

Tidal Wetland Sedimentation in the Yangtze Delta

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ABSTRACT

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Based on the measurement on near-bed current, wave, suspended sediment concentration, sedimentary grain size, organic content, sediment trapped by plants and accretion rate, this article deals with hydrographic processes, accretion-erosion events, surficial deposit as well as their spatial and temporal changes. The near-bed current, wave energy and suspended sediment concentration were much lower on the marsh than on its adjacent bare flat with the same elevation. The median grain size in Φ unit (Φ_{50}) changed between 2.74 and 8.15. The bare flat sediment was mainly composed of very fine sand while the marsh sediment was dominated by silt. The organic content of the sediment was less than 3.0% and had a good correlation with sedimentary grain size. Although the sediment trapped by *S. mariquete* and *S. triquiter* amounted to 64.4mg/stem and 47.6mg/stem, their contribution to the accretion was much less than that by free settling. The annual accretion rate of the tidal marshes in the Yangtze Delta amounted to several decimeters because of the high suspended sediment concentration which was related to the great deal of riverine sediment supply. It is this feature that was responsible for the low organic content and the less contribution of biogenic deposition to accretion.

ADDITIONAL INDEX WORDS: *Tidal wetland, tidal marsh, tidal flat, sedimentation, Yangtze River Delta, China.*

INTRODUCTION

The concept of tidal wetland usually includes the bare tidal flat and the tidal marsh (or swamp). A tidal marsh may be salt marsh, brackish marsh or fresh marsh. Tidal wetland sedimentation, involving hydrodynamics, behavior of sediment and changes in sediment surface, has been an interesting topic in recent years. In the field of hydrodynamics, studies have focused on the attenuation of waves and currents either caused by marsh vegetation or due to variation in space. Flow speeds were found to be inversely related to the distance from the creek edge (FREY and BASAN, 1985; LEONARD *et al.*, 1995). In their *in situ* and laboratory studies, KNUSTON *et al.* (1982) found that marsh plants were most effective in damping waves when the water depth was less than the canopy height. After the canopy was submerged (especially in storms), the effect was greatly decreased. WAYNE (1976) reported that the American *Spartina alterniflora* marsh can reduce the wave height by as much as 71% and reduce the wave energy by 92%. ASANO *et al.* (1992, 1996) and KOBAYASHI *et al.* (1993) also described the influence of marsh plants on wave attenuation. Other studies related the influences of tidal marsh vegetation on current attenuation and sediment transport. In the laboratory, the reduction of near-bed current velocity and boundary shear stress was found to be influenced by the density of stems (ECKMAN, 1983) and the height of stems (SHI *et al.*, 1995). In the field, the bottom velocity and suspended sediment concentration in the seagrass community of the Corner Inlet, Australia, were

reported to be decreased to 40%–60% and 65%–80%, respectively (ZHUANG and SHEBEL, 1991). Many studies have examined the effect of plant communities on sediment retention (SCOFFIN, 1970; GLEASON *et al.*, 1979; ALIZAI and MCMANUS, 1980; STUMPF, 1983; STEVENSON *et al.*, 1988; WANG *et al.*, 1993; LEONARD *et al.*, 1995). The gradual differentiation of sediment load causes a decrease in grain size from the lower flat to the higher flat (EVANS, 1965; PESTRONG, 1972a). This pattern of sediment distribution mainly results from the reduction of water energy across the tidal flat (VAN STRAATEN, 1961; POSTMA, 1967).

Most of the progresses made in this field have derived from regions where the accretion rate was low or even the marsh land was losing such as many coasts in the North America and Europe (VAN STRAATEN, 1961; EVANS, 1965; PESTRONG, 1972b; MACAFFREY and THOMSON, 1980; STUMPF, 1983; STEVENSON *et al.*, 1988; WANG *et al.*, 1993; LEONARD *et al.*, 1995; WILLIAMS and HAMILTON 1995). As for the botanical environment, most studies have aimed at *Spartina* (GLEN-SON *et al.*, 1979; KNUSTON *et al.*, 1982; STUMPF, 1983; FREY and BASAN, 1985; WANG *et al.*, 1993; HUTCHINSON *et al.*, 1995; SHI *et al.*, 1995, 1996) or seagrass communities (FONSECA *et al.*, 1982; WARD *et al.*, 1984; ZHUANG and SHEBEL, 1991; FONSECA and CALAHAN, 1992), although *Salicornia* (BOADEN and SEED, 1985), *Juncus* (LEONARD *et al.*, 1995), algal (ESCARTIN and AUBREY, 1995) and reed (ALIZAI and MCMANUS, 1980) were also related. Up to now, nearly no research has concerned with *Scirpus* though it is one of the primary colonizers on tidal flats of the world. (BOADEN and SEED, 1985). In addition, little work has focused on tidal wet-

