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Flow Resistance and Associated Sedimentary Processes in a *Spartina maritima* Salt-Marsh

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ABSTRACT

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The vertical accretion of salt marshes is mainly due to flow reduction and wave damping by vegetation. However, the details of the hydrodynamics are only partially understood, and have been studied mainly in the laboratory. This study presents detailed field investigations of the water flow in a *Spartina maritima* salt-marsh in the Ria Formosa, a shallow, meso-tidal lagoon in Southern Portugal. Detailed velocity profiles were obtained within and above the 30 cm high canopy using a high-precision velocimeter. Results show that the influence of the bottom becomes negligible a few centimetres above the bed, and that the flow depends on the vegetation density at each level of the canopy. When the canopy is partially emergent or is only slightly submerged, the upward increase of horizontal velocity is roughly linear. A more drastic flow reduction exists when the canopy is well submerged, with a slow, nearly constant velocity in the denser part of the canopy and a faster, logarithmic shaped velocity profile above. This dampening effect of the vegetation is expected to promote sedimentation. However, the short-term sedimentation rate obtained with sediment traps during fair-weather conditions is usually lower in the *Spartina* marsh than in the surrounding areas. Therefore, the effect of the *Spartina* canopy for sediment accumulation seems to be more that of erosion protection during storms than of sedimentation enhancement during normal conditions. Using these results, a simple conceptual model is proposed for the sedimentary processes taking place in the intertidal areas of the studied lagoon.

ADDITIONAL INDEX WORDS: *Velocity profile, hydraulic roughness, sedimentation rate, Portugal, Algarve.*

INTRODUCTION

Coastal salt-marshes contain rich ecosystems and are habitats for many birds and a unique halophyte flora (DOODY, 1992). They also play a significant role in coastal defence, enhancing coastal sedimentation, as the intertidal vegetation decreases water movements and binds sediments (USACE, 1989; BRAMPTON, 1992). A better knowledge of sedimentary processes in salt marshes is necessary for coastal management, especially in view of relative sea-level rise or anthropogenic influence on coastal sediment distribution.

The main difference between salt marshes and bare sediment is the dampening of water flow by the vegetation. Classical fluid dynamic theory describes well the situation above bare unvegetated sediment: the presence of a smooth boundary layer can be assumed and the water flow follows the Law of the Wall (SOULSBY, 1997), which is briefly summarised here. Just above the bed, the boundary layer is composed of a viscous sublayer, where the flow is laminar, and then a buffer layer. Together, these two layers are only a few millimetres thick. Above them, there is an outer layer, where the flow is fully turbulent and the velocity profile has a logarithmic shape (MIDDLETON and SOUTHARD, 1984). This logarithmic profile is described by the Kármán-Prandtl equation: $U_z = U_*\ln(z/z_0)/\kappa$, with z: height above the bed, U_z: velocity at height z, U_*: shear velocity, z_0: roughness length, κ: Kármán constant (0.4). The exact velocity profile depends on the bed roughness (z_0) and the free stream velocity.

The presence of a plant canopy affects strongly the water flow. Over vegetated areas, the velocity profile is severely modified, with a reduction of the mean velocity inside the canopy (FONSECA, 1996). However, above the vegetation a logarithmic shaped velocity profile can be expected (SHI *et al.,* 1995). The following parameters can modify the canopy influence: vegetation type, vegetation density, canopy height, and distance to the vegetation edge in an upstream direction.

Most previous studies on salt marshes have looked at the role of vegetation by investigating the enhancement of sedimentation rate and bed accretion (*e.g.,* FRENCH *et al.,* 1995; ROMAN *et al.,* 1997; BROWN, 1998; REED *et al.,* 1999; CAHOON *et al.,* 2000), erosion reduction (*e.g.,* ALLEN and DUFFY, 1998; BOORMAN *et al.,* 1998), wave damping (KNUTSON *et al.,* 1982; MÖLLER *et al.,* 1999), or long-term evolution of salt marshes (*e.g.,* ALLEN, 1997; DAY *et al.,* 1999; SCHWIMMER and PIZZUTO, 2000).

However, relatively few researchers have explored the cause of this sedimentary process, *i.e.* the hydrodynamic impact of the canopy on the water flow. Some interesting ex-

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periments were conducted with *Spartina anglica* in a laboratory flume (PETHICK *et al.*, 1990; SHI *et al.*, 1995; SHI *et al.*, 1996), however, important differences exist between natural salt marshes and their laboratory models. The natural canopy has a much higher complexity than the cleaned, evenly spaced, and sometimes trimmed plants used in the laboratory. The most remarkable effect on flow-resistance by the vegetation occurs when the canopy is fully submerged, but the flume type used in the above experiments was not deep enough to reproduce this condition. As SHI *et al.* (1996) point out in their conclusions, laboratory experiments "are general indicators of natural sedimentary processes. [. . .] *In situ* measurements are necessary to verify fluid flow patterns in the flume, and to determine their physical significance."

In the literature, we did not find detailed measurements of the flow structure (vertical and horizontal distribution of velocity) in natural salt marshes, except the measurement of velocity intensity with hot-film anemometry on emergent stands of *Spartina alterniflora* and *Juncus roemerianus* by LEONARD *et al.* (1995) and by LEONARD and LUTHER (1995), and some recent results of hot-film anemometry on various salt marshes by LEONARD and REED (2002). Other field studies were only qualitative (STUMPF, 1983; WANG *et al.*, 1993), used inappropriate instruments (KE *et al.*, 1994) or measured only at one elevation (*e.g.*, CHRISTIANSEN *et al.*, 2000; SHI *et al.*, 2000; VAN PROOSDIJ *et al.*, 2000).

The scarcity of field measurements is explained partially by the difficulties of working in salt marshes. Low velocities (0.5–5 cm/s) must be measured with high spatial resolution. Moreover, tidal currents in the intertidal zone are highly variable; therefore all measurements must be acquired in a short time interval. Apart from that, extreme care must be taken to install and operate the equipment without disturbing the vegetation and the muddy substrate.

Numerical models have been proposed to predict the influence of emergent salt-marsh vegetation on turbulence, velocities, and diffusion (NEPF *et al.*, 1997; NEPF, 1999). Other relevant studies of vegetation influence on water flow have been made for seagrass stands (KOCH, 1999; KOCH and GUST, 1999; and literature review in FONSECA, 1996) and for freshwater wetlands (*e.g.*, JADHAV and BUCHBERGER, 1995; SOMES *et al.*, 1999; FISCHER-ANTZE *et al.*, 2001). In the latter environment, most studies concern stiff, emergent plants (*e.g.*, reeds).

The main aim of the present study was to investigate in the field the flow modifications by salt-marsh vegetation, which is assumed to be the major cause of sedimentation enhancement. This paper presents, probably, the first detailed field dataset in the literature of velocity profiles acquired *in situ* in a *Spartina* salt-marsh. The employed measurement method (vertical displacement of a high-precision velocimeter in a short time-interval) is innovative, although a similar principle was used in subtidal seagrass meadows (GACIA *et al.*, 1999) and in freshwater wetlands (LEE and CARTER, 1996; OLDHAM and STURMAN, 2001). We describe the flow structure in relationship to the vertical biomass distribution and we estimate hydraulic roughness (represented here by the roughness length z_0) created by the whole salt-marsh vegetation. Combining these results with data on sedimentation rate and sediment analyses, we propose a conceptual model for sedimentary processes in the intertidal areas of the Ria Formosa lagoon, that describes well intertidal environments with low suspended sediment concentration.

SITE LOCATION AND DESCRIPTION

The Ria Formosa lagoon (southern Portugal) is sheltered from the Atlantic Ocean by a chain of barrier islands and includes over 80 km^2 of tidal flats and salt marshes with some subtidal channels (Figure 1). The tides are semidiurnal, with a maximum spring tide range of 3.4 m (ANDRADE, 1990). Water salinity is close to the salinity of open-sea water. Freshwater influence is negligible, except after rare heavy rainfalls in winter.

