

Article

Deposition Mechanisms of Suspended Sediment in an Estuarine Artificial Lake: A Case Study of the Jiaojiang Estuary

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Abstract

Artificial seawater lakes constructed in estuarine environments are highly susceptible to the intrusion of water containing high concentrations of suspended sediment, which can degrade water quality and threaten ecosystem stability. To clarify the settling mechanisms and sedimentation efficiency under high-turbidity conditions, this study investigated the Baishawan Artificial Lake in the Jiaojiang Estuary, eastern China, through field observations, controlled still-water sedimentation experiments, and a multi-particle size sedimentation efficiency model. Field measurements revealed significant spatiotemporal variability in suspended sediment concentration (SSC), with higher SSC during spring tides than neap tides and a spatial gradient decreasing from the near-estuary zone to the artificial lake and offshore waters. Grain-size analysis showed that suspended sediment was dominated by clay and silt (>98%). Laboratory experiments indicated a two-stage settling process characterized by rapid initial sedimentation followed by gradual stabilization; under high concentration (1.32 kg/m³), SSC decreased by about 85% within 40 min due to concentration-enhanced flocculation, whereas under low-concentration conditions (0.24 kg/m³) approximately 14 h were required to reach the target concentration of 0.01 kg/m³. Model validation demonstrated that the multi-component sedimentation model effectively reproduced the temporal attenuation of SSC. Model application further suggested that when the initial SSC was 0.70 kg/m³ and the water depth was 5.7 m, the sedimentation tank could reduce the SSC to 0.01 kg/m³ within about 16–17 h, with an estimated annual sedimentation volume of ~65,000 m³ and a recommended dredging interval of five years. These results provide quantitative guidance for sedimentation tank operation and sediment management in estuarine artificial lakes and other high-turbidity coastal environments.



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1. Introduction

As a distinctive geomorphic feature in estuarine and coastal areas, artificial seawater lakes not only have the typical characteristics of freshwater lakes but are also subject to long-term marine forcing such as tides and waves, serving as important carriers for coastal ecological protection and landscape construction [1]. Sediment is a fundamental component

of lake evolution, and its sedimentation process directly affects both the landscape integrity and ecological stability in artificial seawater lakes [2–4]. On the one hand, the increase in suspended sediment concentration in water will significantly reduce light transmittance, thereby inhibiting primary productivity in aquatic systems. This problem is particularly prominent in semi-enclosed or enclosed bays and artificial lake environments [5,6]. On the other hand, high suspended sediment concentrations can also alter water physicochemical properties, including dissolved oxygen and temperature. When combined with excessively long water exchange cycles, these changes may increase the risk of ecological problems such as algal blooms [7–10]. The suspended sediment concentration of artificial lakes usually needs to be controlled below 0.01 kg/m^3 . However, when constructing new artificial lakes in high-sediment-laden estuarine areas, the invasion of high-concentration suspended sediment from the open sea through water exchange has become a key problem threatening their ecology and landscape [4]. Therefore, investigating the pre-sedimentation of suspended sediment in artificial lake sedimentation tanks is of great significance for maintaining the water quality stability of lake bodies and protecting the ecological landscape of seawater lakes.

The sedimentation process is not an independent motion of individual particles, but a complex process accompanied by group sedimentation and flocculation [11–14]. It should be noted that while high SSC provides a high collision frequency, flocculation is still constrained by factors such as particle properties (e.g., clay content), electrolytic environment (e.g., salinity), and hydrodynamic disturbances. In environments like the Jiaojiang Estuary, characterized by high salinity and a high proportion of fine particles, high concentration significantly facilitates the flocculation process. Current research on sediment accumulation mainly follows two approaches: field observations and laboratory still water sedimentation experiments. Field observation can directly measure sediment settling velocity in natural environment instruments such as ADV. For example, Li et al. reported that the settling velocity of fine-grained sediment in the Three Gorges Reservoir area varies vertically and is strongly influenced by flocculation [15]; Gao et al. revealed the influence of wind speed on suspended sediment settling velocity [16]. However, field observation is affected by turbulence and vertical water motion, making it difficult to accurately separate the effect of individual factors, resulting in certain measurement errors [17]. Laboratory still water sedimentation experiments allow the settling behavior of sediment to be systematically examined under controlled conditions. Xie et al. studied Taihu Lake and Chaohu Lake and found that the flocculation settling velocity of lake sediment is much higher than that of single-particle sedimentation, and is significantly affected by the initial sediment concentration [18–21].

However, existing studies mostly focus on the sediment deposition process of natural lakes [16], whereas suspended sediment settling in estuarine environments remains insufficiently studied. Under the interaction of runoff and tidal currents, accompanied by repeated sedimentation and resuspension processes, the estuarine sediment concentration exhibits pronounced variability over both tidal and interannual timescales [22,23]. For example, the sediment concentration in the Yangtze Estuary is higher during spring tides than during neap tides [22], and the daily variation in suspended sediment in lagoons is closely related to river discharge [24]. In addition, suspended sediment settling is controlled by multiple factors, including sediment characteristics and composition, water temperature, salinity [18,25–28]. Jing et al. showed that the distribution ratio of coarse and fine sediment particles will affect sorting sedimentation and flocculation sedimentation efficiency [26]; Wang et al. found that seasonal differences in water temperature in the Yangtze Estuary alter the effect of salinity on sediment settling, and they established a corresponding still water sedimentation formula [18]; Mhashhash et al. confirmed that the suspended sedi-

ment settling in the Severn Estuary is synergistically affected by initial concentration and salinity [27]; at the same time, the freshwater flocculation effect of suspended sediment in the upper reaches of the estuary cannot be ignored [29,30].

