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Spatial variations and potential risks of heavy metals in sediments, seawater, and marine organisms of Yuhuan coastal area, China

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Heavy metal pollution in coastal ecosystems poses significant ecological and health risks, yet comprehensive multi-compartment assessments in rapidly industrializing regions like Yuhuan remain scarce. To assess the heavy metal pollution status and potential risks in the coastal area of Yuhuan, this study collected 30 surface seawater samples, 16 surface sediment samples, and multiple marine organism samples in 2023. The concentrations and spatial distribution characteristics of seven heavy metals were analyzed. Multiple indices, including the geo-accumulation index, potential ecological risk index, and bioaccumulation factor, along with principal component analysis, were applied to assess ecological risks and identify pollution sources. The results indicated that heavy metal concentrations in sediments, seawater, and organisms all complied with China's Class I marine environmental quality standards. Mercury posed a moderate ecological risk in sediments (mean $E_r^I=41.08$) and was the dominant contributor to regional ecological risk (51.80%), though the overall ecological risk level of the area remained low (mean $R_I = 79.31$). The pollution load index ranged from 0.003 to 0.09 (mean = 0.04), confirming minimal anthropogenic influence. Marine organisms exhibited a stronger capacity for bioaccumulation of metals from the water column than from sediments, with crustaceans accumulating higher metal levels than fish. PCA revealed that heavy metals in sediments primarily originated from natural processes, agricultural activities, and localized anthropogenic emissions, while those in seawater were mainly associated with industrial wastewater and port activities. This study provides a scientific basis for environmental management, pollution control, and the sustainable development of aquaculture in the Yuhuan coastal area.

KEYWORDS

heavy metals, Yuhuan coastal areas, sediments quality, marine pollution, ecological risk assessment

1 Introduction

The coastal zone, serving as a critical interface between terrestrial and marine ecosystems, is of immense ecological, economic, and social importance. However, it is also a primary sink for anthropogenic pollutants, receiving contaminants from various sources including industrial effluent, agricultural runoff, municipal sewage, and maritime activities (Liu et al., 2025). Among these pollutants, heavy metals have garnered significant global concern due to their persistence, bioaccumulation, toxicity, and non-biodegradable nature (Feng et al., 2023). Heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), copper (Cu), zinc (Zn), and chromium (Cr) are considered pollutants when their concentrations exceed the thresholds established by national or international environmental quality standards (e.g., China's GB 18668–2002 for sediments and GB 3097–1997 for seawater), potentially causing adverse effects on marine ecosystems and human health (AQSIQ, 2002). Metals such as Cd, Pb, Hg, Cu, Zn, and Cr can pose severe threats to marine biodiversity and ecosystem health even at low concentrations (Fan et al., 2022). Furthermore, they can accumulate in marine organisms, potentially biomagnifying through the food web (Zhang et al., 2023). Moreover, recent studies have emphasized the importance of integrated ecological risk indices and multivariate statistics in identifying pollution sources and assessing environmental impacts (Wu et al., 2025).

The Yuhuan coastal area, located in the Taizhou prefecture of Zhejiang Province, China, is a characteristic example of a rapidly developing coastal region (Yang et al., 2017). It hosts a vibrant mix of economic activities, including a thriving aquaculture industry, busy ports, and a concentration of manufacturing, particularly in the hardware, plumbing, and electroplating sectors. While these industries have driven local economic growth, they have also placed considerable pressure on the surrounding marine environment. The discharge of industrial wastewater, combined with agricultural runoff and urban sewage, is suspected to be a primary contributor to the input of heavy metals into the coastal ecosystem (Gao et al., 2016). Consequently, the sediments, which act as both a sink and a potential secondary source of contaminants, the seawater column, and the resident marine organisms in the Yuhuan area are likely exposed to elevated levels of metallic pollution (Lu et al., 2024).

Although the environmental risks of heavy metals in some major Chinese estuaries and bays have been extensively studied, regional-scale investigations in economically vibrant yet ecologically vulnerable areas like Yuhuan remain relatively insufficient (Yao et al., 2021). A comprehensive assessment that simultaneously investigates the spatial distribution of heavy metals across different environmental compartments (sediments, seawater, and marine organisms) is urgently needed. Furthermore, recent investigations have highlighted the critical role of coastal long waves and harbor resonance, triggered by phenomena such as wave groups and modulated by topography through Bragg reflection, in

governing nearshore hydrodynamics and subsequent sediment transport (Zhang et al., 2025; Wu et al., 2025). These processes are directly relevant to the redistribution of contaminants, including heavy metals, in the coastal zone. Such a study is crucial for understanding the transport pathways, bioavailability, and ultimate fate of these contaminants in this specific ecosystem.

Therefore, the objectives of this study are to: (1) determine the concentrations and spatial variations of key heavy metals (e.g., Cu, Pb, Cd, Zn, Cr, Hg, As) in surface sediments, seawater, and representative marine organisms (such as crustaceans and fish) from the Yuhuan coastal area; (2) assess the potential ecological risk in sediments using established indices like the geo-accumulation index (I_{geo}) and potential ecological risk index (RI); and (3) identify potential pollution sources through multivariate statistical analysis. Therefore, this study not only fills a critical gap in regional environmental monitoring but also integrates advanced statistical and ecological risk assessment methods to provide a holistic understanding of heavy metal behavior in the Yuhuan coastal ecosystem, thereby supporting targeted environmental management and sustainable aquaculture development. The findings of this research will provide a critical scientific basis for local environmental management, pollution control, and the sustainable development of the aquaculture industry.