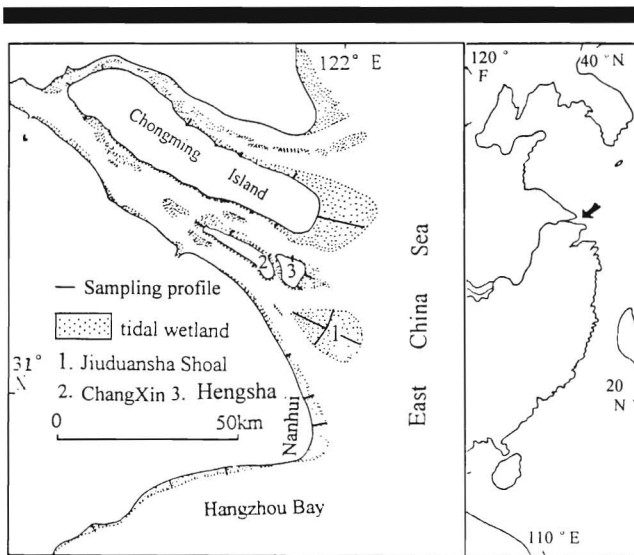


Figure 1. Map of the study area in the Yangtze Delta showing the distribution of tidal wetlands and sapling profiles.

lands like those in the Yangtze Delta which experiences a high accretion rate. This article, based on measurements and sediment sampling on the tidal wetlands of the Yangtze Delta, mainly deals with hydrographic processes, sedimentary features, accretion rate and their interactions. The purpose of the author is to provide a specific example for comparison of tidal wetland sedimentation in the Yangtze Delta with those in other regions and other environments.

STUDY AREA

About 85,000 hectares of tidal wetlands are distributed in the present Yangtze Delta (Figure 1), not including the another 80,000 hectares which has been reclaimed in the past half century (YANG *et al.*, 1997). Yangtze River, the third largest in the world, carries 928×10^9 m³/yr. water and 468×10^6 t/yr. suspended sediment into the East China Sea at 31°N and 122°E on an average (CHEN *et al.*, 1986). 5.1%, 27.6% and 67.3% of the riverine sediment supply are >0.1mm, 0.1–0.05mm and <0.05mm in grain size, respectively, with $d_{50}=0.027$ mm or $\Phi_{50} = 5.21$ (YANG, 1994). More than half of the sediment influx is deposited in the deltaic area (CHEN *et al.*, 1986), which forms new tidal wetlands at a rate of nearly 2,000 hectares per year (YANG *et al.*, 1997). About one third of the present wetland area is colonized by *Scirpus* or reed vegetation. On the eastern coast of the Chongming Island and on Jiuduansha, the intertidal zone can exceed 10km in width, with the uppermost 3–4km being colonized by the marsh vegetation. On many other intertidal shoals, marshes colonize the central and uppermost parts like on Jiuduansha. Water salinity in the deltaic area is usually between 0.1‰ and 15‰ (CHEN, *et al.*, 1986; GSICI, 1996). Two species of *Scirpus*, *S. mariquete* and *S. triquiter*, colonize the tidal wetlands as pioneer plants, respectively in the mean salinity environment of 3.0‰–18.8‰ and <3.0‰ (CHEN *et al.*, 1986). Single *Scirpus* stems can survive in low tidal flats, but

the lowest reach of continuous plant communities is about 30–50cm above the middle tide level due to the limitation of natural conditions such as water energy (YANG and CHEN, 1994).

Tides in the delta are semi-diurnal. According to the historic records from 20 hydrometric stations, the average and maximum tidal ranges are respectively 2.67m and 4.62m at Jiuduansha, 2.62m and 4.64m at the Hengsha Island, 2.45m and 4.49m at the Changxin Island, 2.47 m and 4.49m at the middle southwestern coast of the Chongming Island, 2.59m–3.08m and 4.81m–5.95m along the northern and northeastern coast of the Chongming Island, 1.96m–3.21m and 5.06m along the southwestern mainland coast of the Yangtze River mouth (the tidal range decreases with increasing distance from the river mouth), 3.21m–4.01m (at Jingshan Station) and 5.06m–6.24m (at Jingshan Station) along the east part of the northern coast of the Hangzhou Bay (the tide range increases westward). Tidal current velocity was found to have a maximum of 2.45m/s in the Yangtze River mouth and 3.15m/s in the Hangzhou Bay, although it was normally less than 2.0m/s in the former area and 2.5m/s in the latter area (CHEN *et al.*, 1986; GSICI, 1996). The delta is characterized by monsoon climate, with prevailing winds from the sea in the seasons of summer and autumn and from the continent in the seasons of winter and spring. Waves in the delta are dominated by wind-induced ones. Normally, 4 to 5 storms affect the deltaic coast in a year, half being tropical cyclones and half being cold strong winds (cold waves), with a maximum velocity larger than 30m/s recorded during the Typhoon 9711 in August, 1997. The mean and maximum wave height was measured to be 1.0m and 6.2m on the sea side of Jiuduansha, 0.2m and 3.2m on the south side of the Changxin Island and 0.4m and 4.0m in the northern part of the Hangzhou Bay (CHEN *et al.*, 1986).

