and tidal prism decreased in a tidal creek of comparable size in South Carolina.

Ward (1981) measured short-term variations in TSS flux from tidal cycle to tidal cycle in Bass Creek, Kiawah Island, South Carolina. Bass Creek is similar to Cedar Creek in terms of size, drainage basin area and tidal signal (semi-diurnal tides with strong diurnal inequalities). Bass Creek differs from Cedar Creek mainly in tidal amplitude. Bass Creek experiences a mean tidal range (1·8 m) that is greater than that documented for Cedar Creek. The TSS load variations measured by Ward (1981) are consistent with measurements at Cedar Creek. Ward's data show TSS transports of − 1322 to + 955 kg during spring tides and − 247 to + 675 kg for neap tides. The Cedar Creek data exhibit similar spring/neap variability. At Cedar Creek, non-wind-driven spring tide values ranged from −1390 to +838kg, whereas neap values ranged from −338 to +187 kg.

The similarity between the values presented by Ward and those resulting from this study indicate that tidal range (i.e. tidal energy) is not the sole mechanisms controlling the magnitude of sediment transport in marsh systems. Instead, as suggested by Stevenson *et al*. (1988), any combination of multiple factors may influence sediment transport. In Cedar Creek, the spring/neap variability favours increased transport of sediments during spring conditions when tidal current velocities are capable of maintaining higher suspended loads. The prevailing time–velocity asymmetry of the currents (ebb dominance), usually results in slight exports of material. Consequently, during fair weather, the dominant sediment transport process is an export of materials near or during spring tides to the adjacent embayment where it is likely that the sediments are stored in the subtidal bars.

The role of winter storms

Although fair weather conditions prevail, the process exerting the greatest control over TSS transport in Cedar Creek are winter storms. Stevenson *et al*. (1988) have reviewed the results of numerous studies dealing with the effects of storms on TSS transport in tidal creeks. They concluded that observed differences in the effect of storms on sediment transport may solely reflect the timing of the events; that is, whether the storm occurred during the flood or the ebb phase of the tide and a combination of predominant wind direction, shoreline orientation and the erosional thresholds of adjacent near-shore sediments.

The data collected during this study indicate that an important mechanism for mobilizing and transporting sediment further into the marshes adjacent to Cedar Creek is the passage of extra-tropical low-pressure systems during spring tides. Storm-enhanced transport and deposition is a finding consistent with both depositional data collected in the study area (Leonard *et al*., 1993) and with the observations of other workers who have cited storm occurrence as an important control over marsh deposition (Stumpf, 1983; Baumann *et al*., 1984; Reed, 1989). Unlike previous studies, however, this study has demonstrated that maximum sediment transport into the marsh occurs only when increased wave energies which resuspend sediments are coupled with maximum current speeds (i.e. spring tides or strong tidal surges) which keep the sediments in suspension.

Maximum sediment loads in Cedar Creek coincided with the passage of two extra-tropical low-pressure systems. As these storms approached, moderate south-westerly or westerly winds generated waves which resuspended sediment on the extensive mid-channel bars and subtidal flats in the shallow embayment at the creek mouth [Figure 9(a,b)]; a process commonly observed in other coastal areas (Settlemyre & Gardner, 1977; Ward, 1978, 1985; Ward *et al*., 1984; Reed *et al*., 1985; Reed, 1989; Arfi *et al*., 1993). The passage of both frontal systems and the associated wave resuspension of bottom sediments resulted in TSS increases at both the creek mouth and the transect site, although concentrations at the creek mouth were as much as one order of magnitude greater than those at the transect site (Figure 12). This is primarily attributed to the proximity of the source (i.e. subtidal bars) to the creek mouth sampling site.

As distance into the creek increases, the waves generated in the embayment are attenuated due to the creek's sinuosity and sediment resuspension caused by wave

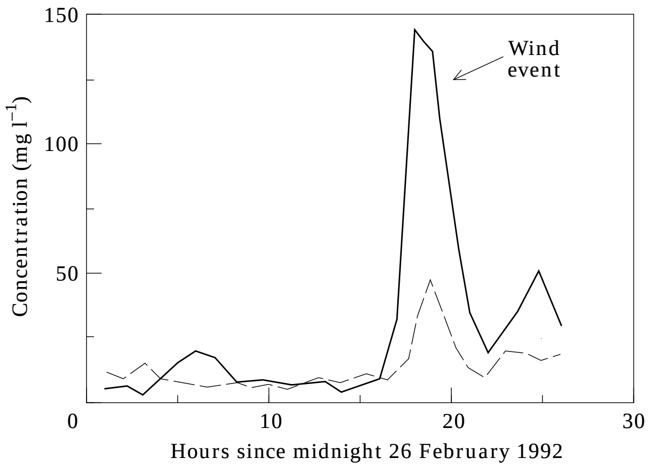

Figure 12. Concentrations measured at the mouth (——) of Cedar Creek and at transect A–A′ (— —) from 26 (00.00 h) to 27 February (01.00 h). The elevated concentrations occurring between hour 16 and hour 22 correspond to the passage of an extra-tropical storm during which sustained westerly winds blew at speeds between 15 and 30 km h^{-1}.

