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Coagulation and Settling of Suspended Sediment in the Jiaojiang River Estuary, China

Yan Li†, Eric Wolanski‡ and Qinchun Xie†

†Second Institute of Oceanography
State Oceanic Administration
P.O. Box 1207, Hangzhou
Zhejiang 310012, China

‡Australian Institute of Marine Science
P.M.B. No. 3
Townsville M.C.
Queensland 4810, Australia

ABSTRACT

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The Jiaojiang River estuary, Zhejiang Province, China, receives a mean freshwater discharge of 211 m^3 sec^{-1} with a mean suspended sediment concentration of 0.18 g l^{-1}. Mean depth is less than 4 m and mean tidal range is 4 m. The water circulation and the distribution of suspended particle size and concentration were measured along the estuary in dry weather conditions in April 1991. The estuary was partially stratified in salinity and extremely turbid, with suspended sediment concentration in the turbidity maximum zone often exceeding 10 g l^{-1}. The tidal currents were asymmetric with stronger peak flood than ebb tidal currents. The suspended sediment was coagulated and the floc population was bimodal with clay-dominant flocs and silt-dominant flocs of median size 50 and 500 μm respectively. The clay-dominant flocs were not destroyed by ambient turbulence and were present throughout the water column. The silt-dominant flocs were very porous, and readily broken by turbulence, had a settling velocity comparable to that of clay-dominant flocs ½ to ⅓ their sizes, and existed only for tidal current speed <0.5 m sec^{-1}. Both flocculation and hydrodynamic processes sort clay particles from silt particles in the estuary.

ADDITIONAL INDEX WORDS: *Estuary, floc, hydrodynamic processes, settling velocity, suspended sediment load, tidal currents.*

INTRODUCTION

The Jiaojiang River is located in the Zhejiang Province of China (Figure 1). The river is 198 km long and drains a basin of 6,519 km^2. Its annual runoff is 6.66 × 10^9 m^3, corresponding to a mean discharge of 211 m^3 sec^{-1}. It carries a sediment discharge of 1.23 × 10^6 tons, corresponding to a mean sediment concentration of 0.18 g l^{-1}. The estuary is shallow with a mean depth less than 4 m. Sea water penetrates about 20 km in the estuary. Macrotides prevail with a mean tidal range over 4 m. The estuary is very turbid and silting at a rate of up to 0.2 m yr^{-1}, requiring constant maintenance dredging for navigation from the sea to the port of Haimen (Jiaojiang City).

The river sediment is mostly silty sand; the suspended sediment in the estuary is fine, with dispensed mean size of 6–8 μm, and more than 95% of the particles are silt (60%) and clay (35%); a turbidity maximum zone is present with unconsolidated fluid mud on the bottom (Bi and Sun, 1984; Fu and Bi, 1989). These investigators suggested that the turbidity maximum, and resulting silting of the estuary, results from the presence of a shallow bar at the river mouth, river sediment inflow, internal estuarine circulation and coagulation. However, none of the previous studies on the Jiaojiang Estuary measured floc size or internal sediment dynamics. Considering the very fragile nature of coagulated flocs, and their importance in estuarine sedimentation processes, special techniques are needed to evaluate their size (see a review in Gibbs and Konwar, 1986; Gibbs *et al.*, 1989). The primary purpose of this study is to evaluate the importance of coagulation in controlling sedimentation process in the Jiaojiang estuary. We show that as a result of coagulation and hydrodynamic processes acting differentially on these flocs, the pathways and fate of clay and silt particles are different in the estuary.

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METHODS AND PROCEDURES

The field study was conducted during April 12–23, 1991, aboard the research vessel 'WEICE No.

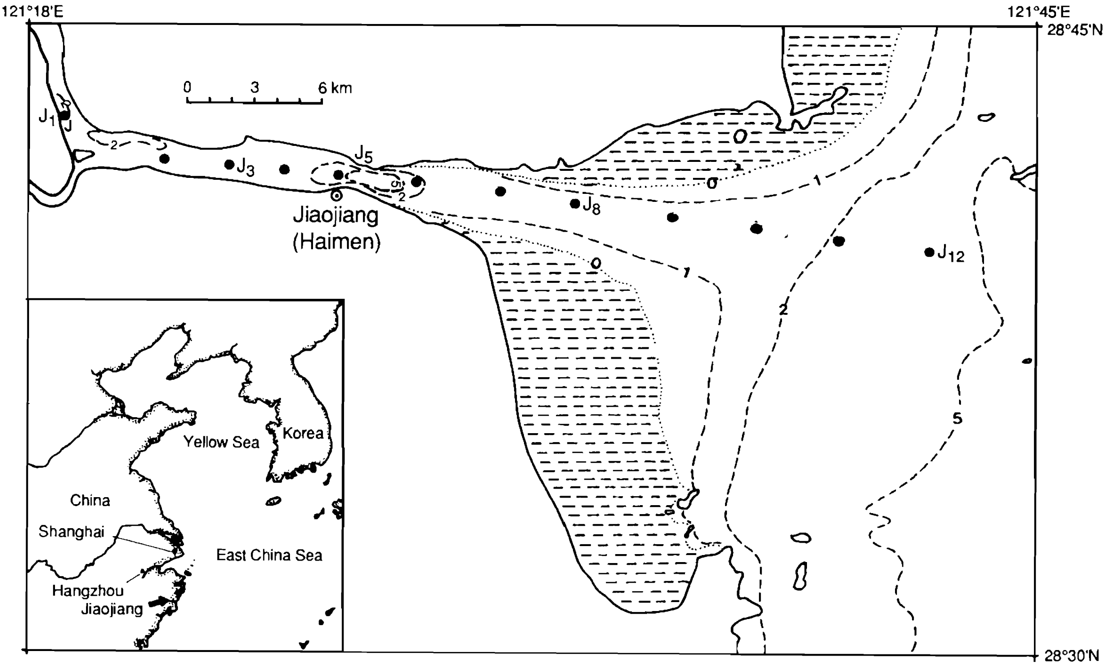


Figure 1. Location map of Jiaojiang estuary with station location. Depths with respect to low water, in metres. The area near Jiaojiang City is dredged.

l^{-1}. At station J5 (see Figure 1), an Inter-Ocean model S4 current meter was deployed at 1.75 m above the bottom. The meter logged velocity data sampled at ½ sec interval and averaged over 1 min. The logging interval was 5 min, so that the meter is operational only one minute in every five. Calm seas prevailed throughout the experiment with negligible waves. At the same site we deployed a string of Analite optical fiber backscattering nephelometers, the bottom sensor was 0.35 m above the bottom. The backscattering nephelometers also recorded data at 5 min intervals and the data was averaged over 1 min after sampling at 1 sec interval.