The suspended sediment concentration (SSC) is high in the study area. In summer, the vertical mean value of SSC was 0.89–15.85g/l on the northern and northeastern coastal area of the Chongming Island, 0.46–0.51g/l on the southwestern coastal area of the Chongming Island, 0.62–0.70g/l on the northeastern water of the Changxin and Hengsha islands, 0.70–0.79g/l on the southwestern water of the Changxin and Hengsha islands and 0.54g/l in the northern coast of the Hangzhou Bay. Within the Yangtze river mouth, SSC is higher in summer than in winter. However, contrary law occurs in the forward area of the river mouth (where SSC changes between 0.1–0.7g/l in the surface and 1.0–8.0g/l near the bottom) and in the northern coast of the Hangzhou Bay. Anywhere in the delta, SSC is greatly influenced by tide and wind conditions. SSC in spring tide is several times as much as in neap tide. In the condition of wind velocity being 10m/s, SSC was measured to be 4 times as much as in fair weather. The mean grain size of suspended sediment in the river mouth was 6Φ – 9Φ on the surface and 5Φ – 7Φ near the bottom; in the Hangzhou Bay, it was respectively 6.5Φ – 8.6Φ and 5.5Φ – 7.5Φ (CHEN, 1986; GSICI, 1996). Large tidal creek system develops only on the eastern coast of the Chongming Island and on Jiuduansha. In other intertidal areas, the current is dominated by longshore component, which is unfavorable to the formation of tidal creeks. High aggradation rates occur

in the northeastern and eastern coasts of the Chongming Island, on Jiuduansha and in the eastern coast of Nanhui. In the eastern coast of the Chongming Island, the shoreline moved seaward at a rate of 200m–300m/yr. in the past several decades. From 1973 to 1995, the area of the tidal wetlands on Jiuduansha increased by 77% (unpublished computation by the author). The reclamation projects have greatly changed the zonation of tidal wetlands with the exception of Jiuduansha. The seawalls constructed for reclamation have been sited near the mean high tidal level. In result, the supratidal zone is often lost. The present highest elevation of Jiuduansha is about 50cm above the mean high tidal level.

METHODS

Experiments for comparison of current, wave and suspended sediment concentration between the marsh and the bare flat were sited in the eastern coast of Nanhui. Measurement on current velocity was also conducted on tidal flats of the islands and the northern coast of the Hangzhou Bay. Representative cross-shore profiles were selected to collect sediment samples and measure the change in elevation of the sediment surface. In order to compare hydrographic processes between a marsh and its adjacent non-vegetated flat with the same elevation, an artificial bare flat was produced by removing part of the marsh vegetation and an artificial "marsh" was formed by "planting" plastic "grass" on a natural bare flat. The cross section of the artificial stems was round, with a diameter of 3mm, just like that of the *S. triquiter* (one of the two primary colonizers). One end of the "stem" was fixed beneath the sediment surface and the rest part emerged above the sediment surface. Couples of field measurement were devised in a line parallel to the contour to obtain data on hydrographic conditions on the marsh and the bare flat (both natural and artificial). In addition, cross-shore profiles from the subtidal zone to the high tidal flat were arranged for current measurement. Near-bed currents were measured with HLJ 1-1 Printing Current Meter. The meter was put 5cm above the sediment surface. Wave spectrums were obtained by watching and recording scale readings on marked stakes. Water samples were collected with 100-ml plastic bottles. The time interval in water sampling was 3 min for the first five samples and 6 min for the rest. Water samples were filtered through standard pre-weighed filters. After the filters were dried in an electric oven at 60°C, they were drawn out and weighed. Sediment trapped by the stems and leaves of the marsh plants was washed using distilled water and processed in the same way as suspended sediment concentration was treated. Surficial deposit was sampled by collecting the top of a few millimeters. The samples were taken into laboratory and analysed for grain size and organic content. The experiment for grain size was conducted jointly using Sieve Method and Tube Method following Stokes Principle. The definition of sedimentary parameters, Φ_{50} , M_z , σ_1 , SK_1 and K_g , followed FOLK and WARD (1957). Accretion and erosion changes in sediment surface were measured through Rod Method and Buried-plate Method. The distance between two adjacent measurement sites in the same profile was usually

100m. In this way, the elevation of sediment surface was periodically measured.

RESULTS

Processes Affecting Sedimentation

Hydrographic processes on the marsh were significantly different from those on the bare flat. In addition, the near-bed current was found to attenuate with increase in elevation in the cross-shore profile.

