Near-Bed Currents and Suspended Sediment Transport in Saltmarsh Canopies

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ABSTRACT

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A field study was undertaken to measure near-bed current velocity, water level and suspended sediment concentration on unvegetated mudflat, and in recently developed *Scirpus mariquete* and *Spartina alterniflora* canopies in the Changjiang Estuary, China. Near-bed current (a combination of both tidal currents and wave motion) velocities were up to 50 cm s^{-1} in saltmarsh canopies and on the mudflat. Near-bed current velocity within a saltmarsh canopy was generally less than that on the mudflat, regardless of the phase of the tides or the tidal current direction. Mean near-bed current velocity was reduced by 16% within the estuarine saltmarsh canopy compared to open mudflat. Reductions in near-bed current velocities within the saltmarsh canopy were larger during ebb tide than flood tide. Suspended sediment concentrations were found to be lower within the estuarine saltmarsh canopies compared to the unvegetated mudflat.

ADDITIONAL INDEX WORDS: *Near-bed currents, sediment transport, saltmarsh.*

INTRODUCTION

Estuarine and coastal saltmarsh sediment processes have been mostly studied in the field. These studies include the hydrodynamic and fine sediment transport processes on the coastal saltmarsh surface (STUMPF, 1983; WANG *et al.*, 1993; HUTCHINSON *et al.*, 1995; LEONARD and LUTHER, 1995; LEONARD *et al.*, 1995a) and the tide-dominated hydrodynamic processes within saltmarsh tidal creeks (BOON, 1975; BAYLISS-SMITH *et al.*, 1979; HEALEY *et al.*, 1981; GREEN *et al.*, 1986; FRENCH and STODDART, 1992; LEONARD *et al.*, 1995b; WANG *et al.*, 1999). Notably, FRENCH and CLIFFORD (1992) studied the characteristics and event-structure of near-bed turbulence in a macrotidal saltmarsh channel. These studies have recognized the fact that estuarine and coastal saltmarsh canopies can exert an influence on intertidal hydrodynamic processes, fine sediment processes and geomorphology (CHUNG, 1985; 1994; SHI *et al.*, 1995a). In China, most intertidal sediment processes studies have been confined to estuarine and coastal intertidal mudflats (SHI and CHEN, 1996), with little work done for estuarine and coastal saltmarsh.

To understand the particular hydrodynamic processes acting on estuarine and coastal saltmarsh surfaces, several researchers have carried out laboratory flume studies of one dimensional unidirectional tidal current-related interactions of the estuarine and coastal saltmarsh canopy (PETHICK *et*