Vertical profiles of temperature, salinity, suspended sediment concentration (SSC) were obtained at stations J1 to J12 (Figure 1) using the 'mud probe' which is a CTD equipped with an Analite, infra-red, backscattering nephelometer (WOLANSKI *et al.*, 1988). This profiler is able to measure SSC from 0.03 to 80 g l^{-1}. Stations J1 and J12 are about 20 km apart, with station J1 near the salinity intrusion limit at high tide, and station J12 in coastal waters. The river is not navigable further upstream of station J1. The data were collected near slack high tide so the data are comparable and not biased by the tidal excursion. Additionally, at stations J1, J5 and J8, time series of such profiles were collected over 1 or 2 tidal cycles. The cross-channel distribution of salinity, temperature and SSC was also occasionally measured using this profiler.

Water samples were taken in Niskin bottles at 5 stations (J1, J3, J5, J8 and J12) at six elevations between the surface and the bottom. Additionally water samples were collected at 0.3 m, 0.6 m and 1 m above the bed using three horizontal samplers which are essentially horizontal Niskin-type bottles 60 cm long and 10 cm diameter, mounted on a solid frame. The Niskin bottles were back on board within half a minute of sampling underwater and water samples were then obtained immediately. The water samples were not taken from these bottles using the normal ports on the bottom of the bottle. In view of the fragile nature of flocs, the samples for the microscope were drawn by lowering a microscopic slide into the sampling bottle through the top opening and holding a wa-

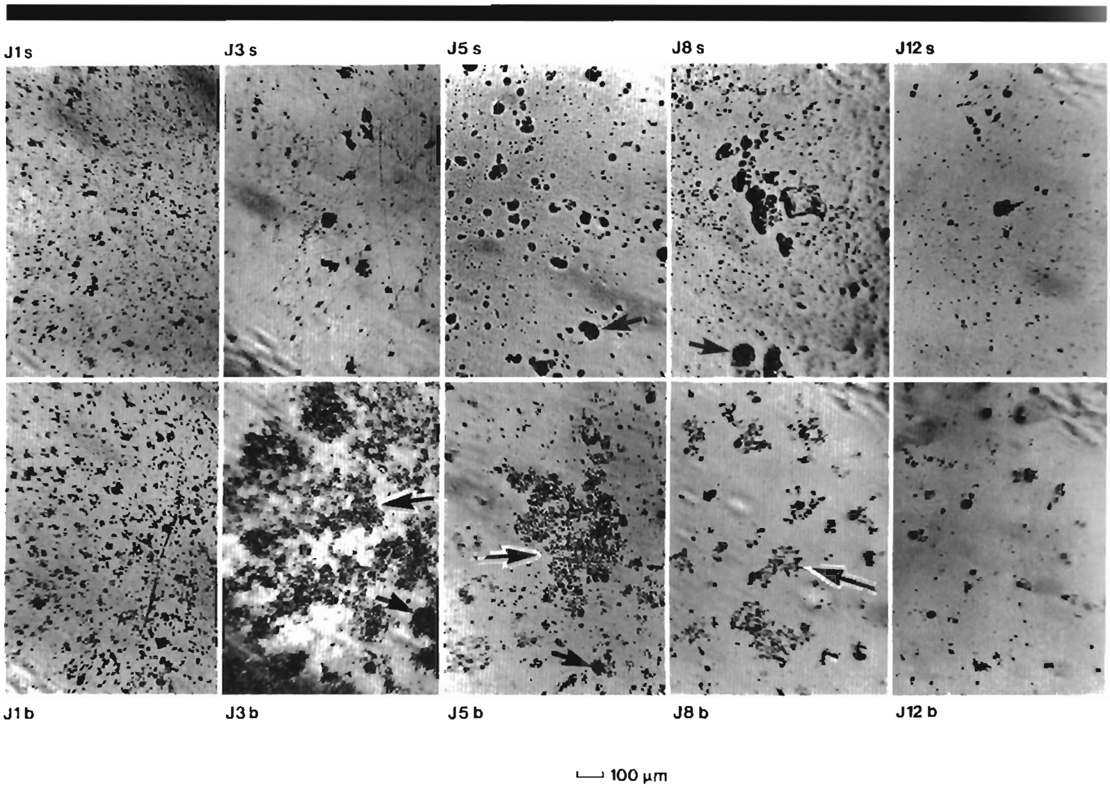
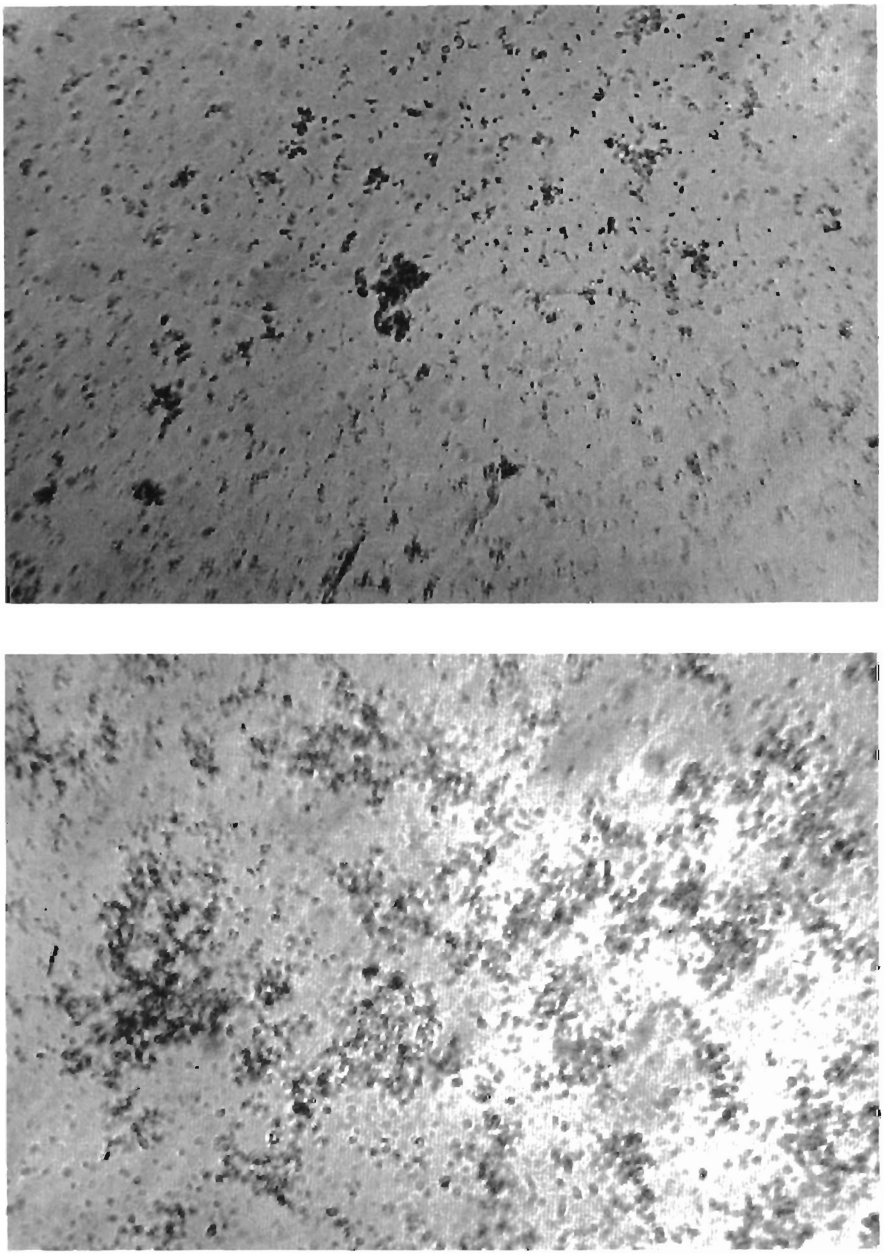


