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Research article

Pollution characteristics, distribution and risk level of heavy metals in sediments of the Yangtze River estuary

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ABSTRACT

Pollution characteristics, distribution, risk and sources of 7 heavy metals in sediments of Yangtze River Estuary were investigated. Total concentration ranges of As, Cr, Cu, Cd, Pb, Zn and Ni were [0, 16.5], [1.48, 51.3], [2.66, 318], [0, 0.99], [35.6, 992], [8, 91.3] and [1.88, 108] mg/kg, respectively. Based on the potential ecological risk index and Geoaccumulation index, it was determined that Pb is the most polluted heavy metal. According to class I standard of "Marine sediment quality" of China, mean baseline levels multiples were Pb (8.34) > Cu (0.57) > Cr (0.37) > Zn (0.355) > Ni (0.352) > As (0.28) > Cd (0.00). The study also found the heavy metal content of Pb is the most serious, but most of the Pb content comes from the residual state, which has minimal impact on the environment. The East Nanhui Shoal was identified as the most polluted sub-area in terms of Pb pollution, followed by other specific locations. Considering the pollution level and transport costs, the study concluded that dredge soils of the Yangtze River Estuary Deepwater Channel are not suitable for the restoration of East Hengsha Shoal.

1. Introduction

In recent years, the continuous degradation of coastal ecosystems, combined with factors such as climate change and human activities, has led to increased attention on the ecological restoration of coastal zones. Dredged soil is a type of sedimentary soil that is commonly found in estuarine and coastal areas [1]. The benefits of dredged soil for land development and wetland restoration have been recognized globally [2].

Nowadays, China's policy guidelines have shifted towards more sustainable and green development practices [3,4]. Besides, an important change in the Yangtze River estuary was that the dredged soil from the Yangtze River Estuary Deepwater Channel was forbidden to be used for land reclamation [5,6]. In this context, how to ecologically utilize the dredged soil of the waterway has become an important issue for the dredging, maintenance and management of the waterway [7,8].

However, the ecological use of the mentioned dredged soil faces a key issue, which is whether the dredged soil is contaminated and whether its various indicators can meet the requirements of ecological cultivation [9,10]. The Yangtze River Estuary, located between Shanghai, and provinces of Jiangsu, Zhejiang, is an important sink of PAHs with frequent human activities [11]. Taking PAHs as the

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indicator, the pollution degree of the three shoals (East Nanhui Shoal, Jiuduansha Shoal and East Hengsha Shoal) at the estuary of the Yangtze River is more serious than that of the South and North Passages, and the dredged soil of the passage can be used for the protection of the shoal [12]. Meanwhile, characteristics of heavy metal pollution are also the critical indicators for evaluating sediment quality [8,13]. The contamination of water by heavy metals is a significant issue, with sediment serving as both a source and a repository of pollutants. Heavy metals originating from human activities, industrial processes, and agricultural practices are discharged into water bodies, where they accumulate in sediment, posing detrimental effects on water quality, organisms, and soil. Furthermore, these contaminated sediments can be transported to other ecosystems through water and food chains, leading to widespread pollution. Consequently, a program was developed to sample sediment and analyze heavy metal concentrations in the Yangtze River Estuary. The sampling was conducted at three shoals (East Nanhui Shoal, Jiuduansha Shoal, and East Hengsha Shoal) and in two passages (South Passage and North Passage) [12,14]. The findings of this research on heavy metal concentrations in sediment can inform the design and assessment of the ecological utilization of dredged soils in the coastal zone and the restoration of the surrounding environment. Additionally, analyzing and evaluating the degree of risk associated with heavy metal pollution can contribute to enhancing local environmental quality and guide subsequent environmental monitoring and management efforts in the region.

2. Materials and methods

2.1. Study area and sampling

Study area is located at the Yangtze River Estuary (121°76′-122°37′E, 31°01′-31°34′N), mainly includes three shoals (East Nanhui Shoal, Jiuduansha Shoal and East Hengsha Shoal) and two passages (South Passage and North Passage). The primary and secondary channels for maritime navigation through the Yangtze River Estuary are known as the North Passage and South Passage, respectively. The three shoals are located along the mouth bar section of the estuary. The sampling plan for this investigation was executed on November 10th to 11th, 2018. A total of 51 sampling sites were strategically positioned within the study area, as depicted in Fig. 1. In addition to collecting samples from the top 3 cm of the bed surface at all sites, samples were also obtained from depths of 10–20 cm at three specific sites (A-2, 29, O-5) and from depths of 20–40 cm at four sites (A-2, 29, O-5, NHDT2). Consequently, a total of 58 samples were gathered and subsequently analyzed. To facilitate comparison, the study area was divided into 10 sub-areas: Lower section of South channel, Yuanyuansha section, North Passage section, South Passage section, Lower beach of South channel, Yuanyuansha Beach, Beach of North Passage, East Hengsha Shoal, Jiuduansha Shoal and East Nanhui Shoal.

All specimens were obtained using a box sampler. These specimens are cubic blocks of mud measuring approximately 40 cm in thickness, with each sample weighing over 100 g. The uppermost 3 cm of the mud block samples are designated as the surface layer, the subsequent 10–20 cm as the middle layer, and the remaining 20–40 cm as the bottom layer [11].

The gathering, preservation, and processing of samples adhere to the Marine Survey Specifications (GB17378.5–2007) of China.