al., 1990; SHI *et al.*, 1995b, 1996; NEPF *et al.*, 1997; SHI, 1997; NEPF, 1999). The coastal saltmarsh canopy has been shown to exert a strong influence on the concentration, settling velocity of flocs, and deposition rate of suspended sediment through damping effects on bed shear stress and turbulence of tidal flow within the canopy (SHI *et al.*, 1996; LEONARD and LUTHER, 1995). A number of studies have also revealed that the saltmarsh canopy could trap and retain sediment out of suspension (GLEASON *et al.*, 1979; ALIZAI and McMANUS, 1980; STUMPF, 1983; LEONARD *et al.*, 1995a; SHI *et al.*, 1996). However, retention of fine sediment on saltmarsh plant surfaces is a small percentage (<5%) of total deposition (FRENCH and SPENCER, 1993; LEONARD *et al.*, 1995a). KNUSTON *et al.* (1982) semi-quantitatively studied the reduction of wave energy in *Spartina alterniflora* marshes and found that *Spartina alterniflora* marshes can decrease incoming wave energy by approximately 26% per meter of vegetation. YANG and CHEN (1995) also suggested that estuarine and coastal saltmarsh plants were less effective at attenuating wave energy at times of elevated water level, *i.e.*, the plants are less effective attenuators when they are submerged. MOELLER *et al.* (1996) found that saltmarshes are extremely effective in buffering wave energy over the range of water depths and incident waves energies on the Norfolk coast, U.K. ROIG and KING (1992) modeled the flows in emergent marsh vegetation. WOOLNOUGH *et al.* (1995) have also attempted to numerically model sediment deposition over the surface of a tidal saltmarsh.
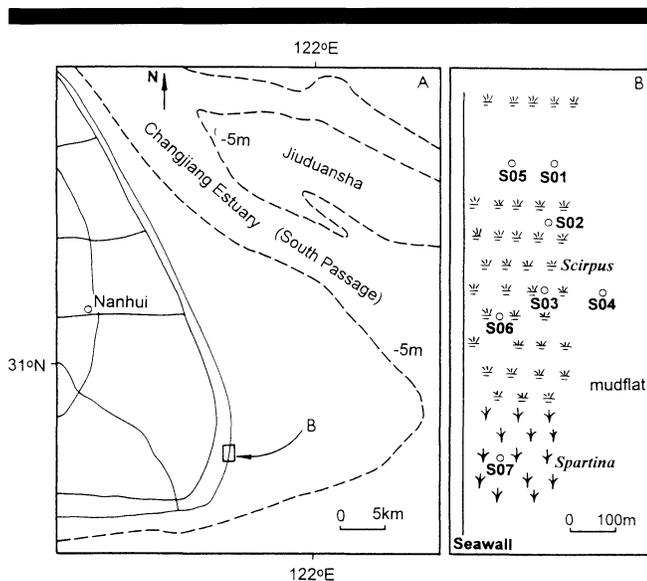
Figure 1. Experimental sites in the Changjiang Estuary.

Other relevant studies have been made of hydrodynamic processes acting on seagrass (ANDERSON and CHARTERS, 1982) and other coastal plants. WARD *et al.* (1984) studied the influence of waves and seagrass communities on suspended particulates in an estuarine embayment. Interaction between water waves and vegetation has also been theoretically studied by several researchers (ASANO *et al.*, 1992; KO-BAYASHI *et al.*, 1993; ASANO and SETOGUCHI, 1996). FONSECA and CAHALAN (1992) evaluated the wave attenuation by four species of seagrass by using a wave tank/flume. Using a laboratory flume, ESCARTIN and AUBREY (1995) studied the flow structure within algal mats.

Despite these studies above, field experiments are still required to clarify the hydrodynamic effects of estuarine and coastal saltmarsh canopy on intertidal fine sediment transport. The primary objectives of this paper are (1) to determine the magnitude of near-bed current (a combination of both tidal currents and wave motion) reduction in different species of estuarine saltmarsh canopies, by comparison with currents on the mudflat; (2) to evaluate how estuarine saltmarsh canopy affects intertidal fine sediment transport processes.

FIELD EXPERIMENTS

Field experiments were carried out during a neap tide on July 10-14, 1995. Tidal regime is purely semidiurnal in the study area. Sites S01, S04 and S05 are located on the mudflat, site S07 within the *Spartina alterniflora* canopy, sites S02, S03 and S06 within the *Scirpus mariquete* canopy (Figure 1). The height of the *Scirpus mariquete* canopy varies from 50 to 75 cm at sites S02, S03 and S06. The vegetation coverage (a visible estimate of stems being present) is 70% and density (a particular number of stems per unit area) is more than 1000 stems m^{-2} for *Scirpus*. There is no tidal creek network in the saltmarsh.

Measurements were made of near-bed current velocity ($\bar{u}$),

water level, and suspended sediment concentration (C). Near-bed current velocity ($\bar{u}$) was measured at 10 cm above the surface by using a HLJ1-1 Printing Electro-magnetic Current Meter. The sampling rate of the current meter is 5 minutes, *i.e.*, one instantaneous measure is taken every 5 minutes. Three different experiments were undertaken to measure the near-bed current velocity in order: (1) To eliminate the influence of locations on current reduction, by comparing the currents on the mudflat (S01) and in the *Scirpus* canopy (S02), these two sites are on a parallel with the embankment (Figure 1); (2) To study the influence of the vegetation, by comparing the currents on the mudflat (S04) and in the *Scirpus* canopy (S03); and (3) on the mudflat (S05), in the *Scirpus* canopy (S06) and in the *Spartina* canopy (S07), which are on a parallel with the embankment.