2 Materials and methods

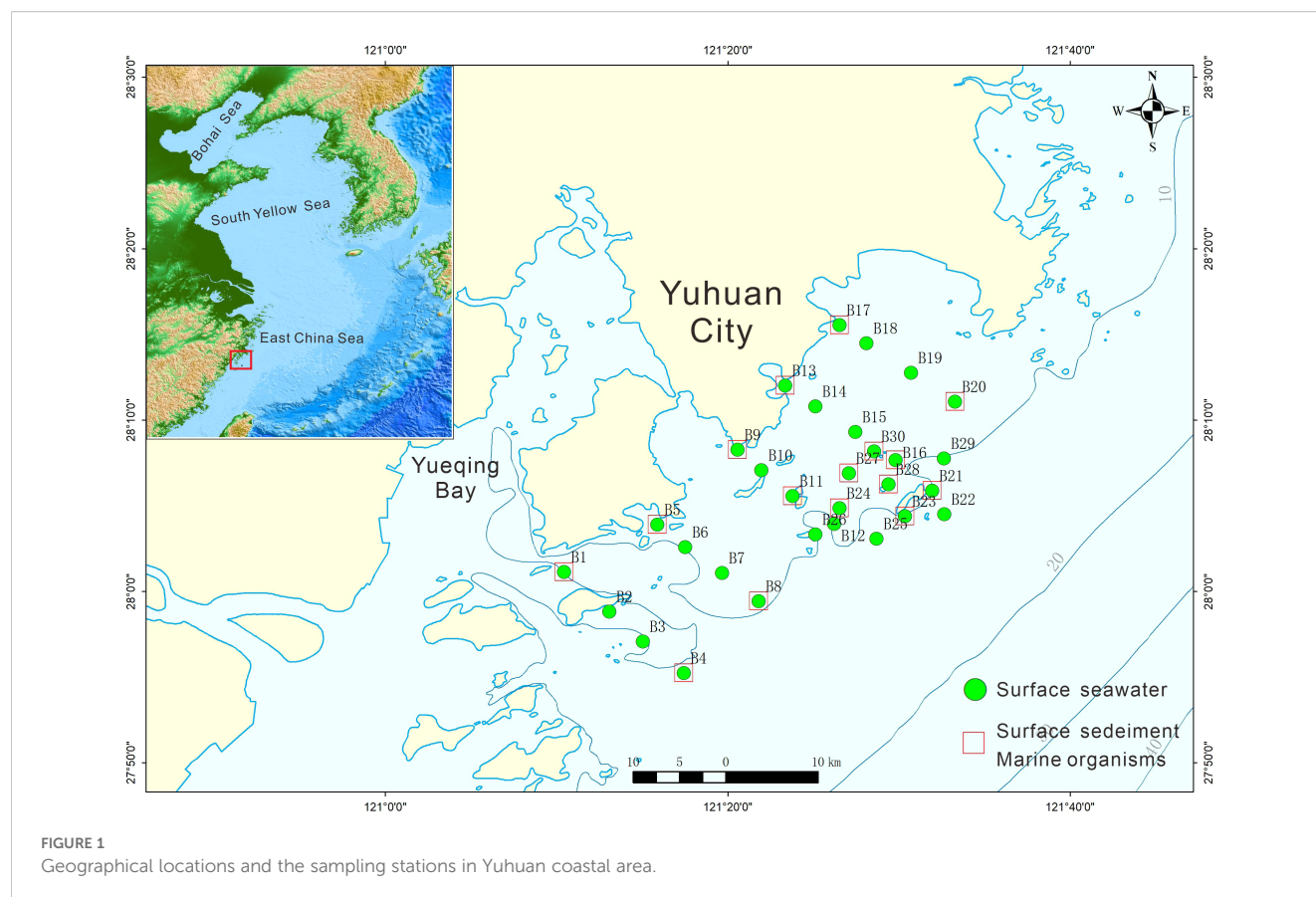
2.1 Sample collection and analytical procedures

In 2023, a total of 30 surface seawater samples, 16 surface sediment samples, and multiple marine organism samples were collected from the coastal region of Yuhuan (see Figure 1). All sampling, preservation, and transportation procedures strictly followed the standards prescribed in the "Specifications for Oceanographic Survey" (GB/T 12763-2007).

2.1.1 Seawater sampling and preprocessing

Surface seawater samples were collected from approximately 0.5 meters depth using a plexiglass water sampler. To prevent cross-contamination, all sample containers were rinsed twice with the sampled seawater prior to final filling. Polyethylene bottles were used for storing samples intended for Zn, Cu, Cr, Cd, Pb, and As analysis, while pre-cleaned glass bottles were employed for Hg. All samples were transported under dark and refrigerated conditions.

For metal stabilization, 2 mL of ultrapure HNO_3 was added to samples for Zn, Cu, Cr, Cd, and Pb analysis; samples for As and Hg were preserved with 2 mL of H_2SO_4 . Filtration was carried out with 0.45 μm glass fiber membranes to eliminate suspended particles. For digestion, 10 mL of HNO_3 was added to 500 mL of seawater, and the mixture was heated on an electric hotplate until evaporated to approximately 10 mL. The residue was then reconstituted to 25 mL using 1% HNO_3 and thoroughly mixed before analysis.



Procedural blanks and certified reference materials were included for quality assurance.

2.1.2 Sediment sampling and pretreatment

Surface sediment samples were acquired with a grab sampler. Approximately 200 g of surface material was collected with a polyethylene spoon, sealed in polyethylene bags, kept in darkness, and refrigerated until analysis. Samples were freeze-dried for 40 hours, homogenized manually with an agate mortar, and sieved through a 160-mesh nylon sieve to achieve consistent particle size.

For acid digestion, 1.0 g of sediment was treated with a 9:3 (v/v) mixture of HNO_3 and HCl (aqua regia) in Teflon containers.

2.1.3 Biological sample collection and processing

Marine organisms were collected via a single-vessel trawl net measuring 40×94 m with a cod end. Trawling was conducted during daylight hours accounting for vessel speed (3–4 knots), current, and wind conditions. Sampling occurred 2–4 nautical miles from predefined stations to ensure representativeness.

Species were taxonomically classified, and biometric parameters (length and mass) were documented. Muscle tissues from fish (pectoral fins) and crustaceans (abdominal segments) were dissected, rinsed with ultrapure water, and stored in pre-weighed 10 mL centrifuge tubes at -20°C .

Digestion adhered to the HY/T 132–2010 standard: 0.1 g of tissue was treated with 9 mL HNO_3 and 3 mL H_2O_2 using microwave-assisted digestion.

2.1.4 Instrumental analysis and quality control

Cu, Pb, Zn, and Cd in seawater were analyzed via graphite furnace atomic absorption spectrometry (GFAAS). Sediment and biological samples were processed similarly, except Zn, which was measured using flame atomic absorption spectrometry (FAAS). A Varian 240 FS AAS (USA) was used for measurements. As and Hg were detected with an XGY-1011A atomic fluorescence spectrometer.

Sediment samples intended for total organic carbon (TOC) analysis were freeze-dried, ground, and passed through a 100-mesh sieve. Inorganic carbon was removed by treatment with 1 mol/L HCl , after which samples were freeze-dried again to constant weight. TOC content was measured using an Elementar vario EL III elemental analyzer (Germany).

Quality control measures included reagent blanks, duplicate samples, and certified reference materials, yielding recoveries between 90% and 110%. Repeat analyses (10% of samples) showed relative standard deviations of 0.05–2.5%, confirming acceptable reproducibility.

2.2 Analytical assessments

Multiple indices were applied to assess heavy metal (HM) pollution risks and identify potential sources, including the geoaccumulation index (I_{geo}), pollution load index (PLI), potential ecological risk index (RI), contamination factor (C_f), water quality index (WQI), single pollution index (P_i), bioaccumulation factor (BAF), and principal component analysis (PCA).

The I_{geo} was calculated as (Equation 1):

$$I_{geo} = \log_2(C_i / (1.5 \times B_i)) \quad (1)$$

where C_i is the HM concentration in sediment and B_i is the regional background value from the studied metals in soils and sediments of Zhejiang province (Wu, 2005). I_{geo} values are categorized from uncontaminated ($I_{geo} \leq 0$) to severely contaminated ($I_{geo} > 5$) (Muller, 1981).