Near-Bed Currents

The mean velocity of near-bed currents was separately 0.08m/s and 0.32m/s on the higher marsh and its adjacent artificial bare flat, 0.37m/s and 0.42m/s on "marsh island" and its adjacent natural bare flat in the transitional zone between the marsh and the bare flat area, and 0.37cm/s and 0.47cm/s on the artificial "marsh" and its neighboring bare flat. Near the mean sea-level in elevation, the spring velocity was 1.54 times as much as neap velocity on the bare flat and 2.97 times as much as neap velocity on the artificial "marsh". It is impressive that the marsh vegetation has significant influence on flows. Based on the measurement, several conclusions were made: (a) the near-bed velocity fluctuates within short time, without systematical increase or decrease; (b) in each of the comparative couples, the near-bed velocity on the marsh is always lower than that on the adjacent bare flat, though the two sites are situated in the same elevation; (c) the current-attenuating parameter of the marsh (defined as the ratio of velocity on the marsh to its adjacent bare flat) is negatively related to the cover ratio of the plant community, according to the comparison between A_1/A_3 and A_2/A_3 , (d) the current-attenuating parameter of the marsh vegetation is negatively related to the distance from the seaward edge of the marsh (because it decreased from 0.84 to 0.70 and to 0.34 as a result of the transformation from C_1 to B_1 and to A_2), (e) the ratio of D_1/D_2 during neap tide (0.37) was much less than that during spring tide (0.71), which suggests that the current-attenuating parameter of the marsh is positively related to the primary current velocity (Table 1).

Across the shore, the near-bed current decreases shoreward from the subtidal area to the marsh. For example, on the eastern coast of the Chongming Island, the mean near-bed velocity was 0.80m/s, 0.49m/s and 0.36m/s respectively in the subtidal zone, the low flat and the middle flat, and the maximum velocity was 1.31m/s, 0.84m/s and 0.57m/s separately in the three sites. In the northern coast of the Hangzhou Bay, the extreme value of velocity was 80cm/s-120 cm/s in the subtidal zone, 60cm/s- 80cm/s on the low flat, 30cm/s-50cm/s on the middle flat and < 30cm/s on the high flat. Similar features were found in the Changxin, Hengsha, Jiuduansha, the eastern coast of Nanhui and the northeastern coast of the Chongming Island.

Waves Before Plant Canopy Was Submerged

Waves in the ellipse-like *S. mariquete* "marsh island" were much lower and longer than those on the adjacent bare flat (Figure 2 and Table 1). The average and maximum wave

Table 1. Hydrographic parameters' ratios of marsh to bare flat as well as the natural conditions.

Parameter & condition	Near-bed current velocity						Near-bed SSC C ₁ /C ₂	Wave height C ₁ /C ₂
	A ₁ /A ₃	A ₂ /A ₃	B ₁ /B ₂	C ₁ /C ₂	D ₁ /D ₂	D ₁ /D ₂		
Mean	0.19	0.34	0.70	0.84	0.71	0.37	0.71	0.45
Maximum	0.33	0.64	0.85	0.95	0.93	0.71	1.13	
Minimum	0.09	0.09	0.38	0.60	0.21	0.13	0.41	
Tidal condition	spring	spring	normal	spring	spring	neap	spring	spring
Above sea-level (m)	1.3	1.3	0.6	0.3	0	0	0.3	0.3
Number of figure couple	16	16	12	19	18	15	9	#

A₁ was in *Spartina alterniflora*; A₂B₁ and C₁ were in *Scirpus mariquete*; D₁ was in artificial *Scirpus triquiter*; A₃ and B₂ were on artificial bare flat; C₂ and D₂ were on natural bare flat. Stem cover ratio was respectively 1.26% at A₁, 0.20% at A₂ and 0.53% at B₁ and C₁. Both A₁ and B₁ were 5 m away from the seaward margin of the corresponding vegetation zone. The major and minor axis of the "marsh island", in the center of which C₁ was located, was respectively 8 m and 5 m. A₁A₂ = A₂A₃ = B₁B₂ = 20 m, C₁C₂ = 10 m, B₁A₂ = 300 m. D₁ was located in the center of the artificial marsh which was 300 m long across shore and 100 m wide along shore. D₁D₂ = 100 m. #23 waves at the bare flat site and 32 waves at the marsh site during the same period. The current velocity was based on a tidal cycle measurement while the SSC (suspended sediment concentration) and wave were respectively on a measurement at the beginning stage of flood submergence

height in the marsh was respectively 43% and 40% as much as that on the bare flat (the average and maximum wave energy in the marsh was 19% and 16% as much as those on the flat because wave energy is positively proportional to the square of wave height), but the average wave period on the marsh was 140% as much as that on the flat. Another measurement at B₁ (on the marsh) and B₂ (on the bare flat) gave the result that when the average wave height was 2.0cm at B₂ and <0.5cm at B₁. Observations made by the author showed: (a) waves on the bare flat have the feature of wind-induced solitary wave while those on the marsh were "swells" in rows (it was difficult for winds to blow the water surface in the marsh due to the cover of vegetation especially before the plant crown was submerged); (b) after a wave migrated shoreward for a certain distance in the marsh, it was thoroughly eliminated. This distance depended upon the original wave energy and the density of the vegetation. The higher the original wave energy, the longer the distance; the denser the plants, the shorter the distance. Normally, waves disappeared after they went shoreward for about 50 meters into the *S. mariquete* marsh.