Water samples were collected at 10 cm above the surface using a number of Niskin bottles (100 ml) on 12 July 1995 at sites S01, S02, S03 and S04. Time interval between water sampling (not the time taken to fill the bottles) was 5 seconds for each of the first 6 samples, and 1 minute for each of the rest of the samples. Samplers were operated manually. Care was taken to ensure the bottles triggered without disturbing the sampling areas. Winds come from NE, SE and NW. NE wind results in high water level. NW wind results in lower water level. Water level was measured by using a marked wooden stake. Water samples were filtered through 40 μm preweighed filters in the laboratory. The filters were washed with distilled water, oven-dried at 60 °C and weighed. Suspended sediment concentrations (SSC) were calculated by dividing the mass of material collected on the filter by 100 ml.

RESULTS

As shown in Figures 2A, 2B, 2C and 2D, near-bed current velocity within a saltmarsh canopy was generally less than that on the mudflat. Maximum near-bed current velocity is 50 cm s^{-1}. Near-bed current velocity was asymmetric in time at flood tide and ebb tide (Figure 2A). Reductions in near-bed current velocities within the saltmarsh canopy were larger during ebb tide than flood tide (2100 hr–2300 hr, 10 July 1995; Figure 2a). Peak currents were reduced by vegetation by 10% between S02 and S01 (Figure 2a), 12% between S03 (saltmarsh) and S04 (mudflat) (Figure 2b), 14% between S03 (saltmarsh) and S04 (mudflat) (0300 hr–0700 hr, 12 July 1995; Figure 2c), 84% between S07 (saltmarsh) and S05 (mudflat), and 78% between S06 (saltmarsh) and S05 (mudflat) (Figure 2d). It is unclear why the currents on 12 July 1995 at 5.5 hr were larger in the canopy than over the mudflat.

