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# Clues to flocculation development by comparing particle size distribution patterns of suspended matter in the water mixing zone of the Changjiang River Estuary

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**Abstract**

Particle size is an important characteristic of suspended matter, and it contains crucial information about the deposition process. Suspended particle samples in the water mixing zone of the Changjiang River Estuary were collected in December 2016. Untreated original grain size and the decentralized grain size of the suspended particles were measured via a laser particle size analyzer. Morphological characteristics and the chemical composition of the suspended particles were also studied systematically using a scanning electron microscope (SEM) with an energy dispersive X-ray spectrometer (EDS). Then, the flocculation and sedimentation of suspended matter in the water mixing zone were explored by combining them with the water mixing processes in the estuary. The average particle size of suspended matter in the mixing zone of the Changjiang River Estuary ranges from Φ5.73 to Φ7.98. The particle size distribution pattern is an abnormal model with a mainly unimodal pattern. In the freshwater area that was dominated by runoff, the suspended matter is mainly composed of fine particles, the settling velocity is slow, and the flocculation is weak. Floc particles were often seen in the mixing zone, with the flocs having a relatively large particle size, a low density and a loose structure appearing at the weak mixing zone; the flocs had a compacted structure in most areas of the mixing zone. The changes of suspended particle size in the estuarine mixing zone promote the settling and deposition of suspended matter, which has an important influence on the bed geomorphology and preservation of the fine suspended particles in the estuary.

**Key words:** water mixing zone, suspended matter, particle size, sedimentation, flocculation, Changjiang River Estuary

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## 1 Introduction

Suspended matter, with a particle size of more than 0.45 μm, is an important component of seawater. It contains mineral rock debris, biological skeleton debris, biological soft tissue debris and flocs (Shi, 2010; Zhao et al., 2023). As an intermediate link of sedimentation, suspended matter plays an important role in the process of oceanic deposition (Li et al., 2015). The estuary is a mixing zone of the river water and the seawater and is controlled by the tidal current and runoff. The intense hydrodynamic conditions keep the suspended matter in constant states of transportation, deposition, and resuspension, which affect and shape the submarine topography and landforms (Liu et al., 2006; Li et al., 2017). Water mixed at the estuary makes the physical and chemical properties of the water body change significantly (Zhu et al., 2022; Liu et al., 2023). Flocculation is strong at the mixing zone, and the size and composition of suspended particles are changed substantially. Flocculation also affects the process of deposition and the contaminated components, such as heavy metals, are redistributed between the suspended matter and dissolved phases (Xia et al., 2004; Wang et al., 2013; Fettweis et al., 2006; Ming and Gao, 2022).

Extensive research has been conducted in different marine areas to understand the role of suspended particle size in the marine deposition process. Li et al. (2003) analyzed the characteristics of the suspended particle size and the spatial distribution of suspended matter in the Changjiang River Estuary. They discovered that the resuspension of surface sediments has an important influence on the suspended particle size in water. Ahn and Grant (2007) investigated the changes in suspended particle sizes in southern California waters and identified three modes with distinct seasonal patterns and along-shore distributions, namely, a dinoflagellate mode, a large particle mode, and a small particle mode. These modes can reflect both the sources of particles and the environmental factors that trigger their occurrences. Pang et al. (2010) investigated the spatial distribution of suspended matter in the Changjiang River Estuary and found that the median size of suspended particles had a significant positive correlation with the water depth in this area. They posited it was the result of the differences in settling velocities of the flocs. Ahn (2012) studied the relationship between the size distribution and

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settling velocities of suspended particles in a tidal embayment. He estimated the source of the suspended matter by the particle size distributions and settling velocities of suspended particles. The autochthonous particles with a large size and fast settling are probably biological debris. Astoreca et al. (2012) researched the concentration, composition and size of suspended particles and their optical properties in the southern North Sea. They found that the particle size distributions revealed a power-law shape along the coasts and a bimodal distribution in the middle of the southern North Sea during the spring phytoplankton bloom.

All the studies mentioned above mainly focus on the types, properties and sizes of suspended particles and the suspended matter concentrations and spatial distributions, the true particle size of the flocs and its changing in water mixing zone of the Changjiang River Estuary are still vague. In this study, water samples obtained from the Changjiang River Estuary in December 2016 were used to measure the suspended particle size of the original samples and the decentralized samples using a laser particle size analyzer. The characteristics of the particle size and spatial distribution of suspended matter in the Changjiang River Estuary were analyzed systematically. Combined with the morphological characteristics of the flocs, the properties of the water temperature and salinity, the mechanism of estuarine flocculation and sedimentary dynamic are explored. The study results would be helpful for better understand to the sedimentation processes in the estuary.

## 2 The study area

The Changjiang River is the largest river in China and Asia. It is the third longest river in the world with a total length of 6 300 km, and a drainage area of 1.8 × $10^6$ $km^2$. Each year, approximately 9.2 × $10^{11}$ $m^3$ of fresh water and 4.8 × $10^8$ t of solid particles are transported from the Changjiang River into the East China Sea (Liu et al., 2007; Chai et al., 2009; Xu and Milliman, 2009; Yuan et al., 2021). In the downstream part of the Changjiang River Estuary, the Changjiang River is divided into the South Branch and North Branch at Chongming Island, the South Branch is divided into South Channel and North Channel by Changxing Island, and the South Channel can be divided into South Passage and North Passage by the Jiuduansha. These divisions see a pattern of three-order bifurcations and show four outlets into the sea. An extremely large delta was formed by these processes (Yang et al., 2000, 2013; Chen et al., 2024). The turbidity maximum zone in the Changjiang River Estuary is located near the estuarine bar, which is approximately 25–46 km in length. The surface sediment concentration is 0.1–0.7 kg/$m^3$, but the bottom sediment concentration is 1–8 kg/$m^3$ and the content starts to increase near the isohaline 2 (Wu et al., 2012; Li et al., 2012). The geographical location, coverage area and sediment concentration of the turbidity maximum zone is mainly dependent on changes in the runoff and tidal current, the sediment concentration and the intensity of the salt-water wedge density current in the estuary (Shen et al., 2008; Uncles et al., 2010; Kitheka et al., 2016). The position of the salt-water wedge in the dry season is moved towards the direction of the runoff and ultimately near the center of South Channel (Xue et al., 2009).

The study area (Fig. 1) is located between 31°–32°N and 121°–122.5°E, which covers the South Branch, South Channel and South Passage in the Changjiang River Estuary. From the Changjiang River to the shelf of East China Sea, this study is conducive to understanding the differences in suspended particle size and composition resulting from significant changes in the physical and chemical properties of the water body in the mixed belt.

