WETLANDS, Vol. 22, No. 2, June 2002, pp. 415–424

FLOW DYNAMICS AND SEDIMENTATION IN *SPARTINA ALTERNIFLORA* AND *PHRAGMITES AUSTRALIS* MARSHES OF THE CHESAPEAKE BAY

Lynn A. Leonard[1], P. Ansley Wren[1], and Rebecca L. Beavers[2]
[1] *Center for Marine Science*
University of North Carolina at Wilmington
5600 Marvin K. Moss Lane
Wilmington, North Carolina, USA 28409

[2] *National Park Service*
Geologic Resources Division
P.O. Box 25287
Denver, Colorado, USA 80225

Abstract: The introduction of invasive species such as *Phragmites australis* in the Chesapeake Bay has been viewed to be deleterious to habitat quality. Little is known, however, on the extent to which the replacement of *Spartina alterniflora* by *Phragmites* affects hydrodynamics and sediment trapping on the surface of impacted marshes. This study examined sediment deposition, sediment mobility, and flow conditions in adjacent *Phragmites australis* and *Spartina alternifora* marshes in Prospect Bay, Maryland, USA in order to determine if differences in plant morphology affect surficial flow properties and particle dispersion patterns. Measures of fine-scale flow dynamics, total suspended sediment (TSS) concentration, and particulate deposition were obtained at various distances from open water across the marsh surface over four sequential tidal cycles in Fall 1999. The hydrodynamic data indicate that both the gross and fine-scale properties of tidal flows were similar in both types of vegetation and that flow conditions were conducive to particle deposition. TSS concentrations did not differ between canopy types and decreased over time in both systems. There was no difference in TSS reduction over distance between *Spartina* and *Phragmites*. The sediment trap data indicate that maximum deposition occurs closer to open water in both *Spartina* and *Phragmites* and that the organic content of deposited matter increased with distance into the marsh interior. This study provides the first *in situ,* high resolution, over-marsh flow data for marshes dominated by *Phragmites*. The data provided herein suggest that differences in vegetative cover do not significantly affect flow regime, sediment transport, and sediment deposition patterns in the marsh systems examined.

Key Words: sedimentation, marshes, Chesapeake Bay, hydrodynamics

INTRODUCTION

The reed grass, *Phragmites australis* (Cav.) Trin. ex Steud., has invaded large areas of mid-Atlantic tidal marsh in the U.S. Replacement of native marsh vegetation has generated concern among resource managers that this vegetative shift could affect biodiversity. Traditionally, the introduction of invasive species has been viewed to be deleterious to habitat quality (Mooney and Drake 1986). The results of recent studies, however, suggest that changes in vegetation may have no impact or may increase the efficacy of some wetland processes. In Willapa Bay, Washington, for example, the invasion of *Spartina alterniflora* Loisel has resulted in enhanced rates of marsh accretion relative to adjacent areas vegetated by the native species (Sayce 1991). In *Phragmites* marshes along the lower Connecticut River, Fell et al. (1998) found that mummichog (*Fundulus heteroclitus* Linnaeus) foraging was comparable in the short term to foraging in nearby marshes that had not been invaded. These workers also observed that the *Phragmites* marshes supported populations of tidal marsh invertebrates that were similar to those found in their uninvaded counterparts. Hence, Fell et al. (1998) concluded that the *Phragmites* marshes of the lower Connecticut River estuary are performing some of the same basic ecological functions as the uninvaded marshes in the area. Nonetheless, in the Chesapeake Bay, where *Phragmites* marsh has replaced other marsh types, the extent of the impact due to this invasion remains unknown.

Quality habitat, capable of supporting the high diversity and abundance of fish commonly found in estuarine ecosystems, is closely tied to the physical structure of vascular plants, abundance of food, and suitable chemical environment (Deegan et al. 1997). In marshes historically dominated by *Spartina alter-*

niflora, the introduction of *Phragmites australis* may alter canopy structure. *Phragmites* marshes typically have moderate to low stem densities, with relatively large spaces between stems relative to marshes dominated by *Spartina* or *Juncus*. Therefore, replacement of *Spartina* by *Phragmites* has the potential for directly affecting the use of these marsh habitats as refuge from larger predators by resident and transient nekton. While environmental factors such as temperature and salinity are recognized to influence the distribution and abundance of fauna, hydrodynamic gradients caused by plant/flow interactions may also affect feeding and recruitment (Shi et al. 1995). Nonetheless, hydrodynamic factors have received little study in estuarine intertidal environments.

Tidal flows on vegetated marsh surfaces are inherently complex. Tidally driven water parcels flood the marsh surface in a fully turbulent state. As these tidal flows spread across the marsh surface, however, flow energies are dissipated by friction with the marsh surface and by wake formation around closely spaced plant stems (Nepf et al. 1997). These patterns are known to affect oxygen and nutrient exchanges at the sediment water interface (Escartin and Aubrey 1995), microclimate regulation between plant stems (Dade 1993), the nutritional environment for suspension-feeding animals (Irlandi and Peterson 1991), larval recruitment (Eckman 1983), and sediment deposition and retention processes (Leonard and Luther 1995). Hydrodynamic exchanges may also influence substrate selection by invertebrate larvae (Butman 1987), the distribution of meiofauna (Palmer 1986), the export of primary (detritus) and secondary production from the marsh surface to the adjoining estuarine waters (Peterson and Turner 1994), and the trophic relationship between protozoan suspension feeders and their prey (Shimeta et al. 1995). Although flow regime may impact many different wetland processes, little field data exist that describe flow behavior through emergent vegetated wetlands, and no published flow data exist for marsh systems vegetated by *Phragmites*.

The primary objective of this study was to examine the relationship between marsh flow hydrodynamics and canopy structure in *Phragmites australis* and *Spartina alterniflora* marshes in the Chesapeake Bay and to evaluate the effect of fine-scale hydrodynamics on particulate transport and deposition patterns. Specific objectives were

(1) to quantify flow structure, particle transport, and particle deposition in two adjacent Chesapeake Bay marshes characterized by different vegetation types: *Phragmites australis* and *Spartina alterniflora*; and
(2) to determine whether detectable differences in flow regime and particle dispersion result in measurable differences in the characteristics of both suspended and deposited particles between disturbed (i.e., invaded) and native marshes.

