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Source: Journal of Coastal Research, 36(sp1) : 459-469

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.459

| Journal of Coastal Research | SI 36 | 459-469 | (ICS 2002 Proceedings) | Northern Ireland | ISSN 0749-0208 |
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# Hydrodynamics and Sediment Transport Through Tidal Marsh Canopies

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**ABSTRACT**

Flow dynamics on the vegetated surfaces of coastal wetlands may impact a wide range of processes including geochemical exchanges at the sediment water interface, larval recruitment and dispersion, and sediment deposition and retention. Nevertheless, little field data exist which describe flow behavior through emergent vegetated wetlands and its control over sediment transport and deposition. The goal of this paper is to describe canopy flow dynamics and suspended particulate transport for a variety of marshes that differ with respect to vegetation type and tidal regime. In situ measurements of tidal currents were collected in micro-, meso-, and macrotidal marshes of the Pacific, Gulf of Mexico and Atlantic coasts of the US and in a UK marsh on the North Sea. Mean flow speeds, vertical velocity profiles, and turbulence intensities were evaluated as were canopy characteristics and total suspended solid (TSS) levels. Broad scale flow characteristics exhibited little variation among sites. Mean flow speeds were almost always less than 10 cm $s^{-1}$ regardless of tidal regime. The presence of vegetation (regardless of type) significantly reduced both flow speed and turbulence intensity relative to adjacent open water areas. Variations in canopy morphology and the physical structure of individual plants control fine scale hydrodynamics, and influence particle advection, and particle settling. Flow speed magnitude and the importance of creek channel processes, however, appear to be most strongly influenced by the tidal regime in each of the marsh types examined.

**ADDITIONALINDEXWORDS:** *salt marsh, flow dynamics*

## INTRODUCTION

The stability of tidal marshes is largely dependent on the synergistic interactions of marsh morphology and hydrodynamics; where the characteristic marsh morphology consists of both vegetative growth and sedimentary features (FREIDRICHS and PERRY 2001). The interplay of these morphologic characteristics results in a complex variety of tidal flows on vegetated marsh surfaces (BURKE and STOLZENBACH, 1983; LEONARD *et al*., 1995; LEONARD 1997; YANG, 1998; CHRISTIANSEN *et al*., 2000). In general, tidally driven water parcels flood the marsh surface in a fully turbulent state (RIDDERINKHOF, 1995). Once within the vegetated canopy, however, both mean flow velocities and energy levels are markedly reduced by plant/flow interactions (LEONARD 1997; NEPF *et al*., 1997; CHRISTIANSEN *et al*., 2000). Flow energies within marsh grass may decrease by an order of magnitude or more compared to unvegetated areas (LEONARD and LUTHER 1995) and appear to be inversely related to distance from open water (CHRISTIANSEN *et al*., 2000) and plant density (LEONARD *et al*., 1995, LEONARD and LUTHER 1995). In addition, the attenuation rate of flow energy in some systems is affected by vegetation type (LEONARD and LUTHER 1995).

Canopy architecture also exerts control over the vertical structure of over-marsh flows in some systems. Flow profiles collected in Spartina alterniflora and Juncus roemerianus canopies in Gulf of Mexico and mid-Atlantic marsh systems, for example, indicate that vertical flow profiles are not uniform and that they deviate from the logarithmic shaped profile encountered in areas lacking vegetation (LEONARD and LUTHER 1995; CHRISTIANSEN *et al*., 2000). LEONARD and LUTHER (1995) further demonstrated that profile shape is affected by both inter and intra-profile biomass distribution and that intraprofile baffling potential is maximum at heights where plant material is most abundant, and interprofile baffling potential is greatest at maximum plant densities. The marked reduction of flow velocities within marsh grass relative to unimpeded flows that may overtop canopies lead to reductions in vertical shear and turbulence in the canopy (FRIEDRICHS and PERRY, 2001). These conditions favor rapid sediment settling and prevent further sediment resuspension (FREY and BASAN, 1985; PETHICK *et al*., 1992; LEONARD and LUTHER 1995; CHRISTIANSEN *et al*., 2000).

The results of previous work have shown that flow magnitudes can vary significantly from site to site even when each system is characterized by a similar tidal range and similar types of vegetation (LEONARD *et al*., 1995; CHRISTIANSEN *et al*., 2000; FRIEDRICHS and PERRY, 2001). With the exception of recent contributions by MOELLER *et al.* (1996; 1999) and YANG (1998), however, the bulk of published data for in situ studies of over-marsh flows has been restricted to low energy systems dominated by monospecific stands of Spartina alterniflora or Juncus roemerianus. This paucity of data limits application of previous findings to the large number of tidal marsh systems characterized by different tidal regimes or vegetation types. The objective of this paper is to use previously unpublished data to examine mean flow properties, flow energy, and sediment transport in marshes characterized by different tidal ranges, geomorphic settings, and vegetation types.

## STUDYAREAAND METHODS

Data for this study were collected in eight different tidal marsh systems in the United States and the United Kingdom (Figure 1). Each study area was characterized by different tidal signatures and vegetation types (Table 1). For the purpose of this paper, the following tidal range definitions are assumed: microtidal-mean tidal range of one meter or less; mesotidal-mean tidal range of 1 to 4 m, and macrotidal-mean tidal range greater than 4 m. During each data collection effort, flow data were collected at one edge position lacking vegetation and at least one position within the canopy. All data presented in this paper were collected during fair weather conditions. Flow data collection began as soon as the marsh surface was topped by the flooding tide and continued over the duration of inundation. For most experiments, water level, total suspended solid concentrations, and sediment deposition were concurrently measured.