## 3 Experimental method

### 3.1 *Field investigation and sample collection*

Members of our research group participated in joint field observation voyages and obtained our research samples in the Changjiang River Estuary in December 2016; these voyages were organized by East China Normal University. Sixteen stations were arranged along the Changjiang River Estuary from the river water area to the seawater area (Fig. 1). The survey vessel was *Hu Pu Yu 41338*. The temperature, salinity and turbidity of the water were measured by ALEC CTD (Model: ASTD120) at each station. Five-liter water samples from the surface, middle (three-fifths of the water depth) and bottom (2 m from the seafloor) layers of the water column were collected using the water collector mounted on the CTD. Approximately 3–5 mL of the water was diluted and sieved through a filter with a pore size of 0.45 μm to obtain the suspended matter after washing the samples with distilled water

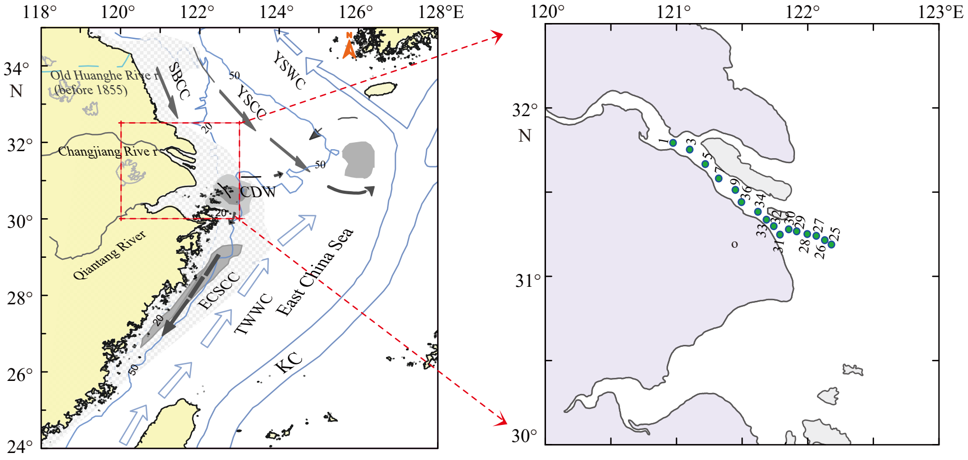

**Fig. 1.** Marine environmental characteristics (left) and sampling stations (right). The depicted circulation system and isobath was modified from Wang (2014), Pang et al. (2018) and Fan et al. (2023). KC: Kuroshio Current, YSWC: Yellow Sea Warm Current, TWWC: Taiwan Warm Current, YSCC: Yellow Sea Coastal Current, SBCC: Subei Coastal Current, ECSCC: East China Sea Coastal Current, CDW: Changjiang Diluted Water.

thrice for desalinization. The filters were naturally dried and hermetically preserved. Sampling was completed during the spring tide period.

### 3.2 *Analysis methods for the concentration and particle size of suspended matter*

(1) Measuring the concentration of suspended matter

The collected water samples were gently shaken and inverted, and were mixed uniformly. Sorted by the turbidity of the water, 80–100 mL water samples were filtered by using a pre-weighed Cellulose Acetate filter membrane with a diameter of 47 mm and a pore diameter of 0.45 μm. The filters were rinsed three times with 10 mL deionized water to remove salt and then were dried at 40℃. Finally, the filters were weighed and the concentration of suspended matter was calculated.

(2) Analyzing suspended particle size

The suspended particle size of the original samples and the decentralized samples were determined using a laser particle size analyzer (Mastersizer 2000, Malven Instruments Ltd., UK) with a small volume sampler. The test range of the particle size is 0.02–2 000 μm, and the error is less than 2%. The data collection was at a 1/Φ4 interval and the average particle size, sorting coefficient, skewness and kurtosis were calculated using the McManus moment formula (McManus, 1988). The test procedures are as follows.

a. Sorted by the concentration of suspended matter, approximately 30–80 mL original water samples were taken and dispersed using ultrasonic vibration for 60 s prior to an instrumental analysis without any reagent. The samples were recycled through the exit end of the small volume sampler.

b. The recycled samples were pretreated using 5 mL 30% $H_2O_2$ and 5 mL 0.5 mol/L $(NaPO_3)_6$ and then were left standing for approximately 12 h to thoroughly remove the organic matter. An ultrasonic vibration was used for 60 s before analysis and the particle size data before and after sample processing was obtained.

### 3.3 *SEM sample observations*

The morphologies and compositions of the suspended flocs were analyzed using scanning electron microscope (SEM) and energy dispersive X-ray spectrometer (EDS). Specifically, samples of approximately 3 mm × 3 mm were cut from the filters for the SEM/EDS analysis and image capture. The filter pieces were glued to copper stubs and gold-coated, after which they were examined using an FEI Quanta 200 scanning electron microscope interfaced with an EDAX Inc. X-ray spectrometer. The operating regime for the SEM/EDS analysis was as follows: a high vacuum, a working distance of 10 mm, an accelerating voltage of 25 kV, an emission current of 100 μA and an X-ray spectrum collection time that exceeded 60 s until the counts/second (c/s) stabilized. The EDS spatial resolution is 0.5 μm.

## 4 Results

### 4.1 *Characteristics of mixed water in the Changjiang River Estuary in winter*

The characteristics of the water temperature and salinity in the Changjiang River Estuary in winter are shown in Fig. 2. The temperature of the water is mainly distributed from 11.5℃ to 13.1℃ and decreases towards the direction of sea. Vertically, the temperature distribution is consistent with no stratification. The salinity of the water is mainly distributed in the range of 0.1–2.0. It shows an increasing trend towards the sea and increases sharply between Stations 28 to 25. Vertically, the salinity curve is tilted towards the land at the bottom, which indicates that a saltwater wedge exists there.

The spatial distribution characteristics for the water turbidity and the suspended sediment concentration are the same. Both are more common in offshore locations than at the nearshore and are more common in the bottom layer than in the surface layer (Fig. 2). The turbidity of the water in the study area distributes from 50 FTU to 1 230 FTU and the average turbidity value is highest between Stations 28 to 25. The concentration of suspended matter ranges from 40 mg/L to 1 943 mg/L, and it also increases significantly from Stations 28 to 25. The sharp increase in the water turbidity and the suspended sediment concentration towards the sea is consistent with the change in the water salinity at the same location.