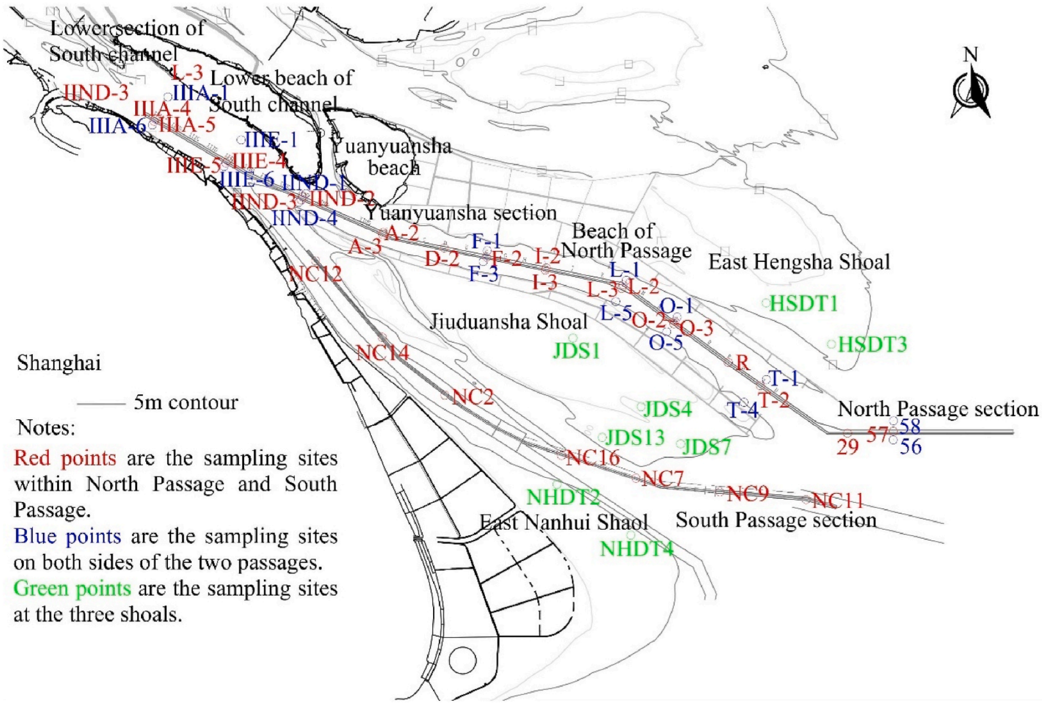
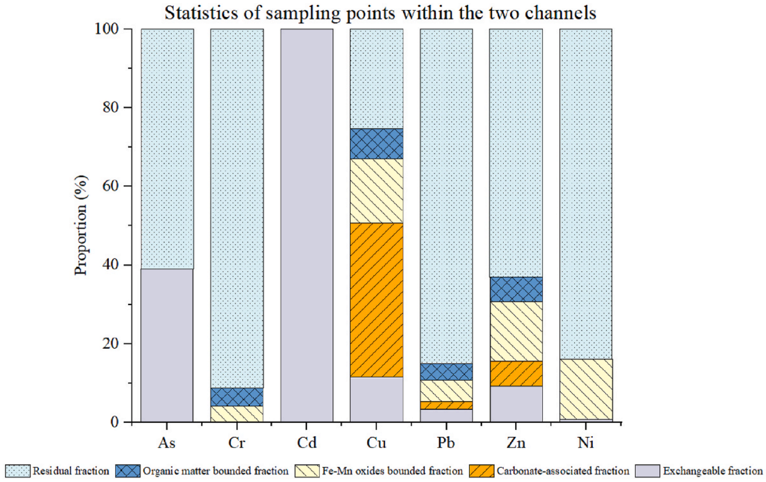
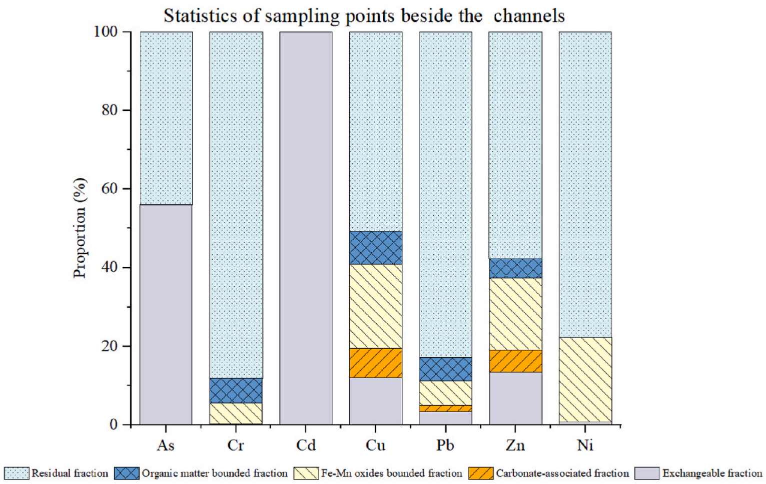


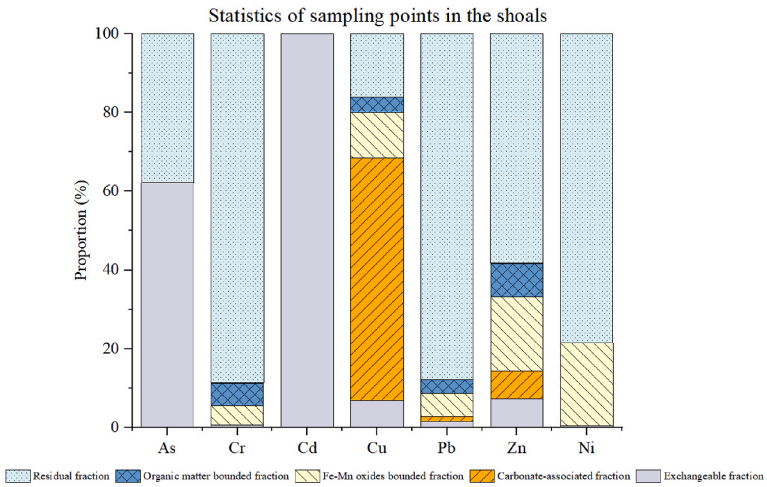
Fig. 1. Sampling sites of study area.



(a)Statistics of sampling sites within North Passage and South Passage



(b)Statistics of sampling sites on both sides of the two passages



(c)Statistics of sampling sites at the three shoals

Fig. 2. Percentages of five chemical fractions of heavy metals in the sediments.

Each sample is ensured to exceed 100 g in weight, and is stored in a sealed plastic bag with proper labeling. The bags containing the samples are then placed in a compact refrigerator set at −20 °C, and subsequently transported to the laboratory [11].

There are eight prevalent heavy metals present in everyday life, including copper (Cu), lead (Pb), chromium (Cr), zinc (Zn), cadmium (Cd), nickel (Ni), arsenic (As), and mercury (Hg). It is worth noting that the natural occurrence of mercury is minimal and has negligible impact on the surrounding environment, thus it is not within the scope of this research.