Although some studies have examined sediment settling in coastal lakes such as lagoons [31,32], most of them are based on field observations. There is still a lack of research on the still water sedimentation process and efficiency evaluation of suspended sediment in artificial seawater lakes in estuarine areas, especially the lack of targeted research on high-sediment-laden estuarine scenarios [33–35]. In this study, we hypothesize that the rapid siltation in such artificial lakes is driven by the synergistic effect of high-concentration suspended sediment (SSC) and salinity-induced flocculation, which significantly accelerates settling velocities beyond the predictions of independent particle theory. To test this hypothesis and address this research gap, this study systematically explores the sediment settling laws in the Jiaojiang Estuary through a combination of field monitoring and controlled laboratory experiments [11,36]. The primary objectives are to: (1) characterize the spatiotemporal heterogeneity of SSC and grain-size distribution under different tidal regimes; (2) quantify the settling dynamics and threshold effects of high-concentration sediment via static sedimentation tests; and (3) develop a multi-component model to evaluate sedimentation efficiency. The expected outcome is to provide a theoretical basis and predictive tool for optimizing water exchange cycles and pre-sedimentation strategies in estuarine artificial lake landscapes.

2. Study Area

This study focused on the Baishawan Artificial Lake located on the north bank of the Jiaojiang Estuary in the central coastal area of Zhejiang Province (Figure 1). The region is situated in a subtropical monsoon climate zone, characterized by an average annual temperature of approximately 17.5 °C and an average annual precipitation of about 1500 mm, with rainfall primarily concentrated from June to September. This area is a typical high-sediment-laden estuarine environment with complex hydrological conditions. The average tidal range of Jiaojiang Estuary is 4.0 m, and the maximum tidal range can reach 6.3 m. The suspended sediment concentration (SSC) exhibits significant spatial–temporal variability. The suspended sediment concentration in the open sea exceeds 10 kg/m³ during spring tides and is about 6 kg/m³ during neap tides [37]. The frequent intrusion of high-sediment-laden water from the Jiaojiang Estuary leads to rapid siltation and increased turbidity within the artificial lake [38,39]. This process not only diminishes the visual clarity and recreational value but also threatens ecological stability by reducing light penetration for submerged vegetation and altering the benthic habitat through excessive fine-grained sediment deposition.

Baishawan Artificial Lake covers an area of about 1.88×10^6 m² with a total storage capacity of 6×10^6 m³ [1]. To solve the problem of sedimentation, a seawater sedimentation tank was built on the east side of the artificial lake as a pretreatment unit for water quality purification. The sedimentation tank covers an area of 3×10^5 m², with a designed bottom elevation of −2.5 m and an operating water level ranging from 1.5 m to 3.2 m. The sedimentation tank controls water exchange through two sets of key sluice gates. The outer one is the tidal intake sluice with a net width of 4.0 m and a bottom plate elevation of −1.5 m, which is used to introduce high-sediment-laden seawater from the open sea. The inner one is the drainage sluice with a net width of 4.0 m and a bottom plate elevation of 0.0 m, which is responsible for introducing the upper clear water after sedimentation treatment into the artificial lake through a combination of gravity flow and pump extraction.

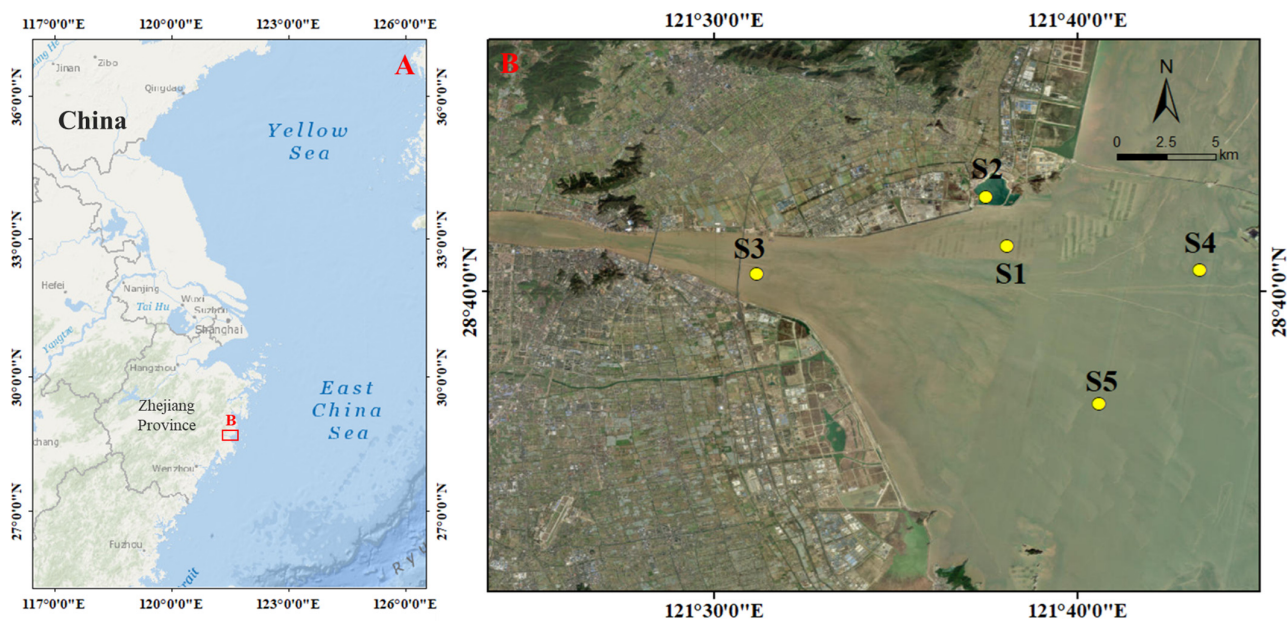


Figure 1. Location of the study area. (A) Map of East China showing the regional context; (B) Detailed view of the Jiaojiang Estuary and the location of the Baishawan Artificial Lake. S1–S5 in subfigure (B) denote the specific sediment sampling locations.