Figure 2. Photomicrographs of flocs at stations J1, J3, J5, J8 and J12 near the surface (s) and bottom (b) from samples taken at the high tide on April 21, 1991. The black arrows with a white border point to 'loose flocs'. The other black arrows point to 'dense flocs'.

ter film about 1 mm thick, following the technique pioneered by Gibbs (Gibbs and Konwar, 1986; Gibbs *et al.*, 1989). The slides were then mounted on a microscope within a minute of the Niskin bottles' recovery and were photographed soon after the flocs settled on the slide. The thickness of the water film was selected so that the flocs on the slide did not overlay. The photograph readily yielded floc size from 5 to 800 μm. Enlarged photographs were digitized to determine floc size distributions. These distributions are referenced to the Wentworth grain-size classification using the 'phi scale'. The distributions refer to volume percentage versus floc size in the range 0.5 to 7.5ϕ. When measuring along-channel distribution, profiles and water samples were collected at high tide at station J1 to J12 (see Figure 1) to be reasonably comparable. Additionally water samples processed in the same manner were also collected at hourly intervals for 1 or 2 tidal cycles at stations J1, J5 and J8, which are located respectively upriver, in the middle and oceanward of the turbidity maximum zone.

The settling velocity distribution of flocs was determined using the Postma's 'pipette' method. A plexiglass, cylindrical, water sampler with a height of 60 cm and a volume of 2.5 l was used to collect water samples. The sampling tube is horizontal when lifted upwards under water. On reaching the surface, the tube rotates to be upright. From this time settling occurs and the sampler performs as a settling tube (McCave, 1979). Samples of 50 ml were siphoned at different depths and time and the weight of suspended sediment of each of these samples was measured. This technique yields the distribution of settling velocities for assumed quartz particles of 63, 31, 16, 8, 4 and 2 μm.

Finally a simple laboratory experiment was carried out to show the large difference between the rates of breakage of clay flocs and clay-silt flocs with increasing turbulence. Salinity was kept at



3a

3b

100 μm

Figure 3. Photomicrograph from laboratory experiment showing (a) 'dense flocs' in a suspension of Jiaojiang estuary clay after settling out the silt, and (b) 'loose flocs' in a suspension of Jiaojiang estuary natural clay and silt sediment.

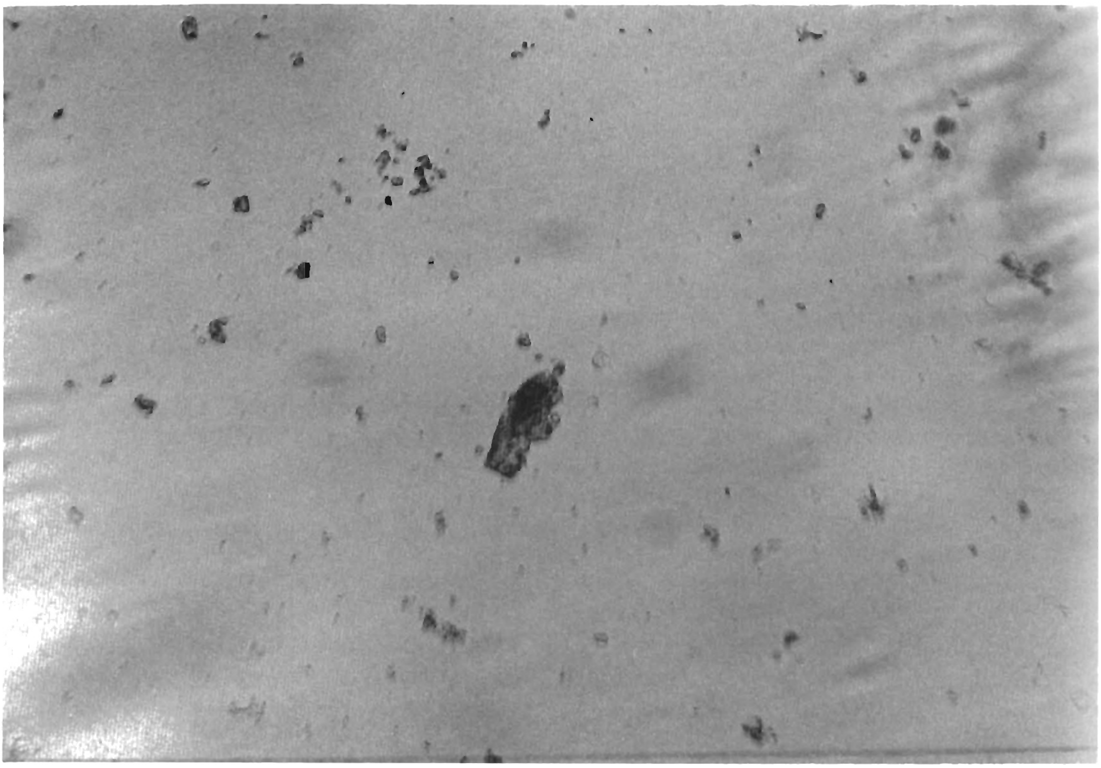


Figure 4. Photomicrograph of pieces of plant and plankton from station J1.

5 ppt and initial SSC was 1–4 g l^{-1} in 60 ml samples held in 150 ml beakers (D = 6 cm, H = 8 cm). The samples contained either natural sediment from the Jiaojiang estuary containing both clay and silt, or clay only after settling out the silt. Supersonic waves were used to break the flocs when needed. Turbulence was generated by a shaker with rates of 2–200 rpm and circular path diameter of 3 cm.

RESULTS AND DISCUSSION

Structure of Flocs

There are two kinds of flocs in the Jiaojiang estuary (Figure 2). The first floc type is called here 'dense floc' and comprises particles of size always <5 μm. This first type appears to be the same as the clay flocs observed in the Chesapeake Bay estuary, the Amazon River plume and in the Gironde Estuary (ZABAWA, 1978; GIBBS and KONWAR, 1986; GIBBS *et al.*, 1989). These flocs look 'dense' on the microscope at a magnification of 40 × but in fact they are very porous with water content >90%. These flocs are usually 'hardy' and not readily broken by ambient turbulence in the estuary as they persist throughout the tidal cycle. The other type of floc is called here 'loose floc' and is made up of aggregation of predominantly silt particles that can individually be recognized on the photographs (Figure 2). 'Loose flocs' are very fragile, as they are readily broken up by stirring on the microscope slide and also by strong tidal currents.