The study area is located in the western part of the Ria Formosa, northward of the Ramalhete Channel (7°58′15″ W/37°0′20″ N), near the field station of the University of Algarve. An intertidal embayment between pisciculture basins forms a 200 × 300 m tidal-flat and salt-marsh area. The seawalls that limit the abandoned eastern basins are no longer maintained and are discontinuous (see Figure 1). Near the channel there is a flat ridge, 40–50 m wide, on which most of the studies were undertaken. About 50–75% of the upper intertidal area is covered by minerogenic salt marsh, dominated by *Spartina maritima* except in the highest locations, which are more diversified (with *Arthrocnemum sp., Sueda maritima, Atriplex portulacoides,* and *Limonium algarvensis*). The remaining surface of the upper intertidal area is unvegetated and consists of muddy sediment. *Zostera noltii* (seagrass with leaves 1–2 mm wide and 25 cm long) occurs commonly in the lower intertidal area. The channel bank is generally sandy. The study area was selected for the healthiness of the vegetation, the size of the salt-marsh area, the importance of the tidal prism (so that significant currents exist), and its accessibility.

Spartina maritima has a typical height of up to 50 cm and its stem and leaves are relatively rigid. The upper limit of the canopy is not well defined because the vegetation is less dense towards the top (see also vertical biomass distribution on Figure 3). During the field work carried out for this study (March and September 2000, April 2001), canopy heights were between 20 and 35 cm. The lower part of the *Spartina* plants was commonly encrusted by green algae, identified as *Enteromorpha clathrata* (FRIEND *et al.*, 2002), and by other epiphytes, that acted to bind dead *Spartina* plants to the canopy in an upright position. Various plant debris was lying on the ground, including fragments of brown algae (*Fucus sp.*).

Velocity profiles were measured at two locations on the salt marsh (B and C, Figure 1), and for comparison on a nearby location on the bare channel bank (D). Location B was on the flat top of the ridge parallel to the channel, at 0.63 m above mean sea-level (MSL). Location C was on the slope of this ridge towards the main channel (gradient 3–5°) at 0.55 m above MSL. At both locations, the sediment was a silty clay with an organic-matter content of 12–15%. The debris of brown algae was locally absent. Canopy height at locations B and C respectively was 30 cm and 25–30 cm. Shoot density per square metre was 2340 (1925 living, 515 dead) and 3030

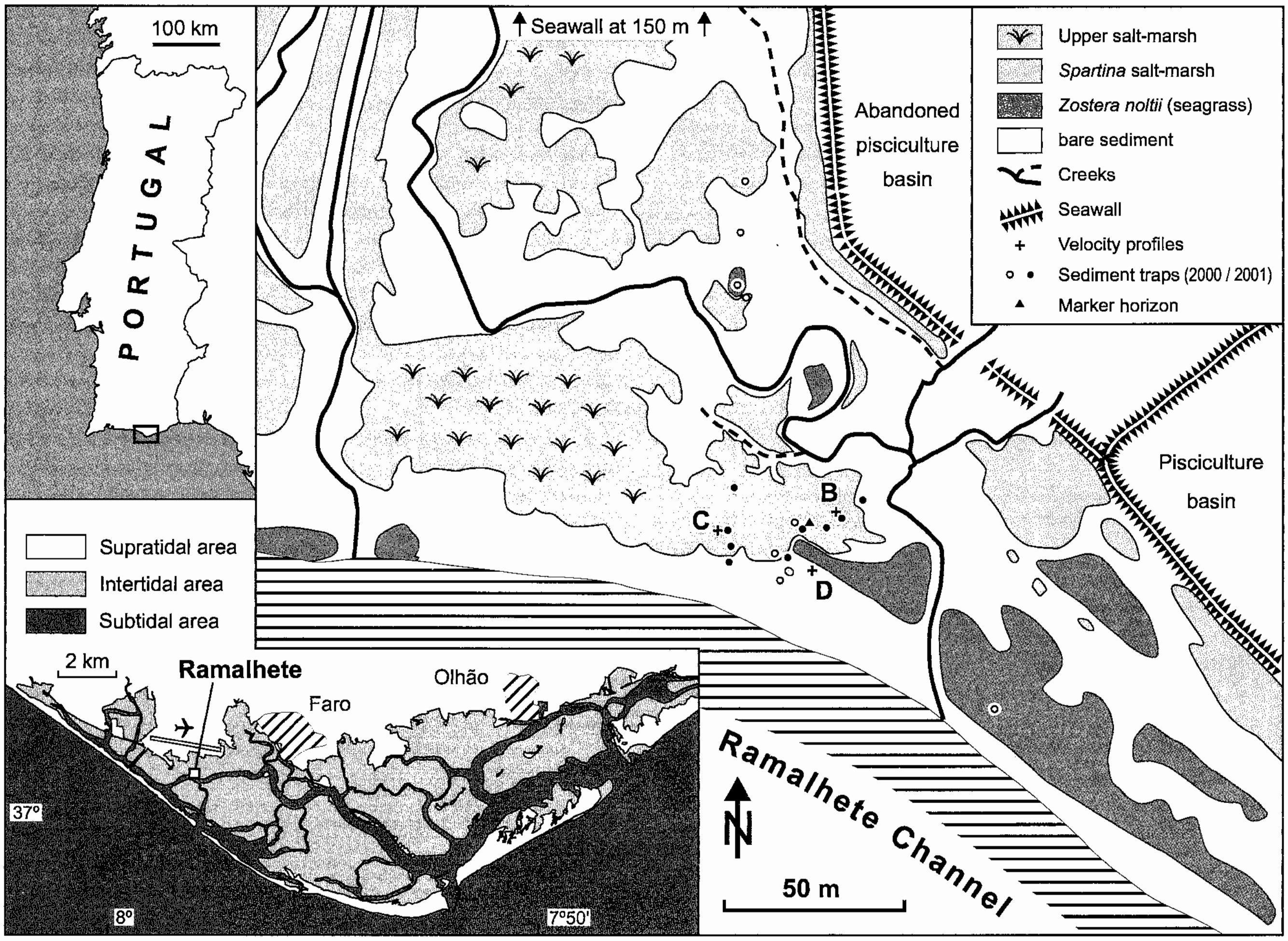


Figure 1. Location map of the Ramalhete area in the Ria Formosa lagoon. Simplified vegetation map, with positions of sediment traps, of the velocity profiles B, C, and D, and of the marker horizon. The EMCM and OBS were located on the bare sediment, 6 m NW from location D. The lower salt marsh, dominated by *Spartina maritima,* is distinguished from the upper, more diversified salt marsh.

(2255 living and 775 dead) respectively. Biomass was 929 g/m^2 and 916 g/m^2 respectively. Location B was 11 m away from the vegetation edge, but in the direction of flow provenance during the experiment (SW to NW) the distance to the vegetation edge was over 20 m. Location C was 8 m away from the vegetation edge. The unvegetated location D was on the sandy channel bank at the top of a small ridge, exactly at mean sea-level.

METHOD

Measurement of Velocity Profiles

For the measurement of velocity profiles we used an Acoustic Doppler Velocimeter (ADV, model Vector by Nortek) mounted on a movable frame to acquire single point measurements at various heights above the bed. This ADV measures accurately three velocity components in a small sampling volume (a cylinder of about 15 mm diameter and 15 mm height) at a distance of 15 cm from the probe. Sensors for temperature and water pressure are integrated in the electronic control unit, which is linked to the probe by a 2 m long cable.

To move the ADV vertically, a simple and cheap system was constructed. A structure supported by two metal posts was installed on the salt marsh (Figure 2). The fixed part of the shifting mechanism was constructed using PVC plates: a vertical plate was mounted on the structure and supported at each end two superposed horizontal plates (Figure 2). The mobile part consisted of two steel bars, which slid trough holes present in the horizontal plates. The ADV probe was attached to the lower end of one bar. A PVC piece linked the two bars at their lower end to prevent rotation of the sensor.