3. Materials and Methods

This study aimed to analyze the spatial-temporal distribution characteristics of suspended sediment in the Baishawan sea area, quantify the still water sedimentation laws and construct a sedimentation efficiency model through a combination of field observation and laboratory experiments, thereby providing a scientific basis for the optimal operation of the sedimentation tank.

3.1. Field Sampling

To investigate the suspended sediment characteristics of the Baishawan sea area, the Zhejiang Institute of Hydraulics and Estuary Engineering carried out field sampling in March 2017. The monitoring stations were arranged as shown in Figure 1, with a total of 5 monitoring stations (S1–S5). The latitude and longitude coordinates of each station are shown in Table 1. Among them, S1 is adjacent to the outer side of the tidal intake sluice, representing the direct water intake source of the sedimentation tank; S2 is located inside the artificial lake; S3 is close to the main stream of Jiaojiang River, significantly affected by river runoff; S4 and S5 are located in the offshore deep water area, more obviously affected by tides. The sampling covered two typical tidal periods: spring tide and neap tide. The variations in sampling depths across different stations in Table 1 are attributed to the dynamic tidal levels and varying bathymetry of the Jiaojiang Estuary. To ensure data comparability, vertical layered sampling was carried out in 6 layers at each station using an XCL horizontal water sampler. The volume of a single sample was at least 500 mL. After collection, the water samples were fully stirred and evenly transferred into polyethylene sample bottles for sealed preservation. The selection of sampling dates for spring and neap tides was based on astronomical tide predictions to ensure they represented the extreme dynamic conditions of the tidal cycle. Specifically, the spring tide sampling captured the maximum tidal range and current velocity, which are the primary drivers of sediment resuspension and transport in the Jiaojiang Estuary. Similarly, the neap tide period represented the minimum dynamic state. This approach aligns with established estuarine monitoring protocols, where the full spectrum of sediment dynamics is characterized by these two boundary conditions.

Table 1. Station locations and water depth.

Station	Latitude	Longitude	Depth (m)
S1	28.6748	121.5194	3.9
S2	28.6397	121.6023	1.3
S3	28.6876	121.6345	4.1
S4	28.7051	121.6820	7.9
S5	28.6766	121.7230	6.4

3.2. Methods

The pre-sedimentation process of suspended sediment is affected by the coupling of multiple factors. Among them, the settling characteristics of fine-grained sediment are closely related to key factors such as initial suspended sediment concentration, water salinity and water depth [11,40]. To accurately evaluate the time threshold required for the sedimentation tank to complete suspended sediment settling, this study first analyzed the spatial-temporal distribution characteristics and core particle size parameters of local suspended sediment in Baishawan based on field measured data, providing a basis for the concentration ratio of subsequent still water sedimentation experiments. Then, through laboratory still water sedimentation experiments, the evolution laws of suspended sediment concentration under different sediment content conditions were clarified. Finally, combined with the experimental results and the multi-component sedimentation characteristics of sediment, a suspended sedimentation efficiency model was constructed to reproduce the entire suspended sediment settling process in the sedimentation tank and quantify the sedimentation efficiency, providing a scientific basis for the optimization of sluice gate operation schemes. The specific research methods are as follows.

3.2.1. Determination of Suspended Sediment Concentration

The suspended sediment concentration was determined using a laboratory gravimetric method. The collected water samples were filtered using a 0.45 µm fiber filter membrane, and the weight of the filter membrane before filtration was measured (recorded as W_1). Then, the filtered filter membrane was placed in an electric constant temperature drying oven and dried in a constant temperature oven at 40–50 °C for 6–8 h. After dehydration, the filter membrane was moved into a silica gel desiccator for cooling and drying for 6–8 h, and weighed again (recorded as W_2). The suspended sediment concentration of each water sample layer by layer can be calculated by the following formula:

$$\rho = \frac{W_2 - W_1}{V} \quad (1)$$

where ρ is the suspended sediment concentration (kg/m³), and V is the volume of water sample (m³). Finally, the vertical average of the suspended sediment concentration was calculated for each station.

3.2.2. Grain Size Analysis

The grain size distribution of suspended sediment was analyzed using a MasterSizer 2000 laser particle size analyzer (Malvern Panalytical Ltd., Malvern, UK), with a measurement range of 0.02–2000 µm. Before the analysis, the collected water samples were pretreated. First, add 6–7 mL of 30% hydrogen peroxide and let it stand for 24 h to remove organic matter. Then add 10 mL of 36–38% concentrated hydrochloric acid to remove calcium carbonate substances. During this period, an appropriate amount of distilled water was added to maintain the pH value stable between 6 and 7. Finally, 10 mL of sodium metaphosphate solution was added, and the sample was fully dispersed by ultrasonication

for 10–15 min, and then tested by the laser particle size analyzer. The grain size classification and parameter calculation were carried out in accordance with the sediment classification standard of the American Geophysical Union (AGU) [41].

3.2.3. Still Water Sedimentation Experiment

Since station S1 station is located immediately outside the tidal intake sluice, its suspended sediment composition is most representative of the inflow sediment entering the sedimentation tank. Therefore, this study selected the water samples collected from the S1 station to carry out laboratory still water sedimentation experiments. First, the suspended sediment concentration and grain size of the water samples collected from the S1 station during spring and neap tides were measured to clarify the proportion of suspended sediment with different particle sizes in the water body, providing a basis for the concentration ratio of the still water experiment. To ensure close consistency with field conditions of the Baishawan artificial lake, the water and sediment samples used in the laboratory experiments were directly collected from the field monitoring stations (S1) in the Jiaojiang Estuary. No artificial or commercial clay was used.