Most turbid estuaries that have been studied are clay dominated. Flocculation processes, enhanced by biological processes (ZABAWA, 1978), can be expected to be different for clay dominated estuaries than for silt dominated estuaries like the Jiaojiang estuary. Among the few silt-dominated estuaries that have been studied are the northern channels of the Fly River estuary in Papua New Guinea. WOLANSKI and EAGLE (1991) have shown that the mud in this estuary is primarily (80%)

made of silt with the clay fraction typically <10%. This mud has a settling velocity that varies with SSC in a similar manner as clay-dominated mud, namely that for SSC <2 g l^{-1} flocculation settling prevails whereby the settling velocity increases with increasing SSC, and for SSC >5 g l^{-1} there is inhibited settling whereby the settling velocity decreases with increasing SSC. The absolute values for the settling velocity are similar to those of clay-based systems (*e.g.*, THORN, 1981; ROSS, 1988; NICHOLS, 1984–1985). In the Fly River estuary however, the large 'loose flocs' common in the Jiaojiang estuary were only rarely observed though the sampling techniques were similar, and this difference may be due to stronger tidal currents and different clay/silt ratios.

There appears to be a relationship between the dominant sediment on the bottom and the nature of the flocs, with 'dense flocs' (clay flocs) dominating where clay dominates on the bottom, and 'loose flocs' dominating where the bed contains both silt and clay. A simple laboratory experiment confirmed that. Figure 3a shows a photomicrograph of a suspension of natural sediment from site J1 from which we had first removed by settling the bulk of the particles >4 μm. Clearly 'dense flocs' are dominant in that figure. Figure 3b shows a photomicrograph of this same suspension without removing the silt. Clearly 'loose flocs' predominate.

In addition, pieces of flora and plankton are occasionally also present, usually as very large particles (Figure 4).

Trends in Size and Concentration of Flocs

The estuary was partially well-mixed in salinity (Figure 5a) though there appears to be a zone of strong vertical mixing slightly up-river of station J8 (at the 16 ppt salinity). There also appears to be two weak fronts, one near station J7, one near station J10, where the horizontal and vertical gradients in salinity were the largest (respectively 1 ppt km^{-1} and 4 ppt m^{-1}).

The turbidity maximum (Figure 5b) was present near station J3 with a concentration of 43 g l^{-1} at 30 cm above the bed. From there, the SSC decreased both up-river and oceanward. At station J1 the near-bottom SSC was 4 g l^{-1}. At stations J5, J8 and J12 the near-bottom SSC was 3.7, 2.0 and 0.34 g l^{-1} respectively. The vertical gradient of SSC was also maximum at J3 where near-bottom and surface SSC values differed by two orders of magnitude. At stations J1 and J12, this difference was smaller, being less than one order of magnitude.

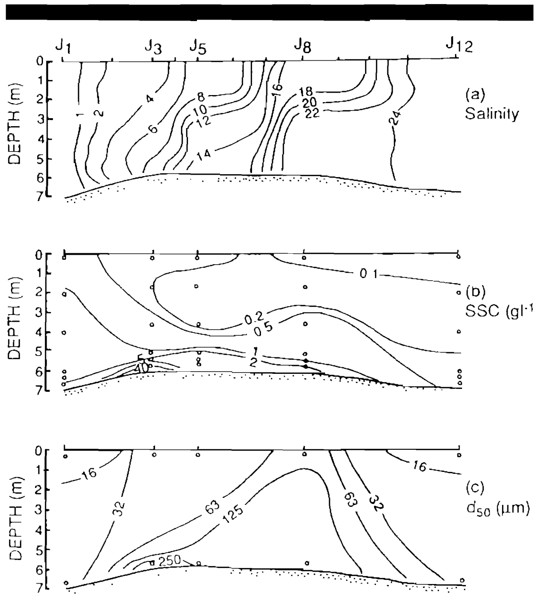


Figure 5. Along-channel distribution of (a) salinity (in ppt), (b) suspended sediment concentration (in g l^{-1}), and (c) median floc size d_{50} (in μm) on the high tide of April 21, 1991.

The median size of flocs (d_{50}) ranged from 10 to 500 μm in the bottom layer (Figure 5c). The highest values were found in the turbidity maximum zone, the peak found at station J3, decreasing on either side with d_{50} of only 40 and 16 μm at stations J1 and J12 respectively. In the surface layer, however, d_{50} varied much less, between 32 and 125 μm, with the maximum found at station J8. The values of d_{50} were only 10 and 16 μm at stations J1 (river side) and J12 (ocean side). The maximum d_{50} was found at station J3 for bottom waters and at station J8 (*i.e.*, oceanward from J3) for surface waters. This suggests a horizontal decoupling by advection between sediment at the surface and at the bottom. Otherwise, if vertical mixing and settling were the controlling processes, one would expect maximum d_{50} more or less at the same stations at or near the turbidity maximum zone. GIBBS *et al.* (1989) reported a similar finding in the Gironde estuary.

The d_{50} (see Figure 5c) was larger at the bottom than at the surface everywhere in the estuary, a situation characteristic also of the Amazon river plume and the Gironde estuary and in plume experiments (VAN LEUSSEN and WINTERWEP, 1990).