2.2. Statistical analysis and pollution assessment

Due to extensive research and testing, Tessier's continuous five-step extraction method has been widely applied and is therefore chosen for use in this study [15]. The analysis of heavy metals in the samples was conducted using the inductively coupled plasma-optical emission spectrometer (ICP-OES), known for its high sensitivity and ability to simultaneously determine multiple elements. The specific parameter settings for the instrument can be referenced in the work of [16].

Common ecological risk analysis of heavy metals are the potential ecological risk index evaluation method proposed by Hakanson、Geoaccumulation index method、SPSS correlation analysis and superscalar multiple method.

Ecological risk of heavy metals is evaluated using the potential ecological risk index evaluation method proposed by Hakanson [17]. Calculation formula is shown in Eq. (1) and Eq. (2):

$$RI = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} T_r^i \times C_f^i \tag{1}$$

$$C_f^i = \frac{C_s^i}{C_n^i} \tag{2}$$

where E_r^i is potential ecological risk factor of each heavy metal, T_r^i is toxic response factor of heavy metal i (e.g., As = 10, Cr = 2, Cd = 30, Zn = 1, Cu = Pb = Ni = 5), C_f^i is contamination factor of heavy metal i, C_s^i is concentration of heavy metal i in sediment, and C_n^i is background value of heavy metal i [18]. Division of different risk levels is shown in Supplementary Table S1.

The Geoaccumulation index method, introduced by Muller in 1969, is utilized to assess the extent of heavy metal enrichment in sediments in comparison to the background geochemical values [19]. The formula for its calculation is shown in Eq. (3):

$$I_{geo} = \log_2\left[\frac{C_n}{K \times B_n}\right] \tag{3}$$

where C_n is concentration of heavy metal n, B_n is geochemical background values of heavy metals n in sediments [18]. K is a factor that takes into account the variation in background values that may be caused by local sediment differences (taken as 1.5).

To measure the degree to which the concentration of heavy metals surpasses the threshold, we employ the excess standard multiple, which is defined in Eq. (4):

$$\text{Excess standard multiple} = \frac{V_m}{V_t} \tag{4}$$

The variable V_m represents the value obtained from measurement, while V_t denotes the threshold value specified in the reference standard.

High-dimensional data are usually faced in practical studies, which provide more information and detail and also better describe the sample. But at the same time, there are also many redundant attributes, high-dimensional data made the research of calculation and more complex. Principal component analysis (PCA) is a commonly used data dimensionality reduction method, which can transform high-dimensional data into low-dimensional data, while trying to retain the information of the original data. PCA based on the principle of the linear algebra, mainly through the projection of the original data to the new coordinate system, and choose to keep the direction of maximum variance as the new axis (the standard to make new data without losing the original data information as much as possible, because the larger the variance, the greater the difference between the data), so as to realize data dimension reduction. Principal component analysis has the following advantages: (1) Correlations between observed and explainable variables. Principal component analysis forms independent principal components after transforming the original index variables, and it is proved that the higher the degree of correlation among the indexes, the better the effect of principal component analysis. (2) Reduce the workload of index selection and no parameter restrictions at all. Principal component analysis can eliminate the influence of correlation among evaluation indexes, so it is relatively easy in index selection.

3. Results

According to Tessier's continuous five-step extraction method, the various chemical phases of the seven heavy metals at the sampling sites were quantified based on the division of the two channels, namely the channel side and the shoal. The corresponding percentages are depicted in Fig. 2(a)–(c).

The total concentration ranges and mean values of the heavy metals are presented in Supplementary Table S2, while the total concentrations of heavy metals in 58 samples are detailed in Table 1. Additionally, the spatial distribution of heavy metal concentrations at all sampling points is illustrated in Fig. 3(a)–(g).

Based on the calculated results, the risk indices for the heavy metals As, Cr, Zn, and Ni are consistently observed to be at a low level across all sampling sites. Evaluation results of Cu show that a few samples are at a moderate level. However, evaluation results of Cd and Pb need to be paid attention, especially for Pb, risk levels of 25.86% and 24.14% of the samples reached considerable and high levels, respectively. In terms of maximum value, risk of both Cd and Pb has reached high level. According to average value, risk for Pb is also at considerable level. Results of RI index show that 44.83% of sampling sites are at moderate risk or higher. Study area as a whole is at low risk based on mean of the RI index, as shown in Table 1.

Mean Geoaccumulation index of the region is ranked as follows: Pb > Cd > Cu > Zn > As > Ni > Cr. Among them, Pb is heavily polluted, Cd is moderately polluted and the rest of heavy metals (As, Cr, Cu, Zn, Ni) are in uncontaminated state, indicating Pb is main polluting element in Yangtze estuary. Considering individual sampling sites, only the index of Cr and Zn are in uncontaminated condition, and there are some sampling sites where Cu concentration reaches heavy contaminated. The most serious is the maximum index of Pb is close to extremely contaminated level, as shown in Fig. 4.

In accordance with the regulations outlined in the "Marine Sediments Quality" of China (GB18668-2002), there are three categories (class I, class II, and class III) established for the management of sediment quality.

The class I is applicable to Marine fishery waters, Marine nature reserves, rare and endangered biological nature reserves, mariculture areas, bathing areas, Marine sports or entertainment areas where the human body is in direct contact with sediments, and industrial water areas directly related to human consumption; The class II is applicable to general industrial water use areas and coastal scenic tourism areas; The class III applies to Marine port waters and Marine development operation areas for special purposes. In addition to qualitative provisions on color, smell, pathogens, etc., the standard also limits the content of 15 kinds of pollutants.

Excess standard multiple was used to assess the pollution levels of heavy metal pollutants. According to maximum excess standard multiple, Pb, Cu, Ni, Cd and Zn were polluted at several sampling sites. As and Cr were in state of non-pollution. In relation to the average excess standard deviation, the pollution level was as outlined below: Pb (8.34) > Cu (0.57) > Cr (0.37) > Zn (0.355) > Ni (0.352) > As (0.28) > Cd (0.00). Only mean excess standard multiple of Pb was greater than 1 and its mean concentration was two times as the class III threshold, which mirrors Pb was in state of serious pollution, as shown in Table 2. In terms of Pb concentration, 38 sampling sites (65.52% of the total sample points) exceeded the threshold of class III, 7 sites (12.07% of the total sample points) exceeded the threshold of class II, 9 sites (15.52% of the total sample points) exceeded the threshold of class I and 4 sites (6.90% of the total sample points) were pollution-free, indicating Pb was the most polluted heavy metal in this study and required more attention for ecological restoration.