The PLI , developed by Tomlinson et al. (1980), was used to evaluate combined HM pollution (Equations 2, 3):

$$CF_i = C_i / C_0 \quad (2)$$

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times \dots \times CF_n} \quad (3)$$

where CF_i is the contamination factor of metal i , C_i is its measured concentration, and C_0 is the geochemical background value. $PLI < 1$ indicates no pollution, while $PLI > 1$ suggests pollution (Chakravarty and Patgiri, 2009).

The RI , proposed by Hakanson (1980), was computed as (Equation 4):

$$C_r^i = C_f^i / C_n^i, E_r^i = T_r^i \times C_r^i, RI = \sum E_r^i \quad (4)$$

where C_r^i is the contamination factor, C_f^i is measured content, C_n^i is background value, and T_r^i is the toxic response factor (e.g., Zn = 1, Cr = 2, Cu = Pb = 5, As = 10, Cd = 30, Hg = 40). E_r^i thresholds are: <40 (low risk), 40–79 (moderate), 80–159 (considerable), 160–319 (high), and ≥ 320 (extreme). RI is classified as: low (<105), moderate (105–210), considerable (210–420), or very high (≥ 420) (Xu et al., 2021).

For seawater, C_f and WQI were calculated as (Kükrer and Mutlu, 2019) (Equations 5, 6):

$$C_f = C_i / C_s \quad (5)$$

$$WQI = \frac{1}{n} \sum_{i=1}^n C_f = \frac{1}{n} \sum_{i=1}^n \frac{C_i}{C_s} \quad (6)$$

where C_s is the limit from China's Seawater Quality Standard (GB 3097-1997). Interpretation followed established frameworks (Baltas et al., 2017; Macdonald et al., 1996; see Table 1).

The single pollution index (P_i) for bioaccumulation was (Equation 7):

$$P_i = C_i / S_i \quad (7)$$

where S_i is the biological baseline from China's "Coastal and Marine Resource Comprehensive Survey Guidelines" (Table 2). $P_i > 1$ indicates exceeding standards (Zhou et al., 2022).

The quantification of HM transfer from environmental matrices to biota was performed using two biota accumulation factors: the bio-water accumulation factor ($BWAF$) and the bio-sediment accumulation factor ($BSAF$). These were determined as follows (Equations 8, 9):

$$BWAF = C_i / C_w \quad (8)$$

$$BSAF = C_i / C_s \quad (9)$$

reflecting metal transfer from seawater (C_w) or sediment (C_s) to organisms (C_i).

2.3 Statistical data analysis

Spatial distributions of heavy metals were visualized using Surfer 23.0. Statistical analyses, including Pearson correlation and PCA, were conducted in SPSS 27.0. Data were preprocessed in Microsoft Excel 2016.

Pearson correlation analysis was used to examine the relationships between heavy metals and total organic carbon (TOC). The correlation coefficient r ranges from -1 to 1, where values close to 1 or -1 indicate strong positive or negative linear relationships, respectively.

PCA was employed to identify potential sources of heavy metals. The method transforms original variables into a set of linearly uncorrelated principal components (PCs) through orthogonal transformation. The factor loadings represent the contribution of each variable to the PC. Varimax rotation with Kaiser normalization (eigenvalue >1) was applied to enhance interpretability. The cumulative percentage of variance explained by the extracted PCs was used to evaluate the adequacy of the model.

TABLE 1 Relationship between C_f , WQI and pollution level in surface seawater.

C_f	Pollution level	WQI	Pollution level
<1	Low	≤ 1	Clean
1-3	Medium	1-2	Slight
3-6	High	2-3	Medium
>6	Serious	>3	Serious

TABLE 2 Various types of biological evaluation standards (units: $\mu\text{g/g}$).

Species	Cu	Pb	Zn	Cr	Cd	As	Hg
Fish	20	2	40	1.5	0.6	5	0.3
Crustaceans	100	2	150	1.5	2	8	0.2

3 Results and discussion

3.1 Concentration of HMs in sediments, surface seawater, and organisms

Analysis of surface sediments from the Yuhuan coastal area indicated the following concentration ranges for heavy metals (HMs), expressed in $\mu\text{g/g}$ dry weight: Cu (10.4–28.9), Pb (9.1–25.8), Zn (86.5–124), Cr (45.2–79.7), Cd (0.04–0.13), As (10.7–16.0), and Hg (0.038–0.069). The corresponding mean values were 20.59, 19.30, 106.32, 57.03, 0.09, 14.04, and 0.05 $\mu\text{g/g}$, respectively (Table 3). All recorded concentrations were found to be within the Class I limits set by China's Marine Sediment Quality Standard (GB 18668-2002) (AQSIQ, 2002). The TOC content in surface sediments ranged from 0.42% to 0.76%, with an average of 0.61%.

To evaluate the extent of anthropogenic contribution, variation coefficients were computed for each metal. The descending order of variability was as follows: Cd (36.34%) > Pb (25.66%) > Cu (22.37%) > Cr (16.90%) > Hg (14.17%) > As (11.17%) > Zn (9.07%). Notably, Cd exhibited considerable variation (>35%), implying strong external inputs and a non-uniform spatial distribution. The remaining elements displayed moderate variability, reflecting relatively consistent distribution across the sampled locations.

In the water column, dissolved metal concentrations (in $\mu\text{g/L}$) ranged as follows: Cu (1.3–2.3), Pb (0.19–0.95), Zn (3.1–18.0), Cr (0.4–2.3), Cd (0.07–0.26), As (1.0–1.3), and Hg (0.017–0.05). Their mean values were 1.64, 0.41, 8.07, 1.35, 0.17, 1.10, and 0.03 $\mu\text{g/L}$, respectively. All values met the Class I requirements of the Seawater Quality Standard (GB 3097-1997).

Biological samples revealed species-specific accumulation trends, with metal levels reported in $\mu\text{g/g}$ wet weight: Cu (0.4–15.6), Pb (0.07–0.16), Zn (2.7–29.7), Cr (0.04–0.23), Cd (0.007–0.824), As (0.2–0.5), and Hg (0.003–0.038). The mean concentrations were 4.09, 0.13, 14.36, 0.08, 0.16, 0.28, and 0.02 $\mu\text{g/g}$, respectively (Table 4).

Spatial distribution of HMs in surface sediments is depicted in Figure 2. With the exception of Cr, both heavy metals and total organic carbon (TOC) showed a cross-shelf gradient with higher concentrations inshore and lower values offshore. Pronounced enrichment was detected in localized zones, particularly near Pishan Island and Dalu Island. In contrast, elevated Cr levels were largely confined to the region between Pishan Island and Dalu Island.

