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Comprehensive assessment of heavy metal pollution in northeast Fuqing Bay: integrating sediments, seawater, and marine organisms analysis with multivariate techniques

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Northeastern Fuqing Bay is crucial for the marine ecosystem in Fujian Province and plays an important role in regional economic development and ecological balance. However, rapid economic and population growth has led to severe heavy metal (HM) pollution from anthropogenic sources and atmospheric deposition. This study comprehensively assessed HMs in surface sediments, surface seawater, and marine organisms in northeastern Fuqing Bay, Fujian Province. A total of 37 surface seawater samples, 22 surface sediment samples, and 4 marine organism samples were collected. The results indicated that certain HMs, such as Hg and Cd, exhibited high coefficients of variation in surface sediments. The concentrations of HMs in both surface seawater and sediments met Class I standards; however, some sediment samples were contaminated with Cd, As, and Hg, and the Cr levels in marine organisms exceeded the permissible limits at certain sampling sites. Analysis of various indices revealed that the mean potential ecological risk index (*RI*) value was 193.12, indicating moderate ecological risk, primarily influenced by Cd and Hg, whereas seawater was classified as having a low ecological risk, with mean *RI* value of 13.52. Marine organisms demonstrated a strong bioaccumulation capacity for certain HMs in seawater. Principal component analysis indicated that HM sources in sediments were mainly wastewater discharge from chemical enterprises, port operations, rock weathering, metal smelting, and agricultural activities. In contrast, HM sources in seawater were partly natural and partly related to anthropogenic activities, such as urban and rural sewage discharge. This study provides an important reference for the ecological restoration of this region.

KEYWORDS

heavy metal pollution, Fuqing Bay, sediments, seawater, marine organisms, ecological risk assessment

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1 Introduction

As a crucial part of the marine ecosystem in Fujian Province, northeastern Fuqing Bay plays a significant role in the regional economic development and maintenance of ecological balance (Liu et al., 2025). This area is rich in fishery resources and serves as a habitat and breeding ground for numerous marine organisms (Fan et al., 2022). It is also an important area for economic activities such as maritime transportation and coastal tourism (Lv et al., 2019). However, with rapid economic development and continuous population growth in coastal areas, large amounts of heavy metal (HM) pollutants enter the area through various channels, including industrial wastewater discharge, agricultural non-point source pollution, urban domestic sewage discharge, and atmospheric deposition. Consequently, it is facing an increasingly severe HM pollution problem (Lv et al., 2019).

HMs, such as Hg, Cd, Pb, Cr, and As, are characterized by high toxicity, difficult degradation, and easy accumulation (Avvari et al., 2022). Once they enter the marine environment, they not only migrate and transfer to seawater, but also continuously accumulate in sediments. Biological magnification of HMs in the food chain poses a serious threat to marine life and human health (Feng et al., 2023; Qiu et al., 2019). Research shows that HM pollution can interfere with the physiological functions of marine organisms, affecting their growth, development, reproduction, and immune processes, thereby leading to a decline in biodiversity and damage to the structure and function of ecosystems (Nour et al., 2022). In seawater, the existing forms and concentrations of HMs are affected by various factors such as pH, redox potential, salinity, and particulate matter content. Changes in these factors can alter the migration and transformation of HMs, as well as their bioavailability (Madadi et al., 2023). As an important reservoir of HMs, the composition, structure, and physicochemical properties of sediments play key roles in HM adsorption, desorption, precipitation, and dissolution. In addition, microbial activity in sediments affects the morphological transformation and bioavailability of HMs (Leung et al., 2021). HM absorption, accumulation, and metabolism in organisms are not only related to the physiological characteristics of the organisms themselves but are also closely related to the concentration and form of HMs in the environment and food chain relationships (Zhang et al., 2023).