Correlation analysis was used to determine the homology of different heavy metals. As, Cr, Pb, Zn, Ni showed significant correlations at the $p < 0.01$ level, as shown in Table 3, indicating these heavy metals are likely to have same origin.

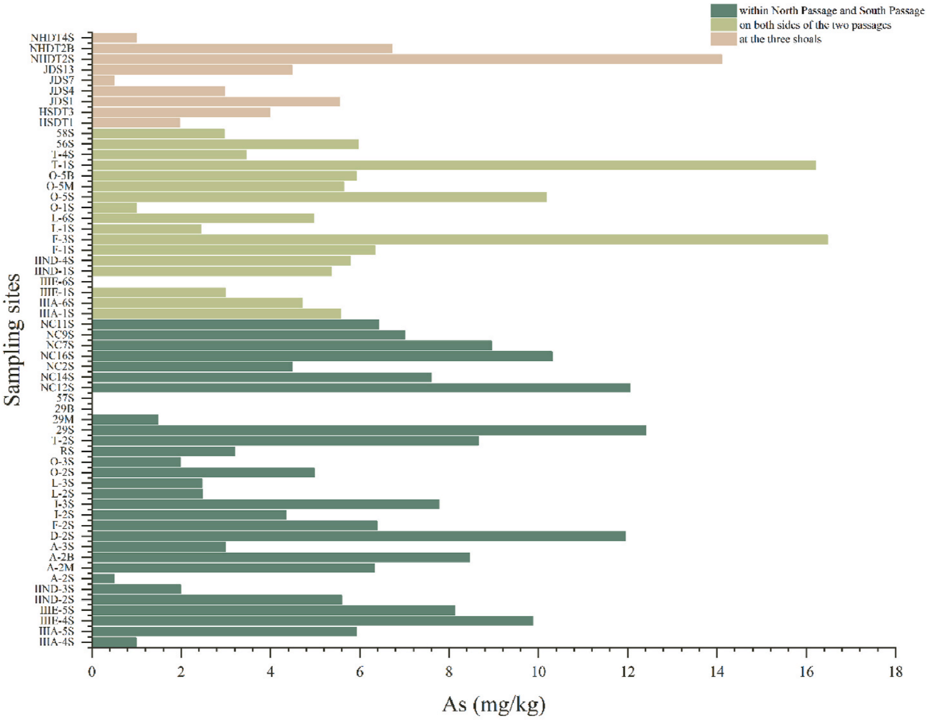
Furthermore, principal component analysis was carried out. The original variables, which may exhibit linear dependence, are subjected to an orthogonal transformation to generate a new set of linearly independent variables, potentially resulting in multiple new linear combinations. The linear combination with the highest variance among the new linear combinations is designated as PC1, which encapsulates the most information from the original variables. There is no shared information between PC2 and PC1, as indicated by their covariance being 0. Similarly, PC3 is uncorrelated with PC2 and PC1, with decreasing variance (PC3 < PC2 < PC1). In spatial terms, each principal component can be conceptualized as a number line, and these number lines are mutually orthogonal. Results of principal component analysis showed that three principal components with eigenvalues greater than 1 reflected 79.16% of information for the heavy metals, as shown in Table 4.

The first principal component (PC1) accounts for 46.25% of the variance, this percentage (Variance Accounted For) can be used as a measure of how much influence a variable has on the total variance. In general, the greater the Variance Accounted For, the higher the variable's contribution to the total variance, its importance, the greater the priority should be given or strengthen the attention. With As, Cr, Pb, Zn, Ni all having high positive charges on the first principal component. Pearson correlation analysis of above heavy metals showed significant correlations with each other. It has been suggested that the source of these heavy metals is mainly human activity, such as surrounding industries and sewage discharged into natural water bodies [20]. Presence of industrial land in the estuary makes the impact of industrial activity inevitable. Previous studies have shown As comes from mining, refining and other industrial wastes, and that Ni also comes from these industrial areas [21]. Pb is commonly found in anti-knock agents in petrol and diesel fuels. High levels of vehicle emissions and ship spills can lead to significant contamination, while anti-corrosion compounds containing Pb are often added to marine coatings, which may contribute to high Pb concentrations in samples [22,23].

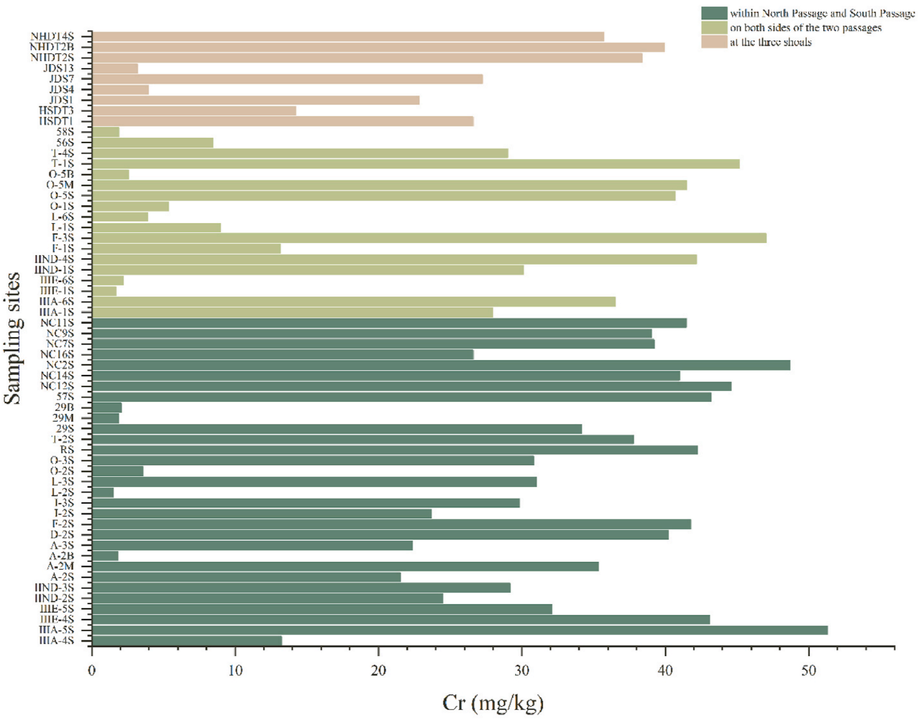
Cu is a primary contributor to PC2. Cu is widely used in industrial production such as painting and electroplating, besides, Cu is also

Table 1
Potential ecological risk assessment results of heavy metals in suspended matter at Yangtze River Estuary.