To understand the reductions in velocity, both direction and speed of flow across the mudflat/marsh area are shown in Figure 3. Obviously, the water flowed mainly north into the area on flood. Currents at S01 and S02 generally have high directional correspondence (and the directions tend to change together) for 4 hr 10 min of flood direction data when current directions are predominantly northwards. However at the start of the direction data (about two hours after the start of the flood) there is a one hour interval when currents are to the southwest at S02 and to the northwest at S01 (Fig-
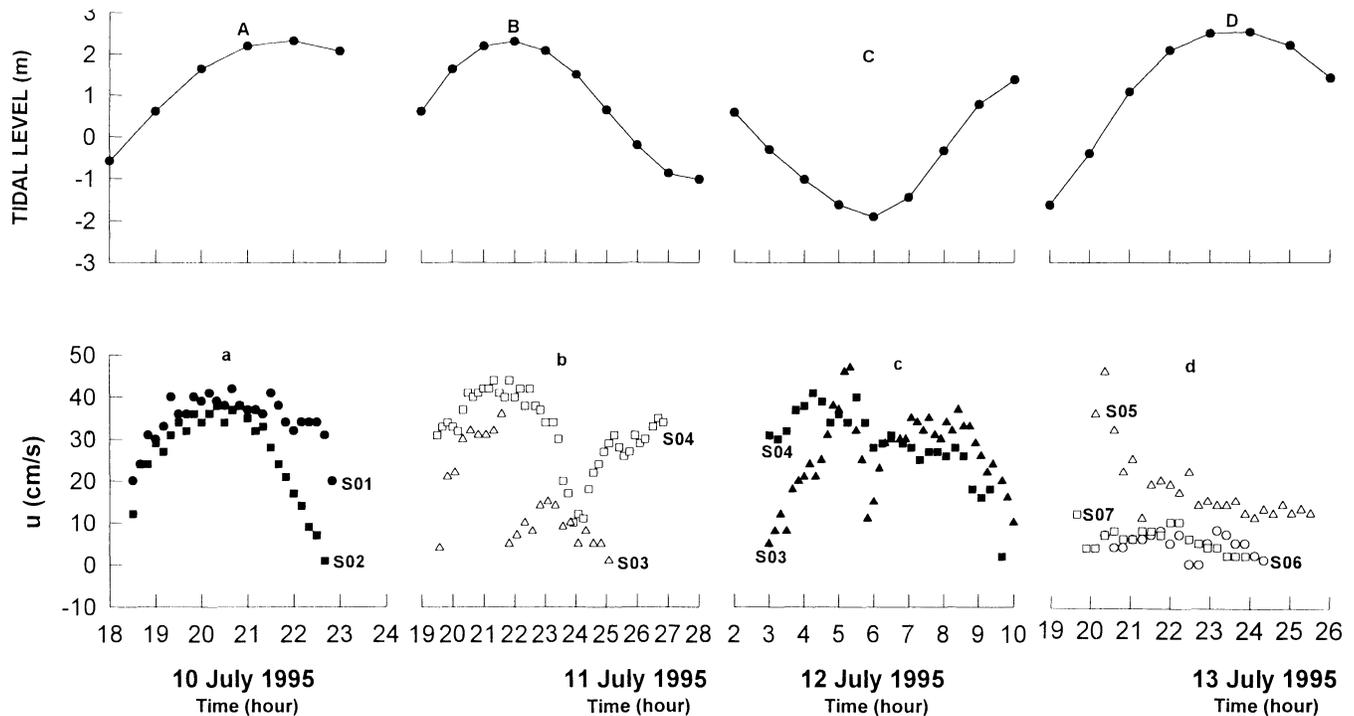
Figure 2. Temporal variations of predicted water level on July 10–14 and measured near-bed current velocity (a) on the mudflat (S01) and in the *Scirpus mariquete* canopy (S02); (b) on the mudflat (S04) and in the *Scirpus mariquete* canopy (S03); (c) on the mudflat (S04) and in the *Scirpus mariquete* canopy (S03); (d) on the mudflat (S05), in the *Scirpus mariquete* canopy (S06) and the *Spartina alterniflora* canopy (S07).

ure 3). Whether direction is north or south, speeds at S01 are always greater than speeds at S02 for 4 hrs of flood data.

As shown in Figure 3, currents at S03 and S04 are generally in the same direction for the times direction data are available, however 1) they are almost always 'northwards' whether the tide is flood or ebb, which is not the expected result. It is odd that ebb and flood currents at S04 are both usually to the north, when ebb/flood directions at S05/S6 are south/north as expected (and flood current at S01/S02 is northwards as expected); 2) soon after the start of the direction data (about halfway through the flood) S03 is south and S04 is north (currents at S03 swing around anticlockwise almost a full circle, i.e., eddying or meandering occurs); 3) some eddying occurs at low water at 0330 hr when directions at both S03 and S04 swing anti-clockwise nearly three-quarters of a circle. Speeds at S04 are greater than speeds at S03 for 1930–0440 hr over a flood to ebb cycle on 11 July 1995, then S03 speeds are greater than S04 speeds on the following ebb (Figure 3). More information is needed for a full explanation of these phenomena.

Directions at S05 and S06 are highly correlated for the three hours of direction data (the directions are generally the same as each other and change together). If high tide is at 2300 hr, then the flood is north and the ebb is south, as expected. Whether direction is north or south, speeds at S05 are always greater than speeds at S06 for 3 hrs of direction data (Figure 3).