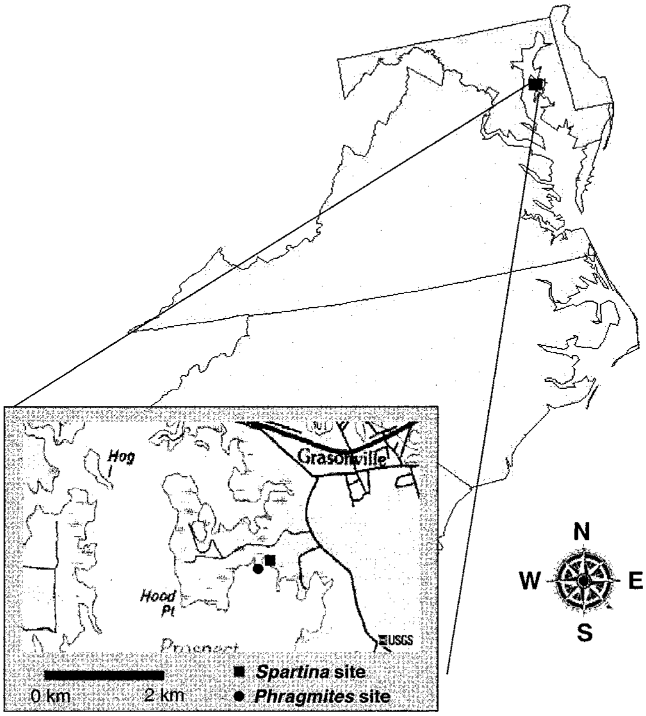

Figure 1. Location of study sites at the Horsehead Wetlands Center near Grasonville, Maryland, USA.

METHODS

This study was conducted in two tidal marsh sites separated by approximately 0.5 km at the Horsehead Wetland Center near Grasonville, Maryland, USA (Figure 1). The first was vegetated exclusively by *Phragmites australis*, while the second consisted of *Spartina alterniflora*. Tides in this area are microtidal (mean tidal range <50 cm), with a strong diurnal inequality. Flow and sediment data were collected at two positions within the canopy interior and at one edge position lacking vegetation, while the marsh surface was inundated at each of the marsh sites (Figure 2). Although the tides during this period were approximately 10 cm higher than the reported mean high spring tide, the 3-m *Spartina* site was not sufficiently inundated to collect reliable flow or sediment data. During this study, maximum water levels on the marsh surface were less than 10 cm and 12 cm for *Spartina* and *Phragmites*, respectively (Figure 3). Hydrodynamic and particle dispersion experiments were conducted over four consecutive tides beginning three days after new moon in September 1999.

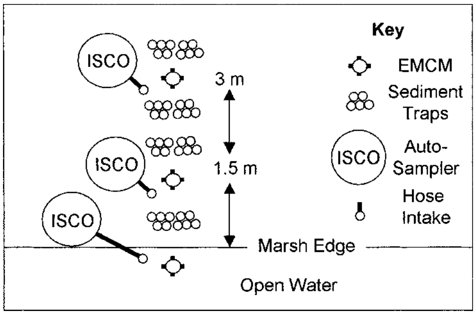

Figure 2. Configuration of equipment and sampling devices at each study site. Open water data were collected adjacent to and slightly below the elevation of the vegetated marsh surface. Water samples and flow data were collected within the vegetated canopy at 1.5 m and 3 m from the marsh edge. Flow velocities were measured using electromagnetic current meters (EMCM).

Flow properties were measured using Marsh McBirney electromagnetic current meters (Models 511 and 512). Three current meters were used per transect, with sensors located in the open water and at 1.5 m and 3 m into the marsh canopy (Figure 2). Sensors were suspended from PVC frames to a level approximately 10 cm above the bed in the open water and approximately 4 cm above the bed on the marsh surface. All flow sensors collected data at a frequency of 4 Hz in one-minute sampling bursts every 10 minutes over the duration of flooding. Approximately 48 hours of high frequency flow data have been collected at the study site. Data were stored in a Campbell CR10X data logger and downloaded to a laptop PC in the field.

Time series of the velocity components were used to calculate time-averaged (U) and turbulent velocities (u′) (Leonard and Luther 1995). Turbulence intensities ($u' = [(u_o - U)^2]^{1/2}$) or the root-mean-square value of the fluctuating components of velocity (u_o) were determined using MATLAB. Flow turbulence was also quantified using the Reynolds Number ($Re = U\rho L/\mu$), where U = mean velocity, ρ = fluid density, L = characteristic length scale, and μ = molecular viscosity of the fluid. Reynolds numbers were calculated for overmarsh flows using both water depth (Re_w) and basal stem diameter (Re_d) as length scales (Leonard and Luther 1995). Radial plots showing the primary direction of tidal inundation and energy spectra were also generated in MATLAB. Water levels were recorded at two positions in the marsh using two RDS WL-40 water-level sensors. Water level was recorded every 20 minutes during inundation. Flow direction and potential wind effects were observed on-site by injecting fluoroscein dye into the surface flow (Leonard 1997). In addition, wind speeds at the water surface during each experiment were measured with a hand-held, digital anemometer and recorded.

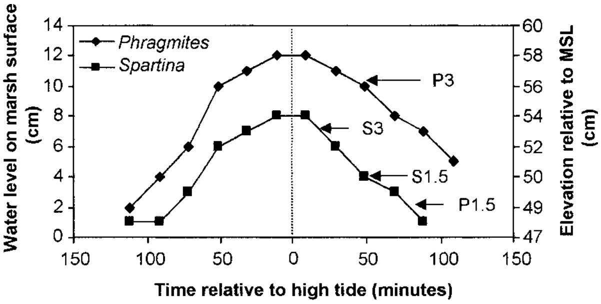

Figure 3. Representative water-level curves measured on the surface of each marsh site during the study. Water-level data were collected in the marsh canopy where the elevation of the marsh surface was 47 cm +MSL. Water levels were measured approximately 1.4 m into the marsh interior at the *Phragmites* (P) site and at 1 m at the *Spartina* (S) site. Arrows on the graph indicate levels when specific sampling sites (at 1.5 m or 3 m from the marsh edge) were inundated. The data shown were collected on 9/11/99 and 9/12/99 for *Spartina* and *Phragmites*, respectively.