The spatial patterns of dissolved metals in surface waters are presented in Figure 3. Cu, Pb, and Zn displayed highest concentrations around Pishan Island, with minima identified in the coastal waters adjacent to Yuhuan City. For Cr and Cd, high-value zones were predominantly nearshore, diminishing toward open waters. Meanwhile, As and Hg showed marked enrichment primarily in the vicinity of Pishan Island.

3.2 Assessment of sediment pollution using ecological risk indices

Correlation analysis can reveal associations among different heavy metal elements, thereby aiding in determining whether they share common pollution sources. It also reflects their geochemical behavior in environmental media, such as water, sediments, and marine organisms. Positive correlations may indicate that elements exhibit similar migration, adsorption, or dissolution characteristics, or demonstrate synergistic effects during bioaccumulation processes.

As shown in Table 5, which presents the correlations between heavy metals and total organic carbon (TOC) in the sediments of the Yuhuan coastal area, strong correlations ($r > 0.6$) were observed between Pb and Zn, Cd and Zn, as well as Hg and Zn and As, while correlations among other elements were generally moderate. Notably, TOC showed significant correlations with Pb and Cd ($r=0.641$ and 0.938).

Table 6 presents the mean and range of I_{geo} values for the seven HMs detected in sediments from the Yuhuan coastal area. Based on

TABLE 3 Heavy metal concentrations in the surface sediments and surface seawater in Yuhuan coastal area.

Heavy metals	Cu	Pb	Zn	Cr	Cd	As	Hg
Surface sediments (unit: $\mu\text{g/g}$)							
Range	10.4-28.9	9.1-25.8	86.5-124	45.2-79.7	0.04-0.13	10.7-16	0.038-0.069
Average	20.59	19.30	106.32	57.03	0.09	14.04	0.05
Variation coefficient/%	22.37	25.66	9.07	16.90	36.34	11.17	14.17
MSQ-1	35	60	150	80	0.5	20	0.2
Surface seawaters (unit: $\mu\text{g/L}$)							
Range	1.3-2.3	0.19-0.95	3.1-18	0.4-2.3	0.07-0.26	1-1.3	0.017-0.05
Average	1.64	0.41	8.07	1.35	0.17	1.10	0.03
Variation coefficient/%	11.54	48.45	53.96	41.20	27.38	7.28	20.06
SQS-1	5	1	20	50	1	20	0.05

MSQ-1 represents the first-class standard concentration of heavy metals according to the Chinese Marine Sediment Quality Standard Criteria (GB 18668-2002). SQS-1 is the first-class standard for the concentration of heavy metals in seawater (GB 3097-1997).

TABLE 4 Heavy metal concentration in marine organism in Yuhuan coastal area.

Species	Value	Cu	Pb	Zn	Cr	Cd	As	Hg
All species	Range	0.4-15.6	0.07-0.16	2.7-29.7	0.04-0.23	0.007-0.824	0.2-0.5	0.003-0.038
	Average (n=16)	4.09	0.13	14.36	0.08	0.16	0.28	0.02
Fish	Range	0.4-0.6	0.09-0.15	2.7-7.9	0.05-0.23	0.007-0.03	0.2-0.2	0.003-0.024
	Average (n=9)	0.5	0.1	5.5	0.1	0.02	0.2	0.016
Crustaceans	Range	6.3-15.6	0.07-0.16	23.6-29.7	0.04-0.11	0.177-0.824	0.2-0.5	0.01-0.038
	Average (n=7)	8.1	0.1	25.7	0.06	0.3	0.3	0.027

the average contamination degree, the elements were ranked as follows: As exhibited the highest level, followed by Zn, Hg, Cu, Pb, Cr, and Cd. All computed I_{geo} values were below zero (Figure 4), suggesting that the sediment in the study area remains uncontaminated (Muller, 1981).

PLI results showed notable spatial variability throughout the region, with values across the 16 sampling stations varying between 0.003 and 0.09 (mean = 0.04), as detailed in Table 6. Spatial distribution mapping (Figure 5) further illustrated that all stations recorded *PLI* values below 1, implying minimal anthropogenic contribution to heavy metal accumulation.

Ecological risk assessment revealed clear differentiation among the metals. The risk coefficients decreased in the order: Hg (highest) > Cd > As > Cu > Pb > Cr > Zn (lowest) (Table 6). Although most metals presented low ecological risk (mean $E_r^i < 40$), Hg was associated with a moderate risk level (E_r^i range: 28.68–52.08). Notably, 62.5% of the sampling sites indicated moderate ecological risk from Hg, underscoring its heightened toxicity even at relatively low ambient concentrations (Tam and Wong, 2000).

The overall *RI* values varied from 59.09 to 95.80, with a mean of 79.31, consistent with a low ecological risk status for the entire region (Table 6, Figure 6). Source apportionment highlighted Hg (51.80%) and Cd (21.07%) as the dominant contributors to ecological risk (Table 6), indicating that their potential environmental impact is disproportionately high relative to their concentration—a result of their elevated biological toxicity compared to the other metals analyzed (Di Bella et al., 2024).

3.3 Assessment of HM contamination in surface waters

The C_f analysis indicated the following concentration ranges for HMs in the surface waters of the Yuhuan coastal area: Cu (0.26–0.46), Pb (0.19–0.95), Zn (0.155–0.9), Cr (0.008–0.046), Cd (0.07–0.26), As (0.05–0.065), and Hg (0.34–1). Their respective mean values were 0.33, 0.41, 0.40, 0.03, 0.17, 0.06, and 0.68 (Table 6). The *WQI* across all sampling sites ranged from 0.21 to 0.46, consistently remaining below the threshold of 1. These results indicate that all monitored heavy metals met the Class I seawater quality standards throughout the study period, reflecting consistently good water quality (Ramadan et al., 2021).

Ecological risk assessment revealed the following descending order of single-element potential ecological risk coefficients: Hg > Pb > Cu > Cd > Zn > As > Cr (Table 6). All individual risk values were below 40 at each sampling site, suggesting a low level of ecological concern. The comprehensive potential ecological risk index (*RI*) ranged from 23.12 to 50.15, with a mean value of 36.85 (Table 6, Figure 6), confirming an overall low ecological risk status in the region (Kükrer and Mutlu, 2019).

3.4 Accumulation of HMs in organisms

Statistical analysis indicated distinct distribution patterns of HM concentrations between the two marine organism groups in the Yuhuan coastal area. The metal concentration rankings in fish and crustaceans were as follows: Zn > Cu > As > Pb > Cr > Cd > Hg for fish, and Zn > Cu > As > Cd > Pb > Cr > Hg for crustaceans. Notably, elevated As levels in both groups point to possible environmental contamination. According to the biological quality benchmarks outlined in China's Coastal Zone and Marine Resource Comprehensive Survey Guidelines, the P_i for all heavy metals in both fish and crustaceans were below 1 (Table 7), indicating compliance with established safety thresholds.

