Impact of Shoreline Ecological Restoration on Suspended Sediment Concentration in Shanghai Coastal Waters

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Abstract: The coastal waters of Shanghai are characterized by high turbidity due to sediment input from the Yangtze River and strong tidal forces. Rapid urbanization has led to shoreline hardening, altering hydrodynamics and sediment transport, resulting in ecological degradation. Although ecological restoration measures have been initiated, their broad impacts on suspended sediment concentration (SSC) remain unclear. In this study, a model for retrieving SSC in Shanghai's nearshore waters was developed using data from the Gaofen-1/Gaofen-2 satellites and the Quasi-Analytical Algorithm (QAA). The exponential model ($SSC = 21.959 \cdot \exp(0.9335 \cdot bbp)$($R^2 = 0.7305$)) . Applying this model to time-series data from 2020 to 2024 revealed that SSC values at traditional hardened shoreline Area were higher and more variable (summer mean = 145 mg/L, standard deviation = 96 mg/L), whereas natural reference areas maintained lower SSC levels (mean = 45 mg/L, standard deviation = 11 mg/L). SSC in Lingang ecological restoration area showed intermediate values (87 mg/L) with reduced variability. During the construction phase (2022 – 2023), SSC temporarily increased but significantly decreased after completion, approaching natural levels again. These results indicate that ecological restoration can effectively stabilize sediment conditions, providing scientific support for coastal management.

Keywords: Suspended Sediment Concentration (SSC),Shoreline Ecological Restoration,Shanghai Coastal Waters, Quasi-Analytical Algorithm (QAA),Remote Sensing Monitoring.

1. Introduction

1.1 Research Background and Significance

In the coastal waters of Shanghai, specifically at the junction of the Yangtze River mouth and the northern shore of Hangzhou Bay, the combined effect of sediment brought by the Yangtze River and the strong tidal force has resulted in water bodies characterized by high turbidity. As the third longest river in the world, the Yangtze River annually transports a huge amount of sediment to the ocean; most of this sediment is deposited at the Yangtze River mouth, while some drifts southward along the coast to the Hangzhou Bay and the surrounding waters of Shanghai, thereby forming a unique dynamic sedimentation environment. The concentration of suspended sediments in the water bodies of this area not only reduces the light transmittance, thereby weakening the photosynthesis of aquatic plants and hindering the self-purification ability of the water body, but also directly affects the siltation, erosion of wetlands and mudflats, as well as the succession of the ecosystem.

1.2 Shoreline Hardening and Ecological Issues

With the rapid urbanization of Shanghai and the expansion of coastal development activities, the coastal structure in this area has undergone significant changes. These hardened coasts have, to a certain extent, altered the hydrodynamic and sediment transport patterns at the mouth of the Yangtze River, mainly manifested as: an increase in wave reflection, resulting in erosion at the base of the embankment; disturbances in the process of material exchange between land and sea, thereby affecting the development of wetlands; and changes in the distribution of alongshore currents, which in turn affect the deposition and transport paths of sediments. This has led to the development of various ecological problems such as the degradation of the wetlands and biodiversity loss. From the perspective of coastal geomorphic dynamics, the profile of the coastline can be classified into two basic forms: "dissipative" and "reflective" coastlines. A "dissipative" coastline has a gentle slope; in this case, the energy of the waves is gradually dissipated over a relatively wide and fragmented region. In the "reflective" coastline, the slope is steeper, and the reflection of the energy of the waves is intense along the coastline. The hardened shoreline makes the coastal environment assume the "reflective" state; this has the effect of increasing the reflection coefficient of the waves and the erosion of the base of the embankment.

1.3 Potential Impacts of Ecological Restoration

In recent years, Shanghai has started to launch a series of ecological restoration activities that focus on restoring a healthy ecosystem in its coast. These activities, such as the launch of the lingang coastal marine ecosystem protection and restoration project, focus on restoring the natural characteristics of this ecosystem. This is done through various activities such as restoring salt marsh plants, changing the terrain of the mudflats, and constructing ecological dikes.

Currently, the role of salt marshes in protecting the coast is widely recognized.Studies have shown that salt marsh vegetation can increase water flow resistance and absorb wave energy, effectively reducing the shear stress at the bottom; at the same time, its roots can reinforce the sediment, thereby increasing the critical shear stress of the seabed and limiting the resuspension of sediment. Shi Benwei (2012) found in his research on the eastern shore of Chongming Island in the Yangtze Estuary that when waves pass through a 9-meter-wide salt marsh belt, the effective height of the waves decreases by 24.1%, the average wave height decreases by 21.8%, and the average wave energy density decreases by 33.3%. Within the salt marsh vegetation belt, the attenuation rate of wave height per unit distance is 30 times that of the bare coast, the average attenuation rate of wave height is 26 times that of the bare coast, and the average attenuation rate of wave energy density is 58 times that of the bare coast.