According to the characteristics of the water salinity and turbidity in the Changjiang River Estuary, the study area can be clearly divided into two zones, including the freshwater area and the mixing zone as shown in Fig. 2. The freshwater area includes Stations 1, 3, 5, and 7, where the water salinity is less than 0.15 and the distribution of the isohaline is sparse. In this area, the

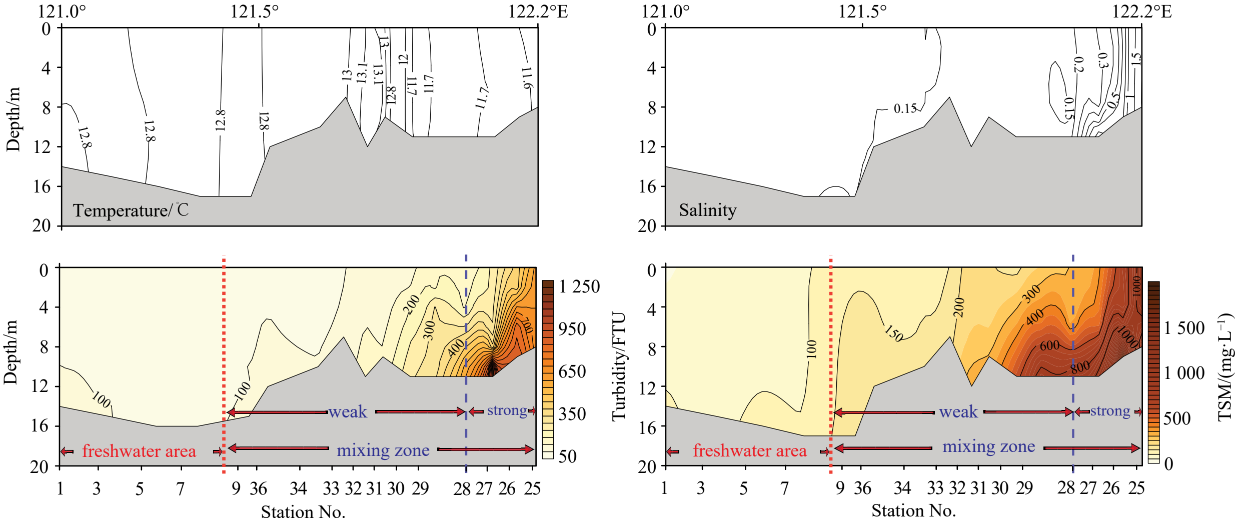

**Fig. 2.** The spatial distribution of the water temperature, salinity, turbidity and suspended matter concentration (TSM) in the study area.

water turbidity is less than 100 FTU and the concentration of suspended matter is less than 150 mg/L. With Changjiang River runoff as the control, the water is mixed uniformly with no stratification phenomenon. In the mixing zone, the salinity of the water is in the range of 0.15–2.0 and substantially increases in the offshore area. According to the 0.2 isohaline, the mixing zone is divided into a weak mixing zone (including Stations 9, 36, 34, 33, 32, 31, 30 and 29) and a strong mixing zone (including Stations 28, 27, 26 and 25). In the weak mixing zone, the water salinity distributes between 0.15 and 0.2. The isohalines are sparse, and the stratification begins to appear. The water turbidity is less than 500 FTU and the concentration of the suspension distributes in the range of 150–800 mg/L. The gradient of the turbidity and concentration changes significantly in the horizontal direction. In the strong mixing zone, the water is mixed violently, and the isohaline is intensive. The salinity is between 0.2 and 2.0 and the salt-water wedge is located here. The water turbidity and the concentration of suspension fluctuates violently, and both reach the peak.

### 4.2 *Characteristics of suspended particle sizes in the Changjiang River Estuary in winter*

The particle size parameters of the original samples are shown in Fig. 3. The average particle size of the suspended matter ranges from Φ5.73 to Φ7.98 and the average value is Φ6.67; these results are similar to the decentralized suspended particle sizes at Xuliujing and Hengsha stations in the Changjiang River Estuary as measured by Tang (2007).

The average particle size in the freshwater area is the finest among all results, which is distributed between Φ6.26 and Φ7.98 and the average value is Φ7.06. With the depth increasing, the suspended particle size becomes coarse and forms a tongue-like distribution. In the weak mixing zone, the suspended particle size is the coarsest in the entire study area. The average particle size ranges from Φ5.73 to Φ7.09 and the average value is Φ6.48. The average particle sizes at some stations in this area are coarser in the surface layer than those in the middle or bottom layers. The coarsest of the suspended particles are located in the bottom layer adjacent to the strong mixing zone. The average particle size in the strong mixing zone is moderate, which distributes between Φ6.15 and Φ7.01 and the average value is Φ6.66. The fine particles are in the surface layer and the coarse particles are in the bottom layers.

The sorting coefficient of the suspended particles ranges from 1.25 to 2.73 and the average value is 1.77, with poor sorting. In the weak mixing zone, the sorting is the worst. The value of skewness ranges from −1.97 to 1.71 and the average value is 1.02. In most layers, the skewness is positive, and the negative skew is mainly found in the surface layers. The characteristics of the kurtosis distribution are similar to those of the sorting coefficient. The kurtosis values are mainly distributed between 1.64 and 3.38, with an average value of 2.29 belonging to a wide kurtosis. In the weak mixing zone, the kurtosis is very wide, and its value is greater than 2.75. These results are shown in Table 1.

The average particle size of suspended matter is changed after the decentralized processing, but its fluctuation range overall is not changed significantly. In the freshwater area, the average particle size of suspended matter changes slightly and its tongue-like distribution tends to be clearer than that in the untreated samples. The change in the average particle size of suspended matter is the most obvious in the weak mixing zone. In the untreated samples, there are some large size particles in the surface layer, but they disappeared after treatment. However, in some other stations, which are different from the above stations, the sizes of suspended particles in the surface layer are larger than that in the middle or bottom layer in the treated samples. In other regions, the particle size is fine at the surface and coarse on the bottom. The coarsest particles are still located in the weak mix-

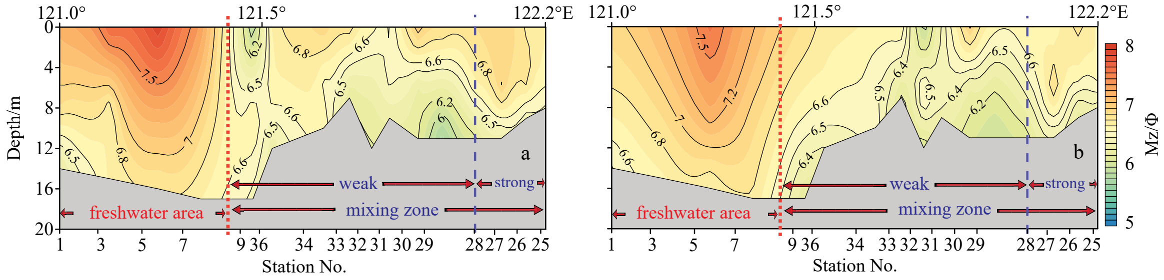

**Fig. 3.** Changes in the average suspended particle size (Mz) in the study area. a. The untreated sample; b. the treated sample.