The experiment used a self-made settling column (as shown in Figure 2a) with a height of 2 m, an inner diameter of 0.5 m and an effective volume of about 0.39 m³, which had good light transmittance and stability. The supporting equipment included a siphon sampling tube, a glass stirrer, a beaker and a ruler.

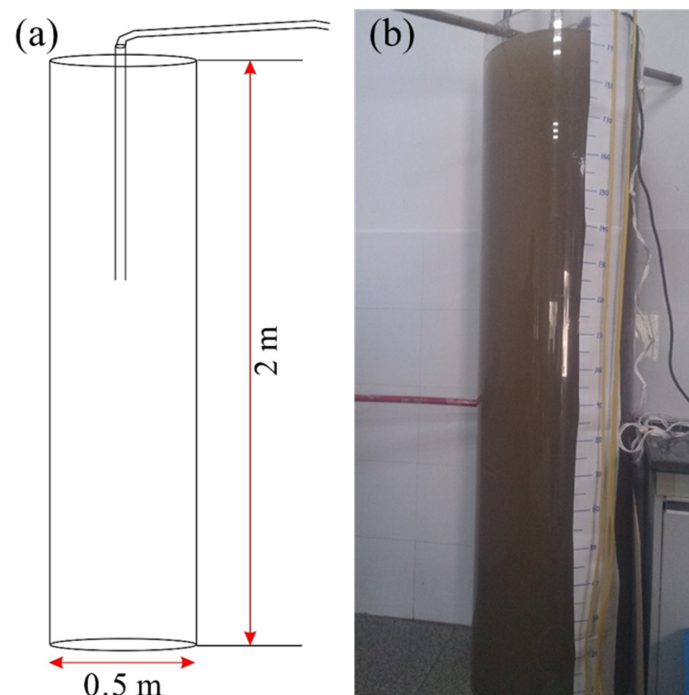


Figure 2. Settling column experiment in the still water. (a) Physical Setup; (b) Schematic Diagram.

Two groups of water samples were established in the experiment, which were prepared according to the average suspended sediment concentration of the S1 station during spring and neap tides. Each group included three replicates to reduce experimental errors. After the prepared water samples were injected into the settling column, they were fully mixed with a glass stirrer to ensure uniform distribution of suspended sediment, after which the settling period was initiated. To accurately capture the dynamic changes in suspended sediment settling, siphon sampling was carried out at the surface, middle and bottom layers of the settling column (0 m, 1.0 m and 1.8 m from the water surface) at 5 min, 10 min, 15 min, 20 min, 25 min, 30 min, 35 min, 40 min, 45 min, 50 min, 55 min, 60 min,

75 min, 90 min, 105 min, 120 min, 150 min, 180 min, 240 min, 300 min, 360 min, 480 min, 600 min, 720 min, 840 min, 960 min, 1260 min and 1440 min after the start of settling. During the sampling process, the siphon sampling tube only moved vertically to avoid disturbing the suspended sediment settling process. After sampling, the water samples were filtered, dried and weighed according to the indoor drying and weighing method in Section 3.2.1, and the suspended sediment quality at each time node and vertical position was recorded to further analyze the variation laws of suspended sediment concentration with time and depth.

3.2.4. Suspended Sedimentation Efficiency Model

Natural sediment consists of multi-particle size components, and the settling velocity of each component is significantly different [35,42]. During the tidal intake period of the sedimentation tank, affected by water flow disturbance, the suspended sediment in the tank is assumed to be well mixed, and it can be approximately considered that the sediment content and component distribution in the water body are uniform. In the sedimentation stage after the end of tidal intake, the water movement in the tank is weak, which approximates still water conditions. Assuming that the settling velocity of sediment with the same particle size is constant under still water conditions, the total mass of suspended sediment in the water body $M(t)$ can be calculated by the following formula:

$$M(t) = H \cdot A \cdot S(t) = \sum_{i=1}^N m_i(t) \quad (2)$$

where $S(t)$ is the water sediment content at time t (kg/m^3); N is the number of sediment particle size groups, which can be determined according to the grain size analysis results; $m_i(t)$ is the suspended sediment mass of the i -th particle size group at time t (kg), $m_i(t) = P_i(t) \cdot M(t)$, and $P_i(t)$ is the proportion of suspended sediment of the i -th particle size group in the total suspended sediment at time t . Therefore, the suspended sediment concentration $S(t)$ at time t can be expressed as:

$$S(t) = \frac{\sum_{i=1}^N m_i(t)}{H \cdot A} \quad (3)$$

For the i -th particle size group, the suspended sediment mass $m_i(t)$ decays linearly with time. When the particles are completely settled, the suspended sediment mass of this particle size group is 0, and its expression is:

$$m_i(t) = \begin{cases} m_i(0) - \omega_i t, & 0 \leq t \leq H/\omega_i \\ 0, & t > H/\omega_i \end{cases} \quad (4)$$

where ω_i is the settling velocity of suspended sediment of the i -th particle size group (m/s), which can be calculated by the Stokes formula:

$$\omega_i = \frac{1}{18} \frac{\gamma_s - \gamma}{\gamma} g \frac{D_i^2}{\nu} \quad (5)$$

where γ_s and γ are the unit weights of sediment and water flow respectively; g is the gravitational acceleration; D_i is the equivalent spherical diameter of particles of the i -th particle size group (m); ν is the kinematic viscosity coefficient of water flow. The suspended sediment concentration variation curve calculated by the above model was compared with the measured data of the still water sedimentation experiment to verify the applicability of

the model, providing theoretical support for the subsequent sedimentation analysis of the sedimentation tank and the operation and scheduling of sluice gates.