The research conducted at the Liaohe Estuary also confirmed that the salt marsh vegetation has a negligible impact on the tidal height, but a relatively significant impact on the tidal flow rate. Moreover, different vegetation types have distinct effects on the flow rate. The salt marsh vegetation has a higher ability

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to retain suspended sediments than the bare muddy substrate. The ability of salt marsh vegetation to retain suspended sediments varies significantly with different tidal stages, and the retention rate follows the pattern: small tide < large tide < small tide. The accumulation of suspended sediments can cause siltation of the salt marsh terrain.

1.4 Research Gaps and Objectives

Although many studies have explored energy dissipation and the impact of salt marsh vegetation on sedimentation, the mechanism of how ecological restoration projects affect the concentration of suspended sediments on a broad regional and temporal scale remains unclear. Traditional monitoring of Suspended Sediment Concentration（SSC） is mainly based on samples collected by boat from fixed sites; although this method is highly accurate, it is limited by the observation density and regional coverage, making it difficult to capture large-scale spatiotemporal dynamics. Satellite remote sensing technology has the advantages of wide observation range, high speed, and repeatability, and is an effective means for monitoring SSC in coastal waters.

This study aims to utilize multi-source remote sensing data to construct an inversion model for suspended sediment concentration based on the QAA algorithm, optimized for the coastal waters of Shanghai. The study systematically analyzes the impact of different coastal types on the distribution of SSC and reveals the influence of coastal ecological reconstruction on its spatial distribution and spatiotemporal changes. The aim is to provide a theoretical basis for optimizing coastal management strategies and scientifically evaluating the effectiveness of ecological restoration.

2. Methodology

2.1 Overview of the Research Area

This study focuses on the protection and restoration project of the coastal marine ecosystem in Shanghai Lingang, and includes representative adjacent coastal areas as control groups. The research area is located in the coastal waters extending from the Nanhui mouth of the Yangtze River to the north bank of Hangzhou Bay. This area has a typical semi-diurnal tidal system, with an average tidal range of 2.5–3.5 meters, and strong tidal currents. The water body turbidity is high throughout the year, affected by various factors such as sediment carried by runoff, re-suspension of tides, and wave agitation. SSC typically fluctuates between 50–1000 mg/L.

The total length of the coastline involved in the coastal ecological restoration project is approximately 17.05 km, and the width of the coastal ecological restoration area is 100–1200 meters. The project is planned to be implemented from 2022 to 2023, and its main contents include: in-situ restoration of breakwaters, artificial fish communities, artificial reef groups, low-tide mussel reef groups, salt marsh vegetation restoration (planting native plants such as reeds and mangroves), and the release of benthic organisms. The geographical location and scope of the project are shown in Figure 1.

To facilitate the comparative study, three different control areas were delineated within the study region (Figure 2):

(1) Lingang Ecological Restoration Area: The scope is consistent with the project, representing the coastal area where ecological restoration has been implemented;

(2) Traditional Hardened Shoreline Area: Located to the north of the ecological restoration area, its main feature is vertical concrete breakwaters; this area is used as the reference benchmark for artificial coastlines;

(3) Natural Reference Area: Located on the north bank of Hangzhou Bay, to the south of the ecological restoration area; this area has relatively original wetlands and mudflats, with the coastline mainly composed of natural mudflats, serving as a reference for the natural coastline.

2.2 Acquisition and Preprocessing of Satellite Data

This study was based on the images obtained from satellites GF-1 and GF-2. The GF satellites are an important part of the Chinese high-resolution optical remote sensing system. GF-1 has a multispectral camera with a resolution of 16 meters and a color camera with a resolution of 2 meters. GF-2 has a color resolution of 0.8 meters and a multispectral resolution of 4 meters. The configuration of the multispectral cameras covers the range of blue light (0.45–0.52 μm), green light (0.52–0.59 μ m), red light (0.63–0.69 μm), and near-infrared light (0.77–0.89 μm), which basically covers the requirements for optical remote sensing of water bodies.Image selection follows the following principles:

(1) Cloud cover is less than 10% to ensure that there is no cloud coverage in the study area;

(2) The time interval between the image and the field measurement is less than 2 hours to minimize the comparison errors caused by tidal water level fluctuations and dynamic changes of suspended sediments;

(3) The image quality is good, with no obvious stripe noise or sensor deviation.