Bioaccumulation potential was evaluated using two key indices: the *BSAF* and the *BWAF*. A *BSAF* value greater than 1 indicates significant accumulation from sediment, while a *BWAF* above 1 suggests prominent bioaccumulation from the water column. As summarized in Table 8, with the exception of Cd in crustaceans, all *BSAF* values were below 1, reflecting limited uptake of HMs from sedimentary sources (Dean et al., 2007). Crustaceans are predominantly benthic or deposit-feeding organisms that obtain nutrients by ingesting organic detritus and microorganisms from sediments. Cd readily adsorbs to sediment particles, leading to significant exposure for crustaceans via the digestive tract as they feed. Furthermore, crustaceans occupy a critical position in aquatic food webs, serving as a key food source for many fish and bird species. Consequently, the high concentrations of cadmium accumulated in their tissues can be biomagnified through the food chain/web, posing a potential ecological and health risk to higher trophic levels, including humans.

In contrast, most *BWAF* values exceeded 1, indicating efficient bioaccumulation from the aqueous phase—even amid generally low

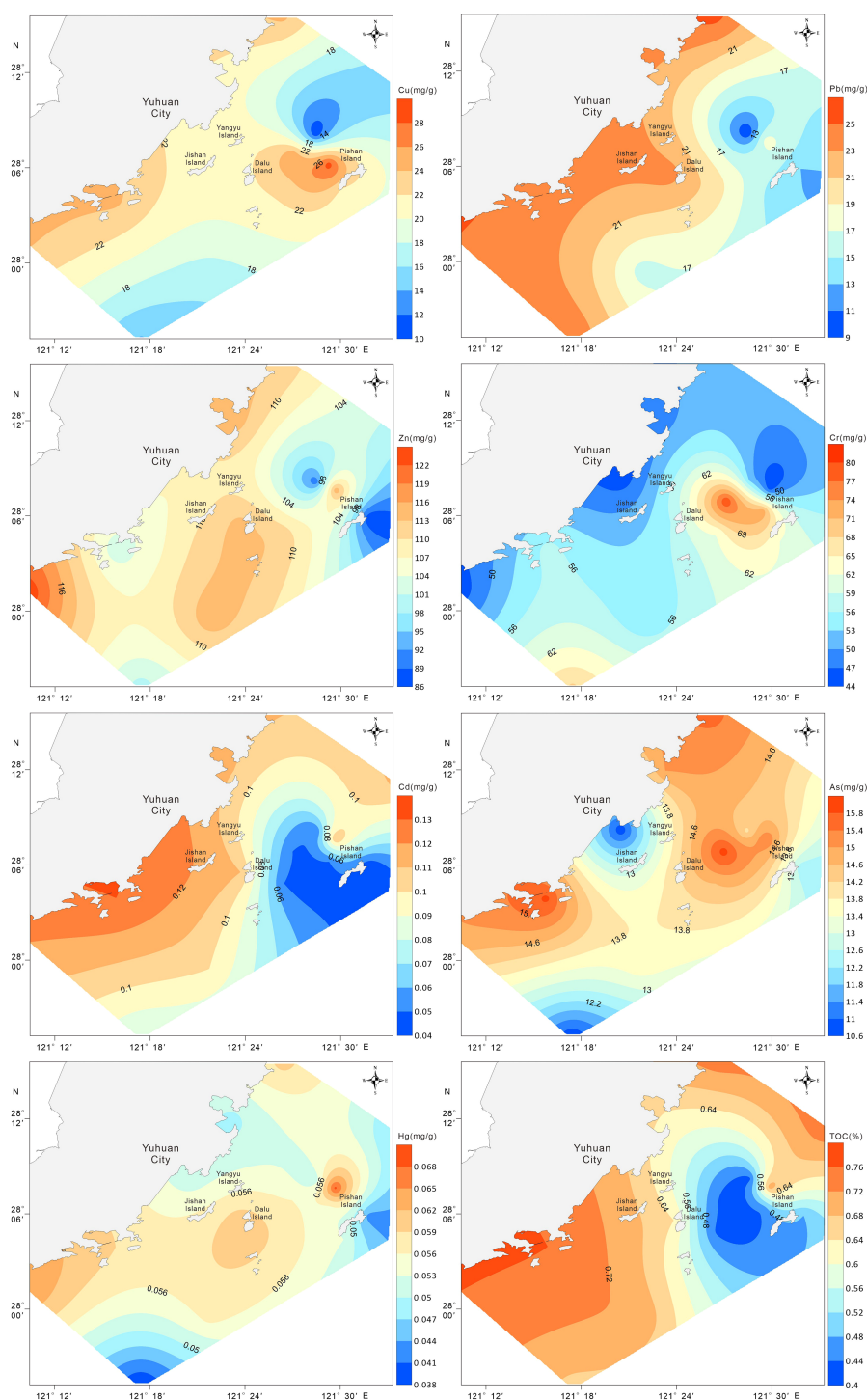


FIGURE 2
Spatial distributions of seven heavy metals in the surface sediments.

dissolved metal concentrations in ambient seawater. This suggests that metals are effectively concentrated through trophic transfer in the water column, consistent with prior research (Harada, 2016; Hoai et al., 2020; Islam and Tanaka, 2004). The divergence in accumulation patterns between sediment and aqueous pathways underscores the complex mechanisms governing metal transfer in marine ecosystems.

3.5 Source identification of HMs

To identify potential sources of HMs in the environment, PCA was conducted using SPSS software. For surface sediments, three principal components (PCs) with eigenvalues greater than 1 were extracted, collectively accounting for 86.25% of the total variance