However for the short interval of coincident direction data

for S05/S06/S07 for 2200–2300 hr, S07 has the opposite direction (southwards) to S05 and S06 (northwards). It is impossible to tell why from the data. Directions at S07 swing around over the data interval e.g. they swing anticlockwise from westward to eastward over 70 min from 2140–2300 hr. Regardless of current directions, speeds at S05 are always greater than at S06 and S07 for a hour mid-flood to mid-ebb period (Figure 3).

The suspended sediment concentrations showed large fluctuations during the sampling periods (flood tide) both over the mudflat and in the saltmarsh canopy, ranging from 0.6 to 3.9 g L^{-1} (Figures 4A and 4B). In Figure 4B, the SSC varied from 2.33 to 3.7 g L^{-1} (S04, mudflat) and from 1.97 to 3.9 g L^{-1} (S03, saltmarsh). 3.7 g L^{-1} and 3.9 g L^{-1} are indicative of high concentration suspension (fluid mud) close to the bed. In general, the suspended sediment concentration within the saltmarsh canopy was lower than that on the mudflat (Figures 4A and 4B). In Figures 4A and 4B, the suspended sediment concentration (an average over the inundation period) at S01 (mudflat) was 26% higher than at S02 (saltmarsh canopy), while the SSC at S04 (mudflat) was 10% higher than at S03 (saltmarsh). Wave activity (inferred from water level) is shown in Figure 5.

DISCUSSION

Estuarine and coastal saltmarsh plants interact strongly with tidal flow, extracting momentum from the fluid via hy-
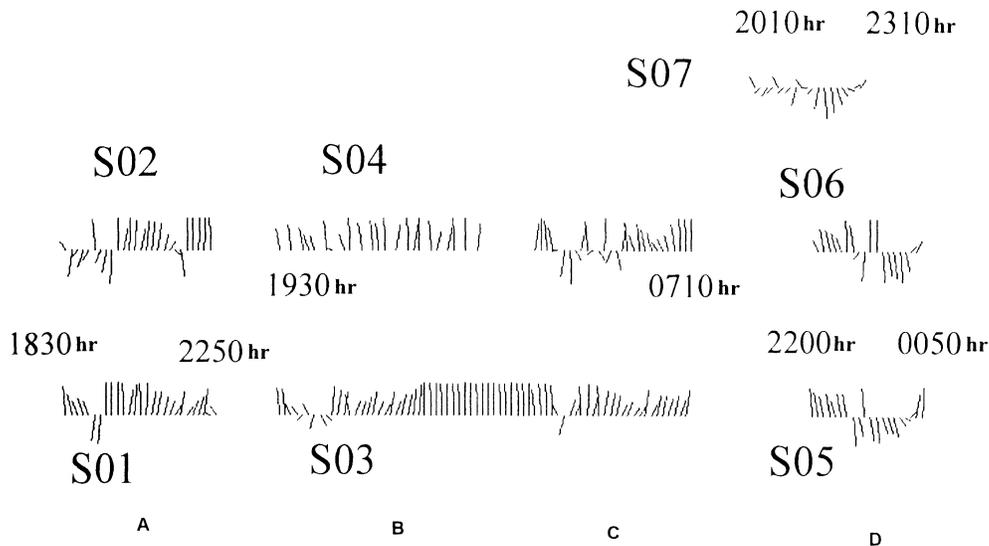
Figure 3. Directions of near-bed currents at sites S01, S02, S03, S04, S05, S06 and S07. A, B, C and D correspond to (a), (b), (c) and (d) in Figure 2, respectively.

drodynamic drag and generating turbulence via disruption. Estuarine and coastal saltmarsh plants can be treated as macroroughness elements in the same way that coastal mangroves are (FURUKAWA and WOLANSKI, 1996; FURUKAWA *et al.*, 1997). Their size, geometry, and numerical density will determine the properties of near-bed flow, including the magnitude of the shear stress exerted on the bed, the rate of fluid transport, and the production of turbulence (ECKMAN, 1983; LEONARD and LUTHER, 1995; SHI *et al.*, 1996). The physical structure of seagrass blades can significantly decrease tidal and wave-induced current velocities (FONSECA *et al.*, 1982). Our field data suggested that hydrodynamic effect of estuarine saltmarsh canopy on current is to reduce both mean currents (Figures 2a, 2b, 2c and 2d) and wave height (Figure 5). Near-bed mean current velocity was reduced by typically 16% in the *Scirpus* canopy compared to the unvegetated mudflat, while wave height was reduced by 60%.