2.3 Field Measurement Data

To provide basis for the development and verification of the model, four field surveys were carried out in the research area from June to September in 2024. In total, 42 points were established for the survey, with the position of the points taking into consideration the gradient of SSC, ranging from clear water with low turbidity in the coastal zone to water with high turbidity in the estuarine zone. In addition, the points were set in areas of different coast types, including the ecological restoration area, hardened coast area, and natural coast area. In each point, the sample of water was obtained, and the SSC value was measured by the filtration weighing method. Meanwhile, the reflectance in the area above the water was measured by a portable spectrometer, as well as the water depth, water temperature, and salinity.

2.4 Parameter Retrieval and Model Development Based on QAA Algorithm

Images underwent preprocessing, including geometric and radiometric correction, to obtain remote sensing reflectance data. The standard QAA procedure was applied to calculate the particulate backscattering coefficient (bbp) as the key parameter for constructing the SSC inversion model. Using 42 synchronized SSC-bbp data pairs (28 for modeling and 14 for validation after removing 2 outliers), an exponential model was established: SSC = 21.959 · exp(0.9335 · bbp) (R^2 = 0.7305).

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \tag{1}$$

Where y_i =calculated suspended sediment concentration
$\hat{y}_i$=measured suspended sediment concentration
$\bar{y}$ =the average suspended sediment concentration

2.5 Model Validation and Spatiotemporal Inversion

Independent validation demonstrated satisfactory model accuracy (RMSE = 37.24 mg/L, MRE = 34%). The validated model was applied to all qualified images from June to September 2024 to generate spatiotemporal distribution maps of SSC mean and standard deviation.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{2}$$

$$MRE = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \tag{3}$$

Where y_i=calculated suspended sediment concentration
$\hat{y}_i$= measured suspended sediment concentration
n=number of validation points

2.6 Regional Division and Trend Analysis for Assessing Coastal Area Impacts

The statistical data for the suspended sediment concentration in each region was derived from the analysis results in 2024. In addition, in order to assess the long-term effect of ecological restoration, the QAA model was used to process the satellite image sequences from 2020 to 2024. Trend analysis and comparative statistics were used to identify changes in sediment distribution patterns, which were directly related to the project implementation schedule. In this way, it is possible to conduct a systematic assessment of the impact on the environment for this large-scale coastal restoration project.

The validated QAA model will be used to process all eligible satellite images from 2020 to 2024. The regional distribution maps for SSC in each satellite image will be used to conduct long-term time series analysis, including the following steps:

(1) Image temporal synchronization: All the results obtained by the SSC inversion will be synchronized in a unified geographic grid (30m resolution) for the purpose of temporal-spatial comparability at the pixel scale;

(2) Zone statistics: According to the vector boundaries of the three control zones (ecological restoration zone, designated waterfront zone, and natural reference zone), the average values, standard deviations, and quantiles of the SSC in the region of the images will be extracted;

(3) Trend analysis: Using the non-parametric Mann-Kendall test, the significant trends in the SSC time series in the region of the images will be identified, and the turning points will be determined;

(4) Distinction of project impact: Based on the trends in the changes in the ecological restoration zone and the control zones, combined with the project construction period (2022-2023) and completion (2024), the impact of the project on the changes in the SSC will be clearly identified.

3. Conclusion

3.1 Spatial and Temporal Distribution Characteristics of SSC in the Summer of 2024

The validated model was applied to 11 valid images captured from June to September in 2024 to generate a regional distribution map of the average value and standard deviation of SSC during this period (Figures 3 and 4). Geographical information analysis revealed the following characteristics:

In terms of the average distribution (Figure 3), the SSC distribution within the study area showed a distinct gradient feature, with higher values in the coastal area and lower values in the offshore area; the contour lines were generally parallel to the coastline. The high-concentration areas (> 100 mg/L) were mainly located along the south channel of the Yangtze River estuary north of Nanhui Mouth and the north bank of Hangzhou Bay; the areas with lower concentration (< 50 mg/L) were located in the offshore waters more than 10 kilometers away from the coast. This distribution pattern was mainly determined by the freshwater diffusion path of the Yangtze River and the tidal transport process, and was consistent with the general distribution pattern of suspended sediment in river mouths around the world.