4. Results

4.1. Suspended Sediment Concentration and Characteristics in Baishawan

The Baishawan coastal waters lie at the dynamic intersection of high-sediment-laden estuarine water and low-concentration coastal water. Field monitoring across five stations (S1–S5) reveals that the average suspended sediment concentration (SSC) ranges from 0.32 to 3.09 kg/m³ (Table 2), exhibiting pronounced spatio-temporal heterogeneity driven by tidal intensity and geographical location.

Table 2. SSC of different stations.

Suspended Sediment Concentration (kg/m ³)	Spring Tide	Neap Tide	Average
S1	1.32	0.24	0.780
S2	0.86	0.26	0.56
S3	4.77	1.41	3.09
S4	0.52	0.14	0.33
S5	0.52	0.12	0.32

Temporally, the SSC followed a clear pattern, with values during spring tides exceeding those during neap tides. For instance, the average SSC at S1 and S2 during spring tides (1.32 kg/m³ and 0.86 kg/m³, respectively) was approximately 3–5 times that observed during neap tides (0.24 kg/m³ and 0.27 kg/m³). Spatially, a significant gradient is observed: near-estuary area (S3) > artificial lake area (S1, S2) > offshore area (S4, S5), with this disparity intensifying during stronger tidal periods. S3, located adjacent to the Jiaojiang River's main stream, maintains the highest average SSC (3.00 kg/m³) due to the combined influence of riverine runoff and tidal resuspension. In contrast, the lake stations (S1, S2) are primarily affected by the intrusion of offshore high-turbidity plumes, with S1 showing higher concentrations than S2 during spring tides due to its greater exposure to the open sea. Meanwhile, the offshore stations (S4, S5) remain relatively stable at lower levels, as they are less influenced by near-shore dynamic disturbances. These results demonstrate that tidal dynamics and proximity to sediment sources are the primary determinants of the SSC distribution in the study area.

4.2. Still Water Sedimentation Process of Suspended Sediment

4.2.1. Suspended Sediment Gradation

Table 3 shows the grain-size distribution of suspended sediment at station S1 during spring and neap tides, and the gradation curve is shown in Figure 3. The results showed that the suspended sediment in Baishawan was dominated by clay particles (<4 µm) and silt particles (4–63 µm), and their cumulative proportions reached 98.2% and 99.21% during spring and neap tides, respectively, which was consistent with the high-sediment-laden characteristics of Jiaojiang Estuary dominated by fine-grained suspended sediment. In addition, the tidal type had a significant regulatory effect on the suspended sediment particle size composition of S1 station. The cumulative proportion of particles ≤ 16 µm during neap tides was 9.2% higher than that during spring tides. This difference primarily reflects the selective resuspension of bed sediment under different tidal energy conditions. During spring tides, the flow velocity in Jiaojiang Estuary was high, and the strong water flow shear force could lift relatively coarse silt particles on the bed surface, increasing the proportion of particles in this interval in the suspended sediment. During neap tides, the

tidal dynamics were significantly weakened, only fine particles ($<16\ \mu\text{m}$) were more likely to maintain a suspended state, and the remaining relatively coarse particles were mainly settled, resulting in an increase in the proportion of fine particle components.

Table 3. Suspended sediment particle size gradation of S1 station during spring and neap tides.

Grain Size (μm)		0.5	1	2	4	8	16	32	63	125	250
$P \leq D$ (%)	Spring tide	2.1	6.8	15.8	31.8	54	76.9	92.2	98.2	99.87	100
	Neap tide	1.7	6	15	32.9	61.3	86.1	96.3	99.21	99.99	100

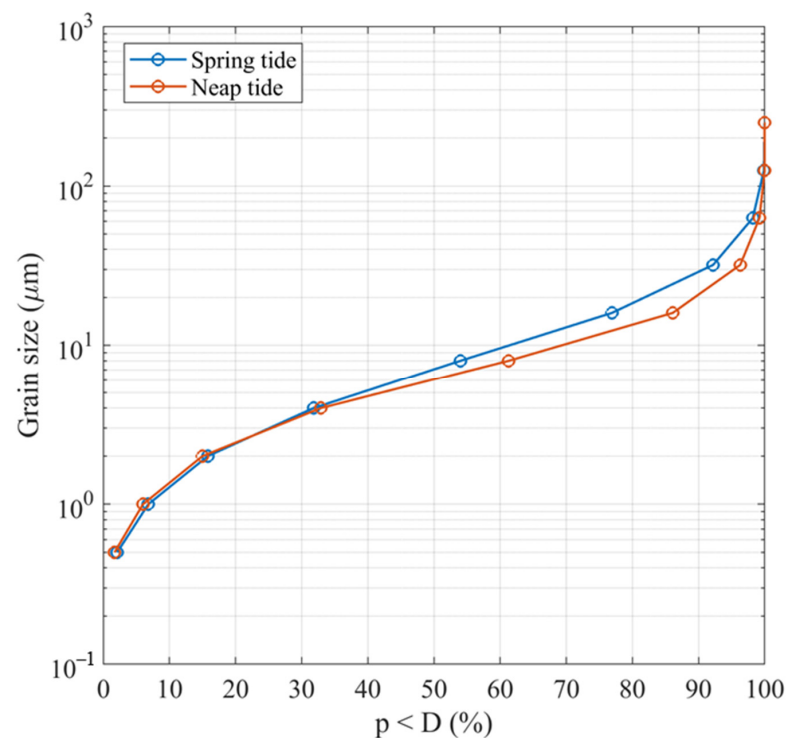


Figure 3. Grain size distribution curve of SSC in Baishawan Bay.