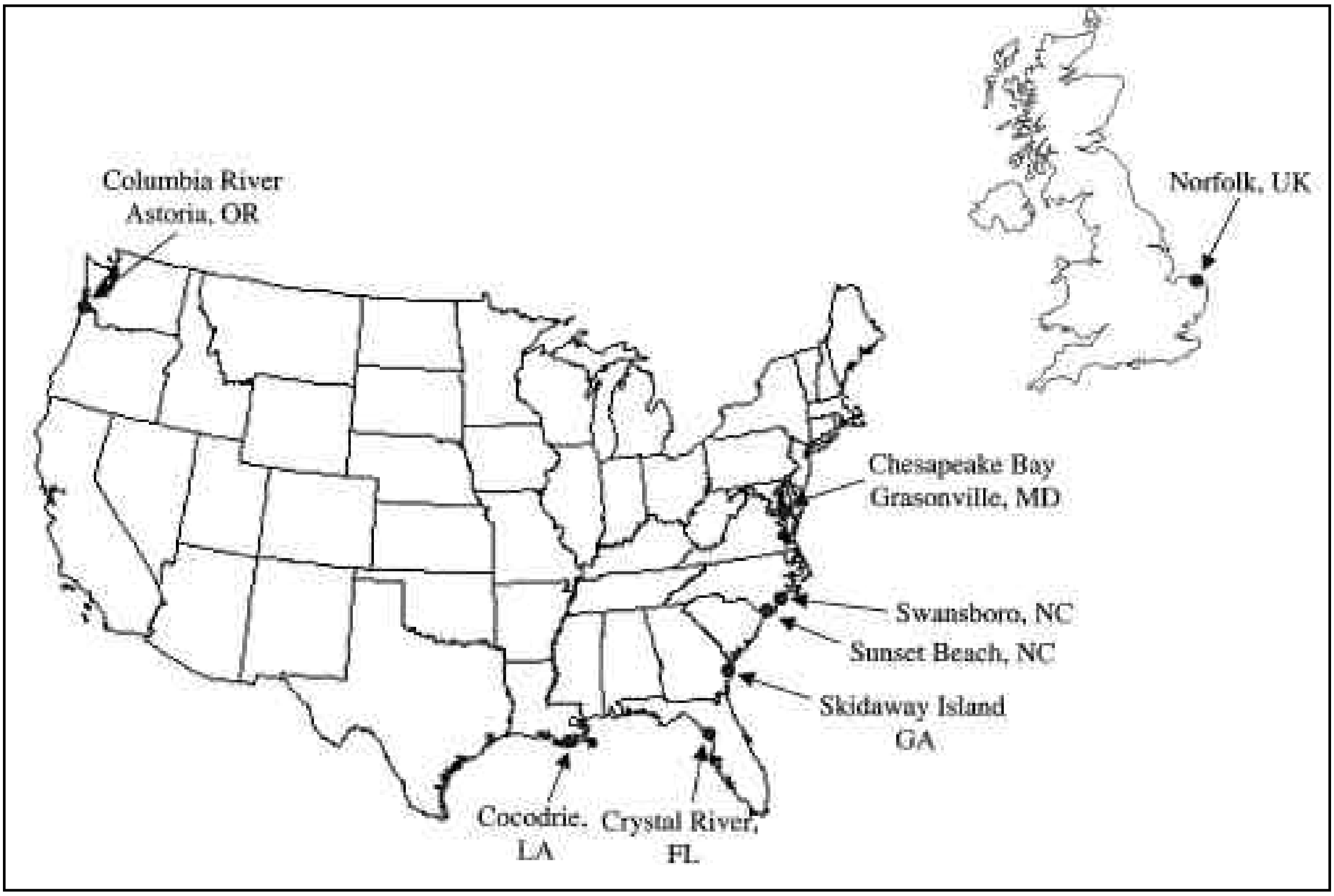


Figure 1. Location of study sites. Study site characteristics are given in Table 1.

Table 1. Study site descriptions and sampling strategies.

| Site | Tides | Vegetation | Flow Measurements |
|---|---|---|---|
| Norfolk, UK (Hut Marsh) | Macrotidal Semi-diurnal (mixed) | *Atriplex portuloides* | Hot-film at 2.5, 5, 10, 15, and 25 cm |
| Columbia River, OR (Youngs Bay) | Macrotidal Semi-diurnal (mixed) Mesotidal | *Scirpus* sp. | Hot-film at 2, 5, and 67 cm |
| Skidaway Island, GA (SKIO) | Semi-diurnal (mixed) Mesotidal | *Spartina alterniflora* | EMCM at 5 cm |
| Sunset Beach, NC (South end) | Semi-diurnal (mixed) Mesotidal | *Spartina alterniflora* | EMCM at 5 cm |
| Swansboro, NC (Intracoastal) | Semi-diurnal (mixed) Micotidal | *Spartina alterniflora* | Hot-film at 10, 20, 30, 50 and 70 cm |
| Crystal River, FL (Cedar Creek) | Semi-diurnal (mixed) Micotidal | *Juncus roemerianus* | Hot-film at 3, 7, 10, 20 and 30 cm |
| Chesapeake Bay (Grasonville, MD) | Semi-diurnal (mixed) Micotidal | *Spartina alterniflora* (site 1) *Phragmites australis* (site 2) | EMCM at 5 cm |
| Cocodrie, LA (Old Oyster Bayou) | Diurnal | *Spartina alterniflora* | Hot-film at 3, 7, 10, and 20 cm |

Flow properties were measured using one of the following methods: 1) hot-film anemometry sensors (GUST, 1988) or 2) Marsh McBirney electromagnetic current meters (EMCM-Models 520). Hot-film sensors were used at the following sites: Columbia River-OR, Norfolk-UK, Swansboro-NC, Crystal River-FL, Cocodrie-LA. When used, these sensors were deployed in arrays will with sensors placed at varying heights above the substrate (see Table 1). The hot-film sensors collected data at a frequency of 5 Hz over 13 to 15 minute sampling bursts for a sampling period of up to 4 hours and the raw data were stored in a Tattletale data logger. Because these sensors do not provide a direction, hot-film data are reported as flow speed. Marsh McBirney EMCMs were used to quantify flows at the Swansboro (NC), Sunset Beach (NC), Chesapeake Bay (MD), and Skidaway (GA) sites. One advantage of the EMCM is that it measures two components of velocity; those required to calculate flow direction and to quantify turbulence. EMCM sensors were suspended from PVC frames to a level approximately 10 cm above the bed in the open water and approximately 5 cm above the bed on the marsh surface. EMCMs collected data at a frequency of 4 Hz in 1-minute sampling bursts every 10 minutes over the duration of flooding. Data were stored in a Campbell CR10X data logger and downloaded to a laptop PC in the field. Regardless of sensor type, flow data were always collected at one open water position adjacent to the canopy and on the surface of the marsh at distances of 1.5 to 3 m from the marsh edge.