Particulate transport was quantified using three ISCO 3500 automated water samplers. These samplers were positioned adjacent to sensor arrays with their intake hoses mounted 1 cm above the marsh surface. Two replicate 500 ml samples were collected once every 20 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, precombusted, 0.45-μm glass fiber filters. Samples were returned to the laboratory, dried at 60°C for 12 hours, re-weighed, and results calculated as 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.

Petri-dish sediment traps (Reed 1992, French et al. 1995) were used to quantify short-term deposition rates on the marsh surface. Traps consisted of precombusted, preweighed glass fiber filters (9-cm-diameter Whatman GF/F) affixed to petri-dish lids and attached to the marsh surface using wire staples. Three sets of ten traps each were deployed in transects extending from the water's edge into the marsh interior. Sediment traps were placed at approximately 1 m, 1.75 m, 2.25 m, and 3 m into the marsh. Traps were deployed at low tide and retrieved following the inundation event. Traps were returned to the laboratory, rinsed with distilled water to remove salts, oven-dried at 60°C, and weighed. Sediment deposition was measured as mass deposited per trap area and expressed in units of mg cm^{-2} day^{-1}. Traps were then combusted

Table 1. Plant canopy characteristics near sediment trap sites. Mean stem densities and diameters are given. Standard deviations are given in parentheses.

Plant Type & Distance from Open Water	Stem Density (stems m^{-2})	Stem Diameter (cm)
Phragmites—1 m	325 (26)	0.82 (0.2)
Phragmites—3 m	400 (18)	0.69 (0.1)
Spartina—1 m	682 (34)	0.48 (0.1)
Spartina—3 m	731 (28)	0.54 (0.1)

at 450°C to determine organic content. Deposition data were log-transformed to reduce the heterogeneity in error variances, and then ANOVA was used to compare sediment deposition among different environments. Fisher's protected lest significant difference (PLSD) test was used to examine differences among environment pairs for deposition rates that were significantly different in the ANOVA ($p < 0.05$).

Following all sampling, a vegetation survey was conducted and the plant cover in the vicinity of the sampling position quantified. Stem densities and basal stem diameters were measured in four 12.5 cm × 12.5 cm quadrats surrounding each velocity sensor. Vegetation characteristics are given in Table 1.

RESULTS

Flow Characteristics

Flow speeds at all locations along the sampling transect were relatively low. Mean flow speeds measured outside and adjacent to the canopy at each site did not exceed 10 cm s^{-1}, and mean flow speeds measured within marsh canopies were less than 5 cm s^{-1} at both the *Spartina* and the *Phragmites* sites (Figure 4). Flow speeds measured outside of the vegetation at the creek edge were generally 2 to 2 1/2 times greater than those measured at marsh interior sites. One-second, time-averaged speed data collected during a 15-second sampling burst are also shown in Figure 4. The high frequency speed data collected in both types of canopy do not seem to differ appreciably. The greatest variability in instantaneous flow speeds occurred in the open water adjacent to the *Spartina* site. The periodicity of the small swells observed during the collection period is clearly visible in the high frequency time series data.

Tidal flows also showed little variability across the transect over the course of each flooding event (Figure 4). Outside of the canopy, the highest flow speeds were measured at the onset and at the conclusion of an inundation event. Speeds during falling tides were slightly greater than those recorded during rising tides.

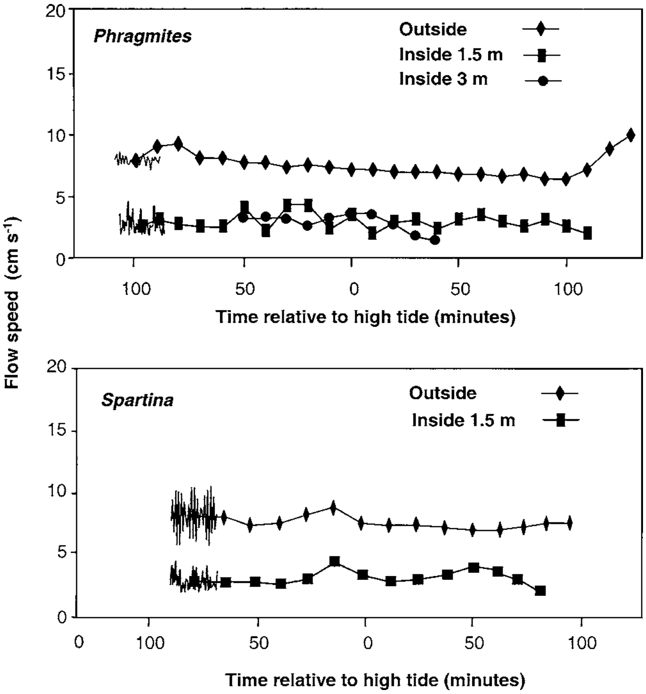

Figure 4. Mean flow speeds adjacent to and inside of *Spartina* and *Phragmites* canopy. Mean speeds were calculated from each 60-second burst. Inserts show raw 4 Hz data collected over approximately 15 seconds.

At the 1.5-m site on the vegetated marsh surface, maximum flows occurred approximately 10 to 20 minutes before high tide for *Spartina* and *Phragmites*, respectively. At the 3-m *Phragmites* site, maximum mean flow speeds of almost 5 cm s^{-1} occurred near high water. No flow data were recovered at the 3-m *Spartina* site.

Flow direction varied in response to interaction with the marsh vegetation (Figure 5). At the marsh edge sites where vegetation was absent, flows were primarily unidirectional and moved from the creek onto the marsh surface during the rising tide. Once inside the canopy, flow speeds were attenuated, and the flow direction showed a greater degree of variation that included a strong bi-directional component. This pattern was observed in both *Spartina* and *Phragmites*. On falling tide, flows within both canopy types were highly variable, but they still showed a strong bi-directional component. Outside of the canopy, ebbing flows showed greater directional variability than their flood counterparts. In addition, the bearing of rising tides differed from the bearing of ebbing tides.