4.2.2. Still Water Sedimentation of Suspended Sediment

To clarify the settling behavior of suspended sediment in Jiaojiang Estuary in the sedimentation tank supporting the artificial lake, still water sedimentation experiments were carried out on the suspended sediment samples from S1 station. Two comparative experiments were conducted: the low-concentration group (neap tide, $0.24\ \text{kg}/\text{m}^3$) and the high-concentration group (spring tide, $1.32\ \text{kg}/\text{m}^3$). The dynamic changes in sediment content in the surface, middle and bottom layers were monitored synchronously. Figures 4 and 5 show the changes in sediment content in each water layer with time under low-concentration and high-concentration configurations respectively. Both experiments exhibited a two-stage pattern, with rapid initial settling followed by gradual stabilization, but affected by the initial sediment content, the duration and sedimentation rate of each stage were significantly different. As shown in Figure 4, the surface layer of the low-concentration group first entered the rapid sedimentation stage, and the suspended sediment concentration rapidly dropped to below $0.05\ \text{kg}/\text{m}^3$ within 2 h, then the sedimentation rate slowed down and stabilized at $0.01\ \text{kg}/\text{m}^3$ after 14 h. The sediment content in the middle layer began to be lower than the average value after 3 h. This phenomenon indicated that in the low-concentration environment, the suspended sediment in the surface layer had basically completed the sedimentation process, the middle layer no longer received sediment input from the upper layer, and the system gradually entered the sedimentation equilibrium state.

However, the bottom layer was still not completely stable because it continued to receive settling particles from the middle and upper layers. Figure 5 shows the sedimentation process of the high-concentration group. The suspended sediment concentration rapidly attenuated from the initial concentration to 0.20 kg/m^3 within 40 min, and then entered the slow stabilization stage. The mechanism behind this rapid attenuation in the high-concentration group (1.32 kg/m^3) is the formation of flocs. Although direct microscopic observation of flocs was not performed, the macroscopic settling behavior provides strong evidence: the concentration dropped by nearly 85% (from 1.32 kg/m^3 to 0.20 kg/m^3) within just 40 min. For particles dominated by clay and silt ($\leq 16 \mu\text{m}$, accounting for over 76.9%), such a high settling rate cannot be achieved through independent single-particle settling according to Stokes' law, which would typically require several hours or even days for such fine particles to settle out of a 2-m column.

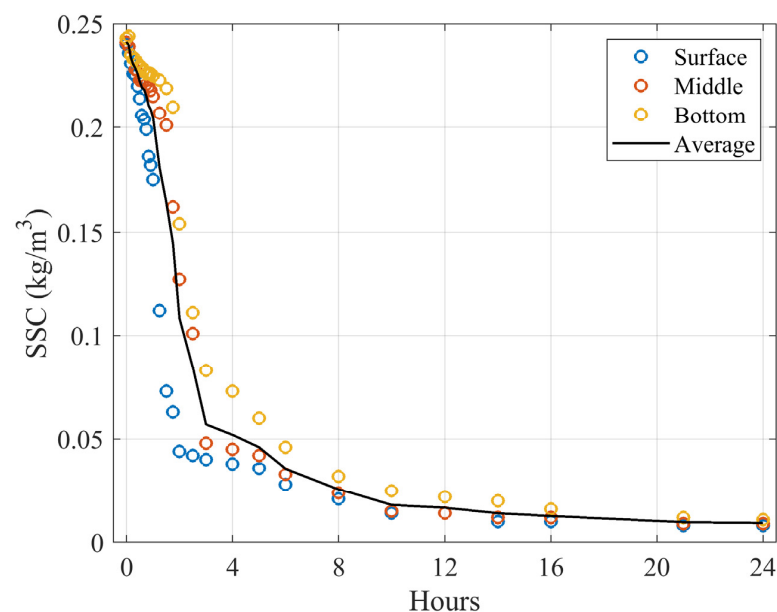


Figure 4. SSC variations at surface, middle, and bottom layers in the settling column under low sediment concentration conditions.

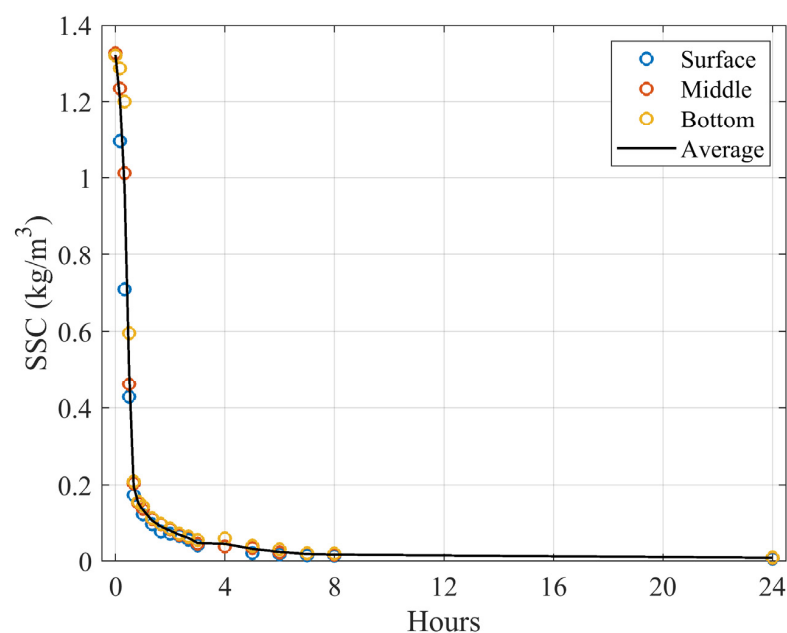


Figure 5. SSC variations at surface, middle, and bottom layers in the settling column under high sediment concentration conditions.