Time series of the velocity components were used to calculate time-averaged and turbulent velocities. During some experiments (e.g. Swansboro, NC), multiple EMCM sensors were simultaneously deployed and each sensor was oriented differently so that both vertical and horizontal turbulence could be detected. Turbulence intensity was computed from the standard deviation of the instantaneous velocities about the mean (KUNDU, 1990) and were computed using MATLAB. Vertical profiles were constructed from hot-film data in order to assess the extent to which plant community structure and variations in plant morphology, either along plant length or intergeneric, affected turbulence development, particle transport and particle deposition. Hydroperiod varied at each site and along positions within each transect, nonetheless, each of the semidiurnal sites were inundated for a period ranging from 2 to 4 hours. The diurnal Louisiana site was inundated for almost twice as long as most of the semi-diurnal sites.

Particulate transport was quantified using ISCO 3500 automated water samplers. These samplers were positioned adjacent to flow sensors and their intake hoses were mounted 5 cm above the marsh surface. In most cases, two replicate 1 L samples were collected once every 15 to 30 minutes beginning as soon as water level on the marsh flooded hose intakes. Hose nozzles were oriented away from the substrate to prevent disturbance during sampling and during line purging between intake events. Following collection, samples were immediately placed on ice and processed within 2 hours. Each sample was filtered through pre-weighed, pre-combusted, 0.45 µm glass fiber filters. Samples were returned to the laboratory, dried at 60 °C for 12 hours, re-weighed, and concentrations given in mg $l^{-1}$. The percentage of organic matter retained on the filters was estimated by loss on ignition at 450°C for 4 hours.

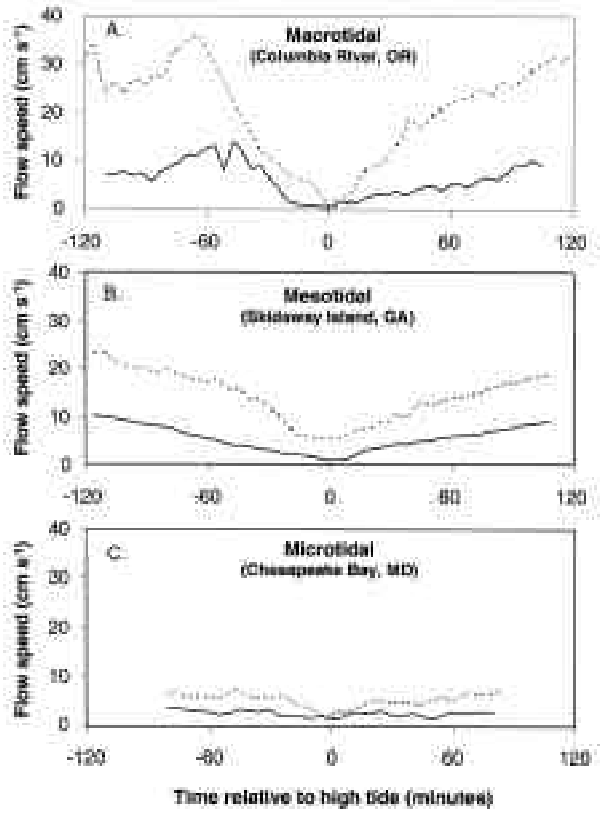


Figure 2. Mean flow speeds measured inside (solid) and adjacent (dashed) to the vegetated canopy in (A) macrotidal, (B) mesotidal, and (C) microtidal systems. Flow speeds on the marsh surface were 2 1/2 to 3 times lower than speeds measured outside of the canopy. All data were collected in semidiurnal systems.

## RESULTS

### Flow Dynamics

### Mean flow characteristics and tidal range

Mean flows were determined by taking the mean for each sampling burst. Where hot-film arrays were used, the mean is a depth-integrated average of speed over that sampling burst. Mean flow speeds in marsh canopies were low, usually less than 10 cm $s^{-1}$, throughout both the flood and ebb portions of tidal inundation regardless of tidal range (Figure 2). For each of the sites examined, flow speeds on the vegetated marsh surface were much lower than speeds measured concurrently in adjacent open water areas. The greatest reduction in flow speed occurred at the macrotidal site where open water flows were reduced by as much as 20 cm s-1 on the marsh surface. In the mesotidal systems, over-marsh flows were generally 5 to 10 cm $s^{-1}$ lower than flows measured in adjacent non-vegetated areas. Over-marsh flow speeds at the Chesapeake Bay (microtidal) site were usually no more than 2 to 3 cm $s^{-1}$ lower than open water speeds.

Flow magnitude on the marsh surface correlated well with flow magnitudes measured concurrently in adjacent open water areas. In general, maximum canopy flow speeds occurred as tidal flows flooded the marsh surface, and again as waters receded from the marsh surface. Minimum flow speeds occurred at or near high water. This pattern of flood deceleration and ebb acceleration on the marsh surface and in adjacent open water areas was most pronounced in the mesotidal systems of the Atlantic coast (Figure 2) and the microtidal systems of the Gulf of Mexico (see also LEONARD and LUTHER, 1995).

The Columbia River macrotidal site also exhibited fairly high speeds at the beginning and end of inundation and minimum speeds at high water. At this site, however, flow speeds actually increased to a maximum on the marsh surface approximately 60 minutes prior to high water, before decelerating to a minimum at high water. A similar speed maximum occurred on the adjacent, unvegetated tidal flat. The tidal flat speed maximum was more than twice the vegetated marsh speed maximum and occurred approximately 10 minutes earlier (Figure 2).