At the *Spartina* site, turbulence intensities measured on the marsh surface were approximately 20 to 30% lower than turbulence intensities measured in adjacent open water. In contrast, turbulence intensities within the *Phragmites* canopy were almost one order of magnitude greater than those measured in the adjacent tidal

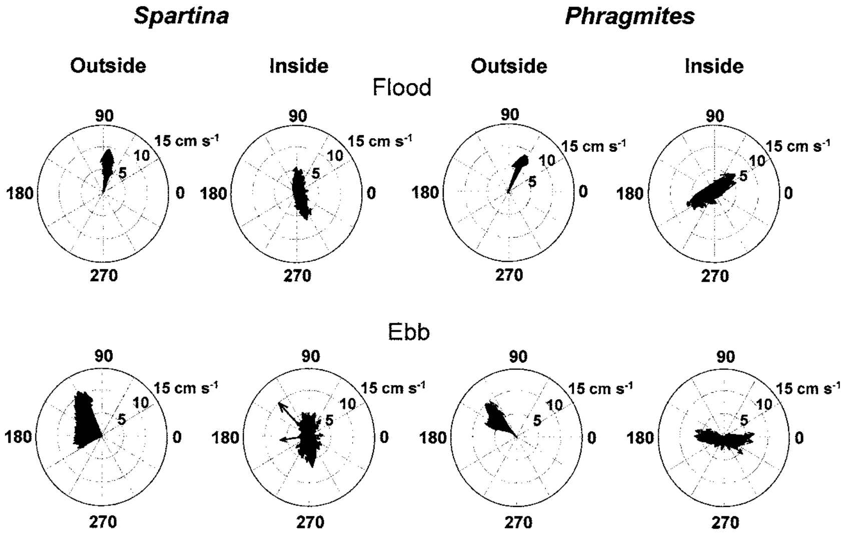

Figure 5. Radial plots showing flow direction inside and outside of marsh vegetation for (A) flood and (B) ebb phases of the tidal cycle. Each plot was constructed from raw data collected over a one-minute sampling burst.

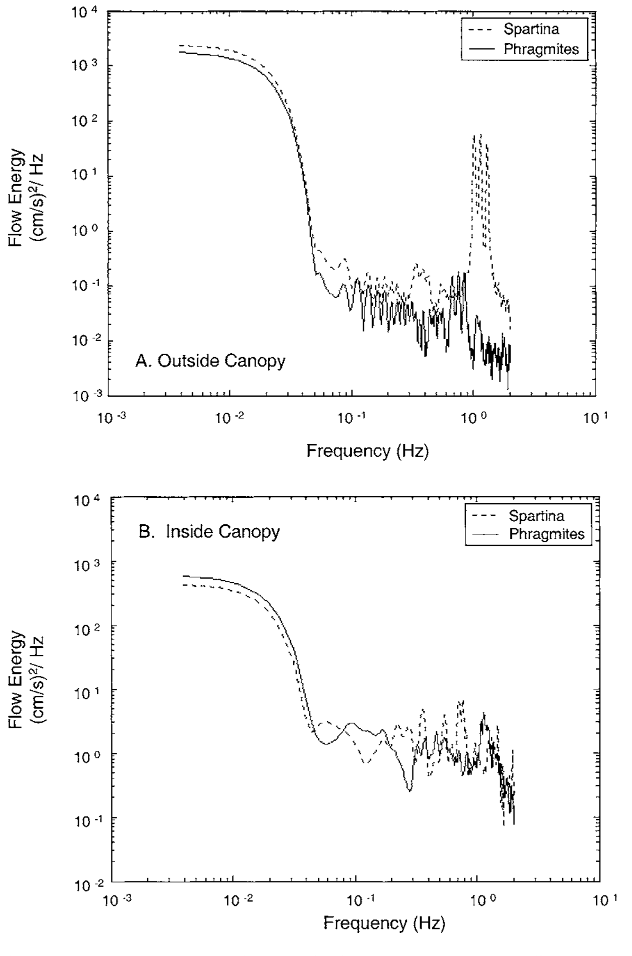

Figure 6. Representative turbulence spectra for flows (A) outside of *Spartina* and *Phragmites* and (B) 1.5 m inside of each canopy. Each spectra was generated from the raw 4 Hz data collected over a one-minute sampling burst.

creek. The reduced turbulence intensities observed in the open water at the *Phragmites* site are likely associated with sensor placement. The current meter placed in the open water was located approximately 15 cm below the surface of the marsh and was, therefore, slightly further from the air/water interface than the sensors located on the marsh surface proper.

In the *Phragmites* canopy, Re_d ranged from 110 to 470 and Re_w ranged from 510 to 1340. In the *Spartina* canopy, Reynolds numbers ranged from 75 to 300 and 385 to 3000 for Re_d and Re_w, respectively. The reported Reynolds numbers indicate that transitional flow conditions (see Kadlec 1990 for critical values) are dominant in both types of canopy over most of the inundation event. Laminar conditions (when $Re_w < 600$) may occur on the surface of either site very early or late in the inundation cycle when low water levels (< 3 cm) and slow velocities (<1.5 cm s^{-1}) prevail.

Power density spectra were generated from three one-minute sampling bursts simultaneously collected both inside of and outside of the vegetation at each site (Figure 6). In open water areas, the total kinetic energy measured adjacent to the *Spartina* site was slightly greater than that measured adjacent to the *Phragmites*, with the greatest energy difference associated with frequencies of 1 to 2 Hz. The difference in spectral shape can be attributed to wave activity at the *Spartina* site; small 1-to-2.5 s waves were observed at this site during sample collection. Inside of the canopy, flow energy was transferred from lower to higher frequencies in both canopy types. For frequencies higher than about 0.3 Hz, flow energy within the canopy actually exceeded energy measured outside of the canopy. Flow energies appear to be comparably atten-