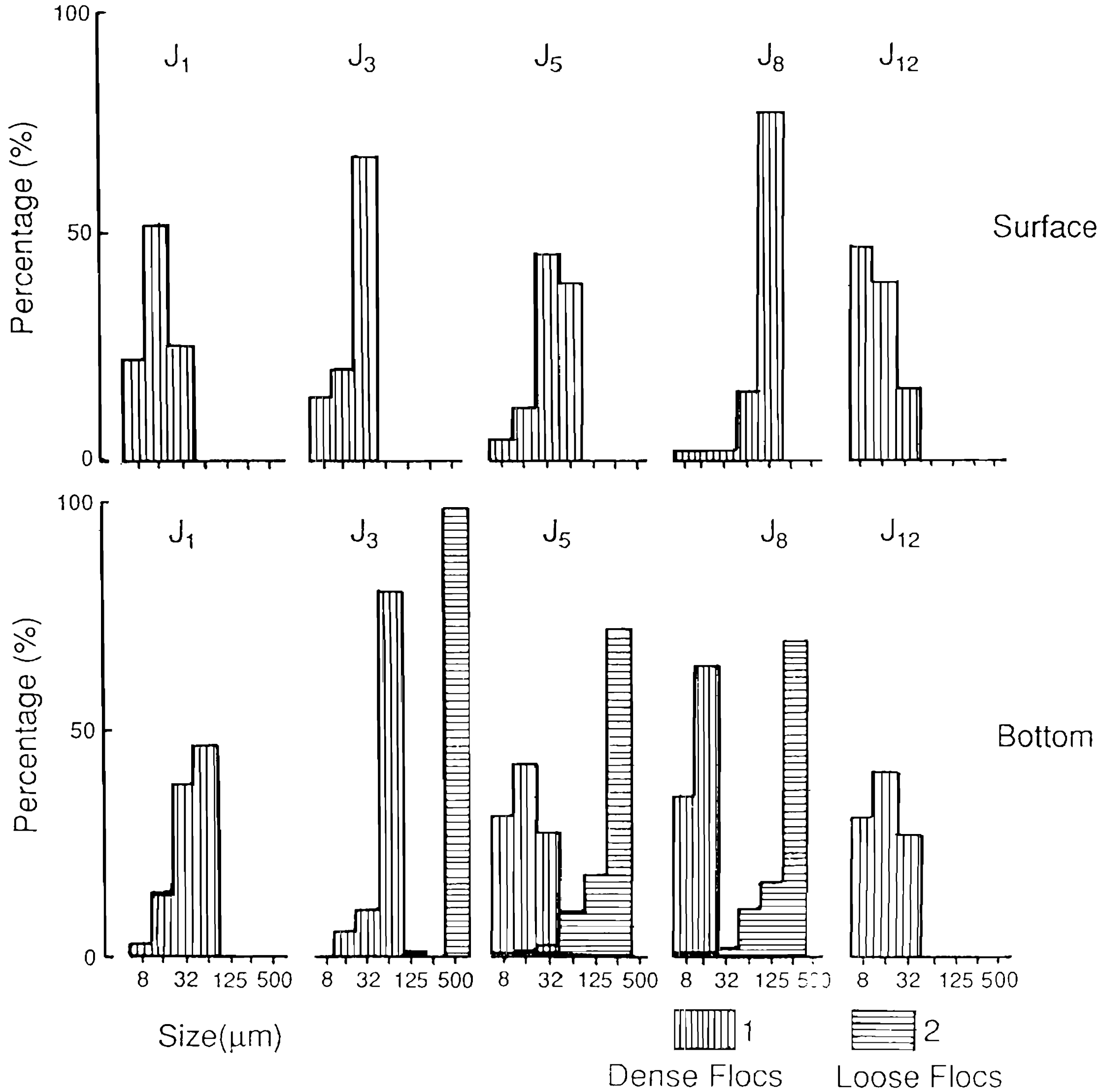


Figure 6. Floc size distribution at the surface and at the bottom at stations J1, J3, J5, J8 and J12 at the high tide of April 21, 1991. For surface samples, only 'dense flocs' (clay-dominated) were observed.

The along-channel distribution (see Figure 6) of floc size for both surface and bottom water samples shows that almost all particles in the turbidity maximum (site J3) were aggregated in flocs. At the bottom, at site J3, aggregation was dominated by 'loose flocs', resulting in a strong positive skewness of the floc size distribution (Figure 6). At stations up-river or oceanward, the skewness of the floc size distribution was smaller or even slightly negative.

It thus appears that there are three zones controlling the fate of the suspended sediment in the Jiaojiang estuary. A turbidity maximum exists at salinity of about 5–10 ppt, with near-bottom concentration exceeding 40 g l^{-1}. In that zone, the d_{50} is the largest (>400 μm) for near-bottom waters and the flocs appear to have aggregated all fine particles including clay and fine silt. Oceanward from the turbidity maximum zone, SSC diminish, but the d_{50} in surface waters increases until coastal waters are reached. Up-river from the turbidity maximum zone, but still within the salinity intrusion (0 < salinity < 1 ppt), the d_{50} at the surface and at the bottom and the SSC diminish and the water mass is dominated by dispersed particles that have not yet coagulated. Again, this situation differs from that in clay-dominant estuaries where all the suspended sediment has already coagulated at salinity as low as 0.1 ppt.

Settling Velocity of Flocs

The distribution of the settling velocity in the floc population is shown in Figure 7a for water samples collected at high tide 1 m above the bottom. The observed values of settling velocity are plotted on the x-axis together with another scale for the size of quartz particles of equivalent fall velocity. Figure 7b shows the floc size distribution.

At station J8, at the river mouth, the distribution of settling velocity (Figure 7a) has only one peak at 0.0016 cm sec^{-1}, the same as a quartz particle of about 1.5 μm in a dispersed solution; however the distribution of floc size (Figure 7b) has one peak at 120 μm.

At station J5, in the turbidity maximum zone, a median fall velocity of 0.08 cm sec^{-1} was found, which is equal to that of a quartz sphere of 15 μm. The floc size distribution has one dominant peak at 500 μm.

At station J1, at the salinity intrusion limit, a median fall velocity of 0.0016 cm sec^{-1} was found which is equivalent to that of a quartz sphere of about 1.5 μm though the median floc size was 16–20 μm. The settling velocity distribution at station J1 has three peaks at respectively 0.04 cm sec^{-1}, 0.003 cm sec^{-1} and 0.0003 cm sec^{-1}. Coincidentally, there were also three peaks in the floc size distribution (Figure 7b) at 8 μm, 32 μm and 125 μm. This suggests that the three peaks in Figure 7a at settling velocity of 0.0003 cm sec^{-1}, 0.003 cm sec^{-1} and 0.04 cm sec^{-1} may be due to, respectively, dispersed particles of silt and clay with size less than 16 μm, small flocs with size 50–100 μm, and large flocs of several hundreds μm size. The relationship between floc size and settling velocity is non-linear because the wet density of flocs is less than that of disperse particles and the density decreases with increasing size (GIBBS, 1985). The Jiaojiang estuary clay-dominant flocs have a settling velocity which differs somewhat, but is comparable to, that of the Chesapeake Bay estuary clay-dominant flocs. The three peaks in the floc distribution at 8 μm, 32 μm and 125 μm would have, in the Chesapeake Bay, a settling velocity of 0.0066 cm sec^{-1} and 0.019 cm sec^{-1} and 0.057 cm sec^{-1} respectively (GIBBS, 1985). On the other hand the silt-dominant 500 μm flocs in the Jiaojiang estuary (site J5, Figure 7b) probably have a settling velocity of order 0.08 cm sec^{-1} (site J5, Figure 7a) which is that of a Chesapeake Bay clay-dominant floc of 190 μm. This suggests that silt-dominant flocs are extremely porous, much more so than clay-dominant flocs as indeed is apparent from Figures 2 and 3b.