Although the ecological status of Fuqing Bay and its adjacent areas has garnered increasing research attention in recent years (Li et al., 2008; Ruan et al., 2000), most previous studies have focused primarily on HM distribution and contamination in surface sediments (Luo et al., 2004; Li et al., 2010; Lin, 2012). Few have provided an integrated assessment across multiple environmental compartments, particularly simultaneous evaluations in seawater columns and marine biota. Moreover, there remains a limited understanding of the transport mechanisms and biogeochemical cycling of HMs within this ecosystem. These knowledge gaps highlight the need for a more holistic approach to HM pollution assessment in the region.

In response, this study presents a comprehensive evaluation of HM pollution in northeastern Fuqing Bay by examining three interlinked compartments: surface sediments, seawater, and marine organisms. The main objectives are: (1) to analyze the spatial distribution and variability of HMs across these media; (2) to identify and apportion potential contamination sources using multivariate statistical methods; (3) to assess ecological risks through established sediment and water quality indices; and (4) to provide a scientific foundation for designing targeted ecological restoration and pollution control strategies. By integrating multiple environmental matrices and applying advanced analytical techniques, this research aims to offer novel insights into the fate, transport, and impacts of HMs in Fuqing Bay, thereby addressing critical gaps in existing literature and supporting informed environmental management.

2 Materials and methods

2.1 Sample collection and analytical methods

In April 2022, 37 surface seawater samples, 22 surface sediment samples, and 4 marine organism samples were collected from northeastern Fuqing Bay (Figure 1). The procedures for collecting, preserving, and transporting these samples adhered to the guidelines outlined in the "Specifications for Marine Surveys" (GB/T12763-2007).

2.1.1 Seawater sampling and pretreatment

Surface seawater samples (~0.5 m depth) were collected using a plexiglass water sampler. Prior to storage, sample bottles were rinsed twice with the sampled seawater to minimize contamination. Polyethylene bottles were used to preserve Zn, Cu, Cr, Cd, Pb, and As samples, whereas Hg samples were stored in pre-cleaned glass bottles. All samples were immediately stored under dark, chilled conditions during transportation.

For stabilization, 2 mL of HNO_3 (ultrapure grade) was added to samples designated for Zn, Cu, Cr, Cd, and Pb analysis, whereas 2 mL of H_2SO_4 was used for As and Hg preservation. Filtration was performed using 0.45 μm glass fiber membranes to remove particulate matter. Digestion involved adding 10 mL HNO_3 to 500 mL seawater, followed by heating on an electric hotplate until concentrated to ~10 mL. The digestate was diluted to 25 mL with 1% HNO_3 and homogenized prior to instrumental analysis. Procedural blanks and certified reference materials were processed simultaneously to ensure quality. The accuracy and repeatability of the analytical procedures were verified through elemental recovery rates, which fell within the acceptable range of 90% to 110% for all measured elements. To evaluate reproducibility, 10% of the samples were analyzed in three replicates, yielding relative standard deviations (RSD) between 0.05% and 2.5% for the determined heavy metal concentrations.

2.1.2 Sediment sampling and pretreatment

Surface sediments were obtained using a grab sampler, and approximately 200 g of surface mud was collected using a