		As	Cr	Cd	Cu	Pb	Zn	Ni	*RI*
Percentages of potential ecological risk index level	Low	100.00%	100.00%	79.31%	93.10%	25.86%	100.00%	100.00%	55.17%
	Moderate	0	0	0	6.90%	24.14%	0	0	41.38%
	Considerable	0	0	18.97%	0	25.86%	0	0	3.45%
	High	0	0	1.72%	0	24.14%	0	0	0
	Very high	0	0	0	0	0	0	0	0
Potential ecological risk index	Maximum	17.9	1.38	228	69.7	228	1.24	18.7	361
	Minimum	0.00	0.04	0.00	0.58	8.16	0.11	0.32	16.6
	Mean value	6.05	0.71	25.7	8.02	102	0.73	2.60	146

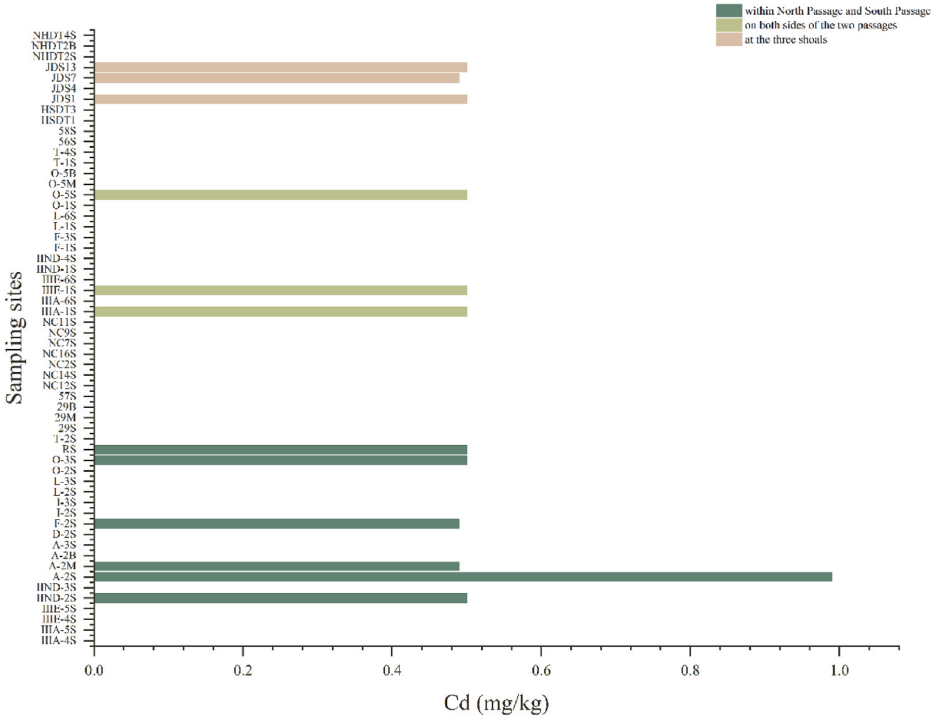


(a) The average total concentration of As in the sediment

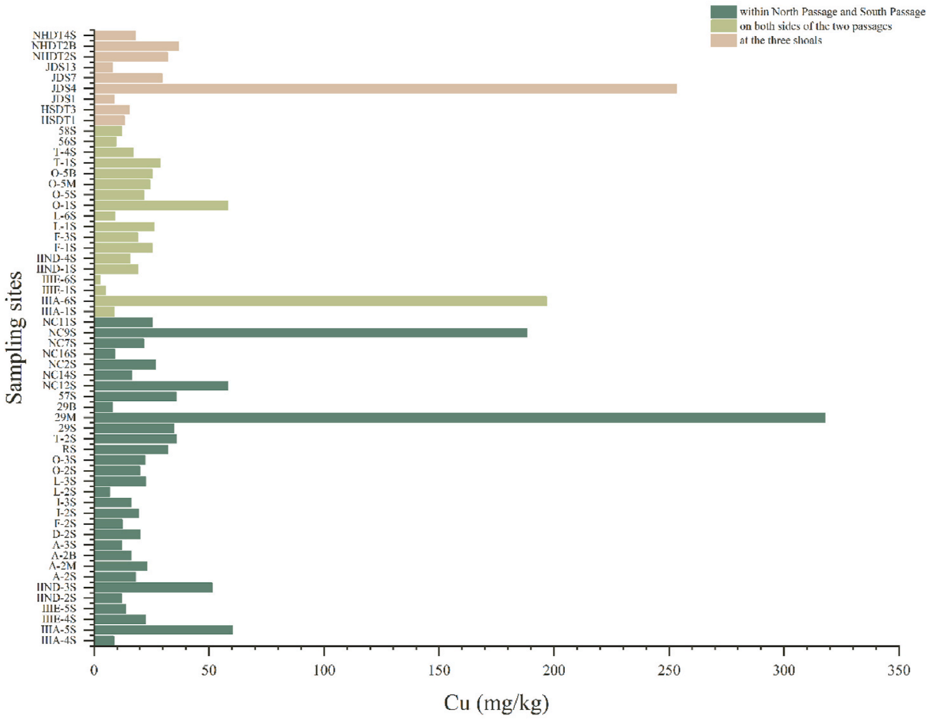


(b) The average total concentration of Cr in the sediment

Fig. 3. The average total concentration distribution of seven heavy metals in this study (unit: mg/kg).