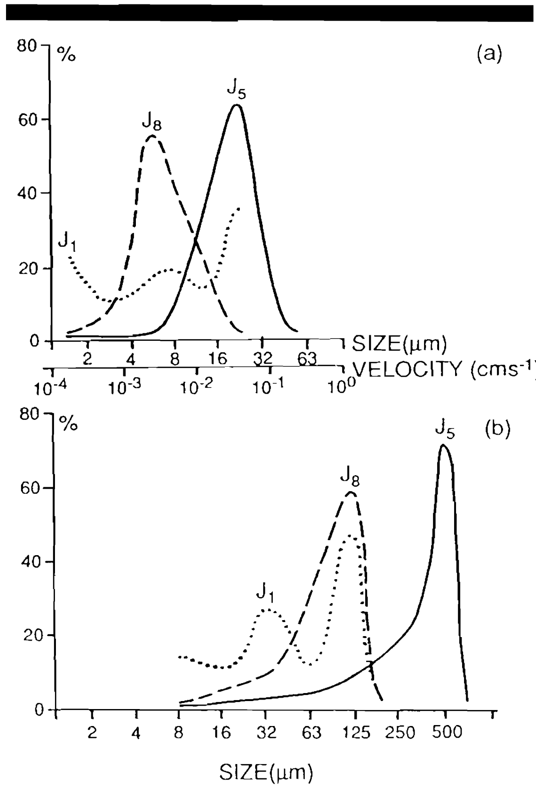


Figure 7. (a) Distribution of the settling velocity assuming quartz particles, for near-bottom water samples from stations J1, J5 and J8. (b) Floc size distribution for the same water samples.

Effects of Salinity and Concentration

Figure 8a shows the dependence on salinity of d_{50} of the flocs for both surface and near-bottom waters. Only very small clay flocs and dispersed silt particles (see also Figure 2) exist for salinity less than 0.1 ppt. The floc size increases rapidly with salinity increasing from 0.1 to 10 ppt. The

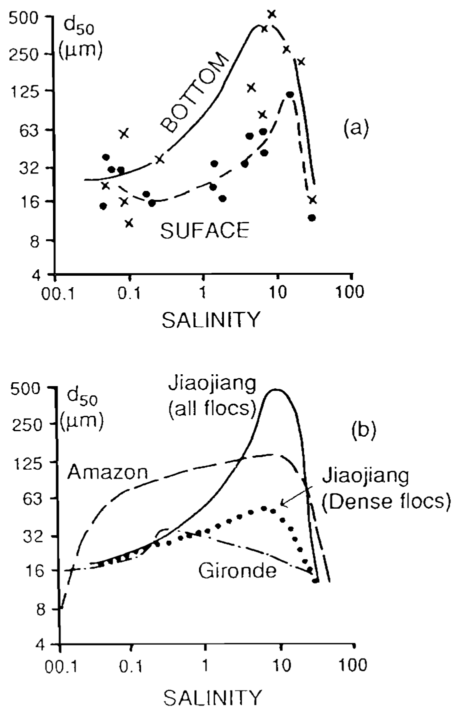


Figure 8. (a) Salinity *vs.* median floc size (d_{50}) calculated on a volume basis for surface (●) and bottom (x) water samples. (b) Salinity *vs.* median floc size (d_{50}) calculated on a volume basis for the bottom samples of the Jiaojiang estuary, the Gironde estuary (adapted from GIBBS *et al.*, 1989) and the Amazon River plume (adapted from GIBBS and KONWAR, 1986).

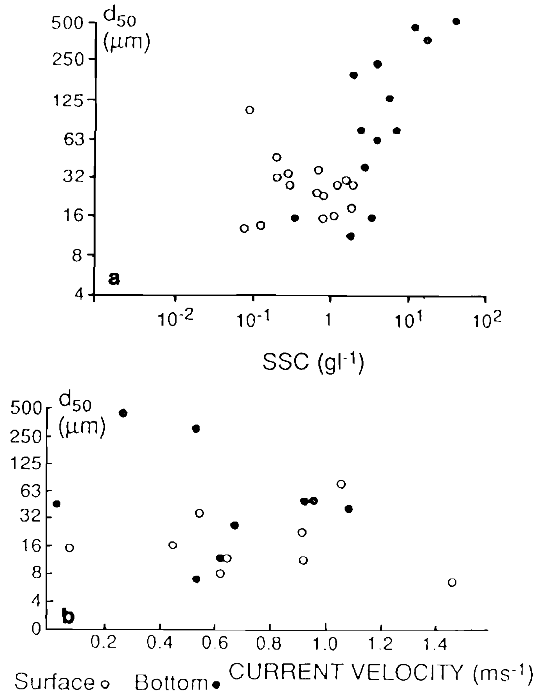


Figure 9. (a) Suspended sediment concentration *vs.* median floc size (d_{50}) calculated on a volume basis for Jiaojiang surface (o) and bottom (●) samples. (b) d_{50} *vs.* current velocity at station J5 over a tidal cycle for both surface and bottom samples.

floc size decreases for salinity greater than 15 ppt. This trend is also apparent for the 99th percentile floc size (not shown).

Figure 8b shows the dependence on salinity of d_{50} for the flocs in the bottom waters, but does not simply repeat Figure 8a because it considers separately 'loose flocs' and 'dense flocs'. Observe that the d_{50} is the same for 'dense flocs' and 'loose flocs' for salinity less than 1 ppt because few flocs exist at such low salinity. At higher salinity, the d_{50} of 'loose flocs' is much larger than that of 'dense flocs', the largest difference occurring for salinity of 10 ppt with corresponding d_{50} of about 550 μm and 50 μm respectively, a factor of 10 difference.

To compare the Jiaojiang estuary with other systems, we have added in Figure 8b the d_{50} curves for the Gironde estuary and the Amazon River plume which are clay-dominated systems. The curves show a similar general behaviour of increasing d_{50} with increasing salinity up to a critical salinity, and a decrease from that point. There are however important differences. The Amazon river plume data show a very rapid increase in d_{50} for salinity increasing from 0.01 to 0.1, with only a small increase in d_{50} for salinity between 1 and 10 ppt. For the Gironde estuary, maximum d_{50} occurs at salinity between 0.1 and 1. In the Jiaojiang estuary however, maximum d_{50} occurs at a salinity of about 10. Maximum d_{50} are of comparable magnitude (30 to 100 μm) for the Jiaojiang 'dense flocs' (clay-dominant flocs), and the Amazon and the Gironde which are clay-dominant systems. However the maximum d_{50} for the Jiaojiang 'loose flocs' (silt-dominant) is much higher, being about 500 μm.

The Jiaojiang estuary thus has three zones with different floc sizes. In the river up to salinity of 1 ppt, coagulation is minimal and the individual particles are dispersed. This is unlike the Gironde and Amazon systems where significant coagulation occurs at salinity <1 ppt. A coagulation zone exists in the Jiaojiang estuary for salinity between 1 and 10 ppt, and this is where the turbidity maximum is also found. Clay-dominated and silt-dominated flocs form, the latest being much larger in size. Finally, hydrodynamic processes reduce the floc size oceanward. Unlike the Amazon and the Gironde, ambient turbulence seems to play a dominant role in the fate of the 'loose flocs' (see later).