According to the distribution of the coefficient of variation (standard deviation/average value) (Figure 4), there were significant differences in the coastal zone water bodies of different areas. The water bodies of the gravel coast zone were highly fluctuating (standard deviation > 100 mg/L), reflecting the intense fluctuations in the SSC in this area due to tides and waves; the water bodies of the natural mudflat coast zone had smaller fluctuations (standard deviation < 40 mg/L), indicating a relatively stable sedimentary environment; the water bodies of the ecological restoration zone had fluctuations at a medium level (standard deviation 40–100 mg/L), between the above two categories.

3.2 The Impact of Different Shoreline Types on Suspended Sediment Concentration (SSC)

Comparative statistical analysis of the three different buffer zone types revealed the influence of different shoreline types on the sediment environment in the adjacent waters:

(1) The traditional hard shoreline creates a highly turbulent environment

The SSC concentration in the area near the hardened shoreline (the brown part in Figure 2) shows a dual characteristic: the average concentration is relatively high (reaching 145 mg/L in summer), and the fluctuation amplitude in time and space is large (standard deviation is 96 mg/L). This phenomenon is mainly due to the strong reflection of wave energy on the hardened shoreline: Moreover, when the waves hit the concrete revetment perpendicularly, nearly complete reflection occurs. This causes superposition of the reflected wave with the next one, which results in a standing wave that increases turbulence in water flow at the root of the revetment and causes continuous suspension of sediment. In fact, the hardened coast imposes a kind of "reflection" state on the coastal environment. This is in sharp contrast to the dissipation of wave energy described in the sandy coast natural state.

(2) Natural Muddy Bottom Maintains a Relative Stable Environment with Less Interference

The SSC in the front waters of the natural reference section (corresponding to the green color in Figure 2) is at a low level with little fluctuation. Specifically, the average value is 45 mg/L in summer, and the standard deviation is only 11 mg/L.Shi Benwein (2012) in the research on the eastern coast of Chongming Island in the Yangtze River Estuary showed that halophytic forest vegetation increases water flow resistance and absorbs wave energy, effectively reducing the shear stress near the bottom. The study also found that in the bare mudflats, the shear stress generated by the coupling effect of waves and water flow is greater than that in adjacent salt marshes. During most of the flood period (70%), the monitoring points with bare mud bottoms are in an eroding state, while the salt marshes almost always show deposition and sedimentation characteristics throughout the flood period.

Research conducted in the Liaohe Estuary also confirmed that salt marsh vegetation has a higher retention capacity for suspended sediment than bare mud bottoms. The retention capacity of suspended sediment by salt marsh vegetation varies significantly with different tidal stages, and its retention pattern follows the following pattern: small tide < large tide < small tide.

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(3) The ecological restoration projects have significant transitional and stabilizing effects.
The average SSC in the coastal ecological restoration area during summer (corresponding to the red area in Figure 2) was 87 mg/L, which was significantly lower than that in the hardened coastal area, and the regional distribution was more uniform (standard deviation 48 mg/L). This result indicates that thanks to the restoration of salt marsh vegetation and the construction of ecological revetments, this coastal area has transformed from an "eroding" state to a "stable" state. The restoration of salt marsh vegetation formed a natural energy buffer zone in the tidal area, effectively weakening the energy of waves; at the same time, replacing the traditional vertical structure with gentle ecological dams significantly reduced the wave reflection coefficient, thereby reducing the risk of river channel undercutting at the base of the dam. The combined effect of the two measures was the effective limitation of the phenomenon of excessive resuspension, without compromising the necessary exchange of water and sediment.
As for the landforms in the coastal zone, the ecological restoration mainly facilitated the transformation of the coastal system from a "reflective" type to an "energy absorption" type. Such a transformation has great importance for the stability of the coastal area in the long run.