Near-Bed Suspended Sediment Concentration

Two understandings originated from the work on near-bed SSC: (a) SSC fluctuated from 0.8017g/l to 1.932g/l on the bare flat and from 0.6257g/l to 0.9135g/l on the "marsh island"; with the ratio of maximal to minimal being 2.4 on the bare flat and 1.5 on the "marsh island"; (b) SSC on the 'marsh island' was normally less than that on the bare flat, the average ratio being 0.71 (Table 1).

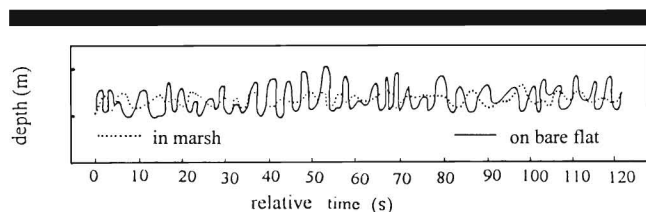


Figure 2. Comparison of the wave process between the marsh and its adjacent bare flat at the beginning of submergence

Sedimentary Features

Organic Content

According to the data of 39 samples (21 samples from marshes and the rest from bare flats) in the deltaic coast, sediment on tidal wetlands was mineral-dominated, with organic matter being only 0.12%–2.83%. Generally, the organic content was higher on the marsh than on the bare flat and on the high marsh than on the low marsh. As shown in Figure 3, organic content was positively related to Mz (mean grain-size in Φ unit), with the relationship being $O(\%) = 0.0041 Mz^{3.09}$ ($r = 0.9434$, $n = 39$, $Mz = 3.18$ – 8.54). No significant increase in organic content has been found in the vertical profile of the deposit stratum even to the depth of 1.5m.

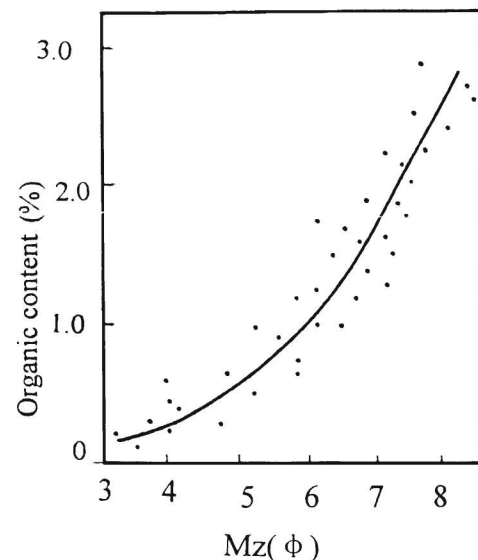


Figure 3. Relationship between organic content and Mz (mean grain-size in Φ unit)

Table 2. Comparison of sediment parameters among different environments of the tidal wetlands.

Environment	Folk and Ward (1957) parameters					Composition (%)		
	Φ_{50}	Mz	σ_1	SKI	Kg	sand	silt	clay
Reed marsh (73 samples)								
Minimum	6.25	6.85	2.34	0.35	0.70	0	47.69	18.93
Mean	7.05	7.68	2.85	0.43	1.22	0.54	67.06	32.40
Maximum	8.15	8.82	3.08	0.54	1.88	10.07	80.99	52.31
<i>Scirpus</i> marsh (86 samples)								
Minimum	3.68	3.78	0.81	0.14	1.01	0.16	34.17	0
Mean	6.23	6.83	2.33	0.45	1.40	8.95	67.42	23.62
Maximum	7.19	7.82	2.83	0.58	1.85	65.83	94.97	36.34
Bare flat (153 samples)								
Minimum	2.74	2.87	0.34	-0.14	1.05	1.09	1.24	0
Mean	3.96	4.12	0.96	0.32	1.35	54.60	44.03	1.37
Maximum	6.18	6.77	2.30	0.74	3.23	98.76	90.07	24.57

Ninety-eight samples were collected from the Chongming Island, 32 from Changxin Island, 18 from the Hengsha Island, 75 from Jiuduansha, 53 from the southwestern coast of the river mouth and 36 from the northern coast of the Hangzhou Bay (Figure 1). The grain-size of sand, silt and clay were respectively 2.0 mm–0.063 mm, 0.063 mm–0.004 mm and <0.04 mm

Grain-Size Parameters

Analysis of 312 samples, 159 from marshes and 153 from bare flats, has enabled the variation in sedimentary parameters in different environments to be revealed (Table 2). The range of Φ_{50} and Mz was respectively 2.74–8.15 and 2.87–8.82, the maximum proportion of sand and clay was respectively 98.76% and 52.31%. Generally speaking, Φ_{50} , Mz and σ_1 increased along the cross-shore section from the low flat to the high marsh. This means that sediment became finer and less sorted with increase in elevation. It must be pointed out that details in distributive pattern of grain size is changeable spatially and temporally. In general, the sediment on the sea side of the islands (here including Jiuduansha) was much coarser than other places. For example, the coarsest sample, with Φ_{50} being 2.74, was collected at the eastern coast of the Hengsha Island. Storms usually coarsened surficial sediments on bare flats and the low margin of marshes. For instance, after Typhoon 9711 (it lasted for 3 days from 19 through 21, August, 1997), a continuous sand sheet covered the low margin of the marsh around Jiuduansha. The sand sheet was 40m–50m in width and its cross-shore section was

convex-lens-like, with the central thickness being 20cm–30cm. Although the storm deposits were dominated by sands (with grain-size being 0.1mm–0.15mm), many shells (full or broken) and mud pellets mixed in the sediment. Beneath the sand sheet were dead *Scirpus* stems and primary silty deposit.