activity is inhibited. Because the prevailing tidal currents are not strong enough to transport the coarse sediments suspended by wave activity at the creek mouth, these materials (e.g. medium to coarse sands, shell fragments, limestone granules) are deposited before reaching the transect site. Most likely, these sediments are deposited just landward of the creek mouth before the first bend in the creek.

Maximum sediment loads, however, are not correlated solely with wind/wave activity. The data show that moderately high-energy events must be coupled with episodes of larger tidal prisms and associated higher current velocities in order to produce maximum sediment loads within the creek system (Figure 9). The first frontal passage (17–18 February 1992) was the weaker of the storm systems, yet concentrations measured at both the creek mouth and transect sites were one order of magnitude greater than concentrations measured during the second event (26–27 February 1992), which exhibited stronger sustained winds, was approximately 12 h longer in duration, and produced minimal set-up.

If all other parameters were held constant, the passage of the second event should have yielded TSS concentrations at the mouth in excess of those measured earlier in the deployment. The stronger second event, however, occurred during a period of low tidal current velocity and tidal prism and, consequently, did not produce large TSS loads. Neap tidal currents of 20 cm s^{-1} or less were incapable of maintaining the high TSS concentrations generated over the subtidal bars seaward of the creek mouth site, and the limited wave activity within the creek precluded resuspension of the subtidally-derived materials. As a result, computed sediment loads were much lower than during the earlier event due to a combination of lower concentrations, lower velocities and reduced tidal prism. These findings are consistent with the work of both Settlemeyer and Gardner (1977) and Ward (1981) who have observed similar increases in sediment transport during the passage of ephemeral higher energy events (i.e. wave formation and scour).

Roman and Daiber (1989) documented ebb-directed transports of POC and DOC five to six times greater than normal during a tropical storm in 1980 in a Delaware tidal creek. During this study, instantaneous TSS loads calculated for the tidal cycle concurring with the passage of the weak frontal system on 17–18 February 1992 exhibited similar exports of five times the normal preceding ebb tide (Figure 10). Unlike Roman and Daiber (1989), who were unable to acquire data during the flood storm surge, this study measured net imports during the storm flood tide of approximately 26 400 kg of material at the transect site. This import value is approximately 54 times the preceding flood event and 10 times the maximum net negative (exporting) sediment load (-2675 kg) measured for any single tidal cycle during fair weather conditions. Clearly, even a short-lived and relatively weak storm event, such as the 17–18 February event at Cedar Creek, may considerably offset the greatest exports occurring during fair weather. This latter observation lends credence to Settlemeyer and Gardner's (1977) conclusion that 'the under-representation of the effects due to ephemeral events in budget studies probably results in lower estimates of inorganic import'.

Larger magnitude events, such as stronger frontal systems, hurricanes or tropical storms, potentially could import much larger quantities of material (Conner *et al*., 1988). Elevated deposition rates (>2 cm) were observed in the west-central Florida marsh system following the passage of an extremely well-developed low-pressure system in March 1993 (Goodbred *et al*., 1993). Tropical storm events, such as those referred to by Conner *et al*. (1988) however, are of less importance temporally in the study area as they occur much less frequently than extra-tropical storms.

For the west-central Florida marsh coastline, where the passage of weak to moderate extra-tropical systems may occur as frequently as once every 5 days during the winter (Hine & Belknap, 1986), these coupled spring tide/storm events could have a very important role in the maintenance of the marsh surface if even a fraction of these sediments were distributed across the levee during high slack water (Settlemyre & Gardner, 1977; Stumpf, 1983; Reed, 1989).

Material sources

Whereas the distribution of suspended sediments within the tidal creek, specifically during storms, suggests that the subtidal bars are the source of the suspended inorganic materials, the composition data seem to confirm it. During the two high-energy events monitored, the contribution of organics to the suspended load decreased to a minimum of 2–3%, and the material in suspension at the creek mouth site was poorly sorted, consisting of a full suite of grain sizes ranging from clay to small gravels and shell fragments. The low organic content and the sediment textures of the materials suspended during storm activity generally reflect the character of subtidal bar sediments.