3.3 Trends in Different Periods

The analysis of the changes in the period from 2020 to 2024 has clearly revealed the evolutionary law of the SSC values, which coincides with the implementation period of the coastal projects:
Before restoration (2020-2021): The SSC values in the ecological restoration area were relatively close to those in the hardened shoreline, with the average difference less than 10% (Figure 5), which also confirms that there was indeed a large amount of suspended sediment and poor retention capacity in the coastal area before the restoration.
During the construction phase (2022-2023): The SSC values in the ecological restoration area showed a significant increasing trend, with the average value in the summer of 2022 slightly higher than that in the same period in 2020 (Figure 6). This increasing trend was primarily caused by the increase in sediment suspensions due to mechanical disturbances in the coastal area, including the reshaping of the beach area and the planting of vegetation in the ecological restoration area. In the meantime, the SSC values in the natural control area remained stable, which further confirms that the increasing trend was not caused by regional climate change or hydrological conditions but was related to the project itself.
After the completion stage (2024): After the completion of the project and the gradual restoration of the ecosystem, the values of SSC in the ecological restoration area showed a significant decline. However, as seen in the figure, the values of SSC in the Hangzhou Bay area also declined. This may be due to the restoration measures taken in the Hangzhou Bay area and the upstream areas, or it may be influenced by the changes in the tidal currents and ocean currents. Nevertheless, it is seen that after the completion of the project, the difference in the values of SSC in the restoration area and the natural reference area has reduced to less than 20%. This trend clearly shows that the ecological restoration not only has a short-term impact but also contributes to the formation of a sustainable and stable sediment environment in the future.
It is worth noting that even though the project was completed, the SSC values in the ecological restoration region remained slightly higher than those in the natural reference region. This indicates that a longer succession stage is required for the complete restoration of the ecosystem. In addition, to fully evaluate the restoration effect, long-term monitoring is still required. In a research by Hou Xuejiao et al. (2024) that involved 349 SSC values in estuarine suspended sediments across the world over the last 20 years, it was found that the changes in SSC values in estuarine regions are affected by different factors, including river transport of sediments, tides, waves, and topography of estuaries. Therefore, it is essential to consider the long-term trends of these background factors in evaluating the effect of ecological restoration.

4. Discussion

4.1 Analysis of the Mechanisms of Ecological Restoration Affecting Sedimentary Environment

By combining the results of this study with existing literature, three main pathways through which ecological restoration projects affect the coastal sediment environment can be identified:
(1) Wave energy attenuation mechanism
Salt marsh vegetation can effectively attenuate wave energy by increasing water resistance. Shi Benwei (2012) conducted research in the Dongtan (at the mouth of the Yangtze River) of Chongming Island, showing that after waves passed through a 9-meter-wide salt marsh vegetation strip, the effective wave height decreased by 24.1%, the average wave height decreased by 21.8%, and the average wave energy density decreased by 33.3%. Within the salt marsh vegetation planting area, the attenuation rate of the effective wave height per unit distance was 30 times that of the bare coast, the average attenuation rate of wave height was 26 times that of the bare coast, and the average attenuation rate of wave energy density was 58 times that of the bare coast. The attenuation of wave energy directly reduced the shear stress near the seabed, thereby preventing the resuspension of sediments.
(2) Bed stability mechanism
The root systems of vegetation penetrate the sediment profile, forming a three-dimensional reinforcing structure, significantly increasing the critical shear stress for submarine erosion. Research conducted on the eastern coast of Chongming Island showed that based on on-site sampling and analysis, the critical shear stress for coastal sediment erosion was 0.103 N/m^2 on the bare coast and 0.116 N/m^2 in the salt marsh. This mechanism can reduce the resuspension of sediments caused by tides and waves.
(3) Sediment consolidation mechanism
The stems and leaves of vegetation increase fluid resistance, thereby slowing local flow velocity and promoting the sedimentation of suspended sediments. At the same time, changes in the turbulent structure of the flow field within the vegetation strip increase the probability of particle collision and agglomeration, forming larger flocs, thereby accelerating the sedimentation process. Research conducted in Liaohe Estuary showed that Salicornia vegetation is more effective at retaining suspended sediments than bare mudflats, and the sediment retention capacity of the salt marsh vegetation changes with the tidal cycle. This mechanism prolongs the retention time of sediments from the soil in the coastal area, thereby promoting the accumulation of muddy substrates.
The combined effect of these mechanisms creates a stable sediment environment in which the restored coastal area can flourish, sustains the water body and sediment exchange that is needed by the ecosystem, and reduces erosion and pollution that is caused by excessive resuspension.

4.2 Long-term Effects of Ecological Restoration

In the long term, the effect of ecological restoration activities on the sediment environment is long-lasting. This is because, according to the analysis of time series data obtained between 2020 and 2024 in this study, the SSC continues to reduce even after the completion of the restoration project and is close to that of the natural reference area, which indicates that the sediment regulation function of the ecosystem is being restored.This result is consistent with the global research conclusions on the changes in river mouth suspended sediment. Hou Xuejiao et al. (2024) studied that the changes in river mouth suspended sediment are not only affected by river sediment transport and river water dynamics, but also by the river mouth topography. Compared with river mouths controlled by river runoff and tides, the suspended sediment concentration in wave-controlled river mouths is lower. This is mainly because wave-controlled river mouths have fewer tributaries and are mainly composed of beaches; this characteristic leads to the inability of wave-dominated river mouths to effectively retain suspended sediment over the long term. Therefore, the stable terrain structure established through ecological restoration is of great significance for maintaining an appropriate suspended sediment concentration.