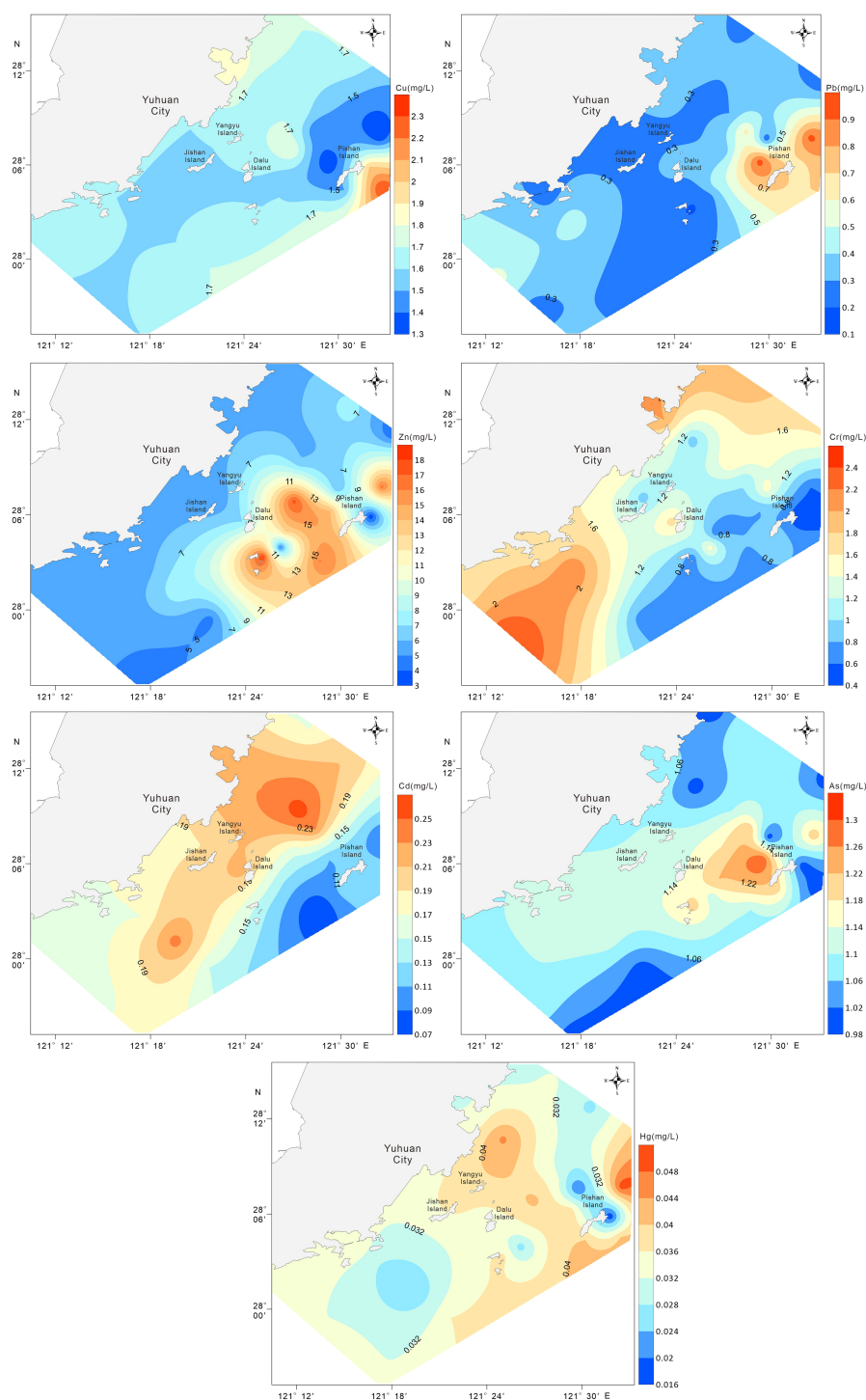


FIGURE 3
Spatial distributions of seven heavy metals in the surface seawaters.

(Table 9), which captures the majority of the dataset's variability (Waykar and Petare, 2016).

PC1, explaining 46.07% of the variance, showed strong loadings for Pb (0.75), Zn (0.83), Cd (0.90), Hg (0.65), and TOC (0.83), suggesting a common origin for these elements. TOC is recognized

as a key factor influencing the geochemical behavior and distribution of heavy metals in sediments (Hu et al., 2018). In this study, the significant positive correlations between TOC, Pb, and Cd indicate that TOC plays a role in metal binding. The high surface-area-to-volume ratio of organic matter, particularly the

TABLE 5 Pearson’s correlation matrix for HMs in Yuhuan coastal area.

	Cu	Pb	Zn	Cr	Cd	As	Hg	TOC
Cu	1							
Pb	0.356	1						
Zn	0.362	.613*	1					
Cr	0.312	-0.201	-0.339	1				
Cd	-0.010	.686**	.579*	-.664**	1			
As	0.458	-0.013	0.347	0.091	0.071	1		
Hg	0.387	0.228	.683**	-0.297	0.370	.683**	1	
TOC	-0.106	.641**	0.480	-.622*	.938**	-0.058	0.240	1

*, Correlation is significant at the 0.05 level (two-tailed).
**, Correlation is significant at the 0.01 level (two-tailed).

humic substances within TOC, contributes to strong adsorption, ion exchange, and chelation effects on HMs. The I_{geo} values for Pb, Zn, Cd, and Hg were all below zero, supporting the interpretation that PC1 represents a natural source.

PC2 accounted for 26.59% of the variance and was characterized by high loadings on As (0.77) and Cu (0.76), along with positive correlations with Cr (0.50) and Hg (0.55). This pattern implies potential derivation from agricultural runoff (e.g., pesticides and fertilizers) or natural lithogenic processes. PC3, which

explained 13.58% of the variance, displayed moderate loadings on Pb (0.60) and Cu (0.44), though its explanatory power was limited. This component may reflect localized or mixed sources, such as shipping operations or resuspended sediments.

In the surface seawater of the Yuhuan coastal area, two principal components were extracted, together explaining 63.13% of the total variance (Table 9). PC1 contributed 44.55% of the variance and exhibited strong positive loadings on Pb (0.70), Zn (0.88), As (0.62), and Hg (0.75), indicating a common source for these elements,

TABLE 6 Background value, I_{geo} , E_r^i , RI , PLI values for surface sediments and C_f , WQI , RI values for surface seawaters of heavy metals in Yuhuan coastal area.

Parameters		Cu	Pb	Zn	Cr	Cd	As	Hg
Surface sediments								
M _{background} ^a (μg/g)		29.3	29.1	96.4	89.8	0.156	11.4	0.053
I _{geo}	Range	-2.08 to -0.6	-2.26 to -0.76	-0.74 to -0.22	-1.58 to -0.76	-2.55 to -0.85	-0.68 to -0.1	-1.06 to -0.2
	Average	-1.14	-1.23	-0.45	-1.26	-1.54	-0.29	-0.56
E _r ⁱ	Range	1.77-4.93	1.56-4.43	0.9-1.29	1.01-1.78	7.69-25	9.39-14.04	28.68-52.08
	Average	3.51	3.32	1.10	1.27	16.71	12.31	41.08
RI (average)		59.09-95.80 (79.31)						
Contributions to RI		4.43%	4.18%	1.39%	1.60%	21.07%	15.53%	51.80%
PLI (average)		0.003-0.09 (0.04)						
Surface seawaters								
C _f	Range	`0.26-0.46	0.19-0.95	0.155-0.9	0.008-0.046	0.07-0.26	0.05-0.065	0.34-1
	Average	0.33	0.41	0.40	0.03	0.17	0.06	0.68
WQI (average)		0.21-0.46 (0.30)						
E _r ⁱ	Range	1.3-2.3	0.95-4.75	0.155-0.9	0.016-0.092	2.1-7.8	0.5-0.65	13.6-40
	Average	1.64	2.06	0.40	0.05	4.97	0.55	27.17
RI (average)		23.12-50.15 (36.85)						
Contributions to RI		4.44%	5.60%	1.09%	0.15%	13.49%	1.50%	73.74%

^aBackground values of heavy metals are the studied metals in soils and sediments of Zhejiang province (Wu, 2005).