The mobile part (including the ADV) was moved by pulling and releasing a cable, which ran over a pulley to a metal post, installed 10-m away on the salt marsh. A metal board with numerous drilled holes (corresponding to pre-determined heights of the ADV) was firmly attached to this post. The system was operated manually. The main limitations of the

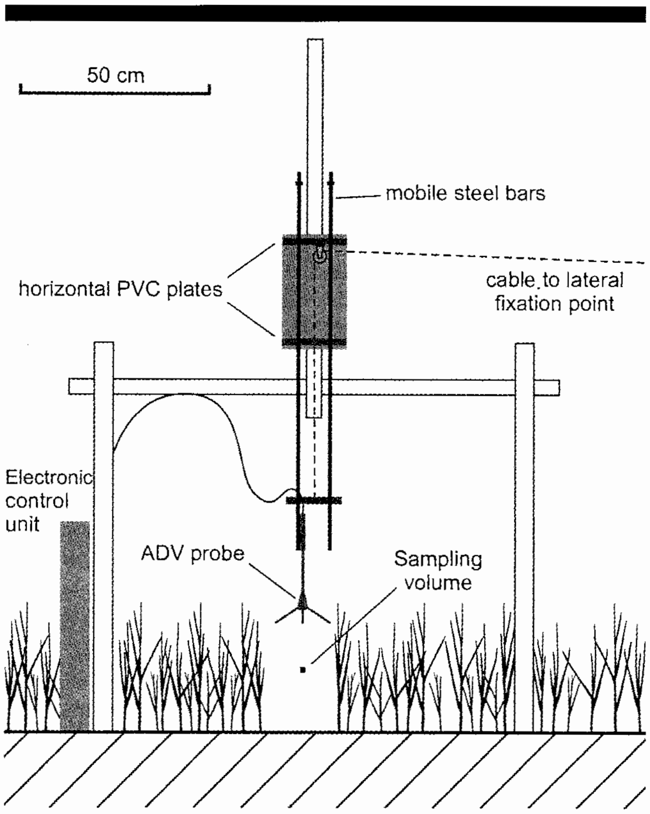


Figure 2. Scale drawing of the rig used to acquire velocity profiles in and above a *Spartina maritima* canopy of about 30-cm height. The mobile part (ADV probe, two steel bars, and PVC plate linking together the bars just above the ADV probe) is operated by pulling and releasing a cable.

profiler system described here are the necessity to have an operator in near proximity, and the impossibility to measure velocities closer than 20 cm to the water surface.

During all operations, particular attention was given not to damage the vegetation. Since an ADV is sensitive to the presence of objects between the probe and the sampling volume, a hole of about 20-cm diameter was cut in the canopy around the probe trajectory.

To acquire a profile of up to 10 points, the probe was positioned for 15 seconds at each height (see Figure 3 for profile examples). Profiles were generally repeated two times to check the presence of tidal-current variability. The typical duration for acquisition of a complete profile was about 4 minutes.

The ADV recorded velocities continuously at 16 Hz. The exact start and end time at each measurement point was defined by combining the information written down during the experiment and the examination of the vertical velocity (each vertical movement of the sensor induces a clear spike in the vertical velocity recorded by the ADV). Velocities were time averaged, and the horizontal velocity and direction calculated. The results were inspected closely for instrument problems or important changes of flow direction within a profile. No more than two data points were rejected for such reasons in any profile. Finally, results of repeat profiles at the same height were averaged.

Topographic, Sedimentological, and Vegetation Measurements

The position (coordinates) and elevation of studied locations and of major topographic features were determined with an optical total station (electronic theodolite).

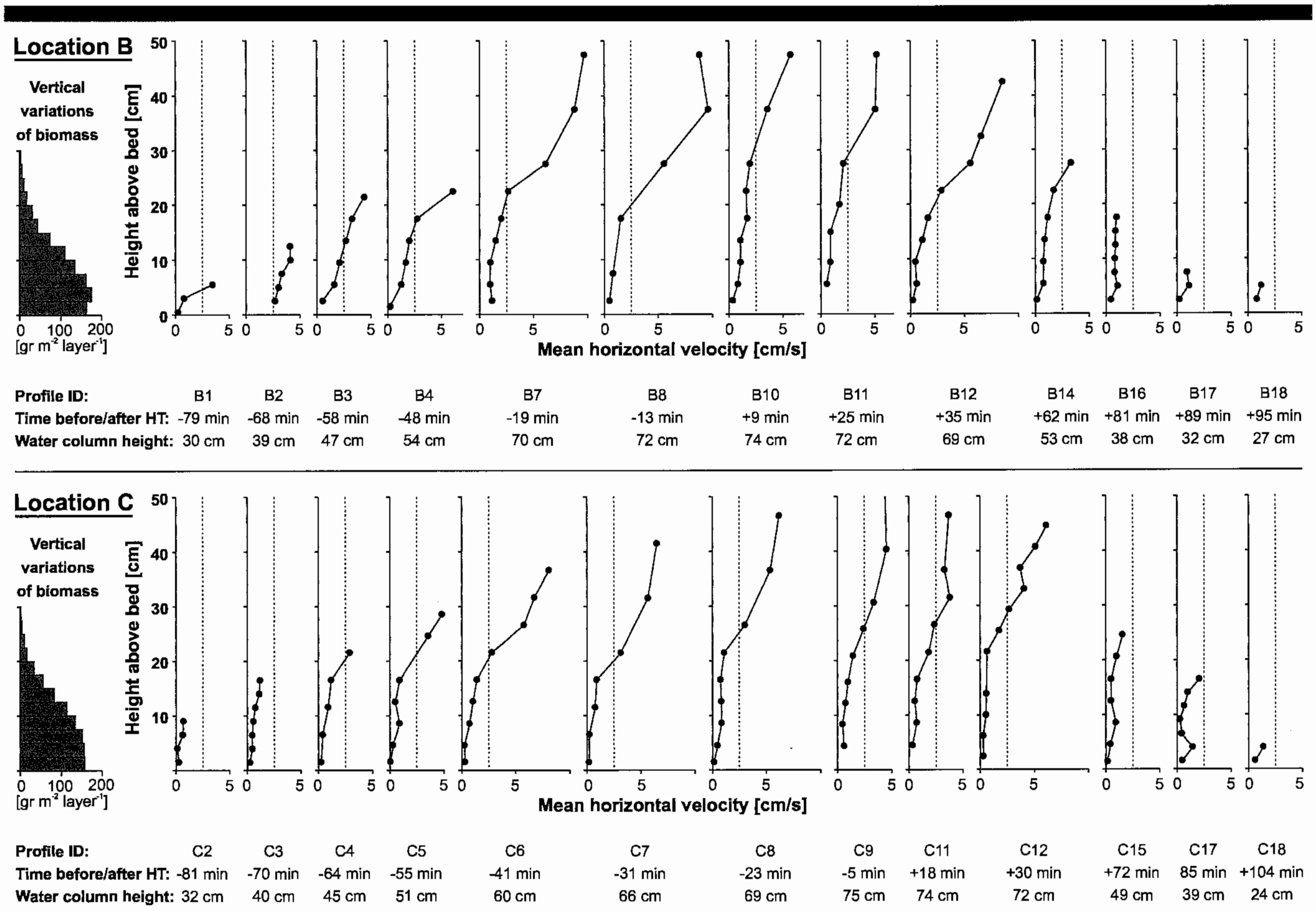
Water level variations were measured using a CTD installed on the channel slope. In order to compare water velocities inside and outside the salt marsh, water flow was measured at an additional point outside the vegetation with an electromagnetic current-meter mounted 15 cm above the bed (Valeport EMCM, model 802 with spherical 5.5 cm head, recording continuously at 8 Hz). Suspended sediment concentration (SSC) was measured at the same location from water samples and with an Optical Back-scatter Sensor (OBS) to characterise the ambient SSC during the measurement of short-term sedimentation-rate (see below). The OBS was calibrated in the laboratory with fresh surface sediment (top 2–3 mm).