Accretion and Erosion

Changes in the elevation of sediment surface are dominated by accretion in many tidal wetlands, especially those in the forward of the delta. Erosion events, normally transient, periodic and recoverable, mainly occur on bare flats. Existence of the marsh vegetation has great influence on the processes of accretion and erosion.

Trapping and Protective Effect of Marsh Canopy

Sediment trapped by plant stems and leaves amounted to 64.4mg/stem and 47.6mg/stem dry weight, on the average, respectively in *S. mariquete* and *S. triquiter* communities. The difference between these two communities was due to the flora structure: (a) 2 to 3 leaves derives from the stem of *S. mariquete*, but there is no leaf on the stem of *S. triquiter*; (b) under the microscope, the surface of *S. triquiter* is much smoother than that of *S. mariquete*.

It was found that the marsh plant covering played an important role in protecting sediment surface and promoting deposition of the fine sediment. The marsh surface kept in accretion even if the bare flat experienced strong erosion. For example, in a period of 100 days from Jun. 15 to Sept. 21, 1987, the marsh surface in the eastern coast of Nanhui accreted for 16.2 cm while the upper bare flat and the lower bare flat was eroded by 9.3 cm and 4.3 cm, respectively. (Figure 4). During a storm lasted 3 days, the bare flat was eroded for 13.7cm while the marsh accreted for 1.2 cm on the average (Figure 4).

Rate of Accretion

The measurement on vertical accretion on Jiuduansha (Table 3) showed that during the 102 days from May 1 to August

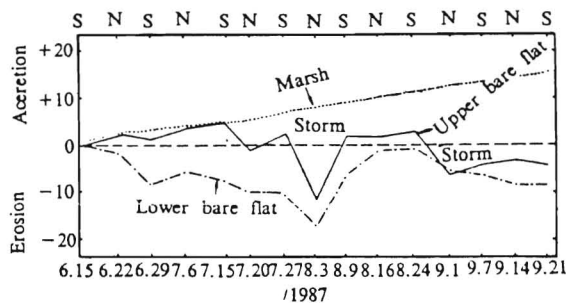


Figure 4. Comparison of erosion-accretion processes between the marsh and the bare flat in a cross-shore profile in the eastern coast of Nanhui (the marsh curve and the bare flat curve stands for the average of 4 sites and the average of 22 sites, respectively).

Table 3. Vertical accretion (cm) in the tidal marshes on Jiuduansha in the growth season of vegetation.

Site name	N1	N2	N3	S1	S2	W1	W2	W3	E1	E2	E3	M1	M2	M3	M4	M5
May 1–Aug. 10, 1997		14			4	6	5	6		10						10
Aug. 10–Nov. 10, 1997	2	11	8	6	4	11	4	7	11	10	6	12	20	9	18	10
Vegetation	Sm	Sm	r	Sm	r	St	St + r	r	Sm	Sm + r	r	Sm	Sm	Sm	Sm	Sm
Relative elevation	L	M	H	M	H	M	H	H	M	H	H	L	M	L	M	L

"Site name" N, S, W, E and M represent different sample profiles. Sm, Sq and r respectively represents *S. marquette*, *S. triquiter* and reed. "Relative elevation" L, M and H respectively represents low, middle and high marshes

10, the 7 marsh sites accreted 4 to 14cm with the average being 7.9cm (0.77mm/d); during the 92 days from August 10 to November 10, the 16 marsh sites accreted for 2 to 20cm with the average being 9.3cm (1.01mm/d) while the bare flat site was eroded for 45cm. According to these data, the average annual accretion on the marsh of Jiuduansha is about 20–30 cm. This is comparable to many other places in the delta. For example, the mean accretion rate of cross-shore profiles was 32–43cm/yr in the eastern coast of the Chongming Island, 5–8 cm/yr. in the northern coast of the Hangzhou Bay and 18 cm/yr. in the eastern coast of Nanhui. High accretion rates were also found, not quantitatively, in the northeastern coast of the Chongmin Island, the upstream head of the Changxin Island and on other intertidal shoals besides Jiuduansha. The maximum accretion rate, shown in site M₂ in Table 3, might be about 40cm in the period from May 1 to November 10, taking into account the similar average results of site N₂, S₂, W₁, W₂, W₃, E₂ and M₅ in the two periods. It can be found from Table 3 that the mean accretion rate of the middle marsh was about 1.5 times as much as that of the low marsh and about 2.0 times as much as that of the high marsh. This may be related to the fact that the low marsh (especially the forward area of the marsh) experienced higher water energy and the high marsh experienced lower frequency of inundation.