For the short intervals of data available, the measured (horizontal) current speeds at S01 and S05 in the semi-enclosed area are always greater than speeds at saltmarsh sites S02, S06, S07 regardless of the phase of the tide or current direction (Figure 3). At sites S03 and S04 directions were nearly always north during both floods and ebbs. Speed at open site S04 was usually greater (and often much greater) than speeds at nearby saltmarsh edge site S03. However for one flood current (and for one 40 min interval near 0500 hr when currents eddy or swing around at S04), speed at S03 was higher than at S04 by 10 to 20 cm/s (Figure 3). Because currents were higher at S03 than S04 for one interval when eddying occurred, this suggests that speeds near the edge of the canopy may depend on current configuration. Unfortunately there are no direction data for the flood current interval. Speeds at S04 are nearly always north, perhaps indicating an unusual current configuration for the interval when speeds at S03 are higher than at S04.

Suspended sediment concentration on the mudflat was 26% higher than that in the *Scirpus* canopy (Figure 4A). This possibly suggests decreased erosion and increased settling in the saltmarsh canopy. However, decreased sediment concentration in the marsh does not necessarily mean decreased erosion and increased settling there. The marsh sites are some tens of m in from the edge and settling might occur there, meaning less advection of sediment to the marsh sites. Unfortunately, there is no evidence of deposition. The decreased erosion may be due to vegetation-induced decrease in tidal currents and wave height, but may be attributed to the ability of seagrass plants to bind sediments and substantially reduce resuspension (*e.g.*, SCOFFIN, 1970; WARD *et al.*, 1984). The vegetation-induced decrease in tidal currents and wave height is probably dependent on stem density as suggested by LEONARD *et al.* (1995a), LEONARD and LUTHER (1995) and SHI *et al.* (1996). The same effect increases also the settling of sediment out of suspension in wakes and eddies behind individual stems, as was documented for the case of mangrove swamps (FURUKAWA and WOLANSKI, 1996; FURAKAWA *et al.*, 1997). By contrast, wakes promote dispersion, and that microturbulence associated with wakes formed in the lee of plant stems may actually retain particles in suspension. The data presented in this paper show that suspended sediment concentration on the mudflat was greater than in the plant canopies. It is possible that the mudflat was in closer proximity to the sediment source. The deposition of storm-suspended sediments is important to coastal saltmarsh (STUMPF, 1983; REED, 1989; GOODBRED, 1995). Further studies are required to understand storm-driven processes in the present saltmarsh study area.