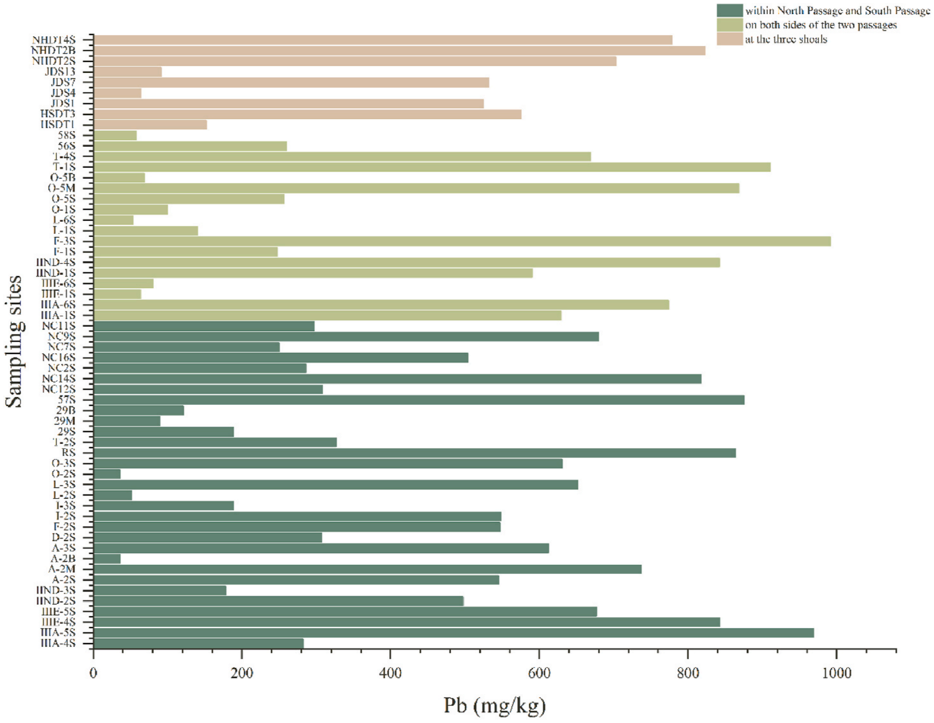


(c) The average total concentration of Cd in the sediment

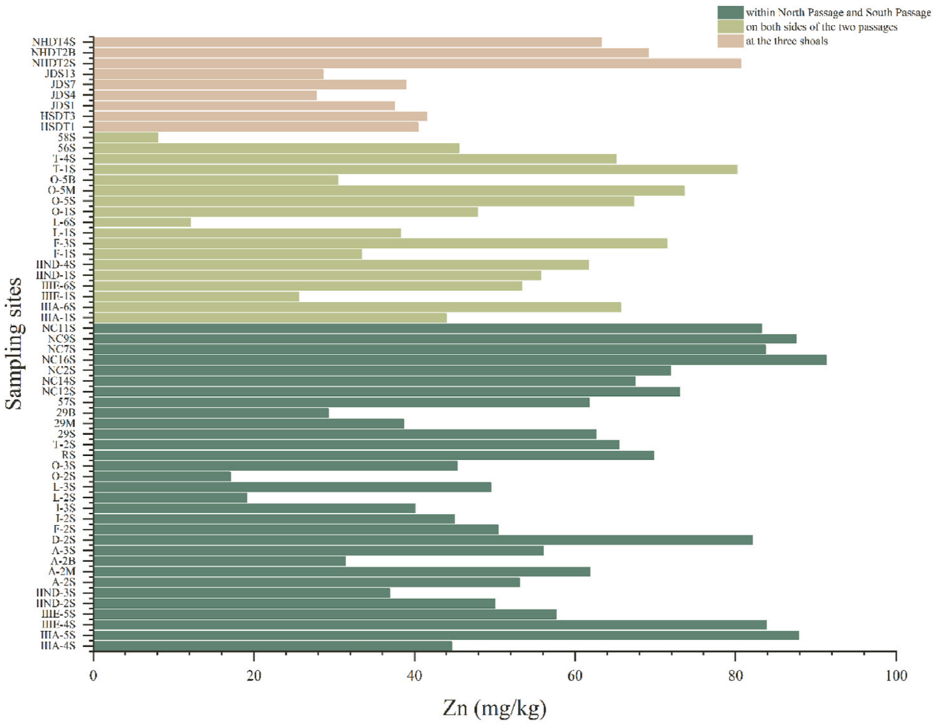


(d) The average total concentration of Cu in the sediment

Fig. 3. (*continued*).

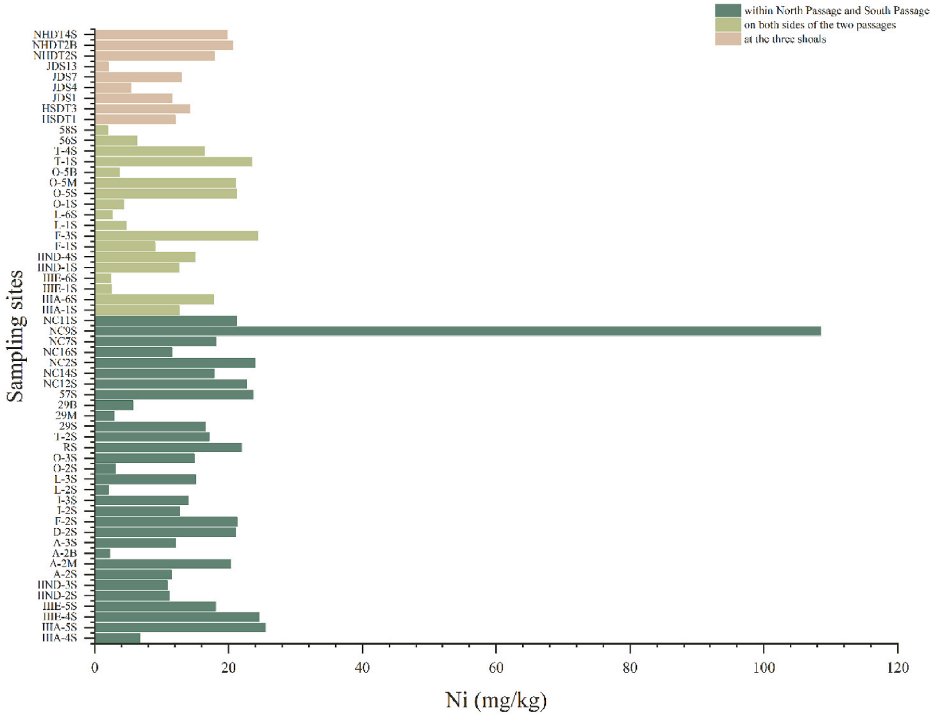


(e) The average total concentration of Pb in the sediment



(f) The average total concentration of Zn in the sediment

Fig. 3. (*continued*).