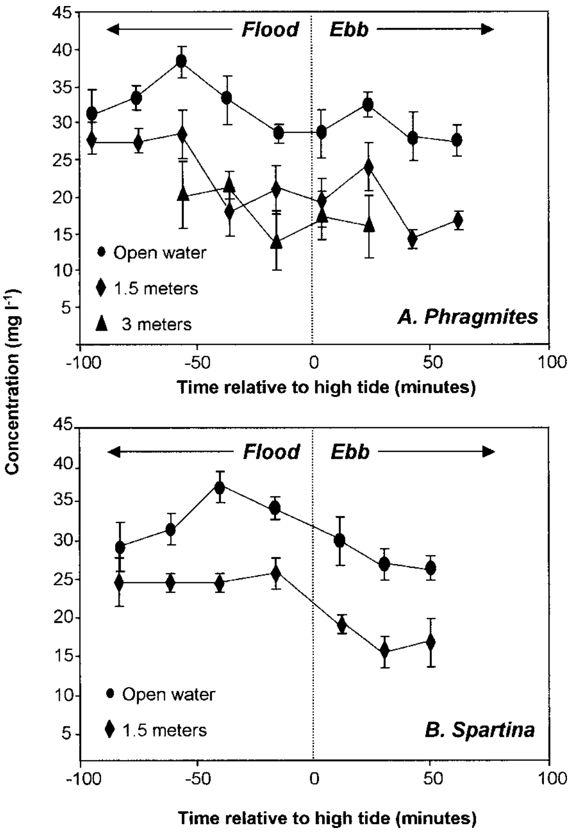

Figure 7. Change in sediment concentration over time and with distance from open water for (A) *Phragmites* and (B) *Spartina*.

uated by both types of vegetation at a relatively short distance (1.5 m) into the marsh.

Sediment Transport

TSS concentrations varied with time relative to high tide and varied between open water and inside the marsh canopy (Figure 7). Outside of the canopy, maximum TSS concentrations occurred 60 and 40 minutes prior to high water for *Phragmites* and *Spartina*, respectively. Over-marsh flow concentrations were usually less than 30 mg l^{-1} and decreased over the duration of inundation. On the marsh surface, TSS concentrations at 1.5 m were significantly lower ($p < 0.0001$) than those in adjacent waters regardless of vegetation type. The lowest TSS concentrations observed (< 15 mg l^{-1}) occurred 3 m into the marsh interior at the *Phragmites* site; however, TSS concentrations measured at 3 m and 1.5 m did not differ significantly. No TSS data were collected at the 3 m *Spartina* site, as this region was not inundated during any of the collection events.

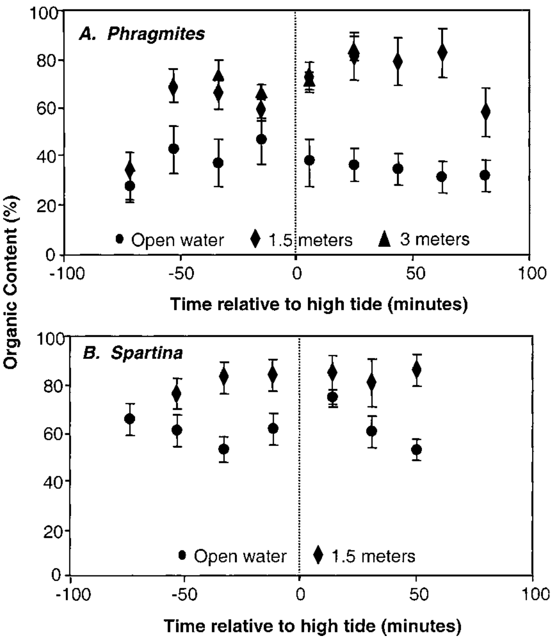

Figure 8. Change in percent organic content of TSS over time and with distance from open water for (A) *Phragmites* and (B) *Spartina*.

The reduction of TSS with distance from the tidal creek was quantified by determining the difference in concentration for each 1.5 m and open water pair. ANOVA was then used to compare concentration change between the two vegetation types over a comparable sampling interval. The results indicated no significant difference ($p=0.86$) in concentration reduction between *Phragmites* and *Spartina*.

Outside of the canopy, the organic content of TSS changed very little over time (Figure 8). Percent organic contents measured during rising tides did not differ significantly from those measured on falling tides adjacent to either the *Phragmites* or *Spartina* canopies (Table 2). Likewise, the organic content of TSS in the *Spartina* canopy also varied little over time (Figure 8), and flood values did not differ significantly

Table 2. Results of ANOVA comparing the percent of organic content in TSS during flood to that measured during ebb.

Station	Condition	P-value	F	df
Phragmites—outside	Flood vs Ebb	0.1831	2.02	1
Phragmites—1.5 m	Flood vs Ebb	<0.0001	92.16	1
Spartina—outside	Flood vs Ebb	0.4635	0.5926	1
Spartina—1.5 m	Flood vs Ebb	0.8497	0.0383	1

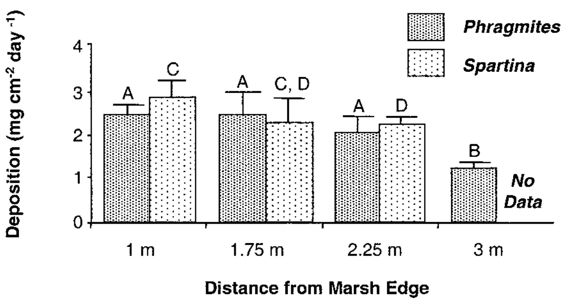

Figure 9. Mean sediment deposition with distance across the marsh surface in *Spartina* and *Phragmites*. Each value was calculated from 10 replicate samples with the exception of the 1 m *Phragmites australis* value. At the 1 m *Phragmites* site, only five traps were retrieved intact. Error bars represent ± one standard deviation. When deposition was measured in both *Phragmites* and *Spartina*, deposition rates were not significantly different at equivalent distances from the marsh edge. Letters denote significant differences in deposition rate with distance from the marsh edge within a specific type of vegetation. Bars with the same letter were not significantly different at $p < 0.05$.

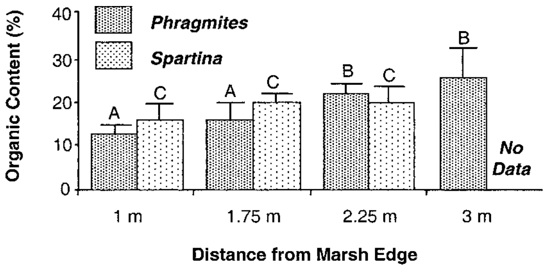

Figure 10. Percentage of organic matter deposited on sediment traps with distance across the marsh surface in *Spartina* and *Phragmites*. Error bars represent ± one standard deviation of the mean. The organic content of deposited material measured in *Phragmites* did not differ significantly from that measured in *Spartina* at an equivalent distance from the marsh edge. The organic content of deposited material was not significantly different at $p < 0.05$ for sites (bars) marked with the same letter.

from ebb values. At the *Phragmites* site, however, the relative percentage of organic matter contained in TSS increased over the inundation event. At this site, the organic content of TSS measured during falling tides was significantly greater than organic content measured during rising tide (Table 2). The percent organic content of TSS in open water was consistently and significantly lower than that of the adjacent canopy flow; thus suggesting that organic content increases over distance. There was, however, no significant difference in the organic content of TSS collected at 1.5 m and 3 m in *Phragmites* ($p = 0.53$).