Sediment samples of the upper 1–2 cm were collected for grain-size and organic-matter content analysis. For grain-size determination, plant fragments were removed manually; organic matter was removed with hydrogen peroxide. After wet-sieving separation at 63 μm, the sand fraction was analysed with a sedimentation balance and the fine fraction with a Sedigraph. The graphic mean in phi (M_z) and the graphic standard deviation (σ_1) were calculated according to FOLK and WARD (1957). The diameter in phi corresponds to the negative logarithm to the base 2 of the diameter in millimetres. The organic-matter content of the sediment was determined by loss on ignition at 450°C for 3 hours after preliminary manual removal of roots and rhizomes.

To quantify the vegetation, the canopy height was measured in the field and 3 plots of 19 cm diameter were harvested at each site. Shoot density (differentiating between living and upright dead shoots) and biomass were determined. For seagrass, the leaf area index (LAI, the leaf area (one side) of the vegetation expressed relative to ground area covered) was also measured. To determine vertical variations in vegetation density, the vertical biomass distribution was measured by cutting the harvested canopy into 2.5 cm segments. Biomass was preferred to LAI because dead plants, encrusting algae, and the rigid *Spartina* stems contribute significantly to the flow resistance, but are not taken into account in the LAI calculation.

Short-term sedimentation rates were measured with sediment traps similar to the design of FRENCH *et al.* (1995): a pre-weighed glass-fibre filter of 47-mm diameter was mounted on a plastic plate and fixed on the ground. Five traps were deployed at each location for 2 tides (one day). After retrieval, the filters were rinsed carefully with deionized water to remove the salt. Sediment deposition was determined by reweighing the dried filters.

Vertical accretion over longer periods was measured as the accumulation of sediments over a 0.5 m^2 marker horizon (coloured fine sand). Two plots were laid on the ridge near the



Profile ID:	B1	B2	B3	B4	B7	B8	B10	B11	B12	B14	B16	B17	B18
Time before/after HT:	-79 min	-68 min	-58 min	-48 min	-19 min	-13 min	+9 min	+25 min	+35 min	+62 min	+81 min	+89 min	+95 min
Water column height:	30 cm	39 cm	47 cm	54 cm	70 cm	72 cm	74 cm	72 cm	69 cm	53 cm	38 cm	32 cm	27 cm

Profile ID:	C2	C3	C4	C5	C6	C7	C8	C9	C11	C12	C15	C17	C18
Time before/after HT:	-81 min	-70 min	-64 min	-55 min	-41 min	-31 min	-23 min	-5 min	+18 min	+30 min	+72 min	85 min	+104 min
Water column height:	32 cm	40 cm	45 cm	51 cm	60 cm	66 cm	69 cm	75 cm	74 cm	72 cm	49 cm	39 cm	24 cm

Figure 3. Velocity profiles acquired at locations B and C within and above a *Spartina maritima* canopy. The dotted line marks the 2.5 cm/s position. On the left, vertical biomass distribution of the canopy, which is 30-cm high at both locations.

channel (Figure 1), and about 100 m northward. However, the latter plot was unsuccessful due to high bioturbation rates, and existence of a rugged microtopography between *Spartina* tufts.

RESULTS

Velocity Profiles

Velocity profiles were obtained for two locations of the salt marsh (B and C, Figure 1). Velocity profiles were also measured at a third location on the bare channel bank (D) for comparison. Measurements were carried out during the afternoon high tides of 9–11 April 2001. The tidal range was decreasing from 3.1 to 2.8 m. The weather was fair with a gentle breeze of variable direction. Water temperature was 17–19°C. Wind waves were negligible (<5 cm) and the limited boat traffic did not interfere with profile acquisition.

Figure 3 illustrates a selection of the 36 horizontal-velocity profiles measured on the salt marsh at locations B and C. The highest point measured was always 20–25 cm below the water surface. Notice that the experiment was not designed to measure the detailed velocity structure in the first few centimetres above the bed. The profiles can be grouped into the three following categories:

(1) The canopy is partially emergent (*i.e.* the canopy base is under water and the top above water), or is only slightly submerged (*e.g.,* B1–B4, C4). The velocity profile is generally linear, sometimes with an acceleration toward the top.

(2) The canopy is well submerged, *i.e.* the water level is well above the canopy top (*e.g.,* B7–B8, C6–C8). Within the denser part of the canopy (up to about 20 cm) the velocity is constant or has a slight linear increase upwards. Above this part, there is a skimming flow with often a velocity profile of logarithmic shape (a skimming flow is a relatively fast flow above a lower layer that is characterized by significantly slower velocities).

(3) The surface current is slow (at slack water and, for location C, at beginning of flood and end of ebb, *e.g.* B10, C3, and C15), and the characteristics described above are only partially developed.

The upper limit of the canopy influence is located at about 20 to 25 cm above the bed, depending on the profile. When the canopy is well flooded, the velocity in the lower part is always slow and independent of the flow above the canopy (Figure 4).

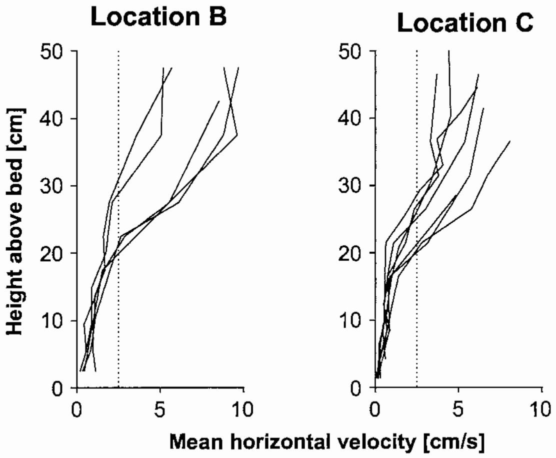
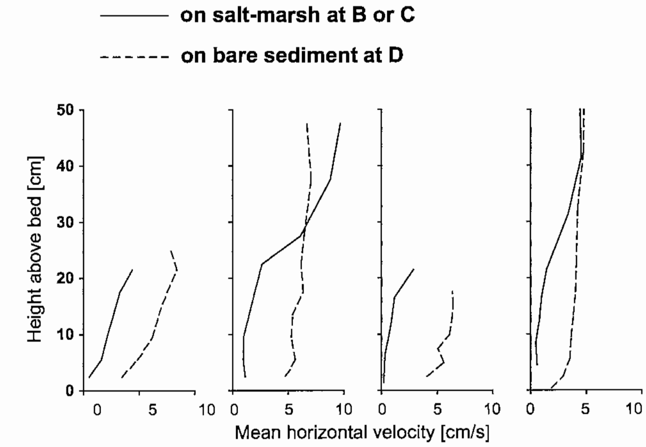


Figure 4. Velocity profiles acquired at locations B and C within and above a *Spartina maritima* canopy when the canopy was well submerged. The dotted line marks the 2.5 cm/s position. The velocity within the canopy below 20 cm is independent of the water flow above the canopy.



Profiles:	B3 / D4	B7 / D7	C4 / D3	C9 / D13
Time:	-58 / -124 min	-20 / -95 min	-64 / -133 min	-5 / +7 min
Water col. h.:	47 / 48 cm	70 / 69 cm	45 / 41 cm	75 / 117 cm

Figure 5. Comparison of velocity profiles on salt marsh (at locations B and C) and on bare sediment (at location D). The three comparisons on the left-hand side are with similar height of water column (abbreviated to "Water col. h."), on the right-hand side is the situation during slack water. Time refers to high tide.