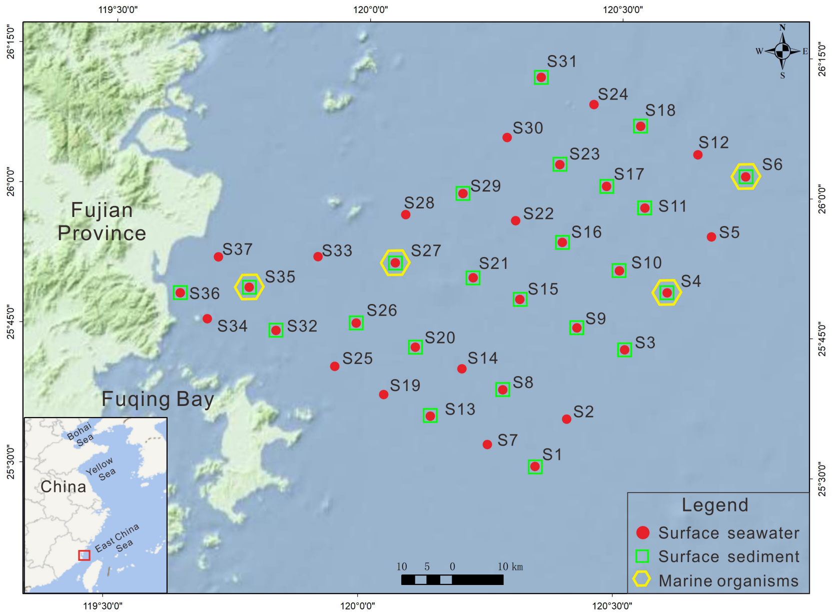

FIGURE 1
Geographical locations and the sampling stations in northeastern Fuqing Bay.

polyethylene spoon. Samples were sealed in polyethylene bags, stored in the dark, and refrigerated until laboratory processing. Freeze-drying was conducted for 40 h to eliminate moisture, followed by manual homogenization using an agate mortar. The dried sediment was sieved through a 160-mesh nylon screen to ensure a uniform 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 vessels.

2.1.3 Biological sample collection and processing

Marine organisms were collected using a single-vessel trawl net (40 × 94 m/49.3 m) with wing and cod-end configuration. Sampling was conducted during daylight, accounting for variables such as vessel speed (3–4 knots), current direction, and wind conditions. Trawling was performed 2–4 nautical miles from the designated stations to ensure representative sampling.

Organisms were taxonomically identified, and biometric data (length and mass) were recorded. The samples were categorized into crustaceans (*Parapenaeopsis hardwickii* and *Metapenaeus joyneri*) and fish (*Cynoglossus abbreviates* and *Collichthys lucidus*). Muscle tissues from the pectoral fins (fish) and abdominal segments (crustaceans) were excised, rinsed with ultrapure water, and stored in pre-weighed 10 mL centrifuge tubes at –20°C.

Digestion followed the HY/T132–2010 protocols, where 0.1 g of tissue was treated with 9 mL HNO_{33} and 3 mL H_2O_2 in a microwave-assisted digestion system.

2.1.4 Instrumental analysis and quality control

Cu, Pb, Zn, and Cd in seawater were quantified using graphite furnace atomic absorption spectrometry. The sediment and biological samples were analyzed similarly, except for Zn, which was determined using flame atomic absorption spectrometry. A Varian 240 FS AAS (USA) was used for the measurements. As and Hg were detected using an XGY-1011A atomic fluorescence spectrometer.

Method validation included reagent blanks, duplicate samples, and certified reference materials, with recovery rates of 90–110%. Precision was assessed via triplicate analysis (10% of samples), yielding relative standard deviations of 0.05–2.5%, confirming method reproducibility.

2.2 Analytical assessments

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

The I_{geo} was first proposed by Muller in 1969 and was determined using the following formula (Equation 1):

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

where C_i represents the HM concentration in the sediments and Bi denotes the background values from Fujian Province, China (Chen et al., 1992). The I_{geo} scale ranges from uncontaminated ($I_{geo} \leq 0$) to severely contaminated ($I_{geo} > 5$), as defined by Muller (1981).

The PLI, which was initially proposed by Tomlinson et al. (1980), is a comprehensive indicator of the integrated contamination status of multiple HMs. The calculation followed the following expression (Equations 2 and 3):

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: μg/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

$$CF_i = C_i/C_{0,} \quad (2)$$

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

where CF_i is the contamination coefficient of the i[th] metallic element, C_i is the measured concentration, and C_0 is the natural geochemical baseline concentration. According to the classification established by Chakravarty and Patgiri (2009), *PLI* values below 1 indicate uncontaminated conditions, whereas values exceeding 1 indicate varying degrees of pollution.