**Table 1.** Particle size parameters of the suspended matter in different zone

| Zone | | σ | | $S_k$ | | $K_u$ | | Mz | |
|---|---|---|---|---|---|---|---|---|---|
| | | untreated | treated | untreated | treated | untreated | treated | untreated | treated |
| FA | Min | 1.25 | 1.56 | −0.97 | −1.76 | 1.64 | 2.02 | 6.26 | 6.48 |
| | Max | 2.18 | 2.09 | 1.12 | 1.42 | 2.66 | 3.00 | 7.98 | 7.63 |
| | AVG | 1.69 | 1.90 | 0.73 | 0.58 | 2.18 | 2.43 | 7.06 | 6.96 |
| WMZ | Min | 1.62 | 1.72 | −1.97 | −0.73 | 2.08 | 2.18 | 5.73 | 5.88 |
| | Max | 2.73 | 2.29 | 1.66 | 1.84 | 3.38 | 2.85 | 7.09 | 7.04 |
| | AVG | 1.83 | 1.93 | 1.08 | 1.25 | 2.36 | 2.49 | 6.48 | 6.45 |
| SMZ | Min | 1.64 | 1.73 | −0.39 | −0.81 | 2.13 | 2.21 | 6.15 | 6.13 |
| | Max | 1.87 | 2.12 | 1.71 | 1.80 | 2.45 | 2.94 | 7.01 | 6.92 |
| | AVG | 1.73 | 1.86 | 1.19 | 1.23 | 2.25 | 2.44 | 6.66 | 6.55 |

Note: FA represents the freshwater area, WMZ represents the weak mixing zone, SMZ represents the strong mixing zone. σ represents the sorting coefficient, $S_k$ represents the skewness, $K_u$ represents the kurtosis, Mz represents the mean grain size.

ing zone and the position remains unchanged. In the strong mixing zone, the average particle size of suspended matter becomes coarse and the distribution trend is not changed significantly.

After the dispersion treatment, the sorting coefficients ranged from 1.56 to 2.29 and the average value is 1.90, denoting poor sorting, and the number of stations with poor sorting ($\sigma$>2.00) is increased. The skewness is changed from –1.76 to 1.84 with an average value of 1.07. The number of the stations with positive skewness decreases, and the number of stations with extremely positive skewness increases. The kurtosis values are mainly distributed between 2.02 and 3.00 and the average value is 2.29. Most of the stations are still at a wide kurtosis. The very wide kurtosis ($K_u$>2.75) occurrence rate is relatively small, but wide values do appear in each zone.

### 4.3 *Frequency distribution patterns of suspended particle sizes in the Changjiang River Estuary in winter*

Forty-eight maps about the frequency distribution patterns of suspended particle size in each station were draw including surface, middle and bottom layer. And we found that the frequency distribution patterns of suspended particle size in the study area is an abnormal distribution. Most layers are shown a unimodal distribution and a few bimodal distributions appearance. There are tail peaks for the fine particles in each frequency pattern. According to the shape of the peaks, the unimodal distributions are divided into sharp unimodal distributions and wide unimodal distributions. The peaks of the sharp unimodal distribution are mainly distributed at Φ7.2, Φ6 or Φ5, and the outline of some sharp unimodal distributions are similar to the shape of asymmetric unimodal distribution pattern. The peaks of the wide unimodal distributions are mainly distributed in the range of Φ5 to Φ7 (Fig. 4). The main peaks of the bimodal distributions are located between Φ6 and Φ8, and the secondary peaks are mainly distributed between Φ0 and Φ2 (Figs 4b and c). Coarse particle content is higher in bimodal distributions than that in unimodal distributions.

The characteristics of each zone in the study area were analysed detailed. The frequency distribution patterns of suspended particle size in the surface layer are mainly shown in a pointy unimodal distribution in the freshwater area. With the depth of water increasing, the kurtosis becomes wide and only one bimodal distribution appears in the bottom layer. In the weak mixing zone, the unimodal distribution, which is similar to the shape of asymmetric unimodal distribution pattern, begins to appear. As the distance from the sea decreases, the wide unimodal distributions gradually change to the unimodal distribution like asymmetric unimodal distribution pattern. In the strong mixing zone, all the frequency patterns are in a unimodal distribution. From the surface layer to the bottom layer, the number of the unimodal distributions like asymmetric unimodal distribution increases. Several representative frequency distribution patterns are shown in Fig. 4.

After the decentralized processing, the difference between the frequency distribution patterns for suspended particle size in the freshwater area and the mixing zones was more obvious. The peak of the frequency distribution in the freshwater area becomes significantly wider. Many unimodal distributions like asymmetric unimodal distribution pattern appeared in the mixing zone, and no such type distribution pattern occurred in the freshwater area.

## 5 Discussion

### 5.1 *Changes in suspended particle size and flocculation in the estuary mixing zone*

The characteristics of particle size for original suspended matter reflect the state of suspended particles in the estuary mixing zone. From the freshwater area to the weak mixing zone, the particle size becomes coarser and then becomes fine in the strong mixing zone; however, the mixing zone particle size is still coarser than in the freshwater area. The change trend in the particle size is regular, and it is related to the flocculation of suspended particles in the estuary mixing process.