The main difference between the two salt-marsh locations (B and C) is a generally weaker current regime at C than at B (during flood, the maximum free-stream current was 10 cm/s at B and 8 cm/s at C; during ebb, it was 9 cm/s and 6 cm/s, respectively). This is due to the different topographic positions of B and C, at the top and on the side of the ridge that separates the main channel from the large intertidal area to the north.

Four representative velocity profiles of the 18 measured on bare sediment are presented in Figure 5. The comparison between velocity profiles measured on the salt marsh (locations B and C) and on the bare sediment (location D) shows the flow modifications due to the presence of vegetation (Figure 5). These measurements were carried out on different days, but in similar weather and sea conditions. The topographic positions of locations B and D are also comparable.

On the bare sediment, the velocity profiles follow the Law of the Wall with the main velocity-increase occurring in the first 5 cm above the bed (Figure 5). In contrast, on the salt marsh, the flow is notably slower in the denser part of the canopy, and the major velocity increase occurs above 15–20 cm.

The comparison between profile B7 and D7 is particularly interesting (Figure 5). Both profiles were recorded with the same height of water column, about 80 minutes after flooding at each location. The water flux (computed assuming a constant velocity above the highest measured point) at locations B and D is similar: 0.044 and 0.043 m^2s^{-1}, respectively. The presence of the canopy shifted the main flow above the canopy (velocity above 30 cm is higher at B than at D). Although the same water flux passes at the two locations, conditions near the ground are completely different.

Further evidence of drastic flow reduction by the canopy comes from the comparison (Figure 6) between the velocities measured simultaneously at location B and on the bare channel bank with the EMCM (location is 0.07 above MSL, 6 m NW from location D, 4 m in front of the salt marsh).

For the bare channel bank, at 15 cm above the bed, important velocity variations occurred during the tidal cycle with

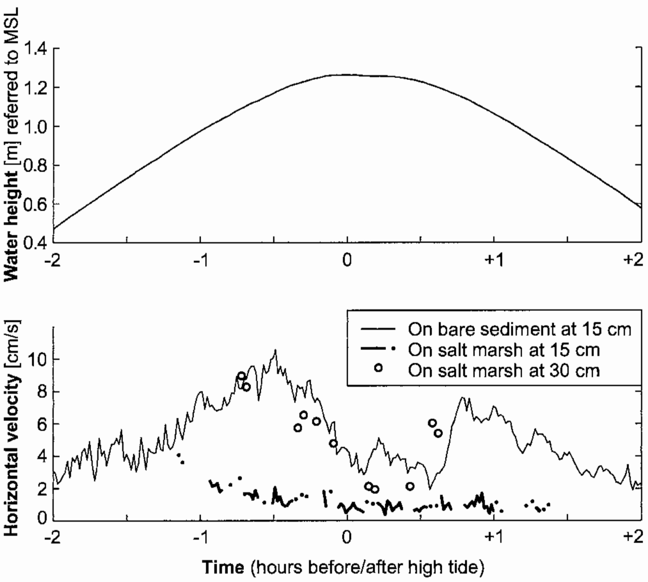


Figure 6. Top: tidal curve. Bottom: Velocity comparison within/outside salt marsh on 9.4.2001. Horizontal velocity (1 minute averages) measured on bare sediment at 15 cm above the bed (continuous measurement with an EMCM) and on salt marsh at location B, within the canopy at 15 cm and above the canopy at 30 cm (only plotted when ADV was positioned at 15/30 cm).

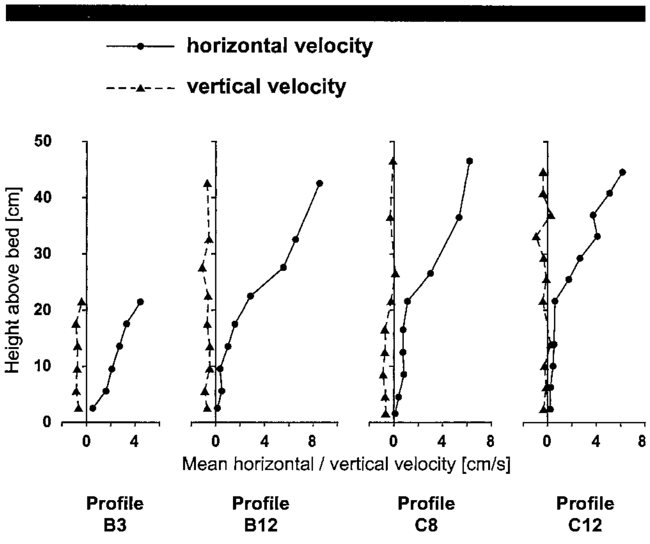


Figure 7. Horizontal and vertical mean-velocities of 4 representative profiles at locations B and C. For the vertical component, the positive direction is upward (the measured velocities are generally downwards, *i.e.* represented with negative values). At both locations the canopy height is about 25–30 cm.

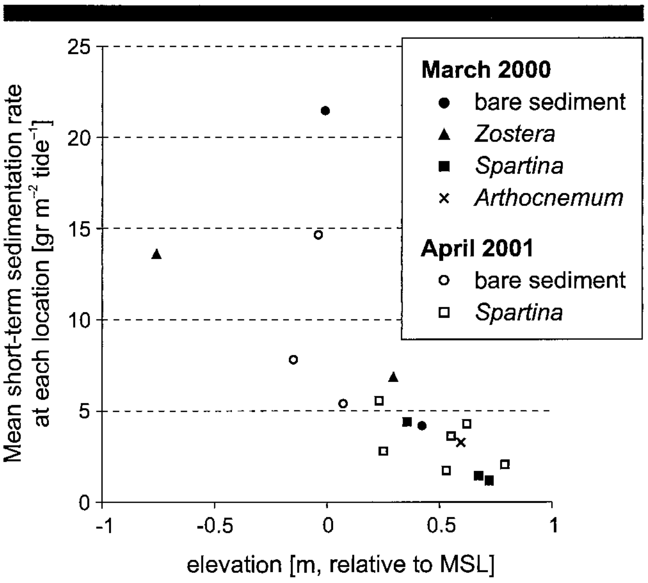


Figure 8. Mean short-term sedimentation rate measured at each location in March 2000 and April 2001. *Zostera* corresponds to seagrass stands, *Spartina* and *Arthocnemum* to salt marsh.

maxima (up to 10 cm/s) due to flood and ebb currents, and a minimum during slack water (Figure 6). At the same elevation in the salt marsh (location B), the current is slow with only small variations: velocity below 2.5 cm/s, except just after the beginning of the flood (1h10′ before high tide), when the upper part of the canopy is still emergent and no skimming flow exists. Nevertheless, velocity records at 30 cm above the bed in the salt marsh show that the same temporal current pattern exists at location B. Therefore, the drastic flow reduction at 15 cm at location B is not related to the position on the ridge but to the presence of vegetation.

The time-averaged vertical velocities are always low, below 2 cm/s (Figure 7). The values are typically below 1 cm/s within the canopy. The mean velocity is generally directed downward.

Sedimentation Rates and Vertical Accretion

Short-term sedimentation rates were measured with sediment traps in March 2000 and April 2001 during fair weather conditions. Traps were deployed during 3 periods of 2 tides in March 2000 (22–23, 24–25, and 27–28 March with tide ranges of 2.55 m, 1.97 m, and 0.97 m, respectively) and during 2 periods in April 2001 (9–10 and 13–14 April with tide ranges of 2.96 m and 1.48 m, respectively). Sampling areas were distributed across the different environments, at 9 sites around the velocity-profile locations in April 2001, and at 8 sites in a larger area in March 2000 (Figure 1).