During non-storm conditions, the source of suspended matter is less straightforward, but appears to be restricted to the marsh surface and the adjacent embayment. There are two reasons for this: (1) an upland or offshore (shelf) source is absent and (2) observational evidence points to local sediment sources existing within the basin.

Slumping of the creek wall is common during low tides in many marsh systems (Pestrong, 1972; Redfield, 1972; Howard & Frey, 1973), particularly when bioturbating organisms are abundant (Letzsch & Frey, 1980). Extensive mass wasting has been observed along Cedar Creek during extremely low tides and provides the primary mechanism by which marsh soils are reintroduced to creek flows. Slumping occurs during extremely low tides when creek walls are over-steepened and the integrity of the walls has been compromised by extensive bioturbation by the fiddler crab, *U. pugnax* (Frey & Basan, 1985) and by seepage which lowers the effective strength of the sediments. The marsh blocks are then physically disaggregated and the materials within them are recycled, by the tidal creek flow, to another section of the marsh. Similarly, waves impinging on the open marine marsh fringe may erode marsh muds and make them available for transport by the prevailing tidal currents (Reed, 1987).

An alternative mechanism for reintroducing marsh muds to tidal flows is biodeposition in the form of faecal pellets. Biodeposition is a sedimentation processes documented almost universally in marsh systems (Pestrong, 1972; Ward, 1981; Frey & Basan, 1985). Faecal materials, identified in the suspended load of tidal creek flows, are most likely carried off of the marsh surface during the ebbing of overmarsh flows. Although undocumented and unquantified by this study, pellets may be transported off of the marsh in the surface microlayer of overmarsh flows. The ' microlayer ' mechanism has been used to explain the removal of diatoms from the marsh surface in other Florida marsh systems (Ribelin, 1978).

Other potential sources of inorganic material transported by tidal flows in Cedar Creek include molluscan silts from biodegraded oyster reefs in the adjacent embayment and very fine quartzose sands from the thin sand veneers which fringe the marsh hammocks. Fine quartzose sands have been observed on and around these bedrock highs. It is possible that as sea-level rises and high tides begin to encroach the hammocks, that these ' pockets of sand ' are re-worked and redistributed within the drainage basin by the tidal currents. The extent of these sands, however, is very limited and therefore may only contribute minimally to the overall marsh sediment budget.

On the other hand, the extensive oyster reefs present both within the tidal creek and the adjacent embayment may provide some component of the inorganic fraction on a regular basis. The oyster bioherms present in the Crystal River Embayment are being actively degraded by the boring sponge, *Clinoa* sp. (Hine *et al.*, 1988). Potentially, these reefs could supply a significant amount of molluscan silt due to their abundance and extent. The relative contributions of these materials to the overall sediment budget, however, have not been quantified. At this time, organic aggregates, faecal material and re-worked marsh muds appear to be the dominant contributors to the total suspended solid load in fair weather tidal flows in Cedar Creek.

Conclusions

The sediment transport trends identified by this study offer a possible explanation as to how this marsh system obtains sediment for surficial deposition despite the absence of an offshore or upland inorganic sediment source. Current velocity, tidal stage, suspended load and meteorological data collected during two sampling periods in Cedar Creek indicate that the time–velocity asymmetry of the tidal currents, spring/neap variations in the tidal cycle and storm activity strongly influence sediment transport patterns.

During fair weather conditions, the net direction of sediment transport (i.e. seaward or landward) is dependent on the time–velocity asymmetry of the tidal currents. In Cedar Creek, the currents are ebb dominant and therefore result in a net export of material when any specific direction of transport can be discerned. During non-storm conditions, then, suspended materials appear to gradually move seaward and may eventually be deposited in the subtidal bars at the creek mouth. The volume of sediment transported by the prevailing tidal currents, on the other hand, is strongly affected by fortnightly variability in the tidal cycle. Total suspended solid loads reflect variations in tidal prisms and the associated differences in velocity regime and suspended solid concentrations.

The composition of the materials transported within the tidal creek flows under normal conditions suggest that the TSS loads consist primarily of (1) sediments derived from the marsh soils at the creek edge or along the open marine fringe, (2) organic aggregates and (3) faecal material.