The *RI*, originally developed by Hakanson (1980), provides a quantitative framework for evaluating potential ecological hazards by incorporating metal-specific toxicity coefficients and regional background concentration. It is calculated as (Equation 4):

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

where C_r^i is the contamination factor for element i, calculated as the ratio of the measured concentration (C_f^i) to the background level (C_n^i). The parameter T_r^i represents the toxic response factor specific to each metal, with established values for common HMs, such as Zn (1), Cr (2), Cu, Pb (5), As (10), Cd (30), and Hg (40) (Hakanson, 1980). This index provides a cumulative assessment of the ecological risks from multiple metallic contaminants.

Individual metal risks (E_r^i) were classified into five progressive categories: minimal risk (<40), moderate (40-79), substantial (80-159), severe (160-319), and extreme (≥320). Similarly, the composite *RI* was categorized into four tiers: low (RI< 105), intermediate (105 ≤ RI< 210), significant (210 ≤ RI< 420), and very high (RI ≥ 420), as per the classification system updated by Xu et al. (2021).

For marine water quality assessment, Cf and WQI have been widely adopted (Küikrer and Mutlu, 2019) and were calculated as follows (Equations 5 and 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_f quantifies the pollution magnitude of individual metals, C_i is the analytical measurement, and C_s represents the regulatory limit of China's Seawater Quality Standard (GB 3097-1997). The variable n indicates the number of monitored elements. The interpretive framework correlating C_f and *WQI* values and contamination levels has been comprehensively documented in previous studies (Baltas et al., 2017; Macdonald et al., 1996), as summarized in Table 1.

P_i was implemented to evaluate HM bioaccumulation in marine organisms and was calculated using the following expression (Equation 7):

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

This index compares the measured tissue concentrations (C_i) against biological reference standards (S_i) derived from China's "Coastal and Marine Resource Comprehensive Survey Guidelines (Table 2)." Current evaluation protocols, as described by Zhou et al. (2022), consider P_i values below 1.0 as compliant with biological quality standards, whereas values above this threshold indicate excessive contamination.

BAF was employed to quantify HM transfer from environmental matrices to biota. Specifically, this study calculated two variants, *BWAF* and *BSAF*, which were determined as follows (Equations 8 and 9):

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

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

These metrics relate organismal metal concentrations (C_i) to their corresponding levels in seawater (C_w) and sedimentary compartments (C_s).

Spatial distribution patterns of the data were visualized through planar maps created with Surfer 23.0. Statistical evaluations, such as principal component analysis and Pearson correlation, were conducted using SPSS 27.0 (IBM Corp.). Preliminary data organization and descriptive statistics were carried out in Microsoft Excel 2016 (Microsoft Corp.).

The use of varimax rotation and the Kaiser criterion (eigenvalues >1) is a standard and widely accepted practice in environmental source apportionment studies using PCA. Varimax rotation was chosen because it maximizes the variances of the squared loadings within each factor, thereby enhancing the interpretability of the factors by making high loadings higher and low loadings lower for each component, which helps in clearer source identification.

3 Results and discussion

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

Surface sediment analysis in northeastern Fuqing Bay revealed the following HM concentration ranges (μg/g dry weight): Cu (14.6-31.8), Pb (19.1-40.9), Zn (32.6-77.9), Cr (17.4-39.2), Cd (0.08-0.43),

TABLE 3 Heavy metal concentrations in the surface sediments and surface seawater in northeast Fuqing Bay.