4.3. Sedimentation Efficiency Evaluation of Baishawan

4.3.1. Model Verification

By comparing the observed values of the still water sedimentation experiment with the predicted values of the sedimentation efficiency model (Figure 6), the results showed that the model captured the nonlinear attenuation of SSC under different initial conditions reasonably well. In the high initial concentration experiment characterized by spring tides, the initial sedimentation rate predicted by the model was significantly slower than the measured value. This deviation was mainly because the model assumed that particles settled independently based on the Stokes formula, ignoring the flocculation effect under high-concentration conditions. During spring tides, due to the extremely high content of fine particles (clay and silt) in the suspended sediment and the increase in collision frequency with the increase in SSC, the particles were very easy to aggregate into flocs with larger size and faster settling velocity. The measured data showed that the concentration of the water body dropped much more rapidly than the model prediction within 60 min of standing, which proved that flocculation significantly improved the effective settling particle size, making the actual sedimentation efficiency better than the theoretical value calculated based on the original gradation. In the low initial concentration experiment characterized by neap tides, the experimental group showed that the model prediction speed was faster than the measured value in the initial stage. In the low SSC environment, the particle spacing was large, the flocculation effect was weak, and the sedimentation behavior should be closer to single-particle sedimentation. However, the decrease in measured concentration had an obvious “lag” phenomenon in the initial stage. This discrepancy was likely caused by residual turbulence present during the initial stage of the experiment. In the low-concentration background, the offset effect of these weak upward forces on the gravitational settling of ultra-fine particles was amplified, resulting in a “hindered” effect. Because the model assumed that particles entered an ideal still-water settling state immediately at the start of the experiment, it overestimated the initial settling efficiency under neap-tide conditions.

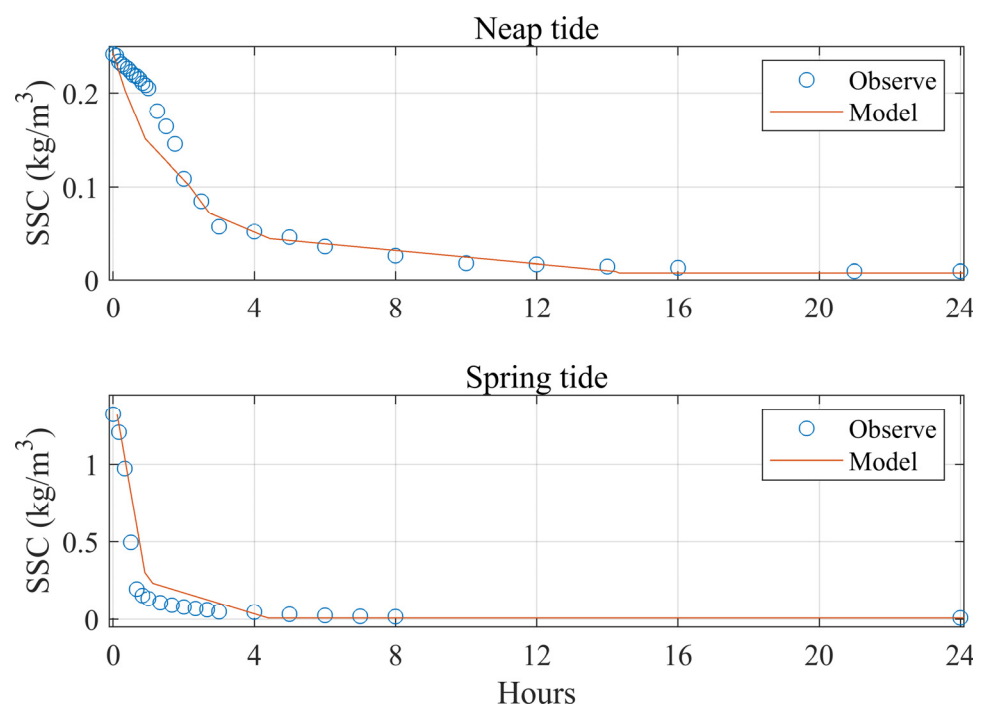


Figure 6. Comparison between observed experimental values and model predictions for still water sedimentation.

4.3.2. Sedimentation Efficiency Evaluation of Sedimentation Tank

The sediment accumulation efficiency model was applied to the calculation of the sedimentation tank. Assuming that the initial sediment content of the sedimentation tank was 0.70 kg/m^3 and the water depth was 5.7 m , the variation process of its sediment content was shown in Figure 7. After about 16 h , the sediment content of the sedimentation tank could decrease to the target value of 0.01 kg/m^3 . This threshold provides a reasonable reference for sluice gate opening. Assuming a monthly water intake of 6 million m^3 for the artificial lake, the same volume would pass through the sedimentation tank each month. After the seawater entered the sedimentation tank for sedimentation, the sediment content dropped to 0.01 kg/m^3 , and all the sediment was considered to be settled. Then the annual total sedimentation volume of the sedimentation tank was about $65,000 \text{ m}^3$, with an average annual sedimentation depth of about 0.2 m . Considering the elevation limit of the bottom plate of the outlet sluice of the sedimentation tank to the artificial lake, it was recommended to dredge once every 5 years.