Sediment transport during winter storms, however, is also an integral part of the overall ' sediment budget ' picture. The data collected during this study indicate that maximum TSS loads only occur when storm passages coincide with periods of increased tidal prisms and current velocities. Although wind/wave activity is the mechanism for resuspending bottom sediments and elevating TSS concentrations locally, elevated tidal current velocities are necessary to maintain concentration levels away from the area of resuspension. Consequently, any materials in storage beyond the creek mouth are resuspended during periods of wave activity and, given the appropriate tidal conditions (i.e. spring tides), are transported landward again. In this way, the passage of extra-tropical low-pressure systems during spring tides results in (1) maximum imports of suspended material within and (2) increased potential for sediment deposition on the marshes adjacent to Cedar Creek and other tidal creeks in the west-central Florida marsh system.

Acknowledgements

Funds to conduct this research were provided by the United States Geological Survey Center for Coastal Geology and Regional Marine Studies. We greatly appreciate the Citrus Country School system and Mr Pat Purcell for providing access to and accommodation at the Citrus School System Marine Science Center. The United States Geological Survey Division of Water Resources (Tampa) and the Center for Coastal Geology and Regional Marine Studies provided valuable assistance in data acquisition. In addition, we thank Walter Bowles, David Schoelhammer, Victor Levesque, Stephen Kinsey, Steve Goodbred, Mark Peebles and David Mallinson for field assistance.

References

Arfi, R., Guiral, D. & Bouvy, M. 1993 Wind-induced resuspension in a shallow tropical lagoon. *Estuarine, Coastal and Shelf Science* **36,** 587–604.

Baumann, R. H., Day, J. W., Jr & Miller, C. A. 1984 Mississippi deltaic wetland survival: sedimentation versus coastal submergence. *Science* **224,** 1093–1095.

Bayliss-Smith, T. P., Healey, R., Lailey, R., Spencer, T. & Stoddart, D. R. 1979 Tidal flows in salt marsh creeks. *Estuarine and Coastal Marine Science* **9,** 235–255.

Boon, J. D., III 1973 Sediment transport processes in a salt marsh drainage system. Ph.D. Dissertation, College of William and Mary, Williamsburg, Virginia, 238 pp.

Boon, J. D., III 1978 Suspended solids transport in a salt marsh creek: an analysis of errors. In *Estuarine Transport Processes* (Kjerfve, B. J., ed.). University of South Carolina Press, Columbia, pp.147–159.

Cahoon, D. R. & Turner, R. E. 1987 Marsh accretion, mineral sediment deposition and organic matter accumulation: clay marker horizon technique: In *Causes of Wetland Loss on the Coastal Central Gulf of Mexico*, (Turner, R. E. & Cahoon, D. R. eds). pp. 259–275.

Childers, D. L. & Day, J. W. 1988 A flow-through flume technique for quantifying nutrient and material fluxes in microtidal estuaries. *Estuarine, Coastal and Shelf Science* **27,** 483–494.

Conner, W. H., Baumann, R. H., Day, J. W., Jr & Randall, J. M. 1988 Influence of hurricanes on coastal systems along the northern Gulf of Mexico: a review. *Wetlands Ecology Management*, **1,** 45–56.

DeLaune, R. D., Baumann, R. H. & Gosselink, J. G. 1983 Relationships among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf coast marsh. *Journal of Sedimentary Petrology* **53,** 147–157.

Folk, R. L. 1980 *Petrology of Sedimentary Rocks*. Hemphill, Austin, Texas, 182 pp.

Frey, R. W. & Basan, P. B. 1985 Coastal salt marshes. In *Coastal Sedimentary Environments* 2nd edn (Davies, R. A., Jr, ed.). Springer, New York, pp. 225–301.

Goodbred, S. L., Hine, A. C., Quigley, W. C. & Stumpf, R. P. 1993 *'Storm of the Century' Makes Contribution to Sediment-starved Coastal Marshes*. Geological Society of America Annual Meeting, Boston, Massachusetts (Abstracts with Programs).

Harrison, E. Z. & Bloom, A. L. 1977 Sedimentation rates on tidal salt marshes in Connecticut. *Journal of Sedimentary Petrology* **47,** 1484–1490.

Hine, A. C. & Belknap, D. F. 1986 Recent geological history and modern sedimentary processes of the Pasco, Hernando, and Citrus County coastline: west-central Florida. *Florida Sea Grant College Publication* No. 79. 160 pp.

Hine, A. C., Belknap, D. F., Hutton, J. F., Osking, E. B. & Evans, M. W. 1988 Recent geological history and modern sedimentary processes along an incipient, low-energy, epicontinental-sea coastline: northwest Florida. *Journal of Sedimentary Petrology* **58,** 567–579.