There appears to be a non-linear relationship (Figure 9a) between d_{50} and SSC though the relationship may be different for bottom or surface waters.

Effects of Turbulence

Turbulence has two dominant effects in the Jiaojiang. Turbulence controls the entrainment and mixing of suspended sediment. It also controls the differential breaking of 'loose flocs' and 'dense flocs'. Figure 9b shows the plot of d_{50} versus current velocity at station J5 over a tidal cycle for both surface and bottom samples. A dominance of large 'loose flocs' was only observed in two samples when the current velocity is less than 0.5 m sec^{-1}. This suggests that the 'loose flocs' are weak and readily broken by turbulence during strong tidal currents. These effects are discussed below.

Entrainment and Mixing

The effects of entrainment and mixing are apparent from an examination of a time series plot of the water velocity, salinity and SSC at the mooring site (station J5) (Figures 10 and 11 showing respectively spring tides and average tides). There was a 0.5–1 hr lag between currents (and salinity) and sea levels. The waters were only weakly vertically stratified in salinity. The peak currents were stronger at flood tide than at ebb tide, an observation typical of the data throughout the observation period (April 12 to 21). This asymmetry should result in tidal pumping of suspended sediment up-river (Postma, 1961, 1967; Dronkers, 1986). The SSC data in Figure 10 (spring tides) also suggest up-river tidal pumping of sediment because depth-averaged SSC are higher at flood tide than at ebb tide. Vertical gradients in SSC at spring tides (Figure 10) were stronger at ebb tide (weaker currents) than at flood tide (stronger currents); on that day a lutocline existed about 1 m from the bottom for about 2 hr at ebb tide. In the absence of salinity gradients, the presence of this lutocline implies that the turbulence was inhibited by the sediment-induced buoyancy effects (*e.g.*, Wolanski *et al.*, 1988, 1989; Ross and Mehta, 1989).

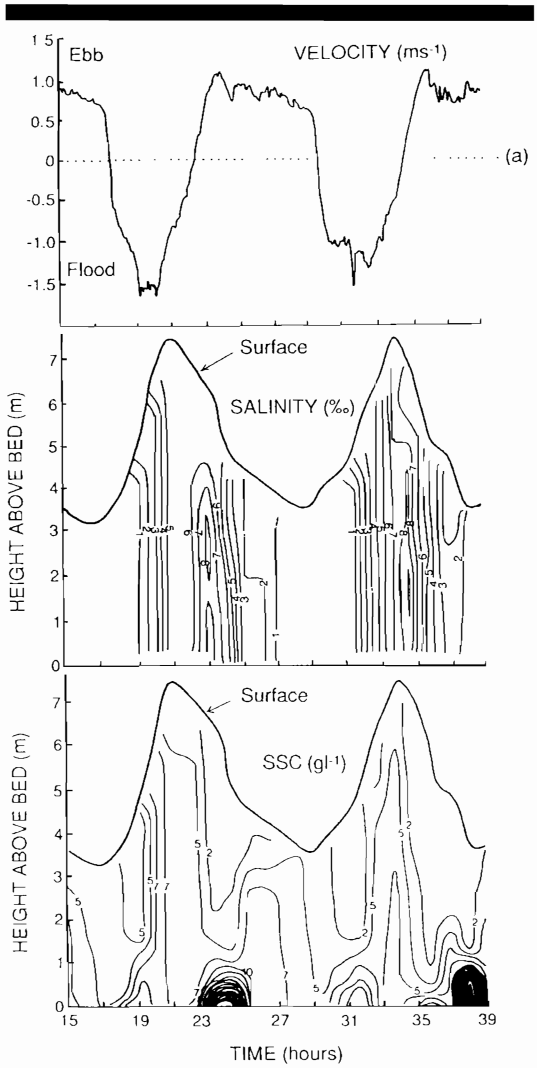


Figure 10. Time series plot (with time in hr) on April 15–16, 1991, of (a) the velocity 1.75 m above the bottom at mooring site J5, (b) the salinity and (c) the SSC (in g l^{-1}).

The tides and the tidal currents were smaller on April 20 (Figure 11) than on April 15 (Figure 10). The effects of tidal turbulence on the SSC profiles are apparent when comparing Figure 10 (spring tides) with Figure 11 (average tides). The water column on April 20 was density stratified in SSC throughout the tidal cycle at both ebb and flood tide, contrary to the situation on April 15–

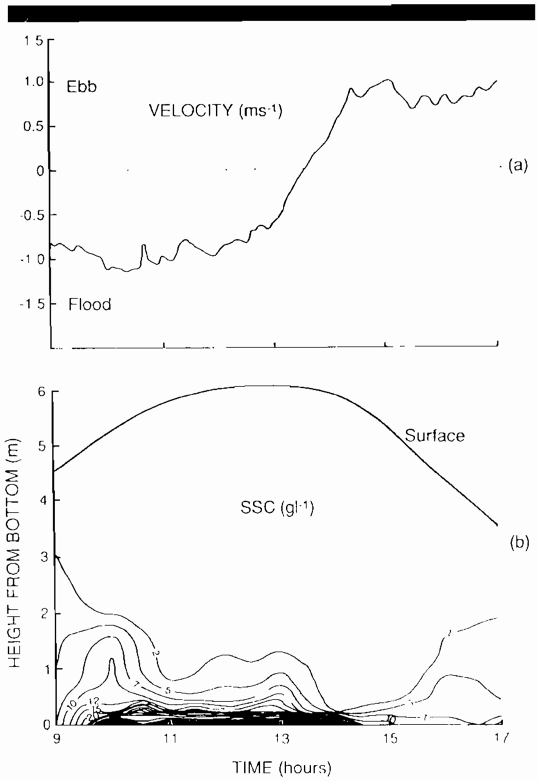


Figure 11. Time series plot (with time in hr) on April 20, 1991, of (a) the velocity and (b) the SSC (in g l $^{-1}$).

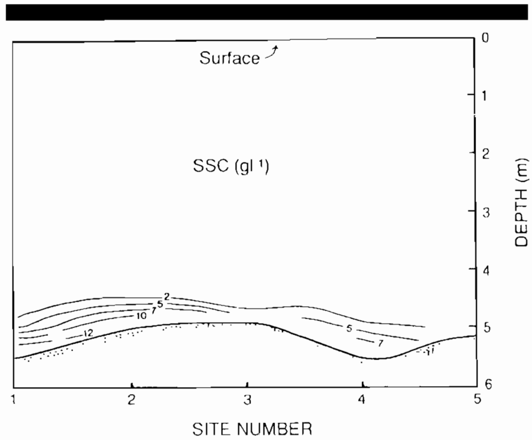


Figure 12. Cross-channel distribution of SSC (in g l $^{-1}$) in a cross-section encompassing station J5 during ebb tide on April 21, 1991.