Sedimentation rates at spring and neap tides are not significantly different from each other, with two notable exceptions: the highest sites are not flooded at neap tide, and the sedimentation rate of the lowest bare areas is higher at spring than at neap tide (this is probably due to higher peak currents in the channel at spring tide, which carries more sediment). Therefore, only the mean values obtained at each location are presented and discussed. These mean values, expressed in g·m^{-2}·tide^{-1}, range from 5 to 21 on the sandy channel bank, from 4 to 15 on the bare muddy areas (these are most of the unvegetated areas more than 25 m away from the channel), from 7 to 14 on seagrass and from 1 to 5 on salt marsh (Figure 8).

Statistical analysis (Pearson's linear correlation coefficient) shows a negative correlation with elevation, with distance from creek and with vegetation density (represented by overground biomass), *i.e.* sedimentation rate is lower on higher, more distant and more densely vegetated locations (Table 1). The observed sedimentation rates depend mainly upon the topographic position (elevation and distance from creek), while the vegetation density has less influence. The relationship is stronger with the inverse of the distance, than simply with the distance. The relationship is weaker with inundation time than with elevation. Multiple linear regression analysis of sedimentation rate as a function of topographic position and vegetation density confirms the negative correlation between sedimentation rate and vegetation density

Table 1. *Correlation of short-term sedimentation rate with elevation, with inundation time, with distance from channel/creek, with inverse of distance from channel/creek, and with overground biomass: Pearson's correlation coefficient R and probability of a random relationship are indicated.*

	March 2000 (n = 24)	April 2001 (n = 18)
Elevation	-0.703 ($p < 0.001$)	-0.573 ($p = 0.013$)
Inundation time	0.607 ($p = 0.002$)	0.418 ($p = 0.084$)
Distance from creek	-0.605 ($p = 0.002$)	-0.625 ($p = 0.006$)
1/Distance from creek	0.687 ($p < 0.001$)	0.738 ($p < 0.001$)
Biomass	-0.657 ($p < 0.001$)	-0.450 ($p = 0.061$)

even when the effect of topographic position is taken into account.

The marker horizon was laid down in March 2000 near the top of the ridge, on the slope facing the channel at an elevation of about 0.7 m above MSL (Figure 1). The vertical accretion, measured 12½ months later, corresponds to 11.4±2 mm/year.

Suspended sediment concentration (SSC) was measured on three occasions in March and September 2000, and in April 2001. During each of these fair-weather periods, an OBS was installed for 2–3 days at different locations on the channel bank. SSC was always low and ranged from 3 to 15 mg/l with a decrease during the tidal cycle: during the ebb flow SSC was typically 3–5 mg/l lower than during the flood flow. This suggests that the embayment was a sediment sink during the measurement periods.

Although only one point measurement of SSC is available, a rough estimation of the sediment budget can be made for this intertidal embayment, making several assumptions (*e.g.*, measured SSC is representative of all the transported sediment). The area of the intertidal embayment is about 60000 m^2. The water level at high tide was between 1.0 m (close to neap tide) and 1.5 m (spring tide) above the lower areas of the intertidal embayment. If an even elevation distribution is assumed (a detailed topographic survey was not undertaken) the mean water height was between 0.5 and 0.75 m and the total water volume between 30000 and 45000 m^3. Assuming that the measured SSC difference between flood and ebb flow of 3 to 5 g m^{-3} is representative of all the water flow, the net sediment input into the embayment is between 90 and 225 kg/tide. Assuming an even sedimentation over the whole area this corresponds to 1.5 to 3.8 g m^{-2} $tide^{-1}$. This is in the same order of magnitude as the results of the sediment traps, especially considering that the traps are located relatively close to the channel, and sedimentation rate is likely to be higher there than inside the embayment.

Characteristics of Surface Sediments

Surface sediments at all locations mentioned above and at several additional sites were analysed for grain-size distribution and organic-matter content. The sediment characteristics depend mainly on the vegetation cover, with finer sediments in more densely vegetated locations. Four environments are defined, presented here in order of decreasing grain size. Sediments are described following the classification of SHEPARD (1954) and the sorting classes of FOLK and WARD (1957).

(1) Bare channel bank: well sorted sand (average graphic-mean (M_z) 2.3 phi), organic-matter content below 1%.

(2) Bare intertidal area: moderately sorted (sometimes poorly sorted) silty sand (average M_z 4.9 phi), organic-matter content between 1% and 4%.

(3) Seagrass meadow (*Zostera noltii*): silt to clayey silt (average M_z 6.7 phi), moderate to poor sorting, organic-matter content between 2% and 8%.

(4) Salt marsh (*Spartina maritima*): poorly sorted clayey silt to silty clay (average M_z 7.5 phi), organic content between 5% and 20%.

It must by underlined that the topographic arrangement of these four environments follows a different order: the seagrass meadows are generally at low elevation, on the channel bank; the bare intertidal areas are commonly in the upper intertidal zone, generally slightly lower than the salt marsh.

An influence due to elevation or distance from the channel (with coarser sediments at locations that are lower or closer to the channel) also exists, but this is clearly less important than the influence of the vegetation cover, when the different environments are considered. That is particularly evident at vegetation edges, where considerable changes in grain size occur over a short distance, independently from elevation. Similar findings have been obtained at other places in the lagoon (NEUMEIER *et al.,* 2001).

DISCUSSION

Flow Resistance of Vegetation

The comparison between our results and previous laboratory experiments that tested *Spartina anglica* plants of 30–45 cm height (PETHICK *et al.,* 1990; SHI *et al.,* 1995; SHI *et al.,* 1996) shows similarity in the general shape of the velocity profiles. These authors also found a linear velocity increase in the lower part of the canopy and a generally logarithmic profile above. However, significant variations exist in some of the details.

PETHICK *et al.* (1990) analysed the limit between these two profile sections, which marks the abrupt increase in the velocity gradient. They found that this limit occurred at lower elevations (3–10 cm) than that found in our results (about 15–20 cm, see also bed roughness calculations below), despite the taller canopy height (45 cm) used in their experiments. Two explanations for this difference are possible. In the experiments of PETHICK *et al.* (1990) the canopy was just submerged, so there is no place for a skimming flow to develop above the canopy (the conditions are similar for our profile B1, which also shows a velocity gradient variation at about 5 cm, Figure 3). Furthermore, PETHICK *et al.* (1990) studied the evolution of this boundary between the two profile sections with distance from the vegetation edge: this limit overall rises with distance from the edge, and this increase still continues at the farthest measured profile (2.6 m from edge, Figure 9.5 of PETHICK *et al.* (1990)). In contrast, our field locations are over 10 m from the vegetation edge and are probably not affected by edge effects.

SHI *et al.* (1995, 1996) point out the presence of a secondary velocity maximum in the lower part of the canopy, which was followed upward by a minimum of about 30% lower velocity in the middle/upper part of the canopy. This feature is also present in the data of PETHICK *et al.* (1990), but not discussed in their text; and in field measurements of velocity intensities in emergent stands of *Spartina alterniflora* undertaken by LEONARD and LUTHER (1995) and LEONARD *et al.* (1995). This velocity maximum corresponds to a lower vegetation density of the *Spartina* canopy near the ground (LEONARD and LUTHER, 1995). We did not observe this (with the exception of the unexplained velocity peak present in profile C17). If a velocity maximum existed at our field location, it would have been visible in our data, although the vertical space

Table 2. *Calculation of U^* and z_o from the logarithmic shaped velocity-profile above the canopy at locations B and C, above the bed at the unvegetated location D. For locations B and C, the obtained U^* is not related to the shear stress on the bed.*