Sediment Deposition

Sediment deposition, as measured by sediment traps, was generally less than 3 mg cm^{-2} day^{-1} and did not vary appreciably between the two study sites (Figure 9). Although sediment deposition appeared to decrease slightly with distance into the marsh interior, the difference was not statistically significant along the first 2.25 m of either transect. At the *Phragmites* site, deposition measured at 1 m was significantly greater than deposition measured at 3 m ($p < 0.05$, $F = 4.49$; $df = 1$). Deposition measured at 3 m was not, however, significantly different from rates measured at 1.75 m and 2.25 m. In the *Spartina* canopy, deposition at 2.25 m was significantly less ($p < 0.05$, $F = 14.93$; $df = 1$) than deposition measured at 1 m. No data were collected at 3 m in the *Spartina.*

Figure 10 shows the percentage of organic matter deposited on retrieved traps. Organic content did not differ significantly between marsh types for data collected at the same distance from the creek edge. The mean organic content retained on the traps ranged from 8 to 35%, where lower values were typically measured closer to the marsh edge. The organic content of material deposited on the sediment traps did not vary significantly with distance across the marsh at the *Spartina* site; however, no data were collected at the 3-m position. In the *Phragmites* canopy, the mean percent organic content of material on the traps increased slightly, but significantly ($p < 0.05$, $F = 7.89$, $df = 3$), with distance into the marsh interior.

DISCUSSION

The Effects of Vegetation on Surficial Flows

The characteristics of canopy flows documented during this study are consistent with those reported for other vegetated marsh systems (e.g., Leonard 1997, Yang 1998, Christiansen et al. 2000). As expected, the overmarsh flow speeds measured in both *Spartina* and *Phragmites* were less than the flow speeds measured in adjacent open water due to plant baffling and frictional effects (Yang 1998). Mean flow speeds measured inside of both types of vegetation were approximately 2 to 2 1/2 times lower than speeds measured outside of the canopy. Surficial flow magnitudes in the study systems were, however, lower than those reported in the literature for other micro and mesotidal, semi-diurnal systems (Leonard and Luther 1995, Yang 1998). The low flow speeds and energies observed in this study are likely due to the very low tidal range and low energy in the Chesapeake Bay system. The marsh surface during this study was flooded by less than 12 cm of water (Figure 3), compared to depths of 45 cm reported by Leonard and Luther (1995) for marshes on the Florida Gulf Coast. The magnitudes of surficial flows observed in both the *Spartina* and *Phragmites* canopies during this study are more similar to those reported for the microtidal, diurnal, *S. alterniflora*-dominated systems of Louisiana (Leonard and Luther 1995). In the Louisiana system examined by Leonard and Luther, less than 20 cm of water inundated the marsh surface during a typical spring tide, and maximum flow speeds under non-storm conditions were also less than 5 cm s^{-1}.

As demonstrated for other systems (Leonard 1997, Christiansen et al. 2000) tidal forcing exerted a dominant control over the mean flow direction on the marsh surface. Plant/flow interactions, however, resulted in greater directional variability than was observed for flows that had not interacted with plants (Figure 5). The bi-directional character of the overmarsh flow data was most likely caused by the production of wake eddys in the lee of plant stems. This observation is corroborated by the spectral data (Figure 6), which show a transfer of energy from lower frequencies to higher frequencies as would be expected during the dissipation of energy via wake formation. Further, plant/flow interactions in both canopy types exerted a strong influence on the instantaneous directional component of open water flows during ebb (Figure 5). Flows receding from the marsh surface showed greater variability in direction than their flood counterparts. These data suggest that the turbulent structures superimposed on the flow while in the canopy continue to exist even after it has exited the canopy.

Although flow data from both types of canopy showed similar directional patterns, the variability of ebbing flows is more pronounced adjacent to the *Spartina* site. One possible reason for this may be differences in stem densities between the two sites. The stem densities recorded for *Spartina* were almost two times those measured in the *Phragmites* canopy (Table 1). If, as suggested above, the dissipation of flow energy occurs when eddys are formed in the lee of plant stems, the presence of more stems should result in more eddys and greater directional variation in the instantaneous velocity measurements. Previous work has shown that increases in stem density may significantly affect both flow speed and turbulence in both *Juncus roemerianus* Scheele (Leonard et al. 1995) and *Spartina* (Leonard and Luther 1995) marshes. The implications of these data on the transport of particulate and dissolved matter are two-fold. First, fluxes across the marsh surface are not simply bi-directional; tidal water parcels flooding the marsh are not necessarily the same parcels ebbing from the marsh surface at any given location. Second, dispersion of materials entrained or dissolved in the flow are favored in areas with greater plant densities. Most important to this study, however, is the fact that differences in canopy composition did not result in appreciable differences in flow structure.

Variations in Sediment Mobility and Deposition

The magnitude and patterns of total suspended solid (TSS) concentrations observed during this study are consistent with those measured in systems having different tidal regimes and/or vegetation types (e.g., Leonard and Luther 1995, Leonard 1997, Yang 1998, Reed et al. 1999, Christiansen et al. 2000). TSS concentrations within both types of canopies were significantly lower than concentrations measured in their adjacent, non-vegetated, counterparts (Figure 7). During this study, TSS levels decreased by as much as 15 mg l^{-1} over a distance of 1.5 m from the creek edge in both *Spartina* and *Phragmites*. While some of the lowest TSS concentrations were observed at the innermost *Phragmites* site, these concentrations did not differ significantly from those measured closer to open water. No TSS data were collected at 3 m in the *Spartina* due to the low water levels and short period of inundation. It is probable, however, that TSS concentration decreased minimally beyond 1.5 m in the *Spartina*, given the proximity of the two sites and the similarities in their hydrodynamic regimes. Thus, the TSS data suggest that the removal of particulates occurs over an extremely short distance from open water regardless of vegetation type in these low energy systems. This finding concurs with Stevenson et al. (1985), who observed little sediment penetration beyond 3 m in a *Scirpus* marsh also in the Chesapeake Bay. In other marshes where higher energy conditions prevail, similar TSS reductions occur across the marsh surface, but they occur over distance scales of tens of meters (e.g., Reed et al. 1999).