(g) The average total concentration of Ni in the sediment

Fig. 3. (*continued*).

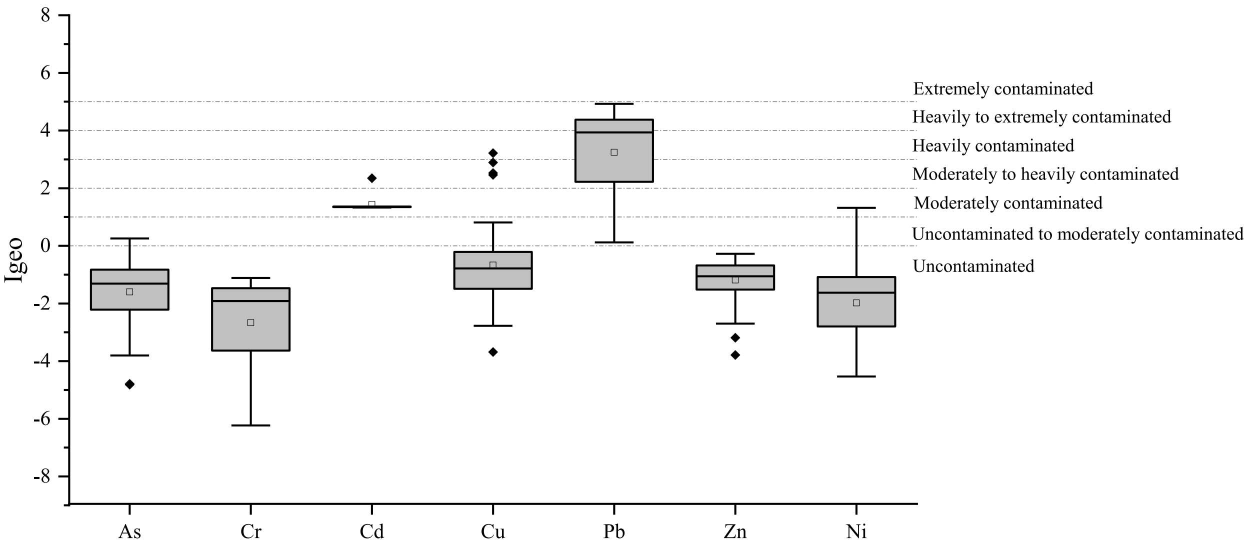


Fig. 4. Geoaccumulation index (I_{geo}) of 7 heavy metals at all sampling points.

found in fungicides and fertilizers commonly used in agriculture [23]. Indicating that the source of Cu is likely to be industrial effluent as well as agricultural activities. In addition, given that most of sampling sites are located in the channel, there is also the potential for Cu contamination from navigation of aged vessels [24,25].

Cd has a high positive charge in PC3,Cd may be derived from the effluent released by chemical facilities engaged in the manufacturing of batteries and chemical products [26].

Owing to the characteristics of the two channels, a significant volume of vessels traverse through them on a daily basis, leading to the inevitable occurrence of fuel seepage and emissions pollution. Furthermore, the extended operation of freight ships results in the

Table 2
Sedimentary pollution level of seven heavy metals.

Heavy metals	Statistics of the measured values of heavy metal concentrations (unit: mg/kg)			Marine sediments quality of China (GB18668-2002) (unit: mg/kg)			Excess standard multiple (= statistics of measured value/class I value)		
	maximum	minimum	mean value	class I	class II	class III	maximum	minimum	mean value
As	16.5	0.00	5.46	≤20	≤65	≤93	0.82	0.00	0.28
Cr	51.3	1.48	29.5	≤80	≤150	≤270	0.64	0.02	0.37
Cd	0.99	0.00	0.00	≤0.5	≤1.5	≤5.0	1.98	0.00	0.11
Cu	318	2.39	19.9	≤35	≤100	≤200	9.08	0.07	0.57
Pb	992	35.6	501	≤60	≤130	≤250	16.5	0.59	8.34
Zn	91.3	8.00	53.2	≤150	≤350	≤600	1.71	0.05	0.355
Ni	108	1.88	14.1	≤40	≤60	≤200	2.71	0.05	0.352

Table 3
Pearson's correlation matrix for heavy metals ($n = 58$).

	As	Cr	Cd	Cu	Pb	Zn	Ni
As	1						
Cr	0.488[b]	1					
Cd	−0.180	0.001	1				
Cu	−0.097	−0.069	−0.167	1			
Pb	0.256	0.746[b]	0.086	−0.057	1		
Zn	0.524[b]	0.831[b]	−0.130	0.041	0.643[b]	1	
Ni	0.284[a]	0.580[b]	−0.057	0.255	0.471[b]	0.599[b]	1

[a] Correlation is significant at the 0.05 level (two-tailed).
[b] Correlation is significant at the 0.01 level (two-tailed).

Table 4
Loadings of heavy metals on significant principal components and statistical characteristics of factor analysis.

	PC1	PC2	PC3
As	0.606	0.022	−0.557
Cr	0.926	−0.152	0.017
Cd	−0.920	−0.687	0.586
Cu	0.032	0.796	0.487
Pb	0.791	−0.242	0.219
Zn	0.916	0.038	−0.052
Ni	0.735	0.265	0.320
Eigenvalues	3.238	1.259	1.044
Variances (%)	46.25	17.99	14.92
Cumulative eigenvectors (%)	46.25	64.24	79.16

potential deterioration and subsequent release of aging surface corrosion protection coatings into the water, thereby amplifying the pathway for Pb contamination. Consequently, it is hypothesized that Pb emanates from sources such as fuel leaks, exhaust emissions, and anti-corrosion coatings. Regarding Cd, given the proximity of several chemical plants, it is assumed that they may serve as the primary origin of Cd.