Location	Profile #	Used Points[1]	Time Referred To HT	Water Column Height	R^2	U_* m/s	z_o cm
B	B7	23, 28, 38, 48	−19 min.	70 cm	0.93	0.037	15.5
	B8	18, 28, 38	−13 min.	72 cm	0.99	0.042	15.4
	B11	28, 38, 48	+25 min.	72 cm	0.87	0.023	18.1
	B12	23, 28, 38, 48	+25 min.	69 cm	0.97	0.034	15.3
C	C6	22, 27, 32, 37	−41 min.	60 cm	0.97	0.039	15.7
	C7	17, 22, 32, 42	−31 min.	66 cm	0.97	0.025	13.5
	C8	22, 27, 37, 47	−23 min.	69 cm	0.97	0.027	17.5
	C9	22, 27, 32, 42	−5 min.	75 cm	0.99	0.019	15.8
	C11	17, 22, 27, 32, 37	+18 min.	74 cm	0.90	0.014	13.2
D	D1	2.5, 5, 7.5	−148 min.	29 cm	0.98	0.0084	0.44
	D2	2.5, 5, 7.5, 10, 13	−144 min.	32 cm	0.99	0.0062	0.24
	D4	2.5, 5.5, 9.5, 14, 18	−124 min.	48 cm	0.99	0.0083	0.49
	D8	2.5, 7.5, 15	−83 min.	78 cm	0.99	0.0034	0.03
	D9	2.5, 7.5, 13	−65 min.	90 cm	0.98	0.0047	0.23
	D10	2.5, 7.5, 13, 18	−41 min.	104 cm	0.96	0.0046	0.05
	D11	2.5, 13, 28	−33 min.	109 cm	0.95	0.0028	0.01
	D12	2.5, 7.5, 13, 18, 23	−12 min.	116 cm	0.99	0.0036	0.04
	D13	0.5, 2.5, 5.5, 9.5, 14, 18, 23	+8 min.	117 cm	0.99	0.0023	0.02
	D14	2.5, 7.5, 18	+19 min.	116 cm	0.99	0.0035	0.06
	D15	2.5, 5.5, 9.5, 14	+42 min.	111 cm	0.90	0.0046	0.03
	D17	2.5, 5.5, 9.5, 14	+73 min.	94 cm	0.99	0.0070	0.09
	D18	2.5, 5.5, 9.5, 14, 18, 23	+94 min.	79 cm	0.89	0.0049	0.06

[1] Height in cm above the bed for the points used in the linear-regression calculation.

between our measurements is larger. This dissimilarity must result from a different structure of the canopy in the Ria Formosa, which is characterised by a nearly constant biomass density at its base due to the presence of epiphytes, dead plants, and debris (Figure 3). On the contrary, LEONARD and LUTHER (1995) described a maximum vertical distribution of plant material at approximately 10 cm above the bed, whereas the laboratory experiments of PETHICK *et al.* (1990) and SHI *et al.* (1995, 1996) were carried out with clean *Spartina* plants.

Our data are not detailed enough near the bed to confirm the logarithmic shape observed by SHI *et al.* (1996) in the lower 20% of the canopy. NEPF *et al.* (1997) and NEPF (1999) also observe this profile shape by using a theoretical model and a simple, cylinder-based laboratory model of emergent vegetation. They point out that above this zone the velocity and turbulence are dominated by vegetation wakes and nearly independent from bottom phenomena.

Our results emphasize the velocity reduction by the *Spartina* canopy, which must also be accompanied by turbulence reduction (NEPF, 1999). This reduction is important when the canopy is partially emergent or is only slightly submerged, and becomes drastic when the canopy is well submerged, with development of a skimming flow above the denser part of the canopy (as illustrated in Figure 4). In the latter situation, a very efficient damping of wave orbital velocities can be assumed, so that the wave-related water movements are strongly attenuated near the bed. In both situations, the *Spartina* canopy has a significant action for sedimentation enhancement and prevention of bed erosion.

The time-averaged vertical velocities are slow and generally directed downward (Figure 7). The reasons for this may be due to either natural flow in the canopy or an artefact of the ADV, which can induce a slight downward flow in nearly still water with the settings used in this experiments (Atle Lohrmann (Nortek), personal communication). These velocities were measured about 5–10 cm from the closest plant (a hole was cut in the canopy to avoid perturbation of the ADV by the vegetation), therefore the data are not adapted to small-scale studies of the flow around stems or leaves (*e.g.,* NEPF and KOCH, 1999).

Skimming Flow Above the Canopy

Above the denser part of the canopy, the velocity profile often has a logarithmic shape. Therefore it can be assumed that the velocity there follows the Kármán-Prandtl equation. For this reason, the boundary layer parameters (shear velocity U_* and roughness length z_0) were computed from the relevant profile points using the traditional method of analysis (BERGERON and ABRAHAMS, 1992).

The linear regression gives acceptable coefficients of determination (R^2) for the majority of profiles with water heights above 60 cm (Table 2). The shear velocity, which is normally directly related to bed shear stress, is difficult to interpret because it is not representative of the conditions near the ground. On the other hand, z_0 is the hydraulic roughness of the whole salt-marsh vegetation. It is a valuable source of information because it controls the flow pattern above the canopy. At location B, the different values of z_0 are well grouped: 15–18 cm. At location C, z_0 is more variable, from 13 to 18 cm. The greater variability at C could be due to the closer proximity of the vegetation edge and the channel (more irregular flow and passage of large turbulent eddies). Notice also that at locations B and C, the biomass below 15 cm represents 88% and 87% respectively of the total canopy biomass.

From the different velocity profiles observed on the salt-marsh, it seems that for large-scale modelling of water flow above a submerged *Spartina* marsh, a constant flow can be assumed within the lower part of the canopy and a logarithmic velocity profile above. For the *Spartina* marsh in the Ria Formosa, this study suggests a constant flow of 1.0–1.5 cm/s within the canopy and a z_0 of the above-canopy flow located at 88% of the vertical biomass distribution. To apply this method to another vegetation type or another geographical region, limited field measurement of velocity profiles should be sufficient to correlate the nearly constant velocity within the canopy to vegetation density and to relate z_0 to the vertical biomass distribution. After this preliminary work, the flow parameters of a salt-marsh location could be determined with a simple vegetation survey.

Velocity Profiles on the Bare Sediment

Two thirds of the velocity profiles at location D (bare sandy channel bank) have a logarithmic shape in their lower part (*e.g.,* profiles D4 and D13 shown in Figure 5). The boundary layer parameters were computed from the lower 3 to 5 points (depending upon profile shape and water height) and are presented in Table 2. The shear velocity, U_*, was 0.0062–0.0084 m/s at the beginning of the flood, then decreased to 0.0023–0.0035 m/s at the end of the flood and during slack water. It rose again to 0.0045–0.007 m/s at the beginning of the ebb (acquisition was terminated two hours after high tide). The associated bed roughness varied from 0.1 to 4.4 mm.

These shear velocities can be compared with the threshold for motion of non-cohesive sediments (at location D the sediment is medium sand with a D_{50} of 0.25 mm). The higher shear velocities at the beginning of the flood (0.0062–0.0084 m/s) correspond to the threshold for motion of quartz grains with 10–20 μm grain diameter (SOULSBY, 1997).

However, it must be remembered that the shear velocity was computed from mean velocities and does not include the effect of waves (which can be important, especially at shallow water-depth). The first velocity profile was also acquired when the water depth was already 29 cm; higher shear velocities can be expected at lower water-depth. Therefore, coarser particles can probably be moved even during fair weather. This was observed for the sediment traps deployed on the channel bank, which collected fine sand.

Sedimentary Processes

The size of our data set on sedimentation rates and accretion thickness is limited compared with other excellent studies conducted in Britain and North America (*e.g.,* STODDART *et al.,* 1989; CHILDERS *et al.,* 1993; FRENCH and SPENCER, 1993; FRENCH *et al.,* 1995). However, in view of the scarcity of such studies on the Iberian coasts and of the specific environmental setting of the Ria Formosa (low concentration of suspended sediments), the data give interesting information.