16 when strong tidal currents maintained vertical homogeneity. Observe that near slack waters near 16 hr in Figure 11 the suspended sediment did not all settle out of suspension. In the bottom 0.5 m of the water column, SSC were >40 g l $^{-1}$, *i.e.*, the suspended sediment were in the inhibited settling range. In that range, settling is inhibited by even minute levels of turbulence resulting in the plugging of micro-channels used in the dewatering process (WOLANSKI *et al.*, 1991); since visual observations showed that the water was always turbulent, even at slack currents, the suspended sediment could not settle out.

Occasional cross-channel surveys in a cross section encompassing station J5 show that the suspended sediment concentration was fairly uniform across that section which is maintained fairly flat by dredging (Figure 12).

The Effects of Turbulence on Flocs

Microscopic observations of water samples from station J5 during a tidal cycle reveal that 'loose flocs' only form near the bottom when the currents are smaller than 0.5 m sec $^{-1}$. At higher velocities, the silt particles are dispersed and do not aggregate in flocs. However the 'dense flocs' (clay-dominated) persist throughout the tidal cycle. Hence clay and silt particles behave differently in the Jiaojiang estuary. The clay particles stay aggregated in flocs typically 40 μm in size during the tidal cycle, and can be found throughout the water column. Silt particles form very large flocs typically 500 μm in size. These 'loose flocs' incorporate both clay flocs and silt particles but exist only for small to moderate tidal currents.

We confirmed this explanation by a simple laboratory experiment where we studied the fate of Jiaojiang estuary sediment in water at 5 ppt salinity. The suspended sediment was in two suspensions, suspension 1 consisting of clay only from station J1 (after removing the silt particles by settling), and suspension 2 consisting of natural clay and silt sediment without filtering out the silt. The suspensions were then stirred by a shaker. We sampled the suspensions in time and measured floc size distribution. 'Dense flocs' with a d_{50} of typically 30–40 μm, formed in suspension 1 (Figure 3a). 'Loose flocs' with a d_{50} of typically 200–500 μm, formed in suspension 2 (Figure 3b). 'Dense flocs' formed in less than 5 min, while 'loose flocs' took 10 min to form. Further, when the suspension was strongly stirred, the 'dense flocs' were also less fragile than the silt-clay flocs. For a shear velocity of about 2 cm sec $^{-1}$, typical of that in the estuary for a tidal current of about 0.6 m sec^{-1}, the 'loose flocs' in suspension 1 were broken and the silt particles were dispersed resulting in very small settling velocities. However the 'dense flocs' were not broken.

A MODEL OF THE TRANSPORT OF CLAY AND SILT PARTICLES

The transport and fate of clay particles in the Jiaojiang is sketched in Figure 13a and are qualitatively similar to those in the Gironde estuary. The internal estuarine circulation and the tidal pumping create a turbidity maximum zone. 'Dense flocs' (clay-dominated) are largest and present in largest number near the turbidity maximum zone at salinity 5–10 ppt. An upwelling mechanism prevails there which brings 'dense flocs' towards the surface and also oceanward because of the internal estuarine circulation. As a result the largest 'dense flocs' are found at the surface oceanward of the turbidity maximum zone. These particles then settle and are entrained back towards the turbidity maximum zone.

However the Jiaojiang estuary differs from the Gironde estuary and the Amazon River plume in having also very large 'loose flocs' which are silt-dominated but comprising also 'dense flocs' (clay-dominated) in their matrix. The dynamics, formation and fate of flocs differ markedly whether they are silt-dominated or clay-dominated. The 'loose flocs' are 500 μm in size but exist only in salinity >5 ppt and when the tidal currents are small or moderate (<0.5 m sec^{-1}) which is also when the internal estuarine circulation is most pronounced during a tidal cycle. 'Loose flocs' can thus be expected to exist during a neap tide cycle or only for short periods during spring tides. 'Loose flocs' of 500 μm in size have a settling velocity equal to that of a typical 'dense floc' of 190 μm, because they are extremely porous. The 'loose flocs' exist only near the bottom and are entrained upriver by the internal estuarine circulation towards the turbidity maximum zone. They are however not carried upwards as the flocs either break up if the currents are >0.4 m sec^{-1}, or have a too large settling velocity to be upwelled the rest of the time. At neap tide then, the silt particles are aggregated in the turbidity maximum zone with little vertical mixing (Figure 13b). At spring tide however, the 'loose flocs' are broken and the silt particles are dispersed as individual particles. The settling velocity of the individual silt particles is one to two orders of magnitude less than that of the flocs. The silt particles thus are carried nearly passively by the strong tidal currents which disperse them widely in the Jiaojiang estuary (Figure 13c).

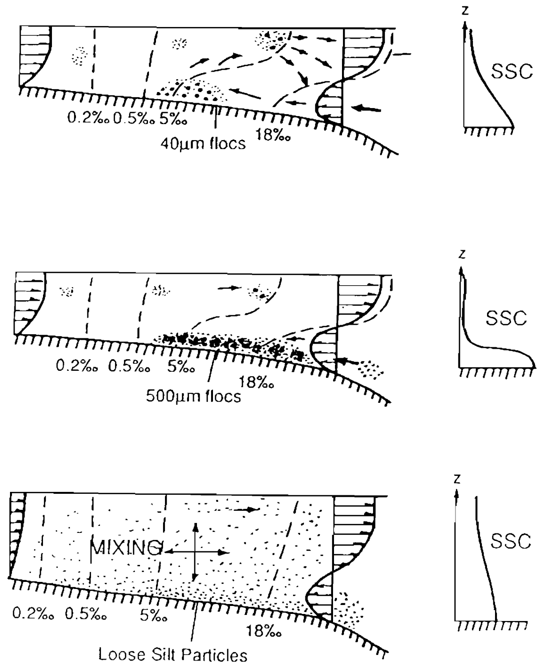


Figure 13. Cross-section of estuary showing transport pathways of flocs, salinities and current profiles for (a) clay flocs (adapted from GIBBS *et al.*, 1989), (b) silt-dominant 'loose flocs' at neap tides and (c) silt particles at spring tides. The SSC curve is the vertical profile of SSC at the turbidity maximum zone.

This suggests that in the Jiaojiang estuary, silt particles are aggregated at neap tides and dispersed at spring tides, while clay particles are aggregated at all tides.

Because the SSC in the bottom 0.5 m are always high (>10 g l^{-1}) at the mooring site near the turbidity maximum zone, the particle settling velocity in that range is small and in the inhibited settling range. Settling is also inhibited by the turbulence plugging the micro-channels used in the dewatering process. As a result the bulk of the sediment remains in suspension.

Our study suggests that the Jiaojiang estuary is silting in dry weather conditions, both by river inflow but mostly by tidal pumping into the estuary the Changjiang River sediment found in coastal waters. During occasional river floods, particularly after a typhoon, the large freshwater discharge and the shallow waters presumably result in saltwater being completely flushed out of the system, resulting in an export of sediment. It may be that the construction of dams on the river will result in decreasing the amplitude of such flushing and accelerate the siltation of the estuary.

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