Flow speeds measured at the microtidal Chesapeake Bay site showed the least variation of all the sites (Figure 2). Flows were consistently between 6 cm $s^{-1}$ and 2 cm $s^{-1}$ adjacent to the canopy and flow speeds fluctuated between 4 cm $s^{-1}$ and 1 cm $s^{-1}$ within the canopy. Although flows decreased to a slack water minimum near high tide in the adjacent open water, no distinct period of slack water occurred on the marsh surface at this site.

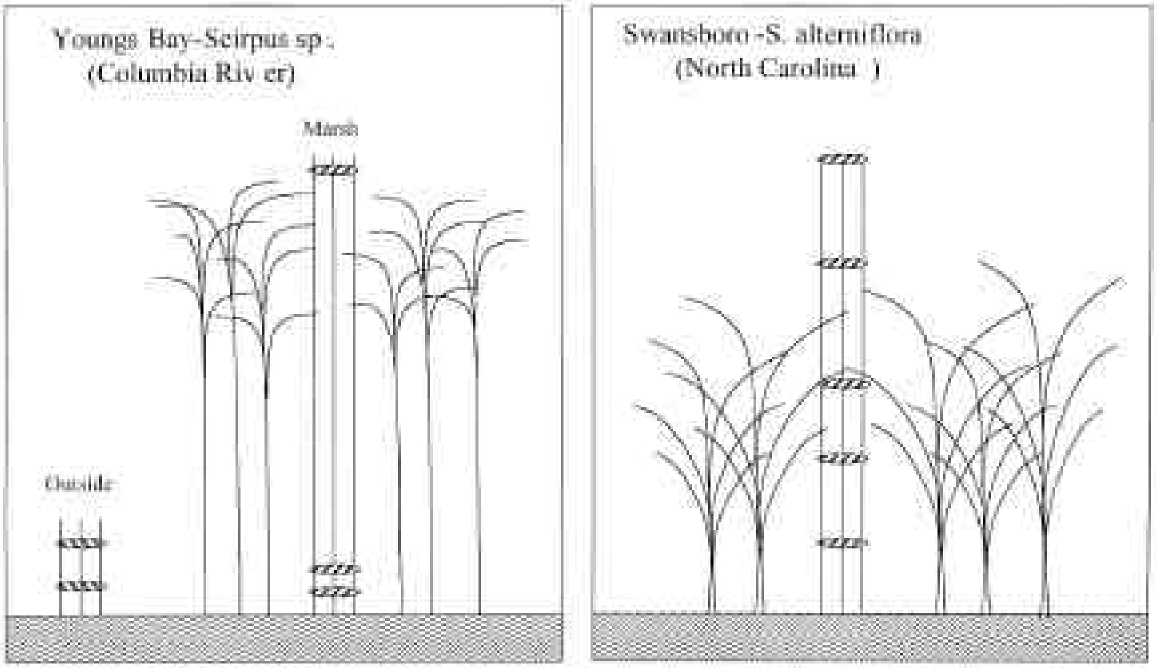


Figure 3. Schematic showing sampling strategy for measuring flow speeds within *Scirpus* sp. (Columbia River, OR) and *S. alterniflora* (Swansboro, NC). Flow data were collected using hot-film anemometry sensors.

## Vertical variations in flow speed and turbulence

Hot-film sensors were deployed in vertical arrays at macro and mesotidal sites to examine vertical variations in flow speed (Figure 3). Flow speeds measured at two locations within each canopy and just above the top of the canopy at each site (Figure 4) clearly demonstrate the attenuation of flow speed in the marsh grass relative to unimpeded flows above the canopy. Regardless of tidal range, flow speeds within the canopy were less than 6 cm s-1 while unimpeded, above canopy flow speeds were as high as 9 cm $s^{-1}$. The differences in flow speed magnitude measured above and within the canopy were greater during rising water than during falling water for both sites. For the macrotidal site, the maximum flow speed recorded occurred at the top of the canopy just before water levels fell below its surface. This measurement, however, is most likely an outlier that should be discounted as simultaneous increases in flow speed were not observed either within the canopy or on the adjacent tidal flat.

Vertical velocity profiles constructed for mesotidal *Spartina alterniflora* (Figure 5) and macrotidal Atriplex portulacoides (Figure 6) marshes also show that mean flow speeds and turbulence intensities are not uniform within the canopy. Further, these profiles demonstrate that the shape of the profile varies with different canopy characteristics. The profile shown in Figure 5 was collected in a *S. alterniflora* canopy and exhibits a shape consistent with those measured in other *S. alterniflora* systems (LEONARD and LUTHER,

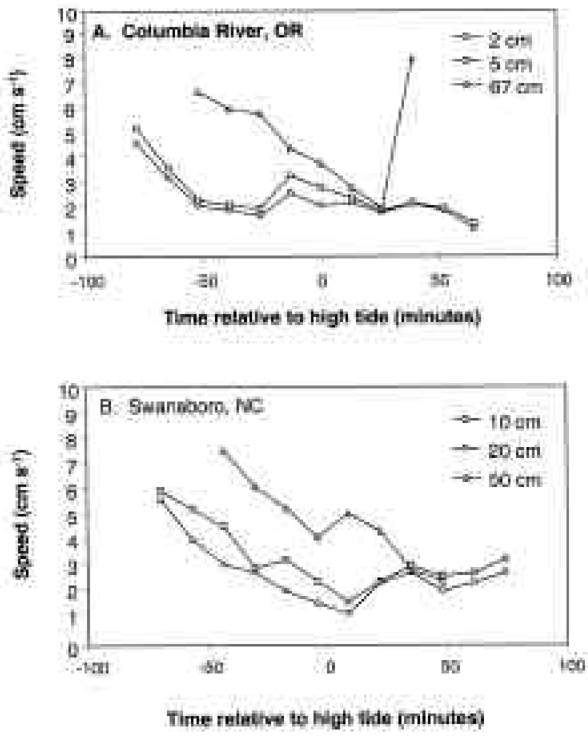


Figure 4. Time series of flow speeds at various heights above the marsh surface in a A) macrotidal and B) low mesotidal marsh. Positions of sensors relative to the canopy are shown in Figure 3.