The TSS data further suggest that most suspended sediments are removed from overmarsh flows during the rising tide. Sediment concentrations measured adjacent to the vegetation and at 1.5 m into 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. Previous studies conducted in *Spartina*, *Juncus roemerianus*, and *Atriplex portulacoides* (L.) Aellen marshes (Leonard et al. 1995, Leonard 1997, Reed et al., 1999, Christiansen et al. 2000) obtained results similar to those presented here.

Differences in canopy composition also seemed to have little impact on the organic content of particles entrained in the flow over the course of an inundation event. During the initial phases of marsh flooding, the percent organic content of TSS in overmarsh flows was similar to that observed in open water (Figure 8).

As time progressed, however, the organic content of TSS of overmarsh flows in both canopy types exceeded simultaneous measures of organic content in open water. This pattern is most apparent in the *Phragmites* canopy, where the percent organic content of TSS in flood flows was significantly less than ebb. In the *Spartina* canopy, the organic content of TSS did not differ significantly between flood and ebb even though the highest TSS organic values observed occurred as the water receded from the marsh surface.

These data indicate that overmarsh flows are relatively enriched in organic matter during marsh inundation in both types of canopy. Organic enrichment may occur either through the addition of organic matter or through the preferential loss of inorganic matter as flood waters advect across the marsh surface. In the systems examined here, however, the preferential deposition of the denser, inorganic fraction of TSS during the initial phase of inundation is the most plausible explanation for the observed increases in TSS organic content. First, laminar to transitional flow conditions existed in both canopies throughout marsh inundation–conditions that would favor particle deposition. Second, the low flow velocities and turbulence intensities measured during this study are insufficient to maintain individual inorganic particles greater than about 46 μm in suspension. Analysis of surface sediments collected at these sites, indicates that the mean grain size of disaggregated inorganic sediments was 56 μm and 60 μm at the *Phragmites* and *Spartina* sites, respectively. Although Kastler and Wiberg (1996) showed that tidal currents of comparable magnitudes (3 cm s^{-1}) may produce shear velocities sufficient to resuspend aggregate particles and all but the coarsest of the individual particles comprising deposited sediment in the study area, the TSS data provided no indication that significant resuspension was occurring. TSS concentrations decreased over both time and distance in both canopy types. Thus, it appears that not only is particulate deposition favored in both marsh types, but that deposition of the inorganic fraction is favored within 1.5 m of the creek.

Sediment deposition rates in the *Phragmites* and *Spartina* canopies did not differ over the scales measured during this study. Maximum deposition occurred closer to open water and gradually, but significantly, decreased with distance into the marsh interior at both sites (Figure 9). Further, the sediment trap data indicate that the interiors of both the *Spartina* and *Phragmites* marshes tend to receive slightly more organic than inorganic material (Figure 10). As was shown for the TSS data, deposition of inorganic particles is favored in close proximity (less than 1.5 m) to open water, also the region where maximum total deposition is occurring. This finding concurs with Kastler and Wiberg (1996), who showed that the organic content of deposited materials increased toward the interiors of two marshes on the Delmarva peninsula. One of the obvious shortcomings of this study, however, was the loss of sediment traps near the creek edge. At both sites, but particularly the *Phragmites* site, the data are incomplete due to the loss and destruction of sediment traps by waves. In addition, the data quality has been compromised by our inability to collect data at the innermost *Spartina* site.

CONCLUSIONS

The paucity of detailed field measurements of canopy flow has been due largely to the limitations associated with existing technologies (Pethick et al. 1990). This has been especially true for microtidal systems such as the Chesapeake Bay. The data presented in this report constitute the first *in situ* tidal flow measurements obtained within *Phragmites australis* known to these authors. While differences in individual plant structure or canopy composition have been used to explain fine scale variations in flow (e.g., Leonard and Luther 1995) and spatial patterns in wetland sedimentation (Pasternack and Brush 2001), this study found no such differences in flow characteristics, particle dispersion, and sediment deposition.

We attribute our findings to the very low water levels encountered during this study, which restricted plant/flow interactions to the base of the plant. Because water levels were lower than the lowermost leaves, plants expressed themselves to the flow as simple cylinders. Consequently, similarities in stem density, stem diameter, sediment supply, and flow properties in the canopies examined resulted in comparable sedimentation on the surface of both marsh systems. This is not to suggest, however, that morphological differences between *Spartina* and *Phragmites* are inconsequential. Differences in canopy structure may be extremely important during high energy episodic events (such as during storms) when higher water levels and a higher sediment supply may occur. Under storm conditions, morphological differences between vegetation types may not only affect flow properties as suggested by Leonard and Luther (1995), but they may also affect direct sediment trapping on the plant surface as suggested by Stumpf (1983), Leonard et al. (1995), and Yang (1999).

While the actual mechanisms controlling sediment deposition across the surface of a marsh may vary from system to system (Cadee and Dijkema 1998, Reed et al., 1999, Yang 1999 Christiansen et al. 2000), it appears that the differences between *Phragmites australis* and *Spartina alterniflora* are of little consequence in the microtidal environments examined in this paper. Our results indicate that flow patterns, TSS concentrations, and sediment deposition patterns in selected *Phragmites* marshes of the Chesapeake Bay do not differ from those in nearby *Spartina* marshes under non-storm conditions.

ACKNOWLEDGMENTS

This research was supported by grant #G99-14 from the Marsh Ecology Research Program (to LAL) administered by the Academy of Natural Sciences and funded jointly by Sea Grant and New Jersey Public Service and Gas Company and also by the Center for Marine Science at UNCW. This work could not have been completed without the assistance of S. Avau, R. Civelli, T. Alphin, M. Posey, and J. Nearhoof. We thank the Horsehead Wetlands Center for providing accommodation, access to the study sites, and valuable field assistance. The authors also gratefully acknowledge useful comments provided by two anonymous reviewers.