The wind-driven and tidal currents carry sediment laden water over the saltmarsh canopy at the flood tide. There the currents are smaller due to the saltmarsh vegetation; as a result turbulence is also smaller. As a result some sediment
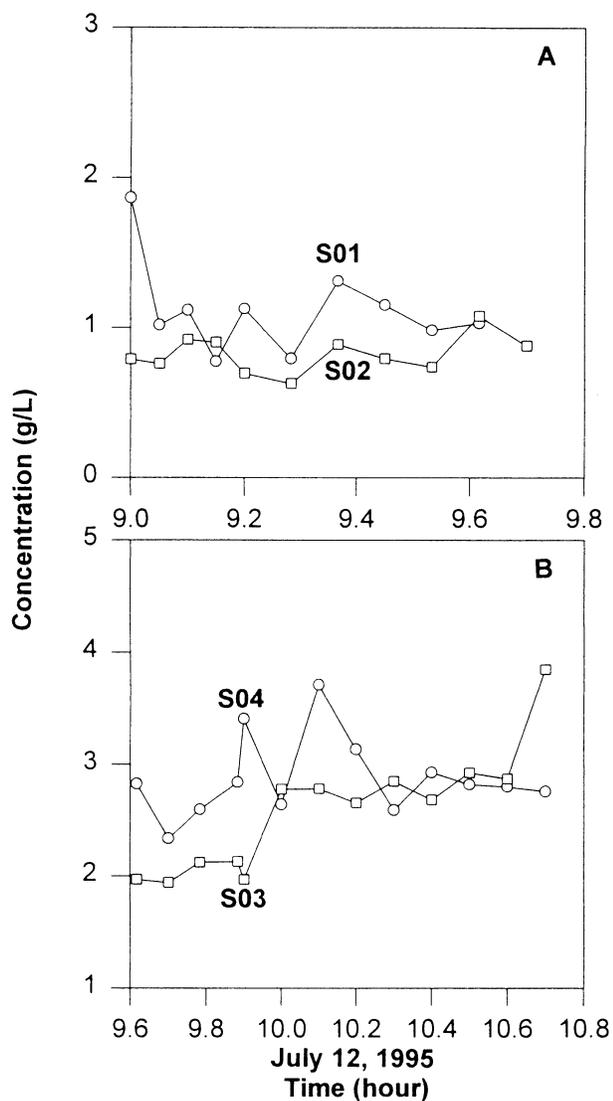
Figure 4. Temporal variations in suspended sediment concentration (A) on the mudflat (S01) and within the Scirpus mariquete canopy (S02) and (B) on the mudflat (S04) and within the Scirpus mariquete canopy (S03) (July 12, 1995).

Figure 5. Measured water depth in the Scirpus mariquete canopy (S03) and on the mudflat (S04) (July 12, 1995).

the canopy which is responsible for the reduction in speeds. This result is independent of wave measurements. Wave damping would then further decrease the potential for material to remain in suspension. By reducing turbulence and by trapping sediment, estuarine saltmarsh canopy can suppress resuspension in comparison to non-vegetated areas or enhance deposition. As a result, suspended sediment concentrations were found to be lower within saltmarsh canopies compared to unvegetated mudflats. The estuarine saltmarsh canopy will therefore enhance deposition of fine sediment.

ACKNOWLEDGMENTS

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drops out of suspension and what does not drop out is exported at the ebb tide. The saltmarsh canopy is thus a porous filter.

CONCLUSIONS

Estuarine saltmarsh canopy plants reduced near-bed mean current velocity within the canopy by 16%. Near-bed current velocity was less than 50 cm s^{-1} in saltmarsh canopies and on the mudflat. Reductions in near-bed current velocities within the saltmarsh canopy were larger during ebb tide than flood tide. Current speeds in the canopy were generally lower than on unvegetated mudflat, regardless of the phases of the tides or the tidal current direction. This suggests it is indeed
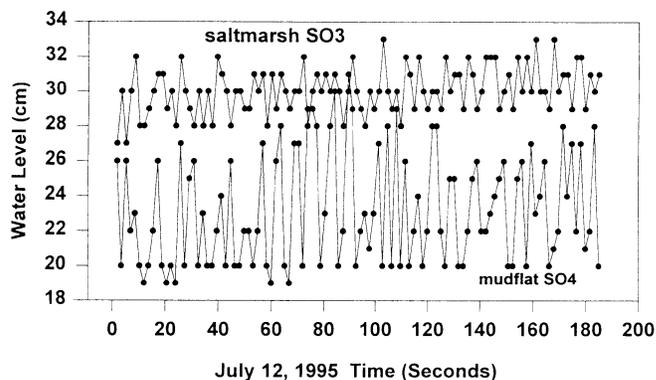
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