In the context of sea level rise and climate change, these factors may increase the frequency and intensity of storms, so the protection and restoration of salt marsh vegetation are particularly important. This study confirms that the coastal areas after restoration can maintain a relatively stable sediment environment, which is of positive significance for enhancing the resilience of coastal areas in the face of climate change.

4.3 Limitations and Future Prospects

This study has the following limitations:

(1) Limitation of time coverage: Due to the limitations of satellite data acquisition, some months lack images, resulting in discontinuous time series. Future research can integrate remote sensing data from multiple sources (such as Sentinel-2, Landsat, GF-4, and GF-6, etc.) to construct a higher time-resolution SSC time series.

(2) Failure to consider vertical structure: This study only focuses on the surface SSC and does not involve the vertical distribution of suspended sediment. Field observations show that there is usually a significant vertical gradient in highly turbid water bodies, and the turbidity of the surface water may underestimate the total load of suspended sediment. Future research can combine hydrodynamic and vertical mixing parameterization models to assess the reserves of suspended sediment throughout the water column.

(3) Insufficient verification of the mechanism: In the analysis of the mechanism of wave energy attenuation and sediment stability, it is mainly based on the inference of the literature and lacks sufficient verification of the mechanism. In the future research, a comprehensive monitoring system can be established in the ecological restoration region. With the help of the satellite remote sensing images, the empirical data can be obtained for the analysis of the mechanism.

5. Conclusion

The research takes the protection and restoration project of the coastal marine ecosystem as a case study. Based on high-resolution remote sensing images and the QAA semi-analytical algorithm, an inversion model of SSC in coastal waters of Shanghai was developed. In this research, a systematic analysis of the influence of the ecological restoration project on the sediment environment was conducted. The conclusions are as follows:

(1)The exponential model $SSC = 21.959 \cdot \exp(0.9335 \cdot bbp)$ established by using the particle backscattering coefficient (bbp) is valid for coastal waters of Shanghai with high turbidity. In addition, through validation of the established model, it can be seen that the value of RMSE is 37.24 mg/L and MRE is 34%, which meets the requirements of remote sensing monitoring.

(2)Different coastal types have a decisive impact on the sediment environment of adjacent waters: The coastal zone of the traditional hardened coast has a higher SSC value and greater fluctuation (average 145 mg/L, standard deviation 96 mg/L), which is due to the strong reflection of wave energy on the hard breakwater; The natural mudflat maintains a less disturbed and stable environment (average 45 mg/L, standard deviation 11 mg/L), which confirms the key role of the original wetland vegetation system in effectively dispersing energy and the sediment consolidation process; The values in the SSC ecological restoration area (average 87 mg/L, standard deviation 48 mg/L) are significantly lower than those in the hardened coastal zone area, indicating a transition from an "erosive" state to a "stable" state.

(3) The long-term development trend further confirms the sustainability of the restoration benefits: As mentioned above, the analysis of satellite images from 2020 to 2024 demonstrates the development trend of SSC changes, which corresponds to the implementation period of the coastal project. Before the restoration (2020-2021), the SSC characteristics were similar to the natural coastline; In the period of construction (2022-2023), the SSC level was relatively higher due to the disturbance of the construction work; In the period of completion (2024), the SSC level decreased statistically and gradually tended towards the natural reference area. All this further confirms the positive impact of restoration not only in the short term but also in the long term.

(4)The main ways in which ecological restoration affects the sediment environment include the absorption of energy by plants, reinforcement of substrates by plant roots, and sedimentation and subsidence of suspended sediment. These three factors interact to improve the sediment environment. The capacity of salt marsh plants for energy absorption over a given distance may be 26 to 58 times that of a bare muddy substrate.

(5) Long-term, a coastal environment that has been restored may be able to support a relatively stable sediment environment, which is important in improving the resilience of the coast to sea level rise and effects of global warming.