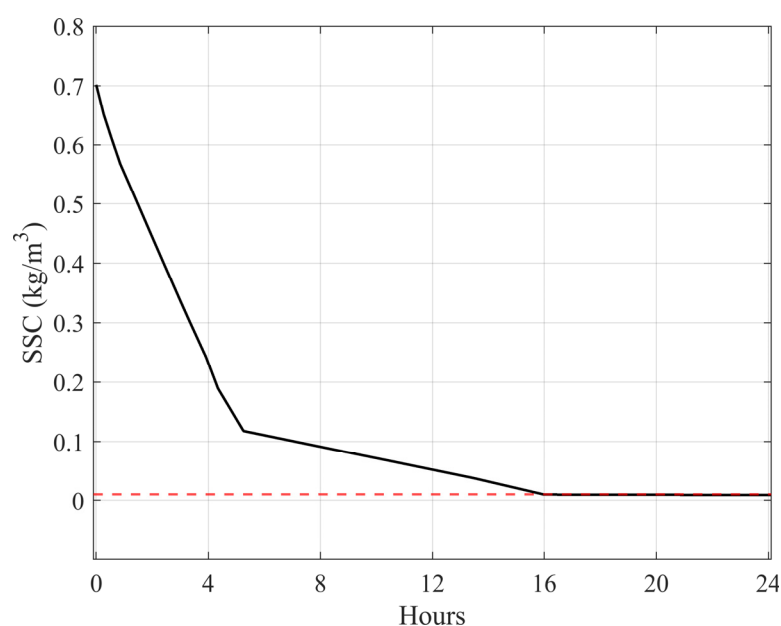


Figure 7. Variation curve of sediment content in sedimentation tank with time. (The red dashed line indicates the target suspended sediment concentration threshold of 0.01 kg/m^3).

5. Discussion

The Baishawan Artificial Lake serves as a microcosm of global coastal engineering challenges, where water is transferred from high-energy, high-sediment-laden estuarine environments into relatively quiescent artificial basins. Our findings regarding the concentration-dependent settling behavior underscore a critical transition in sediment dynamics. The significant discrepancy observed between Stokes-based theoretical predictions and our measured settling rates provides macro-level verification that flocculation is the primary driver of rapid deposition in the Jiaojiang Estuary. While this study is based on a specific case, the pattern identified here—namely, that high sediment concentrations promote flocculation and accelerate settling—has broader relevance to similar systems. The suspended sediment characteristics in the Jiaojiang Estuary share high physical similarities with other major deltaic regions, such as the Yangtze River Estuary and Hangzhou Bay, making our multi-particle size component model a transferable tool for similar geographical units worldwide.

However, several limitations should be acknowledged. Firstly, our laboratory experiments were conducted under static conditions to isolate core variables. In a real-world artifi-

cial lake, low-intensity turbulence from wind-induced waves or residual tidal currents may influence floc collision frequency and shear-induced breakup. Thus, the static settling rates reported here represent a theoretical maximum. Secondly, due to the high turbidity of the samples, direct in situ measurement of floc micro-structure was not feasible. Future research should incorporate low-shear flume experiments and high-resolution imaging techniques to further characterize floc micro-morphology and long-term consolidation processes.

6. Conclusions

Using the Baishawan Artificial Lake in the high-sediment-load Jiaojiang Estuary as a case study, this study systematically investigated the spatial-temporal distribution characteristics, still water sedimentation laws and sedimentation tank sedimentation efficiency of suspended sediment in the estuarine artificial lake through a combination of field sampling and monitoring, laboratory still water sedimentation experiments and the construction of a multi-particle size component sedimentation efficiency model, providing a scientific basis for the maintenance of artificial lake ecological landscapes, the setting of water exchange cycles and the optimal operation of sedimentation tanks. The main research conclusions are as follows:

1. The suspended sediment concentration in Baishawan was synergistically regulated by tides and location, showing significant spatial-temporal heterogeneity. The concentration during spring tides was generally higher than that during neap tides (the concentration of S1 station during spring tides was 5 times that during neap tides). The spatial distribution followed the gradient order of near-estuary area (S3, 3.09 kg/m³ on average) > artificial lake area (S1, S2) > offshore area (S4, S5), and the spatial difference changed positively with tidal intensity. The suspended sediment was dominated by clay and silt (cumulative proportion of 98.2% during spring tides and 99.21% during neap tides). Tidal dynamics had a selective regulatory effect on the particle size composition. The proportion of ultra-fine particles with particle size $\leq 16 \mu\text{m}$ during neap tides was 9.2% higher than that during spring tides, which determined the nonlinear characteristics of the sedimentation process.
2. The still water sedimentation showed concentration-dependent characteristics of “rapid in the initial stage and stable in the later stage”. The sediment content of the low-concentration group (0.24 kg/m³) stabilized at the target value of 0.01 kg/m³ after 14 h; the sediment content of the high-concentration group (1.32 kg/m³) rapidly attenuated to 0.20 kg/m³ within 40 min. The significant discrepancy between the Stokes-based model predictions and the measured settling rates provides macro-level verification that flocculation is the primary driver of rapid deposition at high concentrations in this estuarine environment.
3. The multi-particle-size sedimentation-efficiency model effectively reproduced the attenuation trend of suspended sediment concentration. The results of sedimentation tank sedimentation efficiency evaluation carried out by using this model showed that when the initial sediment concentration was 0.70 kg/m³ and the water depth was 5.7 m, it took 16 h of sedimentation to reduce the sediment concentration to the target value of 0.01 kg/m³. This time threshold provided a reasonable reference for sluice gate scheduling. Calculated based on the monthly water intake of the artificial lake of 6 million m³, the annual total sedimentation volume of the sedimentation tank was about 65,000 m³, with an average annual sedimentation depth of 0.2 m. Considering the elevation limit of the outlet sluice bottom plate, it was recommended to adopt a dredging cycle of once every 5 years to ensure the long-term stable operation of the sedimentation tank.

In conclusion, this research clarifies the non-linear sedimentation dynamics in a tide-dominated artificial lake, highlighting the critical role of salinity-induced flocculation in accelerated siltation. The established multi-component model and the derived operational thresholds offer a robust, science-based framework for managing coastal reservoirs. These findings not only provide immediate practical guidance for the maintenance of the Baishawan Artificial Lake but also serve as a valuable reference for the design and sustainable operation of similar coastal engineering projects in high-sediment-laden estuaries worldwide.

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