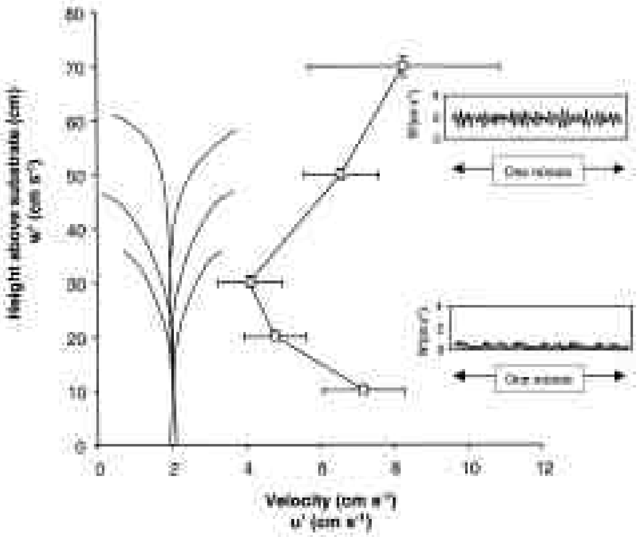


Figure 5. Vertical speed profile collected in a mesotidal *S. alterniflora* canopy (Swansboro, NC). Horizontal error bars indicate measured u' values and vertical error bars indicate measured w' values. Turbulence intensities (u' and w') were calculated from EMCM data collected at a frequency of 4 Hz for a one-minute sampling burst. Insets show time series of the instantaneous fluctuations of w' measured at 20cm and 70 cm above the bed during the sampling burst.

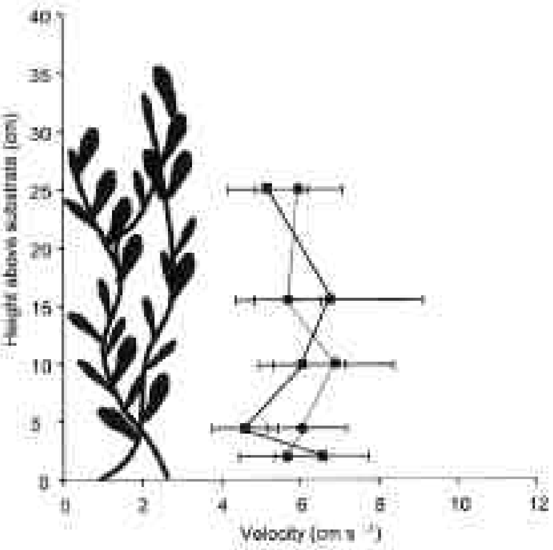


Figure 6. Vertical speed profile measured in A. portuloides marsh, Norfolk, UK. Error bars indicate the magnitude of instantaneous fluctuations of speed around the mean. Data were collected using hot-film probes that sampled at a frequency of 5 Hz over a one-minute burst. The solid line and dashed line indicate profiles collected during separate, and consecutive inundation events.

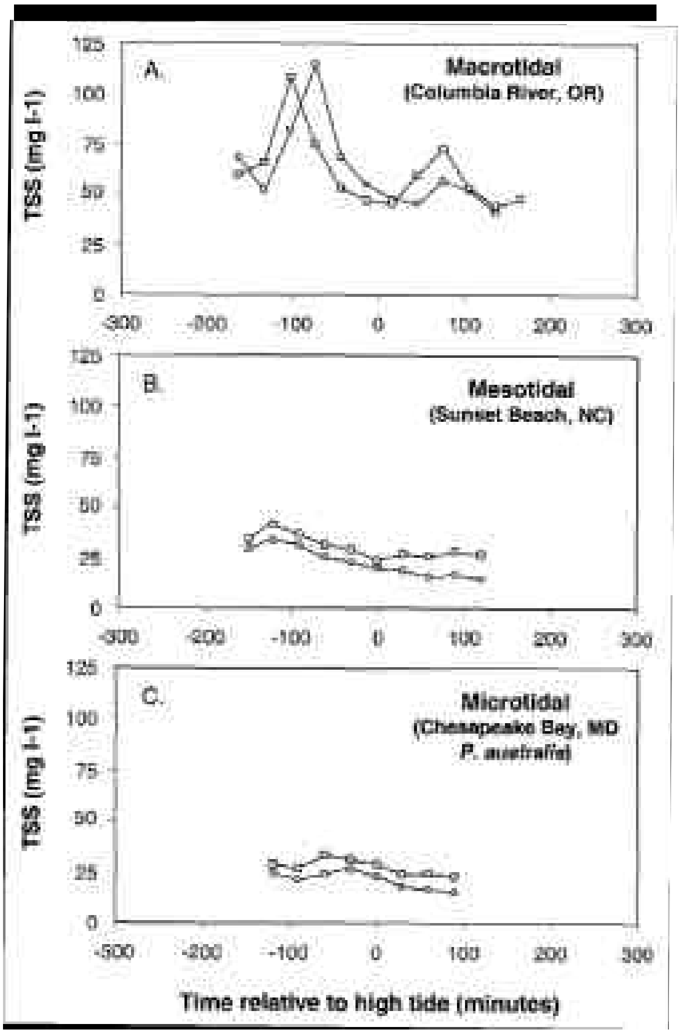


Figure 7. Figure 7. Time series of TSS concentrations measured inside (circles) and adjacent (squares) to the vegetated canopy in (A) macrotidal, (B) mesotidal, and (C) microtidal systems.

1995; CHRISTIANSEN *et al*., 2000). A "kink" in the profile occurs between 10 and 30 cm where both flow speeds and turbulence intensities (u' and w') are reduced (LEONARD and LUTHER, 1995). The turbulence intensity values shown in Figure 5 demonstrate that vertical turbulence within the canopy is less than that above the canopy and is substantially lower than the horizontal component.

The shape of the *A. portulacoides* profile is less predictable (Figure 6). The structure of *A. portuloides* is more vine-like and yields a more complex canopy than the rather stiff stems and leaves of *S. alterniflora*. Consequently, vertical profiles measured in *A. portuloides* have an irregular shape that can not be easily described as a function of canopy characteristics. Further canopy complexity arises from the fact that *A. portulacoides* is slightly buoyant and shifts its position in the canopy with every flooding event. As a result, maximum flow speeds and turbulence intensities may occur at different heights in the water column for subsequent inundation events (Figure 6).