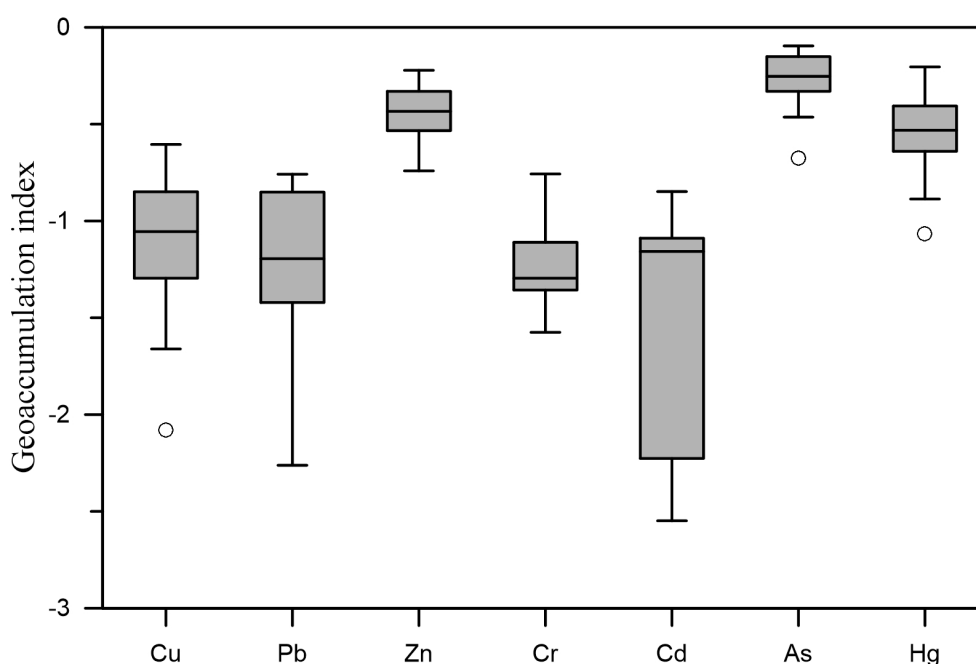


FIGURE 4
The I_{geo} of seven heavy metals in the sediments in Yuhuan coastal area.

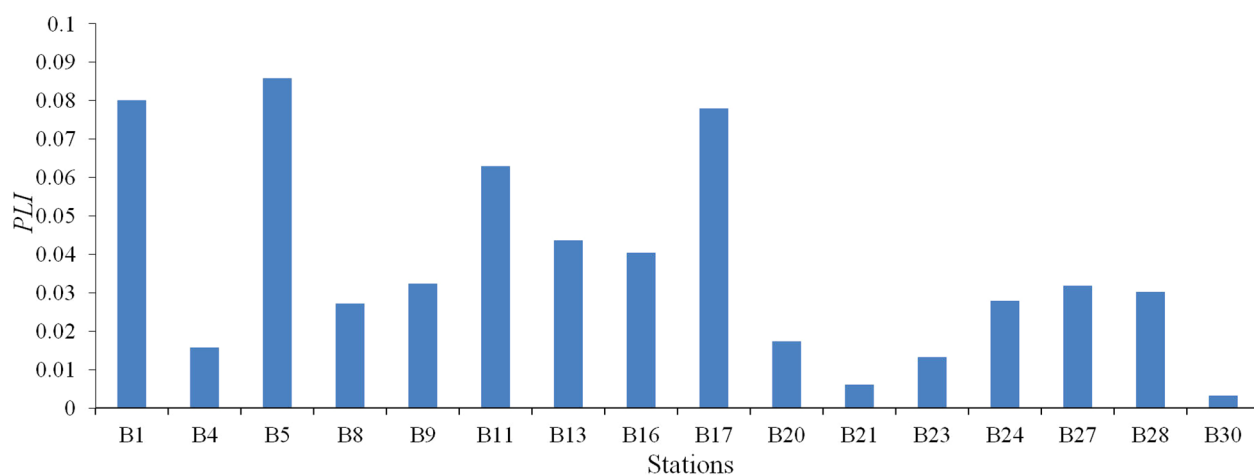


FIGURE 5
Spatial distribution of pollution load index (PLI) for heavy metals in surface sediments.

potentially linked to coastal industrial effluents, port operations, and/or atmospheric deposition. PC2, explaining 18.58% of the variance, was marked by significant loadings on Cd (0.48) and Hg (0.50), suggesting a distinct source such as electroplating discharges or other localized emissions. It may also be associated with physicochemical processes in the water column, including

solubility changes and transitions between particulate and dissolved phases.

While PCA offers useful insights into potential pollution sources, several limitations must be acknowledged. First, the outcomes depend on the initial variable selection and data normalization methods. Second, factor interpretation remains subjective, relying on loading

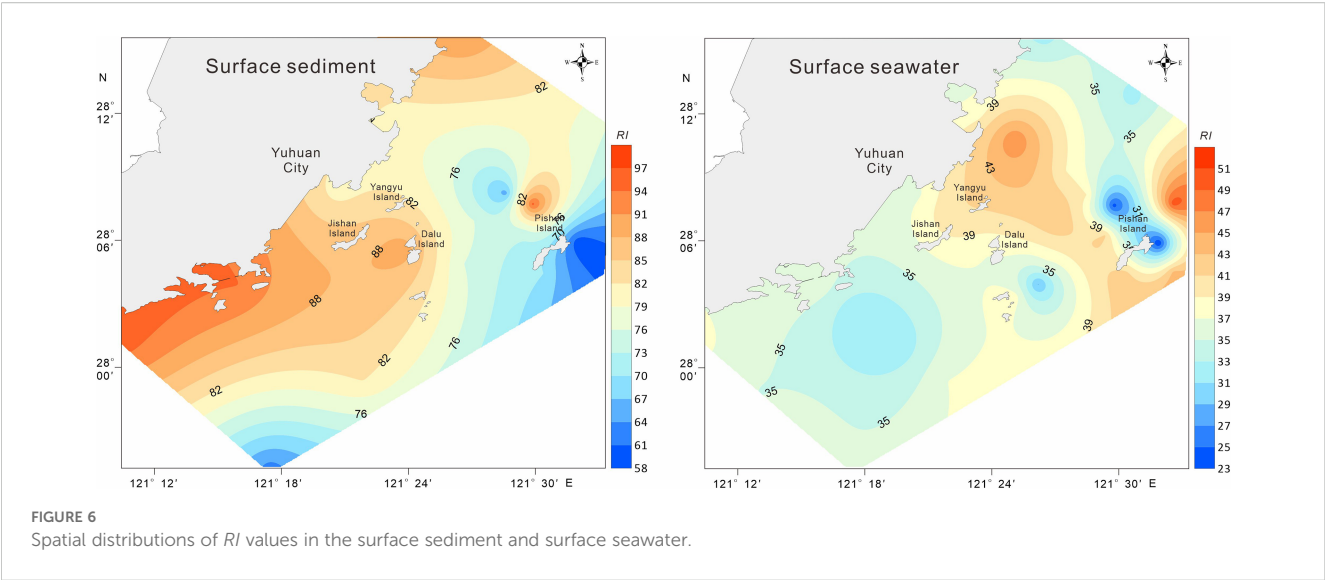


TABLE 7 Standard index (P_i) of heavy metal content in organisms in the study area.