LITERATURE CITED

Butman, C. A. 1987. Larval settlement of soft-sediment invertebrates: the spatial scales of pattern explained by active habitat selection and the emerging role of hydrodynamic processes. Oceanography and Marine Biology Annual Review 25:113–165.

Cadee, G. H. and K. Dijkema. 1998. The influence of salt marsh vegetation on sedimentation. p. 403–414. *In* D. Eisma (ed.) Intertidal Deposits: River Mouths, Tidal Flats, and Coastal Lagoons. CRC Press, Boca Raton, FL, USA.

Christiansen, T., P. L. Wiberg, and T. G. Milligan. 2000. Flow and sediment transport on a tidal salt marsh surface. Estuarine, Coastal and Shelf Science 50:315–331.

Dade W. B. 1993. Near-bed turbulence and hydrodynamic control of diffusional mass transfer at the sea floor. Limnology and Oceanography 38:52–69.

Deegan, L. A., J. T. Finn, S. G. Ayvazian, C. A. Ryder-Kiefer, and J. Buonaccorsi. 1997. Development and validation of an estuarine biotic integrity index. Estuaries 20:601–617.

Ekman, J. E. 1983. Hydrodynamic processes affecting benthic recruitment. Limnology and Oceanography 28:241–257.

Escartin, J. and D. G. Aubrey. 1995. Flow structure and dispersion within algal mats. Estuarine Coastal and Shelf Science 40:451–472.

Fell, P. E., S. P. Weissbach, D. A. Jones, M. A. Fallon, J. A. Zeppieri, E. K. Faison, K. A. Lennon, K. J. Newberry, and L. K. Reddington. 1998. Does invasion of oligohaline tidal marshes by reed grass Phragmites australis (Cav) Trix ex Steud, affect the availability of prey resources of the mummichog, Fundulus heteroclitus L? Journal of Experimental Marine Biology and. Ecology 222:59–77.

French, J. R., T. Spencer, A. L. Murray, and N. S. Arnold. 1995. Geostatistical analysis of sediment deposition in two small tidal wetlands, Norfolk, UK. Journal of Coastal Research 11:308–321.

Irlandi, E. A. and C. H. Peterson. 1991. Modification of animal habitat by large plants. Oecologia 87:307–318.

Kadlec, R. H. 1990. Overland flow in wetlands: Vegetation resistance. Journal of Hydraulic Engineering 116:691–706.

Kastler, J. A. and P. L. Wiberg. 1996. Sedimentation and boundary changes of Virginia salt marshes. Estuarine, Coastal and Shelf Science 42:683–700.

Leonard, L. A. 1997. Controls of sediment transport and deposition in an incised mainland marsh basin, southeastern North Carolina. Wetlands 17:263–275.

Leonard, L. A., A. C. Hine, and M. E. Luther. 1995. Surficial sediment transport and deposition processes in a *Juncus roemerianus* marsh, west-central Florida. Journal of Coastal Research 11:322–336.

Leonard, L. A. and M. E. Luther. 1995. Flow hydrodynamics in tidal marsh canopies. Limnology and Oceanography 40:1474–1484.

Mooney, H. A. and J. A. Drake. 1986. Ecology of Biological Invasions of North America and Hawaii. Springer-Verlag, New York, NY, USA.

Nepf, H. M., J. A. Sullivan, and R. A. Zavistoski. 1997. A model for diffusion within emergent vegetation. Limnology and Oceanography 42:1735–1745.

Palmer, M. A. 1986. Hydrodynamics and structure: interactive effects on meiofauna dispersal. Journal of Experimental Marine Biology and Ecology 104:53–68.

Pasternack, G. B. and G. S. Brush. 2001. Seasonal variations in sedimentation and organic content in five plant associations on a Chesapeake Bay tidal freshwater delta. Estuarine, Coastal and Shelf Science 53:93–106.

Peterson, G. W. and R. E. Turner. 1994. The value of salt marsh edge vs. interior as a habitat for fish and decapod crustaceans in a Louisiana tidal marsh. Estuaries 17:235–262.

Pethick, J. S., D. Legget, and L. Husain. 1990. Boundary layers under salt marsh vegetation developed in tidal currents. p. 113–123. *In* J. B. Thornes (ed.) Vegetation and Erosion. Wiley and Sons, Inc., New York, NY, USA.

Reed, D. J. 1992. Effect of weirs on sediment deposition in Louisiana coastal marshes. Environmental Management 16:55–65.

Reed, D. J., T. Spencer, A. L. Murray, J. R. French, and L. Leonard. 1999. Marsh surface sediment deposition and the role of tidal creeks: Implications for created and managed coastal marshes. Journal of Coastal Conservation 5:81–90.

Sayce, J. R. 1991. *Spartina* in Willapa Bay: A case history. p. 27–29. *In* T. F. Mumford, P. Peyton, J. R. Sayce, and S. Harbell (eds.) Spartina Workshop Record, Seattle Washington, November 14–15, 1990. Washington Sea Grant Program, University of Washington, Seattle, WA, USA.

Shi Z., J. S. Pethick, and K. Pye. 1995. Flow structure in and above the various heights of a saltmarsh canopy: a laboratory flume study. Journal of Coastal Research 11:1204–1209.

Shimeta, J., P. A. Jumars, and E. J. Lessard. 1995. Influences of turbulence on suspension feeding by planktonic protozoa; experiments in laminar shear fields. Limnology and Oceanography 40: 845–589.

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

Stumpf, R. P. 1983. The processes of sedimentation on the surface of a saltmarsh. Estuarine, Coastal and Shelf Science 17:495–508.

Yang, S. L. 1998. The role of *Scirpus* marsh in attenuation of hydrodynamics and retention of fine sediment in the Yangtze estuary. Estuarine, Coastal and Shelf Science 47:227–233.

Yang, S. L. 1999. Tidal wetland sedimentation in the Yangtze delta. Journal of Coastal Research 15:1091–1099.

Manuscript received 1 October 2001; revisions received 28 January 2002 and 27 February 2002; accepted 1 March 2002.