The average particle size of suspended matter in the freshwa-

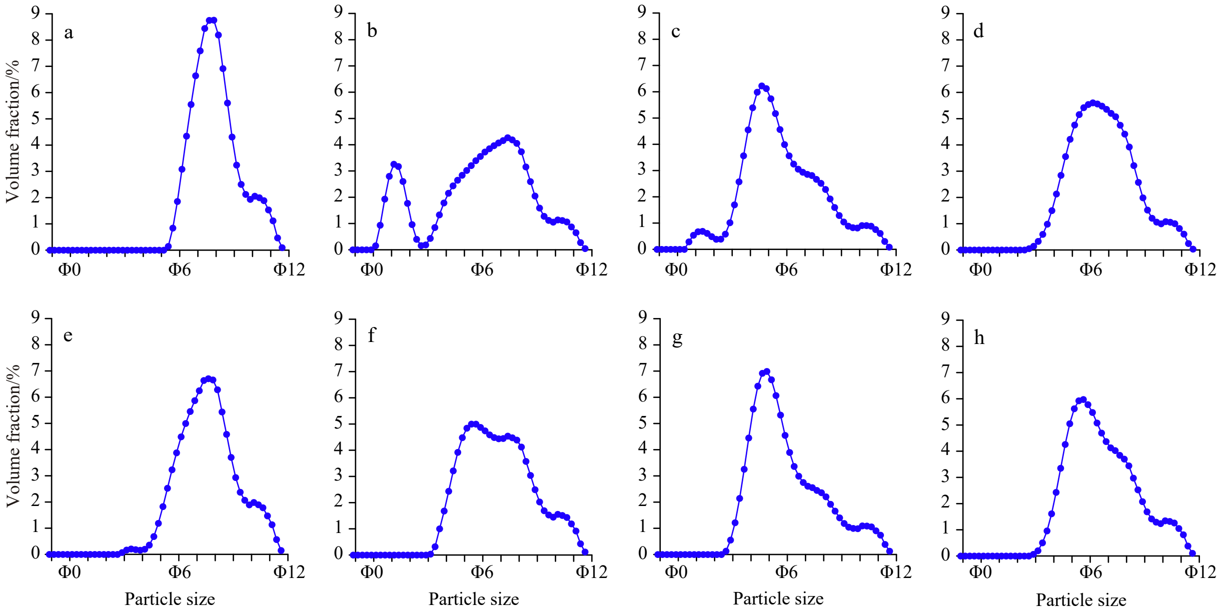

**Fig. 4.** Frequency distribution patterns of the suspended particle size. a, b, c and d represent the un-treated samples; e, f, g and h represent the decentralized samples. a(e) is the surface layer sample of Station 5, b(f) is the surface layer sample of Station 9, c(g) is the bottom layer sample of Station 29, d(h) is the middle layer sample of Station 25.

ter area is the finest of the three different zones, and the change trend of particle size in this area did not change significantly between the original samples and the decentralized samples. The above phenomenon is mainly caused by two reasons. One is that fine sediments carried by the Changjiang River runoff are predominant in this area and the process of decentralization has little impact on that type of suspended particles. The other reason is that the concentration of suspended matter in the freshwater area is lower than 150 mg/L, which results in a low probability of suspended particles colliding with each other. Additionally, the salinity of the water is less than 0.15 (10–13 is the optimal salinity to flocculate) (Jiang et al., 2002; Chen et al., 2005; Gao et al., 2009), causing the weak flocculation of the fine sediments. Even though the flocs can be formed, the particle size of the flocs is small. The average particle size of suspended matter in this area is fine and the overall change trend of the particle size after the decentralized treatment has few comparative differences with the original samples. The hydrodynamic condition in the freshwater area is relatively stable, so the difference in the settling velocity is the main reason that causes the fine suspended particles to mainly distribute in the surface layer and the coarse suspended particles to mainly distribute in the bottom layer. The morphological characteristics of the flocs in this area with a loose structure and a small particle size are shown in the SEM images. Most of the flocs are formed by adsorbed or flocculated between mineral particles (Figs 5a, b and c). The proportion of flocs in all the suspended particles in the freshwater area is low.

The average particle size of suspended matter in the weak mixing zone is the coarsest of all zones. With the seawater intruding, the content of electrolytes increases drastically, and the surface properties of suspended particles are changed significantly. The double charge layer around a fine particle is damaged and the stability of suspended particles is reduced substantially, thus showing that the flocculation occurs strongly (Jin et al., 2002; Liu et al., 2006; Xu et al., 2018). After the decentralized processing, the particle size of suspended matter changes dramatically. We presumed that the flocs formed by the estuary mixing process result in the overall coarsening of the suspended particles in the weak mixing zone. At the beginning of the zone, where the water salinity is low, the particle size of suspended matter increases significantly (Fig. 3a). However, after the dispersion treatment, the particle size of suspended matter is restored to the normal state (Fig. 3b). This indicates that the coarsening of suspended matter is due to the formation of flocs with a large particle size and loose structure. The loose flocs are then disappeared after the dispersion treatment. The frequency distribution patterns of the suspended particle size for the original samples and the decentralized samples show that the patterns before decentralizing are either bimodal or flattened unimodal distributions, and after the dispersion treatment they become a unimodal distribution and the sub-population at the coarser end disappears (Figs 4d, e, g and h). This result assumes that the size of large flocs mainly distributes between Φ1 and Φ2. The SEM images indicate that the particle sizes of flocs in the weak mixing zone are larger than those in the freshwater area, and the structure is also very loose (Fig. 5d), which is consistent with the results analyzed via the suspended particle size. However, in some stations near the strong mixing zone, flocs with a large particle size and a firm structure are found (Fig. 5e). The EDS pattern reveals that the organic matter is involved in the formation of floc particles (Fig. 5f), and the relative content of the flocs with organic coatings (Pang et al., 2018) is high.

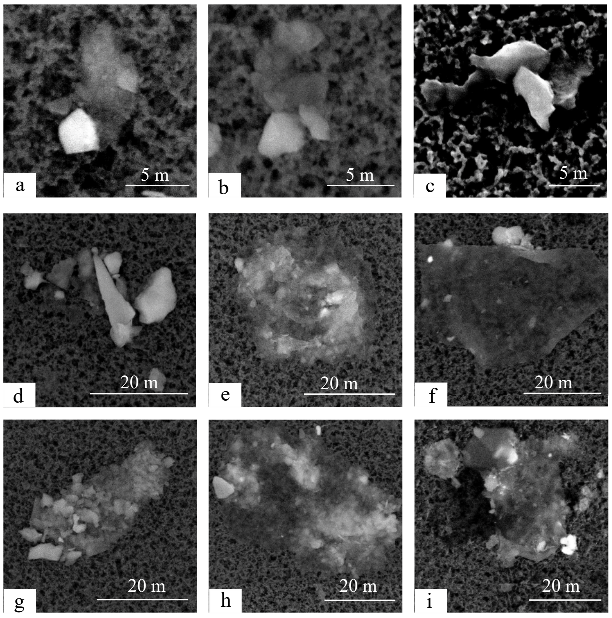

**Fig. 5.** The morphological characteristics of suspended floc particles in the study area. a, b and c represent the floc particles with loose structure and small particle size in the freshwater area; d, e and f represent the floc particles in the weak mixing zone and d is a loose floc, e is a compact floc, f is a floc rich in organic matter; g, h and i represent the floc particles with compact structure in the strong mixing zone.