Species	Stations	Value	Cu	Pb	Zn	Cr	Cd	As	Hg
All	16	Range	0.02-0.16	0.04-0.08	0.07-0.2	0.03-0.15	0.01-0.41	0.03-0.06	0.01-0.19
		Average	0.05	0.06	0.15	0.05	0.09	0.04	0.09
Crustaceans	7	Range	0.06-0.16	0.04-0.08	0.16-0.2	0.03-0.07	0.09-0.41	0.03-0.06	0.05-0.19
		Average	0.08	0.07	0.17	0.04	0.17	0.04	0.13
Fish	9	Range	0.02-0.03	0.05-0.08	0.07-0.2	0.03-0.15	0.01-0.05	0.04-0.04	0.01-0.08
		Average	0.03	0.06	0.14	0.06	0.03	0.04	0.05

TABLE 8 *BAF* of heavy metals in Yuhuan coastal area.

Species	Stations	<i>BSAF</i>							<i>BWSF</i>						
		Cu	Pb	Zn	Cr	Cd	As	Hg	Cu	Pb	Zn	Cr	Cd	As	Hg
Crustaceans	B1	0.27	0.01	0.20	0.001	2.08	0.03	0.45	3.88	0.31	4.42	0.03	1.66	0.37	0.83
	B4	0.45	0.01	0.27	0.001	2.93	0.03	0.76	3.94	0.48	6.24	0.03	1.23	0.30	0.91
	B8	0.48	0.01	0.21	0.001	2.96	0.03	0.58	4.82	0.70	5.25	0.06	1.97	0.40	0.92
	B11	0.29	0.01	0.21	0.001	2.03	0.02	0.62	3.94	0.50	3.39	0.03	1.01	0.27	1.15
	B16	0.87	0.01	0.21	0.001	7.49	0.01	0.29	10.40	0.54	4.09	0.04	5.49	0.20	1.00
	B17	0.26	0.01	0.23	0.001	1.61	0.03	0.47	3.76	0.42	4.76	0.03	1.04	0.50	0.97
	B20	0.51	0.00	0.30	0.002	2.82	0.02	0.21	5.07	0.30	7.32	0.07	2.21	0.30	0.25
Fish	B5	0.02	0.00	0.07	0.001	0.23	0.01	0.22	0.31	0.38	1.42	0.03	0.18	0.18	0.38
	B9	0.03	0.00	0.07	0.002	0.19	0.02	0.25	0.38	0.35	1.36	0.05	0.12	0.19	0.38
	B13	0.03	0.01	0.07	0.001	0.20	0.01	0.29	0.32	0.30	1.33	0.03	0.10	0.18	0.42
	B21	na	0.01	0.03	0.002	0.18	na	0.53	na	0.23	0.87	0.30	0.06	na	1.35
	B23	0.02	0.01	0.05	0.004	0.32	na	0.06	0.27	0.19	0.36	0.23	0.13	na	0.08
	B24	0.03	0.01	0.07	0.002	0.14	0.01	0.38	0.40	0.30	0.62	0.14	0.05	0.16	0.65

(Continued)

TABLE 8 Continued

Species	Stations	BSAF							BWSF						
		Cu	Pb	Zn	Cr	Cd	As	Hg	Cu	Pb	Zn	Cr	Cd	As	Hg
	B27	0.02	0.01	0.04	0.002	na	na	0.32	0.28	0.36	0.21	0.13	na	na	0.44
	B28	0.02	0.01	0.04	0.001	0.14	0.01	0.24	0.46	0.13	0.34	0.06	0.06	0.15	0.34
	B30	0.05	0.01	0.04	0.001	0.16	0.01	0.47	0.36	0.17	0.41	0.05	0.03	0.16	0.73

* na means no data.

TABLE 9 Extracted three principal components in surface sediments and two principal components for surface seawater.

Parameter	Surface sediment			Surface seawater	
	PC1	PC2	PC3	PC1	PC2
Cu	0.25	0.76	0.44	-0.36	-0.78
Pb	0.75	-0.05	0.60	0.70	-0.18
Zn	0.83	0.28	0.04	0.88	0.02
Cr	-0.61	0.50	0.47	-0.61	0.42
Cd	0.90	-0.33	0.02	-0.66	0.48
As	0.30	0.77	-0.37	0.62	0.03
Hg	0.65	0.55	-0.41	0.75	0.50
TOC	0.83	-0.45	0.06		
Eigenvalues	3.69	2.13	1.09	3.12	1.3
Percentage of variance	46.07	26.59	13.58	44.55	18.58
Cumulative % eigenvector	46.07	72.66	86.25	44.55	63.13

patterns and contextual knowledge of the study area, thereby incorporating expert judgment. Additionally, PCA assumes linear relationships among variables and may not adequately represent complex interactions or minor sources. Finally, unlike receptor modeling approaches, PCA does not provide quantitative estimates of source contributions. Thus, the current results should be considered an initial identification of major source categories rather than a precise apportionment of their impacts.

4 Conclusion

This study provides a comprehensive assessment of heavy metal pollution in the Yuhuan coastal environment. The main conclusions are as follows:

1. Concentrations of all heavy metals in surface sediments and seawater were within China’s Class I standards, indicating generally good environmental quality.
2. Ecological risk assessment revealed low overall risk in the study area, although Hg and Cd were identified as priority

pollutants due to their high toxic response and significant contributions to the *RI*.

3. Correlation and PCA analyses indicated that heavy metals in sediments originated from natural sources, agricultural activities, and industrial discharges, while seawater metals were influenced by coastal industries, port operations, and atmospheric deposition.
4. Bioaccumulation assessment showed limited uptake from sediments but significant accumulation from the water column, highlighting the role of trophic transfer in metal bioavailability.
5. It is important to note that this study represents a single sampling event conducted in 2023. Heavy metal concentrations are subject to temporal fluctuations driven by seasonal hydrological cycles and anthropogenic activities. Consequently, our findings should be interpreted as a snapshot in time and may not capture long-term trends or annual averages. Future studies should incorporate seasonal and multi-annual sampling designs to better elucidate the dynamics and long-term behavior of heavy metals within this ecosystem.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SZ: Investigation, Conceptualization, Writing – original draft, Methodology. CD: Methodology, Writing – original draft, Funding acquisition. JW: Supervision, Software, Writing – original draft. MZ: Writing – original draft, Resources, Methodology. XC: Project administration, Methodology, Writing – original draft. YZ: Writing – original draft, Formal Analysis, Validation. JY: Visualization, Methodology, Writing – original draft. XM: Software, Writing – original draft, Formal Analysis.

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