This study confirms the effectiveness of satellite remote sensing in evaluating the results of coastal ecological restoration, thereby providing a scientific basis for optimizing coastal management strategies and assessing the effectiveness of ecological restoration. It is recommended to incorporate sediment environment monitoring into the routine assessment indicators of future ecological restoration projects and strengthen interdisciplinary research to better clarify the coupling mechanism between physical processes and ecological responses.

6. Figure

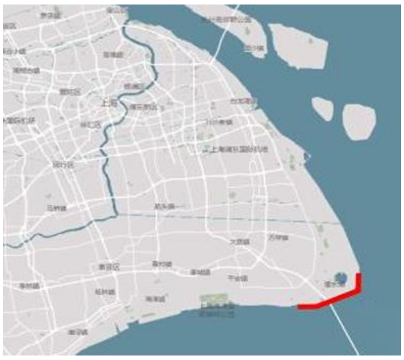

Figure 1. Location and scope of the project

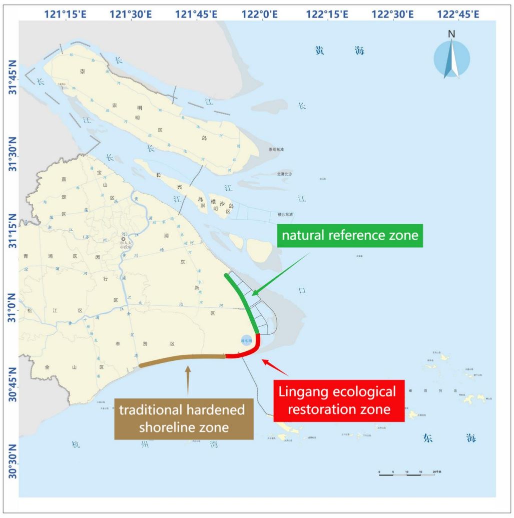

Figure 2. Three Types of Buffer Zones.