The average particle size of suspended matter in the strong mixing zone becomes fine, but it was still coarser than that in the freshwater area. The difference between original and decentralized samples for the particle size of suspended matter was not significant. Although the concentration of suspended matter and the salinity of water in the strong mixing zone are higher than those in the weak mixing zone, the interaction of tidal currents, runoff and water masses is intense in this zone (Liu et al., 2010). Under these conditions, the destructive effect of the shearing force from the strong hydrodynamic environment is greater than the facilitation from the high concentration of suspended matter and the high salinity of water (Guo and He, 2011), so the content of loose flocs with large particle size is reduced and the average particle size of suspended matter becomes fine. The surviving flocs have a firm structure and are not damaged or destroyed easily. According to the above analysis, we posit that the dispersion process has little effect on the change in particle size of suspended matter in the strong mixing zone. The SEM images show that the particle size of flocs in the strong mixing zone is large, and most of the floc particles are tightly bound (Figs 5g, h and i). Compared with the number of suspended particles, the content of flocs is relatively high in the strong mixing zone.

### 5.2 *Sedimentation of suspended particles in the estuary mixing zone*

The probability cumulative curves (Fig. 6) and *C*-*M* diagrams (Fig. 7) of the particle size of suspended matter are drawn in detail. Both figures show that the suspended particles are moved by suspension transportation in the whole study area.

The probability cumulative curves of the particle size of suspended matter in the freshwater area distribute in the manner of one-section distribution, which indicate that the suspended particles are primarily moved by suspension transportation. In the *C*-*M* diagram, the values of *C* and *M* of the suspended

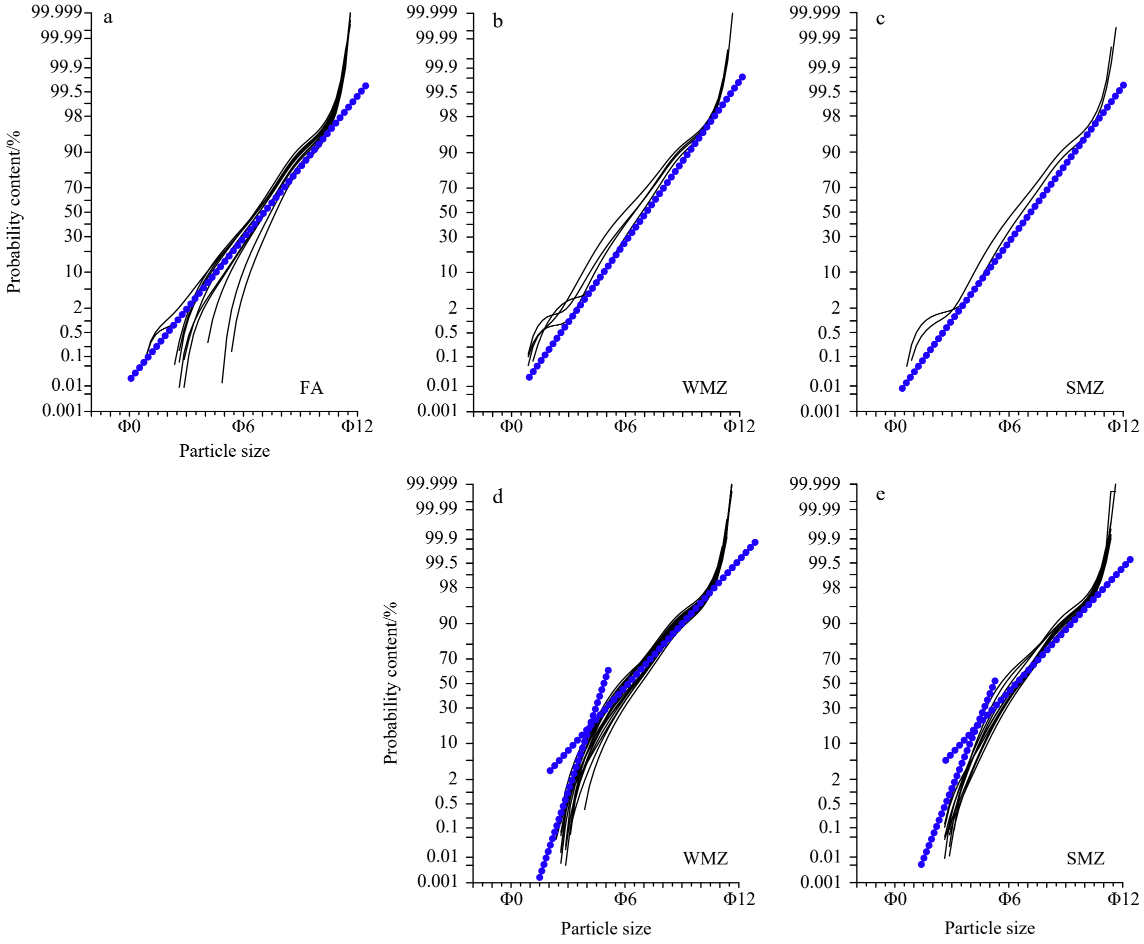

**Fig. 6.** Probability cumulative curves of the suspended particle size. a, b and c represent one-section distribution, d and e represent two-section distribution.

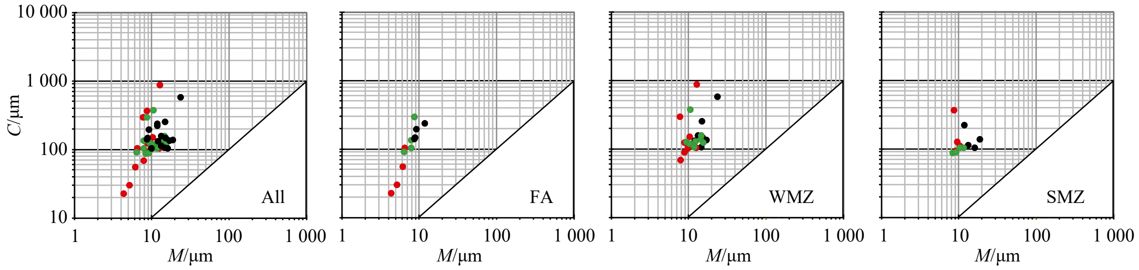

**Fig. 7.** *C*-*M* diagrams of suspended particle size in each zone. *C* represents the particle size corresponding to 1% on the accumulation curve, *M* represents the median grain size. All represents *C*-*M* diagram of the suspended particle size in the study area, FA represents *C*-*M* diagram of the suspended particle size in the freshwater area, WMZ represents *C*-*M* diagram of the suspended particle size in the weak mixing zone, SMZ represents *C*-*M* diagram of the suspended particle size in the strong mixing zone. The red dots represent the suspended particles in the surface layer; the green dots represent the suspended particles in the middle layer; the black dots represent the suspended particles in the bottom layer.

particles are small, and they change synchronously in the freshwater area. Additionally, the shape of the *C*-*M* curve is roughly parallel to the line of *C* equal to *M*, which shows that the suspension transportation belongs to the gradual suspension sub-collectivity.