The short-term sedimentation rate observed with the sediment traps during fair weather shows a strong relationship with topographic parameters, *i.e.* negative correlation with elevation and distance from creek. A similar relationship was observed in several previous studies (*e.g.* FRENCH and SPENCER, 1993; FRENCH *et al.,* 1995; REED *et al.,* 1999). However, these authors demonstrated that on a local scale (some tens of meters) elevation does not often correlate with sedimentation rate, because of the presence of levees along creeks, and that on this scale only creek proximity is a significant parameter. The absence of levees in the studied area (the channel parallel ridge is probably one of the numerous relict structures present in the lagoon, ANDRADE, 1990) explains the good correlation with elevation that we observed. However, the data set is too small to reach a definitive conclusion on the relative importance of elevation and distance from creek.

The negative correlation of the sedimentation rate with vegetation density is different from the expected long-term trend. The general view of sedimentary functioning of salt marshes assumes a sedimentation enhancement by the vegetation (*e.g.,* STUMPF, 1983; USACE, 1989; FRENCH and SPENCER, 1993; ESSELINK *et al.,* 1998). This is also indicated by the velocity measurements presented above. However, our data show lower sedimentation rate on the salt marsh than on less densely vegetated or bare areas. This is probably related to the overall low SSC during the observation periods, as well as the sediment depletion before the water reaches the denser vegetated areas, and the smaller water volume flowing above the salt-marsh (lower flow velocity and reduced water depth).

This paradox of lower sedimentation rates on the salt marsh suggests that important sediment transport occurs only during exceptional events, as STUMPF (1983) proposed for a Delaware salt-marsh and CARLING (1982) for a Welsh salt-marsh. During a high-energy storm event, currents and waves will have an important erosion potential. Important erosion must then occur in unprotected, bare areas, whereas flow resistance by the canopy and sediment binding by the roots strongly reduce erosion on the salt marsh. The erosion protection of a flexible seagrass canopy is less effective, as suggested by our visual observations of turbidity increase over *Zostera noltii* stands produced by moderate waves.

During and after storms, or when exceptional winter floods carry terrigenous sediments to the lagoon, much more sediment is transported in suspension, and the trapping effects of salt marshes and seagrass beds are probably more efficient. In such conditions, the trend observed with the sediment trap can be inverted as more sediment is trapped in the salt marsh than deposited on the unvegetated areas.

These deductions are corroborated by the vertical accretion within the salt marsh. The sedimentation rates measured in March 2000 on the salt marsh close to the marker horizon were 1.2 g m^{-2} $tide^{-1}$ (same elevation as the marker horizon) and, in April 2001, 2.8 and 1.7 g m^{-2} $tide^{-1}$ (respectively slightly lower than, and at the same elevation as the marker horizon). The sedimentation rate can be converted to accretion by assuming a dry bulk density for the sediment. An average value of 1000 kg m^{-3} was estimated from our sediment analyses (average water content (ratio water weight/total weight): 60%), similar to the measurements of AMOS and MOSHER (1985). A simple time-extrapolation of these sedimentation rates from fair-weather periods to an annual basis (assuming similar conditions during the whole year) gives an accretion of 0.9–2.0 mm/year. The discrepancy between these extrapolated values and the accretion actually measured on the marker horizon (11.4±2 mm/year) point out that fair-weather sedimentation cannot account for long-term accretion in the salt marshes of the Ria Formosa and that most sedimentation occurs during individual events.

From all this it follows that the short-term sedimentation rate measured during fair weather is not representative of mid- to long-term vertical accretion. It represents more the sediment mobility (*i.e.* movement of sediment particles even over short distances) than the long-term sediment deposition (*i.e.* allochthonous sediment input to an area). This applies particularly to bare sediment, seagrass stands, sparse salt-marshes, and other areas potentially subject to important erosion. To observe the long term evolution it is necessary to use marker horizons or other methods measuring the accretion over longer periods (for example the "sedimentation-erosion table" developed by BOUMANS and DAY, 1993).

We have seen that during the fair-weather observation-periods the salt-marsh does not enhance sedimentation. Therefore another important conclusion is that the effect of the *Spartina* canopy seems to be more of erosion protection during storms than sedimentation enhancement during normal conditions. It is difficult to evaluate how much this observation depends on the generally low concentration of suspended sediment in the Ria Formosa. BROWN (1998) reached a similar conclusion for a salt marsh in the Humber Estuary (England).

Conceptual Model

It is possible to outline a general picture of the sedimentary processes that are probably active in the different intertidal areas. Three different kinds of conditions can be distinguished: (1) "Normal conditions" characterised by low suspended sediment concentration (SSC) and negligible or moderate waves; these conditions prevail over 90% of the year; (2) "High energy conditions" during storm events with important waves in the lagoon; (3) "High SSC conditions" dominated by sediment settling after a storm or when exceptional winter floods carry continental sediments to the lagoon. These last conditions are probably similar to those found in an estuary with a high sediment load. Unfortunately, our observations of sedimentation rate are limited to the normal conditions.

During normal conditions, the sedimentation rate depends mainly on elevation and creek proximity. High sediment mobility and deposition prevail in the low areas, particularly on the bare channel bank and a little less in the low-elevation seagrass stands. A part of the material deposited here is probably remobilised within a few days. The trapping effect of the salt-marsh canopy is moderate (mainly fine sediment is captured), and the sedimentation rate in the salt marsh is low, less than on the slightly lower elevated mudflats. In other words, the sedimentation rate seems to be controlled by the energy necessary to carry a particle from the channel, which is locally the sediment source, to a particular location; this "transport energy" depends on horizontal and vertical distance and on the interposed vegetation.

During high energy conditions, important sediment remobilization occurs in the bare areas. The vegetation exerts an important protection against erosion. This protective effect is more limited for seagrass and probably very efficient for salt-marsh vegetation, which also traps the coarsest sediments mobilised by the storm. Indeed salt-marsh sediments contain a sand fraction of 5–10%, which can only be transported there during such conditions. CARLING (1982) reached a similar conclusion by comparing the grain size of surface-sediment and fair-weather suspended-sediment.

During high SSC conditions, sediment settling occurs on all areas. On the bare areas, mainly coarse and medium-sized sediments are deposited. The trapping effect of the vegetation is probably more effective than in normal conditions as the SSC increases in and above the canopies. In particular, the salt marsh captures the whole grain-size range of sediment in suspension. Therefore, it is possible that the sedimentation rate then is higher within the vegetation than on the surrounding bare areas.

The resulting arrangement of sediment types depends strongly on the vegetation cover. On the bank of the main channel, the sandy sediment is well sorted by the channel-induced high turbulence-intensity. On the other intertidal areas, a sediment gradient exists from bare areas over seagrass stands to salt marsh. This corresponds to a fining of grain size, a worsening of sorting and an increase of organic-matter content. This gradient is roughly independent of the topography, but it is controlled mainly by the presence and the density of vegetation.

CONCLUSIONS

The *Spartina maritima* canopy induces two different shapes of velocity profile: (1) a roughly linear profile when the canopy is partially emergent or is only slightly submerged; (2) a drastic flow reduction in the lower section when the canopy is well submerged, with a slow, nearly constant velocity in the denser part of the canopy and the development of a logarithmic velocity profile and skimming flow above. The maximum effect of vegetation resistance occurs under the second set of conditions.

An important difference from previous laboratory studies is the absence of a first velocity maximum in the lower part of the canopy. This is due to a more complex structure of the natural canopy and emphasises the importance of analysing the vertical distribution of vegetation density in the field.

These velocity measurements suggest the possibility of modelling large-scale water flow above a salt marsh by considering a constant flow within the lower part of the canopy, and a logarithmic velocity profile above.

During fair weather, sedimentation rates in the intertidal areas of the Ria Formosa depend largely upon elevation and distance from creek. The vegetation cover has less influence; and the sedimentation rate is correlated negatively with the presence and the density of vegetation. Probably this pattern of sediment accumulation varies considerably during storms and periods with high SSC.

The effect of the *Spartina* canopy on sediment accumulation seems to be more that of erosion protection during storms than that of sedimentation enhancement during normal conditions.

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