**Suspended particulate matter distributions**

Concentrations of total suspended solids (TSS) varied between sites and were strongly influenced by TSS concentrations in the adjacent "source" water (Figure 7). The highest TSS concentrations observed occurred at the macrotidal Columbia River site. Concentrations as high as 120 mg $l^{-1}$ were measured within the *Scirpus* sp. canopy. These levels, however, occurred as short-lived pulses that generally coincided with a similar TSS peak observed at the adjacent open water sampling site. Concentrations measured on the surfaces of meso- and microtidal marshes were always much lower those observed at the macrotidal sites and were usually less than 30 mg $l^{-1}$. At both the meso- and microtidal sites, time-series of TSS concentration on the marsh surface reflect subtle fluctuations in TSS measured in adjacent open water (Figure 7b and c). Further, TSS concentrations at these sites were usually 5 to 15 mg $l^{-1}$ less than concurrent measures of TSS in open water.

In general, TSS concentrations on the surfaces of each of the marshes examined were similar to those measured in adjacent open water during the initial phase on inundation. Temporal variations in TSS over the duration of the flooding event, however, differed between sites. At the Columbia River macrotidal site, TSS concentrations increased following initial flooding and reached a maximum approximately 1 1/2 hours before high water (Figure 7a). Although not shown here, a similar TSS peak also occurred at about the same time in the flooding cycle in the macrotidal UK system (REED *et al*., 1999). TSS concentrations then decreased on the surface of the marsh for the remainder of the inundation event. At the mesotidal sites, TSS concentrations on the marsh surface gradually decreased linearly during each inundation event (Figure 7b and 8a,b).

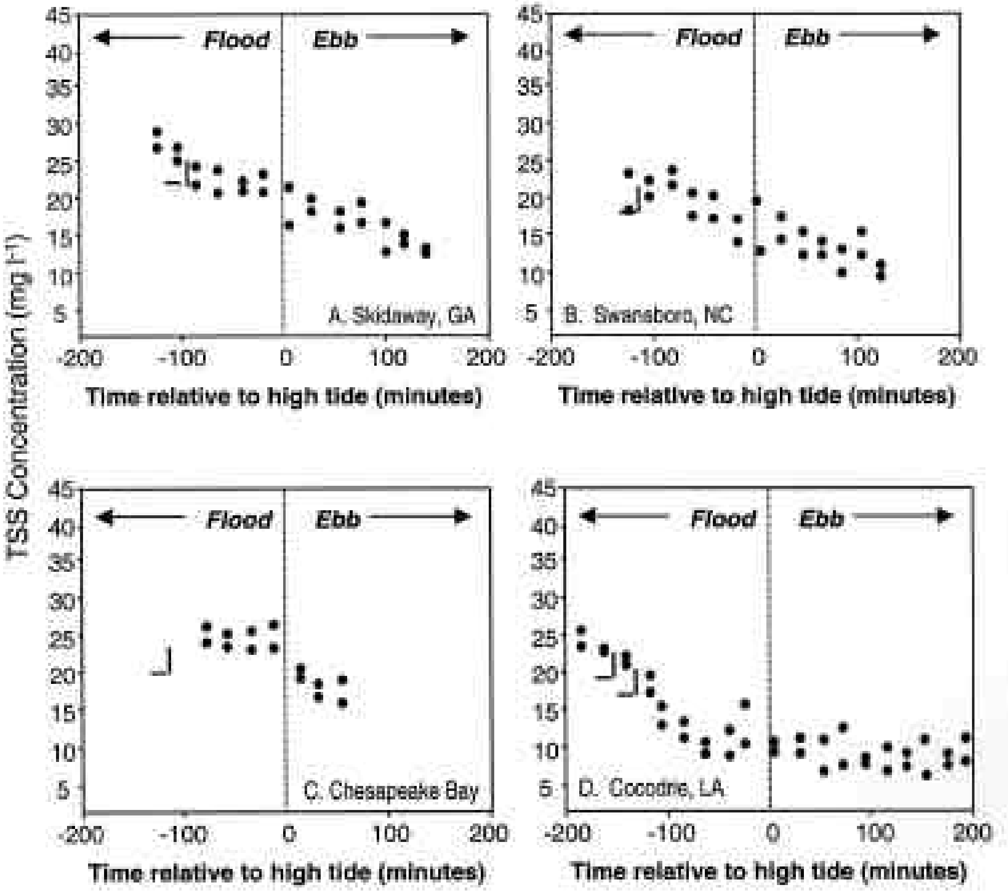


Figure 8. Figure 8. TSS concentrations measured on the surface of three semidiurnal marshes: A) Skidaway, GA (macrotidal), B) Swansboro, NC (low mesotidal), and C) Chesapeake Bay, MD (microtidal) and one diurnal marsh: D) Cocodrie, LA(microtidal). All data were collected at 5 cm above the bottom in *S. alterniflora*.

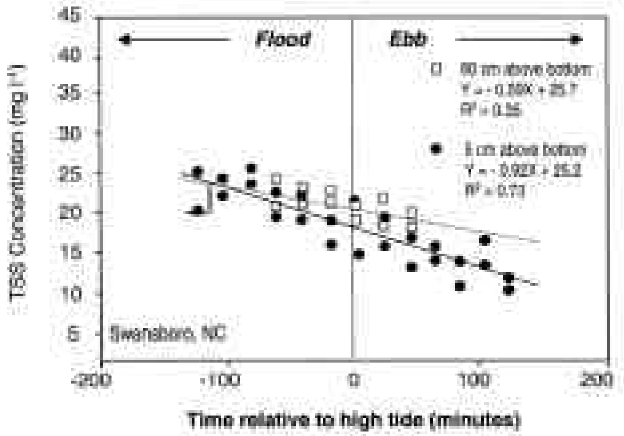


Figure 9. Figure 9. TSS concentrations measured within and above a mesotidal *S. alterniflora* canopy. TSS concentrations decreased over time at both sites; however, the rate of decrease within the canopy was twice the rate above the canopy.