The probability cumulative curves of the particle size of suspended matter in the weak mixing and strong mixing zones show mainly two-section distributions and the section point is near Φ4, both of which are due to gradual suspension sub-collectivity. A few samples present a one-section distribution. In the weak mixing zone, the values of *C* and *M* begin to increase, and the suspended matter presents the characteristics of graded suspension transport sub-collectivity. With the influence of resuspension increasing, the values of *C* in this zone change more obviously. This phenomenon can illustrate that some large particle size suspended matter exists in this zone. We speculate that those large size particles mainly are flocs and bio-detritus suspended in the water. The value of *C* in the strong mixing zone is smaller than that in the weak mixing zone. The shape of the *C*-*M* plot in the strong mixing zone is roughly parallel to the horizontal axis, so the suspended matter belongs to the uniform suspension transport subcollectivity. This indicates that the process of fine particles deposition is stable in the strong mixing zone.

To understand the deposition process of suspended matter in the mixing zone of the Changjiang River Estuary, the settling velocity of suspended particles is estimated according to the empirical settlement formula of suspended matter concentration (Shi, 2010):

$$W_s = mC^n, \tag{1}$$

where $W_s$ is the settling velocity of suspended particles (mm/s); $C$ is the suspended matter concentration (g/L); $m$ is a constant, equal to 2.73; $n$ is a constant, equal to 0.84.

The settling velocity of suspended particles ranges from 0.18 mm/s to 4.77 mm/s in the study area. The sedimentation rate of suspended particles in the freshwater area is the slowest at under 0.47 mm/s. In the weak mixing zone, the sedimentation velocity of suspended particles is increasing and mainly between 0.42 mm/s and 2.47 mm/s. The sedimentation velocity of suspended particles mixing zone in the strong mixing zone increases rapidly, and is from 1.02 mm/s to 4.77 mm/s. The high settling velocity of suspended particles in the mixing zone is beneficial to maintain the bed geomorphology and preservation of the fine suspended particles.

## 6 Conclusions

The average particle size of suspended matter in the strong mixing zone of the Changjiang River Estuary is coarser than in the freshwater area but is finer than in the weak mixing zone. The distribution patterns of suspended particles in the water mixing zone is an abnormal model that was mainly composed by a unimodal mode. The suspended particles are transported by suspension transportation in the whole study area.

The changes of grain sizes between untreated and treated total suspended particles matter in the Changjiang River Estuary suggest that flocculation processes mainly occur in the mixing zone, and more solid flocs exist at the strong mixing zone. The flocculation processes would promotes the settling and deposition of suspended particles, which has an important influence on the formation of bed geomorphology and estuarine sedimentation.

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## References

Ahn J H. 2012. Size distribution and settling velocities of suspended particles in a tidal embayment. Water Research, 46(10): 3219–3228, doi: 10.1016/j.watres.2012.03.038

Ahn J H, Grant S B. 2007. Size distribution, sources, and seasonality of suspended particles in southern California marine bathing waters. Environmental Science & Technology, 41(3): 695–702

Astoreca R, Doxaran D, Ruddick K, et al. 2012. Influence of suspended particle concentration, composition and size on the variability of inherent optical properties of the Southern North Sea. Continental Shelf Research, 35: 117–128, doi: 10.1016/j.csr.2012.01.007

Chai Chao, Yu Zhiming, Shen Zhiliang, et al. 2009. Nutrient characteristics in the Yangtze River Estuary and the adjacent East China Sea before and after impoundment of the Three Gorges Dam. Science of the Total Environment, 407(16): 4687–4695, doi: 10.1016/j.scitotenv.2009.05.011

Chen Hongyu, Cheng Yu, Wang Ying, et al. 2024. Microplastics: A potential proxy for tracing extreme flood events in estuarine environments. Science of the Total Environment, 918: 170554, doi: 10.1016/j.scitotenv.2024.170554

Chen Qingqing, Meng Yi, Zhou Juzhen, et al. 2005. A review on flocculation of fine suspended sediments and its controlling factors in the Yangtze River Estuary. The Ocean Engineering (in Chinese), 23(1): 74–82

Fan Jiayu, Fan Daidu, Wu Yijing. 2023. Spatiotemporal variations of heavy metal historical accumulation records and their influencing mechanisms in the Yangtze River Estuary. Science of the Total Environment, 854: 158733, doi: 10.1016/j.scitotenv.2022.158733

Fettweis M, Francken F, Pison V, et al. 2006. Suspended particulate matter dynamics and aggregate sizes in a high turbidity area. Marine Geology, 235(1–4): 63–74, doi: 10.1016/j.margeo.2006.10.005

Gao Lei, Li Daoji, Ding Pingxing. 2009. Quasi-simultaneous observation of currents, salinity and nutrients in the Changjiang (Yangtze River) plume on the tidal timescale. Journal of Marine Systems, 75(1–2): 265–279, doi: 10.1016/j.jmarsys.2008.10.006

Guo Leicheng, He Qing. 2011. Freshwater flocculation of suspended sediments in the Yangtze River, China. Ocean Dynamics, 61(2–3): 371–386, doi: 10.1007/s10236-011-0391-x

Jiang Guojun, Yao Yanming, Tang Ziwen. 2002. Analysis of influencing factors on fine sediment flocculation in the Changjiang Estuary. Acta Oceanologica Sinica, 21(3): 385–394

Jin Ying, Wang Yigang, Li Yu. 2002. Experimental study on flocculation of cohesive fine grain sediment at Yangtze River Estuary. Journal of Hohai University (in Chinese), 30(3): 61–63

Kitheka J U, Mavuti K M, Nthenge P, et al. 2016. The turbidity maximum zone in a shallow, well-flushed Sabaki Estuary in Kenya. Journal of Sea Research, 110: 17–28, doi: 10.1016/j.seares.2015.03.001

Li Jun, Gao Shu, Zeng Zhigang, et al. 2003. Particle-size characteristics and seasonal variability of suspended particulate matters in the Changjiang River Estuary. Oceanologia et Limnologia Sinica (in Chinese), 34(5): 499–510