Erosion Events

Erosion during a storm is usually severe on the bare flat. During the storm period from 25th to 28th, September 1983, with a maximum wind velocity of 19m/s, the cross-shore profile was eroded by 27cm to 37cm in the northeastern coast of the Chongming Island, 60cm in the eastern coast of the Chongmin Island, 40cm in the southwestern coast of the Chongming Island and 30cm in the eastern coast of Nanhui. Seasonal erosion on bare flats occur in summer and autumn when winds come from the sea. This is especially significant in the forward of the delta where the coast face the open sea. Erosion produced in summer and autumn is compensated or even exceeded by accretion in winter and spring. The seasonal change in the elevation of sediment surface is usually greater in the middle flat than in the low flat and the high flat. For instance, in the eastern coast of the Chongming island, the difference between the highest elevation and the lowest elevation in 1984, was 30cm, 30cm, 48cm, 100cm, 55cm and 6cm respectively at sites where the primary elevation (above the Theoretic Lowest Tidal Level) was 0.14m, 0.64m, 1.21m, 1.74m, 1.95m and 3.3m (the elevation of the middle tidal level is about 2.0m).

DISCUSSION

The marsh acts as an enormous permeable obstacle for the motion of flood water. The friction between water and the vegetation slows flows and the friction between air and the vegetation weakens the wind. Before the canopy is submerged, it is difficult for the wind to blow the water surface and generate waves because of the sheltering of the vegetation. This is part of the cause why wave-damping is most effective when the water depth is less than the plant height (KNUSTON, 1982). When the water (either currents or waves) moves through the plants, part of the energy loses due to the resistance of stems and leaves. It decreases the flow speed and the wave height. The attenuation of hydrodynamics in turn causes a decrease in the sediment-load capacity of the water. As a result of this, accretion is enhanced, erosion is hindered and the deposit become finer. The influence of marsh plants (*Scirpus* and reed) on wave, current and suspended sediment concentration is comparable to those of *Spartina* and seagrass found by WAYNE (1976) and ZHUANG *et al.* (1991). Sediment particles trapped by plants will settle down on the sediment surface due to winds, rains or the death of the plants. The amounts of 64.4mg/stem and 47.6mg/stem will raise the sediment surface by 0.08mm in *S. marquette* community and 0.03mm in *S. triquiter* community, taking into account the stem density in the measured sites. The annual accumulation through this mechanism will be much greater because some of the sediments trapped by the plants will deposit in some way and new sediments in the flood water will adhere to the plants again before they wither and fall. However, even if the sediment surface was raised by the amount given above in each of the near 500 tidal cycles in the growth season, the total accumulation would be only 4.0cm and 1.5cm respectively in the *S. marquette* community and the *S. triquiter* community, accounting for only about 5% to 10% of the total accretion. So the sediment-trapping effect of the marsh vegetation on vertical accretion is much less important than hydrodynamic sedimentation in this delta. This result agrees with that given by LEONARD (1995) in a marsh of the west-central Florida where the contribution of sediment retention by *Juncus roemerianus* to the total deposition was 4% to 5% on the average and 9% as the maximal. However, it seems contradictory to the conclusion by STUMPF (1983) that the sediment trapped by *S. alterniflora* in the Delaware salt marsh can account for about half of the total deposition.

In many tidal marshes of the world, the accretion rate is only a few millimeters per year (FREY and BASAN, 1985). Whether or not the accretion rate is able to balance the effect

Table 4. Accretion rates of different tidal marshes in the world.

Location	AR (mm/yr)	Local SLR (mm/yr)	Marsh Vegetation	Reference
Dovey Estuary, England	5			RICHARDS (1934)
Delaware, U.S.	6			STEARNS & MACCREARY (1957)
Long Island, NY, U.S.	4.7 to 6.3	2.9	<i>S. alterniflora</i>	ARMENTANO & WOODWELL (1975)
Connecticut, U.S.	2 to 5	2.5	<i>S. patens</i>	HARRISON & BLOOM (1977)
Barataria Basian, LA, U.S.	7.5	9.2		DELAUNE, et al. (1978)
Georgia, U.S.	4			LETZSCH & FREY (1980)
Lewes, Delaware, U.S.	5	3	<i>S. alterniflora</i>	STUMPF (1983)
Chesapeake Bay, U.S.	1.7 to 3.6	3.9		STEVENSON, et al. (1985)
Norfolk, UK	5.6	2		FRENCH & SPENCER (1993)
West-central, FL, U.S.	1.2 to 7.2	1.5 to 2	<i>J. roemerianus</i>	LEONARD et al. (1995)
Fraser Delta, Canada	2.6 to 20.5		<i>Sirpus</i> et al.	WILLIAMS & HAMILTON (1995)
Yangtze Delta, China	50 to 500	2	reed, <i>Sirpus</i>	This study