4. Discussion

The levels of heavy metals in sediments within estuarine environments were evaluated and compared with data from similar representative regions [27–31]. The levels of Ni and Cd in the Yangtze River estuary are similar to those found in other areas of the estuary (Supplementary Table S3). The concentration of Zn is the lowest among the selected areas for comparison. Furthermore, the concentration of As is only higher than that of the Brisbane River estuary and is at a relatively low level. The most concerning issue is Pb pollution, with the highest average concentration in the six selected regions. When compared with other estuaries in China or other countries, the Pb concentration in the Yangtze River estuary is several times higher.

As Pb exhibited the highest concentration among the seven heavy metals examined in this study, it was selected as the indicator element for spatial pollution analysis within the region. The study focused on analyzing the spatial distribution of pollution attributed to Pb, and the mean values and exceedance multiples of Pb in ten sub-areas are presented in Table 5. The mean excess standard multiple of Pb in the 10 sub-areas all exceeded five, and the average Pb concentration in each sub-area surpassed the class III threshold. East Nanhui Shoal was the most polluted sub-area, followed by Yuanyuansha Beach, the lower section of South channel, South Passage section, Yuanyuansha section, North Passage section, lower beach of South channel, beach of North Passage, East Hengsha Shoal and Juduansha Shoal. The Pb concentration in sediments from the North Passage and South Passage was found to be lower than that in East

Table 5
Mean Pb concentrations and excess standard multiples for different divisions.

Spatial divisions	Mean concentration of Pb (mg/kg)	Mean excess standard multiple (= mean concentration of Pb/class I threshold)
Lower section of South channel	692	11.54
Yuanyuansha section	434	7.24
North Passage section	387	6.46
South Passage section	449	7.48
Lower beach of South channel	387	6.44
Yuanyuansha Beach	716	11.93
Beach of North Passage	385	6.42
East Hengsha Shoal	364	6.06
Jiuduansha Shoal	303	5.05
East Nanhui Shoal	768	12.80

Nanhui Shoal, but higher than in East Hengsha Shoal and Jiuduansha Shoal. This suggests that sediments from the deepwater channels of the Yangtze River Estuary (South Passage and North Passage) have the potential to be utilized in the ecological restoration of East Nanhui Shoal. By examining the locations of these sampling sites and the spatial distribution of heavy metals in ten sub-areas, this study offers insights that can be used as a reference for the ecological application of dredged soils.

Through the analysis of the data in Tables 5 and it is evident that the Pb content obtained through Tessier's continuous five step extraction method is the highest among the heavy metals. However, it is noteworthy that the majority of the lead is found in the residual state, indicating a relatively limited environmental impact.

From the above data, the spatial distribution of heavy metals in the study area can be seen. The analysis of the spatial distribution of heavy metals in the 10 divided areas can provide a reference for the subsequent ecological use of dredged soil.

(1) For sampling points in the channels: Starting from the section of South channel, concentration of Pb fluctuates in the high range. Along North passage, Cu concentration curve is relatively stable. In the lower part of North Passage and the outer soil outside the entrance, Cu concentration at point 29 M reached peak value of 318 mg/kg, which is severely polluted. In the South Passage section, peak point occurs at NC9S with 188 mg/kg, which is moderate pollution.
(2) For sampling points on both sides of the channel: The longitudinal distribution of Pb content shows a high-low alternating distribution with a large fluctuation range. For the spatial distribution of Cu concentration, only at the local point IIIA-6B in the lower section of South channel reached the peak of the content curve at 196 mg/kg, which is a moderate pollution level.
(3) For sampling points at entrance shoal: For Pb element, its concentration fluctuates greatly in the lateral spatial distribution, and it can be found that the majority of the East Nanhui Shoal area is highly polluted, while the Jiuduansha Shoal and East Hengsha Shoal have high pollution in the local area. For the elemental content of Cu, in the lateral spatial distribution, the concentration peaked at the JDS4 sampling point in Jiuduansha Shoal, reaching 253 mg/kg, which is in a highly polluted state, while the rest of the heavy metal content is in a gentle curve distribution at a lower level in the spatial distribution.

5. Conclusions

The East Nanhui Shoal exhibited the highest levels of Pb pollution, followed by Yuanyuansha Beach, the lower section of the South channel, the South Passage section, the Yuanyuansha section, the North Passage section, the lower beach of the South channel, the beach of the North Passage, East Hengsha Shoal, and Juduansha Shoal. Although the average concentration of Pb in the findings is the highest, the majority of the Pb is present only in a residual state, which has minimal impact on the environment. The average concentration of Cu shows moderate to high levels of pollution at certain sampling sites within the research area, indicating the need for continued attention to Cu pollution in local areas. Furthermore, As, Cr, Pb, Zn, and Ni exhibited significant correlations at the $p < 0.01$ level, suggesting a high likelihood that these heavy metals are homologous.

Dredged soil extracted from lightly contaminated sub-areas can be repurposed for ecological rehabilitation in heavily contaminated sub-areas. The prioritization of usage is as follows: The middle and lower section of North Passage corresponds to the section of Jiuduansha near the South Passage, the middle and lower section of North Passage corresponds to the upper section of East Hengsha Shoal, the middle section of South Passage corresponds to the side of Jiuduansha Shoal near South Passage, and the middle section of South Passage corresponds to the upper section of East Hengsha Shoal. Considering that the overall pollution level in South Passage is higher than that in North Passage, the decision was made to prioritize the use of dredged soil from North Passage for ecological purposes.

Data availability statement

The data of this study will be available if they are required.

CRediT authorship contribution statement

Xingpo Liu: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Chen Ding:** Writing – review & editing, Writing – original draft, Investigation. **Hailong Qin:** Writing – original draft, Investigation, Formal analysis. **Yiqing Zhang:** Writing – original draft, Investigation, Formal analysis. **Yunqi Jiang:** Writing – original draft, Formal analysis. **Zhiheng Li:** Writing – original draft, Methodology, Investigation, Formal analysis. **Jiangshuai Wu:** Writing – original draft, Investigation, Formal analysis, Data curation. **Haifeng Cheng:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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