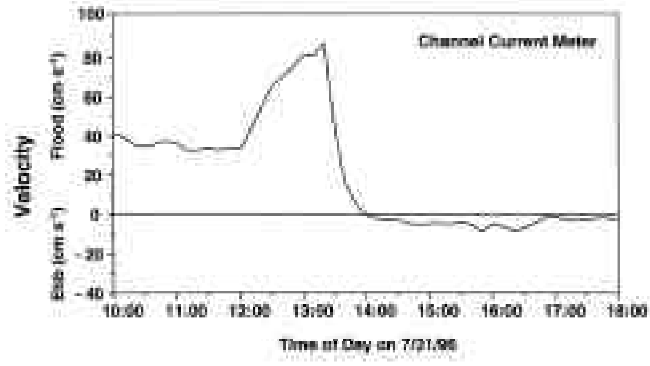


Figure 10. Flow velocities measured using an S4 current meter deployed in the tidal creek channel nearest to the Columbia River marsh sampling site. Note the large flood velocity pulse occuring 60-90 minutes prior to high tide.

TSS time series constructed for the microtidal sites exhibited different patterns depending on the frequency of flooding (Figure 7c and 8c, d). TSS concentrations at the semi-diurnal Chesapeake Bay site showed very little variation over the course of an inundation event. Initial concentrations of 23 to 28 mg $l^{-1}$ on the marsh surface were maintained during rising water and then gradually decreased to 15 to 18 mg $l^{-1}$ during falling water (Figure 8c). In the diurnal Louisiana system (Figure 8d), initial TSS concentrations of 23 to 26 mg $l^{-1}$ decreased linearly over the first three hours of inundation and then remained relatively constant at 7 to 12 mg $l^{-1}$. Although not shown here, the same patterns have been observed for other marsh sites in the Mississippi delta plain (LEONARD, 1994).

Temporal variations in TSS concentration were also examined at two different heights, one within the canopy and the other above the top of the inundated canopy, at one of the mesotidal *Spartina alterniflora* sites (Figure 9). TSS concentrations measured at 5 cm and 60 cm above the bottom were fairly similar initially (19 to 25 mg $l^{-1}$), but began to differ during falling water. Although concentrations decreased linearly at both heights during the tidal cycle, the rate of decrease was different for each. TSS concentrations within the canopy decreased at a rate approximately one and one-half times the rate observed above the canopy.

## DISCUSSION

### Spatial Variations in Flow Dynamics

The characteristics of over-marsh flows documented during this study are consistent with those reported previously for other vegetated marsh systems (LEONARD *et al.*,1995; LEONARD, 1997; CHRISTIANSEN *et al.*, 2000). In general, flow speeds decreased as maximum high water was approached and increased again on the falling tide. Mean flow speeds appear to be controlled by tidal forcing where the highest over-marsh flow speeds occurred at the Columbia River site (highest tidal range) and the lowest occurred at the Chesapeake Bay sites (lowest tidal ranges). These results are consistent with CHRISTIANSEN *et al.* (2000) and REED *et al.* (1999) who observed that flow velocities across a given marsh surface increase with tidal range in both mesotidal and macrotidal systems, respectively.

Flow speeds across the vegetated surface of each system examined were reduced relative to flow speeds in adjacent open water. As suggested by LEONARD and LUTHER (1995), YANG (1998), FRIEDRICHS and PERRY (2001) and others, flow speeds on the marsh surface were attenuated due to a combination of plant baffling and frictional effects. The greatest absolute reduction in flow speed occurred in the macrotidal systems where flow speeds in the canopy were as much as 20 cm $s^{-1}$ less than flow speeds in unvegetated areas. These reductions, however, constituted at most a three fold reduction in flow magnitude.

Flow speeds on the surface of mesotidal marshes were also 2 to 3 times lower than flows across adjacent unvegetated areas, even though the absolute change in speed rarely exceeded 10 cm $s^{-1}$. At microtidal sites, where flow speeds were less than 10 cm $s^{-1}$ prior to marsh contact, flow magnitudes in the marsh were further reduced 2 to 2.5 times. While tidal range, and hence flow energy, appear to control the absolute magnitude of over-marsh flows, the fact that flow speeds were attenuated to a similar degree in all of the systems examined suggest that a universal relationship may exist that describes flow speed reductions within the canopy. Site specific parameters most likely to be important components of this relationship include: degree and type of vegetation, potential for wave activity, and surface gradients (LEONARD *et al*., 1995; EISMA and RIDDERINKHOF, 1998; CHRISTIANSEN *et al*., 2000).

### Influence of Creek Channel Processes

FRENCH and STODDART (1992), LEONARD (1997), and REED *et al*. (1999), have demonstrated that sediment deposition on the surface of salt marsh is intricately linked to flow dynamics in adjacent tidal creeks. While deposition was not directly examined in this study, the temporal and spatial patterns of TSS concentrations presented clearly indicate that open water processes are an important control over sediment delivery to the marsh in each of the systems examined. Temporal variations in TSS concentration closely followed increases and decreases in open water flow speeds. Distinct peaks in TSS concentrations occurred either in conjunction with, or shortly after, velocity peaks in open water flows (e.g. Figure 2 and 7).

Flood velocity pulses, or periods of peak velocity apparently related to marsh inundation, have been documented in many macrotidal creek systems (BAYLISS-SMITH *et al*., 1979; FRENCH and STODDART, 1992; REED *et al*., 1999). Maximum TSS concentrations in tidal channels typically coincide with these velocity peaks and have been shown to increase as the magnitude of the flood pulse increases (REED *et al*., 1999). At the Columbia River site, a large velocity pulse in the creek channel (Figure 10) neared its maximum approximately 60 minutes prior to high water. Similar peaks in flow speed occurred adjacent to and within the marsh canopy at approximately the same time (Figure 2). Maximum TSS concentrations, however, did not coincide with the flood velocity pulse in the channel or the peak flow speed on the marsh. Instead, TSS levels inside and adjacent to the canopy begin to rise as channel velocities begin to intensify (Figure 7 and 10). Maximum TSS concentrations on the marsh surface occur just before the flood velocity pulse in the creek reaches its maximum. The timing of these events suggest that 1) flow acceleration and higher velocities in the channel may have increased the pool of sediment available for delivery to the marsh surface, and 2) increased flow speeds adjacent to and on the marsh surface maintained these sediments in suspension until they were deposited within the vegetation.