AR: accretion rate SLR: sea level rise

of sea level rise is an important topic for these marshes (WANG *et al.*, 1993). Table 4 indicates the great difference in accretion rate of the tidal marshes between the Yangtze Delta and coasts in America and Europe. It shows that the accretion rate of the marsh in the Yangtze Delta is 10 to 100 times as high as those of other studied marshes in the world. What is the reason for this difference? It should be attributed to the great difference in SSC and tidal influx. The tidal influx is directly related to the tide range while SSC is related to both the sediment supply and the water energy. Table 5 provides a comparison of hydrographic and sedimentary processes. Taking an example of the comparison between the Yangtze Delta and Delaware, the mean tidal range, mean current velocity of the tidal cycle (MCVT), suspended sediment concentration (SSC) and sediment trapped by plants (STP) of the former is 3 to 5 times, 1 to 6 times, 50 to 60 times and 50 to 70 times as much as the latter. The proximity of the ratio of tidal range to that of current velocity is reasonable because tidal current is directly proportional to tidal range. So is reasonable the proximity of SSC to STP since stems have more chances to trap sediment in the condition of higher SSC. That SSC ratio is much higher than MCVT ratio may be both due to the correlation between current velocity and sediment-load capacity (normally sediment-load capacity is directly proportional to the 2nd to 3rd power of current velocity) and due to the great sediment supply of the Yangtze River.

The shoreward increase in organic content usually reflects both the influence of marsh plants as a deposit source and the increase in clay proportion, as pointed out by WILLIAMS and HAMILTON (1995). The organic content of the tidal wet-

land sediment in the Yangtze Delta is much lower than those of not only the peaty, organic-dominated tidal marshes in the Gulf coasts (KOLB and VAN LOPIK, 1966; HATTON *et al.*, 1983) and New England (MCCAFFREY and THOMSON, 1980) but also the mineral-dominated tidal marshes in many places in the world. For example, the organic content of the surficial sediment in the tidal marsh of the Fraser Delta is 45% in the high marsh, 23.9% in the middle marsh and 3.1%-6.4% in the low marsh (WILLIAMS and HAMILTON, 1995); the organic content was reported to be 14% in *Spartina* marshes and 18% in *Salicornia* marshes in California (PESTRONG, 1972a, 1972b) as well as 8% to 9% in mangrove swamps in the southern China (YNANG, 1988). The low organic content in the Yangtze deltaic wetlands is clearly related to the high accretion rate due to the great amount of riverine sediment supply. The high correlative coefficient, 0.94, between the organic content and the sedimentary grain size results in a hypothesis that the organic content in the tidal wetlands of the Yangtze Delta is controlled by the sedimentary process and not by the accumulation of organic matter.

SUMMARY AND CONCLUSIONS

The near-bed current velocity attenuates shoreward from > 100cm/sec in the subtidal zone to < 10cm/sec in the high marsh. Compared with the adjacent bare flat of the same elevation, the mean near-bed current velocity decreases to 19-84%, the mean wave height and the mean near-bed suspended sediment concentration at the beginning of the submergence decreases to 45% and 71%, respectively, in the marsh area. The influence of marsh plants on hydrographic

Table 5. Comprehensive comparison of hydrographic and sedimentation processes in tidal marshes of the Yangtze Delta and the Atlantic and Gulf coasts in America.

Location	Mean tidal range (m)	MCVT (cm/s)	SSC (mg/l)	STP (g/m ²)	AC (mm/yr)	Reference
Lewes, Delaware, U.S.	0.8	≤5	10 to 50	1.78 to 2.92	5	STUMPF (1983)
West-central, FL, U.S.	0.9	4	5 to 15	0.04 to 0.77	1.2 to 7.2	LEONARD et al. (1995)
Terrebonne, LA, U.S.	0.3	2 to 4	10 to 30			Wang et al. (1993)
Yangtze Delta, China	2 to 4	4 to 30	626 to 2322	80 to 212	50 to 500	This study

MCVT: mean current velocity of tidal cycle; SSC: suspended sediment concentration; STP: sediment trapped on plants; AC: accretion rate

processes is related to the species and density of the plant community, the distance from the low marsh edge and the primary hydrographic processes themselves. The effect of *Scirpus* in this studied area is comparable to those of *Spartina* and seagrass found in other regions. The attenuation of hydrodynamics in the marsh enhances deposition, impedes erosion and results in finer deposit.

Compared with most previously studied areas in Europe and America, tidal wetlands in the Yangtze Delta have much higher suspended sediment concentration which causes a very high accretion rate. Higher SSC may temporarily results from stronger currents and higher wave energy, but the controlling factor which causes the high accretion rate in the Yangtze Delta should be attributed to the abundant sediment supply from the river. Although the amount of sediment trapped by the marsh plants in the Yangtze Delta is tens of times as larger as those of other marshes, its contribution to the total deposition is relatively lower in view of the high accretion rate in this area.

The organic content of tidal wetland sediment in the Yangtze Delta, less than 3%, is much lower than those found in many wetlands of the world. It is reasonable to attribute it to the high accretion rate.

Tidal wetlands in the Yangtze Delta, with fresh to brackish marsh vegetation, high water energy, large suspended sediment concentration and high accretion rate, provide a distinctive example for comparative research on coastal sedimentation in the world.

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