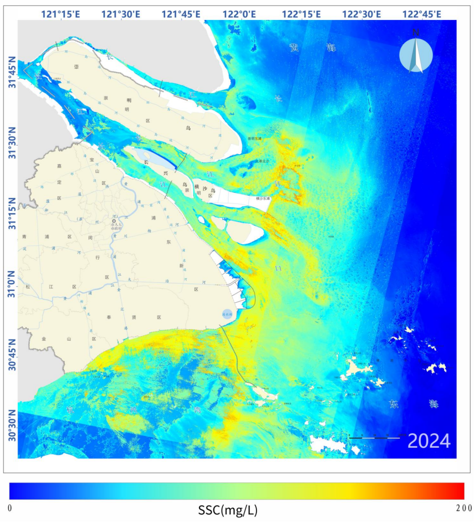

Figure 3.Mean SSC Map from June to September 2024

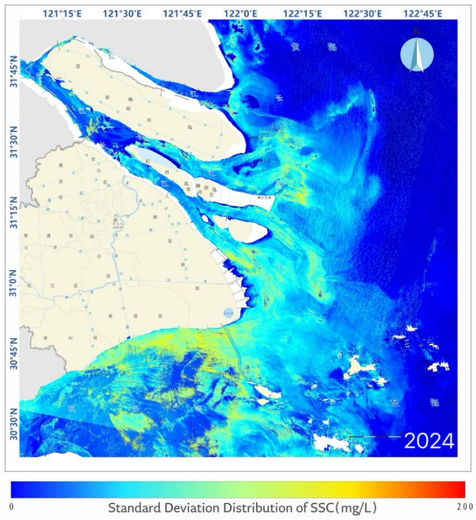

Figure 4.Standard Deviation Distribution of SSC Map from June to September 2024

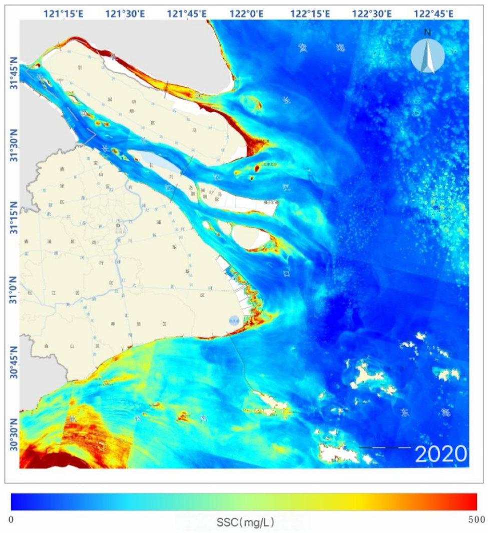

Figure 5.Mean SSC Map from June to September 2020

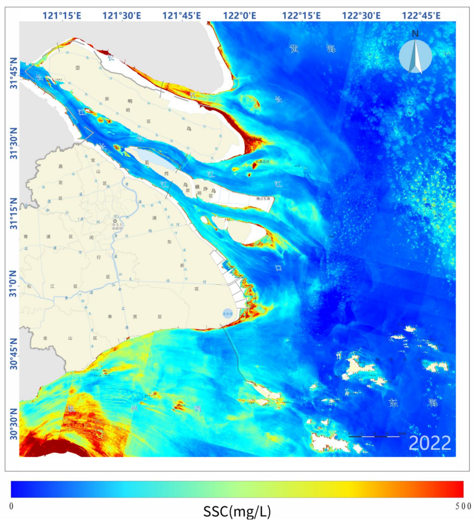

Figure 6.Mean SSC Map from June to September 2022

References

Hu Yuekai, Shao Yujie, Zhou Bin, et al. Remote sensing monitoring of suspended sediment concentration based on GF-4 satellite in the Hangzhou Bay[J]. Haiyang Xuebao, 2020, 42(9): 134-142. doi:10.3969/j.issn.0253−4193.2020.09.014.

DENG Zhitian, QIU Qi, SUN Yonghua, et al. Inversion of suspended sediment concentration based on Tiangong-2 and QAA algorithm[J]. Journal of Capital Normal University (Natural Science Edition), 2019, 40(6): 75-82.

DENG Ruru, HE Yingqing, QIN Yan, et al. Measurement of water absorption coefficient in optical bands (400-900 nm) by separating the impact of suspended sediments[J]. Journal of Remote Sensing, 2012, 16(1): 174-191.

Li X H, Sun D Y, Yang Y Q, et al. A Semi-Analytical Algorithm for Inherent Optical Properties Retrieval in Coastal and Inland Waters[J]. Remote Sensing, 2025, 17(3): 678-692. DOI: 10.3390/rs17030678.

Liu H L, Wang D X, Zhang X Y, et al. Improved Quasi-Analytical Algorithm for Secchi Disk Depth Retrieval in Optically Complex Coastal Waters[J]. Journal of Geophysical Research: Oceans, 2025, 130(4): e2024JC021234. DOI: 10.1029/2024JC021234.

Li Z L, Sun J Q, Wang Y J, et al. Calibration of QAA for CDOM and Backscattering Retrieval in the Yangtze Estuary[J]. Remote Sensing of Environment, 2023, 287: 113432. DOI: 10.1016/j.rse.2023.113432.

Shi Benwei. A Study on Sedimentary Dynamics in the Salt Marsh – Light Beach Transition Zone at Dongtan, Chongming, Yangtze River Estuary [D]. East China Normal University, 2012.

Feng Lian, Hou Xuejiao, Jaap H. Nienhuis, et al. Sustained increase in suspended sediments near global river deltas over the past two decades [J]. Nature Communications, 2024.

Huang Haijun, Yan Liwen, Yang Xiguang, et al. Remote sensing inversion of the average particle size of suspended sediments in the surface layer of nearshore waters [J]. Journal of Wuhan University (Information Science Edition), 2015, 40(2): 25–30.

Chen Shuaikang, Han Zhen, Li Pixue, et al. BRDF-corrected inversion of chlorophyll a concentrations in coastal waters of Shanghai [J]. Journal of the Yangtze River Scientific Research Institute, 2024, 41(9): 169–177.

Cai F, Zhao S, Qi H,et al. Morphological and sedimentary features of sandy – muddy transitional beaches in estuaries and bays along mesotidal to macrotidal coasts [J]. Earth Surface Processes and Landforms, 2020, 45(7): 1660–1676.

Anthony E J, Aagaard T. The lower shoreface: Morphodynamics and sediment connectivity with the upper shoreface and beach[J]. Earth-Science Reviews, 2020, 210: 103334.

Chen Y, Li Y, Zhang C, et al. Barred beach profile equilibrium investigated with a process-based numerical model[J]. Continental Shelf Research, 2021, 222: 104432.

Chen J, Guo J, Shi L, et al. Sand-mud transition dynamics at embayed beaches during a typhoon season in eastern China[J]. Marine Geology, 2021, 441: 106633.

Numerical simulation study of hydrodynamic processes and suspended sediment retention in the salt marsh vegetation zone of the Liaohe Estuary [J]. East China Geology, 2025.