Flood velocity pulses have also been documented for tidal creeks in low mesotidal settings (LEONARD 1997). These pulses may also result in an elevated TSS concentration (such as shown in the Sunset Beach example in Figure 7); however, the magnitudes of both the velocity pulse and the TSS concentration are usually less than those observed in macrotidal systems. This study found no evidence that a flood velocity pulse affected sediment transport processes in microtidal systems.

### Plant-Flow Interactions and Sediment Transport

Flow speeds measured within and above *Spartina alterniflora* and *Scirpus sp*. demonstrate that 1) flow speeds on the surface marsh are reduced at all heights relative to unvegetated areas, and 2) flow speeds within the canopy are reduced even further relative to unimpeded flows above the plants. In the macrotidal system, unimpeded flows above the canopy were as much as 5 cm $s^{-1}$ greater than concurrently measured speeds within the canopy. The greatest difference in flow speed occurred during the initial phases of canopy submergence and decreased until water levels dropped below the flow sensor. The same general trend occurred in the mesotidal system where unimpeded flows above the canopy were, at most, 3 cm $s^{-1}$ greater than flows within the canopy. These data reiterate the importance of frictional resistance provided by the canopy surface in reducing upper water column flow speeds in all systems (BURKE and STOLZENBACH, 1983; SHI *et al*., 1995). This result is especially relevant to those systems where the vegetation is routinely submerged such as those that experience large tidal ranges or frequent storm surges.

Vertical velocity profiles constructed within mesotidal Spartina alterniflora canopies have shapes similar to those measured in microtidal *S. alterniflora* marshes and mesotidal *Juncus roemerianus* marshes (LEONARD and LUTHER, 1995). These data indicate that for vegetated canopies with relatively consistent distributions of biomass with height, the shape of the vertical profile can be anticipated if the distribution of biomass within the canopy can be quantified. In canopies with more complex or variable architecture, such as *Phragmites australis* where abundant wrack is common or the *Atriplex portulocoides* examined here, profile shapes can vary substantially between subsequent flooding events.

In salt marshes, suspended particles consist of inorganic particles ranging in size from fine sands to clays, organic detritus, and organic aggregates (KASTLER and WIBERG, 1996; CHRISTIANSEN *et al*. 2000). The finest and least dense of these materials have been shown to make their way furthest into the interiors of many marsh systems (ORME, 1990, FRENCH and SPENCER, 1993; KASTLER and WIBERG, 1996). The TSS data presented in this paper suggest that most suspended sediments are removed from over-marsh flows during the rising tide. Sediment concentrations measured adjacent to and within the vegetation during flood tides were consistently higher than those measured during ebb tides. Such reductions in TSS concentration during the early phases of marsh inundation seem to occur regardless of vegetation type or tidal regime. Further, data collected in diurnal systems indicate that TSS concentrations reach a steady state after 3 to 4 hours and that for the remainder of inundation, additional losses are negligible. This result has important implications for management because it suggests that increasing hydroperiod without introducing additional sediment does not enhance deposition.

The distribution of biomass directly affects sediment advection and dispersion on the marsh surface. Measurements of u' and w' in Spartina alterniflora indicate that most of the turbulence within the canopy lies in the horizontal plane. Because values of u' were 1.5 to 2 times greater than w' values, it seems likely that turbulence within the canopy is more likely to promote advection of particles rather than vertical mixing. These conditions would facilitate particle delivery to the interior of the vegetated marsh; especially of those particles that are very fine or those exhibiting relatively low densities. Further, lower turbulence intensities and reduced vertical shear (SHI *et al*., 1995) may enhance deposition of the settleable fraction within the vegetation relative to above it. The data presented in Figure 9 support this observation. While TSS concentrations decreased over time at both heights, the concentrations within the canopy decreased at the twice the rate as concentrations higher in the water column.

## CONCLUSIONS

Sediment depositional processes in salt marshes are controlled by a combination of physical and biological factors that, together, may affect both the delivery and retention of materials. Because tidal marshes occur in a range of physical settings, they constitute a diverse group of ecosystems in which the most important factors affecting sediment deposition may vary from system to system (CHRISTIANSEN *et al*. 2000; YANG 1999; REED *et al*., 1999; DIJKEMA 1997). Nonetheless, the results presented in this paper in addition to those recently reviewed by FRIEDRICHS and PERRY (2001) suggest that certain relationships may be common to a variety of systems. The most important findings of this study are:

1) Mean flow speeds in marsh canopies are 2.5 to 3 times lower than speeds adjacent to the canopy regardless of tidal range;

2) Surficial flow speeds were usually less than 10 cm s- regardless of tidal range; however, maximum speed appears to increase with tidal range;

3) Flood velocity pulses in tidal creek channels may affect flow dyanamics and sediment transport on the marsh surface; however, the importance of this mechanism declines as tidal range decreases;

4) Most suspended material is removed from over-marsh flows during the rising tide.

5) Flow speeds, turbulence intensities, and vertical shear are diminished in the vegetated canopy. These factors not only promote sedimentation, but increase the rate of sedimentation relative to unimpeded flows;

6) Within the vegetation, turbulence contributes more to lateral advection rather than vertical mixing;

## ACKNOWLEDGMENTS

This project was supported by grants from the United States Geological Survey, the National Science Foundation (Columbia River LMER), and the Marsh Ecology Research Program. In addition, the authors gratefully acknowledge support provided by the Horsehead Wetlands Center, Skidaway Institute of Oceanography, Louisiana Universities Marine Consortium Laboratory, and UNCW's Center for Marine Science. This study could not have been completed without the contributions of Nina De Luca, Walter Bowles, Tom Spencer, Jon French, Wendy Morrison, Rebecca Beavers, Ansley Wren, and Kim Nelson.

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