Howard, J. D. & Frey, R. W. 1973 Characteristic physical and biogenic sedimentary structures in Georgia estuaries. *American Association of Petroleum Geologists Bulletin* **57,** 1169–1184.

Hutton, J. G. 1986 Bedrock control, sedimentation and Holocene evolution of the marsh archipelago coast: west-central Florida. M.S. Thesis, University of South Florida, Tampa, Florida, 154 pp.

Leonard, L. A., Wright, E. E., Quigley, W. C. & Hine, A. C. 1993 *Sediment Transport and Deposition in Microtidal Marsh Systems*. Geologic Society of America Annual Meeting, Boston, Massachusetts (Abstracts with Programs).

Letzsch, S. W. & Frey, R. W. 1980 Deposition and erosion in a Holocene salt marsh, Sapelo Island, Georgia. *Journal of Sedimentary Petrology* **50,** 529–542.

Pestrong, R. 1972 Tidal-flat sedimentation at Cooley Landing, southwest San Francisco Bay. *Sedimentary Geology* **8,** 251–288.

Pethick, J. J. 1980 Salt-marsh initiation during the Holocene transgression: the example of the North Norfolk marshes, England. *Journal of Biogeography* **7,** 1–9.

Ranwell, D. S. 1964 *Spartina* marshes in south England. II: Rate and seasonal patterns of sediment accretion. *Journal of Ecology* **52,** 79–94.

Redfield, A. C. 1972 Development of a New England salt marsh. *Ecological Monographs* **42,** 201–237.

Reed, D. J. 1987 Temporal sampling and discharge asymmetry in salt marsh creeks. *Estuarine, Coastal and Shelf Science* **25,** 459–466.

Reed, D. J. 1989 Patterns of sediment deposition in subsiding coastal salt marshes: the role of winter storms. *Estuaries* **12,** 222–227.

Reed, D. J., Stoddart, D. R. & Bayliss-Smith, T. P. 1985 Tidal flows and sediment budgets for a salt-marsh system, Essex, England. *Vegetatio* **62,** 375–380.

Rejmanek, M., Sasser, C. E. & Peterson, G. W. 1988 Hurricane-induced sediment deposition in a Gulf Coast marsh. *Estuarine, Coastal and Shelf Science* **27,** 217–222.

Ribelin, R. W. 1978 Salt marsh detrital aggregates: a key to trophic relationships. Ph.D. Dissertation, Florida State University, Tallahassee, Florida, 143 pp.

Roman, C. T. 1981 Detrital exchange processes of a Delaware salt marsh. Ph.D. Dissertation, University of Delaware, Newark.

Roman, C. T. & Daiber, F. C., 1989 Organic carbon flux through a Delaware Bay salt marsh: tidal exchange, particle size distribution, and storms. *Marine Ecology Progress Series* **54,** 149–156.

Settlemyre, J. L. & Gardner, L. R. 1977 Suspended sediment flux through a salt-marsh drainage basin. *Estuarine, Coastal and Shelf Science* **5,** 653–633.

Stevenson, J. C., Kearney, M. S. & Pendleton, E. C. 1985 Sedimentation and erosion in a Chesapeake Bay brackish marsh system. *Marine Geology* **67,** 213–235.

Stevenson, J. C., Ward, L. G. & Kearney, M. S. 1986 Vertical accretion in marshes with varying rates of sea level rise. In *Estuarine Variability* (Wolfe, D. A., ed.). Academic Press, New York pp. 241–259.

Stevenson, J. C., Ward, L. G. & Kearney, M. S. 1988 Sediment transport and trapping in marsh systems: implications of tidal flux studies. *Marine Geology* **80:** 37–59.

Stumpf, R. P. 1983 The process of sedimentation on the surface of a salt-marsh. *Estuarine, Coastal and Shelf Science* **17,** 495–508.

Ward, L. G., 1978 Hydrodynamics and sediment transport in a salt-marsh tidal channel. In *Proceedings of the 16th Coastal Engineering Conference*. American Society of Civil Engineers, New York, pp. 1953–1970.

Ward, L. G. 1981 Suspended-material transport in marsh tidal channels, Kiawah Island, South Carolina. *Marine Geology* **40,** 139–154.

Ward, L. G. 1985 Influence of wind waves and tidal currents on sediment resuspension in middle Chesapeake Bay. *Geology Marine Letters* **5,** 71–75.

Ward, L. G., Kemp, W. M. & Boyton, W. R. 1984 The influence of waves and seagrass communities on suspended particulates in an estuarine embayment. *Marine Geology* **59,** 85–103.