Li Yunhai, Li Dongyi, Fang Jianyong, et al. 2015. Impact of Typhoon Morakot on suspended matter size distributions on the East China Sea inner shelf. Continental Shelf Research, 101: 47–58, doi: 10.1016/j.csr.2015.04.007

Li Dongyi, Li Yunhai, Xu Yonghang. 2017. Observations of distribution and flocculation of suspended particulate matter in the Minjiang River Estuary, China. Marine Geology, 387: 31–44, doi: 10.1016/j.margeo.2017.03.006

Li P, Yang Shilun, Milliman J D, et al. 2012. Spatial, temporal, and human-induced variations in suspended sediment concentration in the surface waters of the Yangtze Estuary and adjacent coastal areas. Estuaries and Coasts, 35(5): 1316–1327, doi: 10.1007/s12237-012-9523-x

Liu Hong, He Qing, Wang Zhengbing, et al. 2010. Dynamics and spatial variability of near-bottom sediment exchange in the Yangtze Estuary, China. Estuarine, Coastal and Shelf Science, 86(3): 322–330

Liu Qizhen, Li Jiufa, Lu Weichang, et al. 2006. Review on the organic-flocculation of fine sediments in estuaries. Marine Science Bulletin (in Chinese), 25(2): 74–80

Liu Qinqin, Liu Xiaojian, Chen Jian, et al. 2023. Experimental study on flocculation and sedimentation characteristics of cohesive fine sediment measured using ultrasound in the Pearl River Estuary. International Journal of Sediment Research, 38(6): 880–890, doi: 10.1016/j.ijsrc.2023.09.001

Liu J P, Xu K H, Li Anchun, et al. 2007. Flux and fate of Yangtze River sediment delivered to the East China Sea. Geomorphology, 85(3–4): 208–224, doi: 10.1016/j.geomorph.2006.03.023

McManus J. 1988. Grain size determination and interpretation. In: Tucker M E, ed. Techniques in Sedimentology. Oxford: Blackwell Scientific, 63–85

Ming Yue, Gao Lei. 2022. Flocculation of suspended particles during estuarine mixing in the Changjiang Estuary-East China Sea. Journal of Marine Systems, 233: 103766, doi: 10.1016/j.jmarsys.2022.103766

Pang Yue, Fan Dejiang, Hu Zhizhou, et al. 2018. The properties and spatial distributions of flocs adjacent to the Yangtze Estuary. Continental Shelf Research, 167: 87–98, doi: 10.1016/j.csr.2018.07.012

Pang Chongguang, Yu Wei, Yang Yang. 2010. Characteristics and its forming mechanism on grain size distribution of suspended matter at Changjiang Estuary. Environmental Science (in Chinese), 31(3): 618–625

Shen Zhiliang, Zhou Shuqing, Pei Shaofeng. 2008. Transfer and transport of phosphorus and silica in the turbidity maximum zone of the Changjiang Estuary. Estuarine, Coastal and Shelf Science, 78(3): 481–492

Shi J Z. 2010. Tidal resuspension and transport processes of fine sediment within the river plume in the partially-mixed Changjiang River Estuary, China: a personal perspective. Geomorphology, 121(3–4): 133–151, doi: 10.1016/j.geomorph.2010.04.021

Tang Jianhua. 2007. Characteristics of fine cohesive sediment's flocculation in the Changjiang Estuary and its adjacent sea area (in Chinese)[dissertation]. Shanghai: East China Normal University

Uncles R J, Bale A J, Stephens J A, et al. 2010. Observations of floc sizes in a muddy estuary. Estuarine, Coastal and Shelf Science, 87(2): 186–196

Wang Liang. 2014. High-resolution sedimentary record in the typical mud areas of East China Sea and its response to climate and environmental changes (in Chinese)[dissertation]. Qingdao: Ocean University of China

Wang Yaping, Voulgaris G, Li Yan, et al. 2013. Sediment resuspension, flocculation, and settling in a macrotidal estuary. Journal of Geophysical Research: Oceans, 118(10): 5591–5608, doi: 10.1002/jgrc.20340

Wu Jiaxue, Liu J T, Wang Xia. 2012. Sediment trapping of turbidity maxima in the Changjiang Estuary. Marine Geology, 301–306: 14–25

Xia Xiaoming, Li Yan, Yang H, et al. 2004. Observations on the size and settling velocity distributions of suspended sediment in the Pearl River Estuary, China. Continental Shelf Research, 24(16): 1809–1826, doi: 10.1016/j.csr.2004.06.009

Xu Kehui, Milliman J D. 2009. Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam. Geomorphology, 104(3–4): 276–283, doi: 10.1016/j.geomorph.2008.09.004

Xu Hui, Zhang Dawei, Xu Zhizhen, et al. 2018. Study on the effects of organic matter characteristics on the residual aluminum and flocs in coagulation processes. Journal of Environmental Sciences, 63: 307–317, doi: 10.1016/j.jes.2016.11.020

Xue Pengfei, Chen Changsheng, Ding Pingxing, et al. 2009. Saltwater intrusion into the Changjiang River: A model-guided mechanism study. Journal of Geophysical Research: Oceans, 114(C2): C02006

Yang Shilun, Eisma D, Ding Pingxing. 2000. Sedimentary processes on an estuarine marsh island within the turbidity maximum zone of the Yangtze River mouth. Geo-Marine Letters, 20(2): 87–92, doi: 10.1007/s003670000042

Yang Yunping, Li Yitian, Sun Zhaohua, et al. 2013. Trends and causes of suspended sediment concentration variation in the turbidity maximum zone at the Yangtze River Estuary. Acta Geographica Sinica (in Chinese), 68(9): 1240–1250

Yuan Shuai, Wang Yan, Liu Ruhai, et al. 2021. Behaviour and distribution of arsenic in seawater and suspended particulate matter in the adjacent area of the Changjiang Estuary during summer and autumn. Ecotoxicology and Environmental Safety, 227: 112884, doi: 10.1016/j.ecoenv.2021.112884

Zhao Lei, Song Changchun, Fang Chong, et al. 2023. Spatiotemporal variation of long-term surface and vertical suspended particulate matter in the Liaohe Estuary, China. Ecological Indicators, 151: 110288, doi: 10.1016/j.ecolind.2023.110288

Zhu Wenwu, Li Jiufa, Li Weihua. 2022. Observations of fine sediment flocculation in the turbidity maximum of the Changjiang Estuary. Journal of Sea Research, 179: 102150, doi: 10.1016/j.seares.2021.102150