Heavy metals	Cu	Pb	Zn	Cr	Cd	As	Hg
Surface sediments (unit: µg/g)							
Range	14.6-31.8	19.1-40.9	32.6-77.9	17.4-39.2	0.08-0.43	5.4-11.5	0.009-0.122
Average	22.36	28.33	56.40	25.56	0.23	9.04	0.08
Variation coefficient/ %	22.91	22.71	26.04	18.66	43.59	18.89	47.09
MSQ-1	35	60	150	80	0.5	20	0.2
Surface seawaters (unit: µg/L)							
Range	0.03-0.69	0.01-0.22	0.15-2.13	0.025-0.277	0.001-0.011	0.013-0.193	0.001-0.033
Average	0.33	0.12	1.31	0.13	0.01	0.07	0.02
Variation coefficient/ %	44.87	43.25	42.63	41.85	41.41	46.38	50.92
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 northeastern Fuqing Bay.

Species	Value	Cu	Pb	Zn	Cr	Cd	As	Hg
All species	Range	0.3-2.7	0.51-1.56	4.4-13	0.1-0.4	0.01-0.05	0.15-0.9	0.01-0.02
	Average	1.35	0.88	7.48	0.22	0.03	0.49	0.01
Fish	S4 (*C. lucidus*)	0.3	0.9	13	0.4	0.02	0.9	0.02
	S6 (*C.abbreviatus*)	2.7	0.54	7.2	0.1	0.05	0.63	0.01
Crustaceans	S27 (*M. joyneri*)	0.6	1.56	4.4	0.26	0.05	0.15	0.01
	S35 (*P. hardwickii*)	1.8	0.51	5.3	0.1	0.01	0.26	0.01

As (5.4-11.5), and Hg (0.009-0.122), with corresponding mean values of 22.36, 28.33, 56.40, 25.56, 0.23, 9.04, and 0.08 µg/g (Table 3), respectively. All the measured concentrations complied with the Class I standards specified in China's Marine Sediment Quality (GB 18668-2002) (Administration of quality supervision, inspection and quarantine of the People's Republic of China (AQSIQ), 2002).

Variation coefficients were calculated to assess the anthropogenic influence on metal distribution. The metals exhibited the following order of variability: Hg (47.09%) > Cd (43.59%) > Zn > Cu > Pb > As > Cr (18.66-26.04%). Notably, Hg and Cd demonstrated substantial variation (exceeding 35%), suggesting significant external influences and a heterogeneous spatial distribution. The other elements showed moderate variability, indicating relatively uniform distribution patterns across the sampling sites.

In the water column, dissolved metal concentrations (µg/L) ranged as follows: Cu (0.03–0.69), Pb (0.01–0.22), Zn (0.15–2.13), Cr (0.025–0.277), Cd (0.001–0.011), As (0.013–0.193), and Hg (0.001–0.033), with mean values of 0.33, 0.12, 1.31, 0.13, 0.01, 0.07, and 0.02 µg/L respectively. All measurements satisfied Class I seawater quality criteria (GB 3097–1997).

Biological samples exhibited species-specific metal accumulation patterns (µg/g wet weight): Cu (0.3–2.7), Pb (0.51–1.56), Zn (4.4–13), Cr (0.1–0.4), Cd (0.01–0.05), As (0.15–0.9), and Hg (0.01–0.02), with mean concentrations of 1.35, 0.88, 7.48, 0.22, 0.03, 0.49, and 0.01 respectively (Table 4). Maximum concentrations of Zn, Cr, As, and Hg were found in *C. lucidus*, whereas *C. abbreviatus* accumulated the highest Cu and Cd levels. *M. joyneri* showed the highest Pb and Cd concentrations in crustaceans, whereas *P. hardwickii* showed minimal accumulation of Pb, Cr, and Cd.

The spatial patterns of HMs in the surface sediments from northeastern Fuqing Bay are shown in Figure 2. High concentrations of Cu, Zn, Cd, and As were observed in the central region, in contrast to the lower levels of Pb, Cr, and Hg in the same area. Notably, higher accumulations of Zn, Cr, and As were detected near Changle City, likely attributable to anthropogenic influences.

Figure 3 illustrates the spatial variability of dissolved HMs in surface waters across the study area. The distributions of Pb, Zn, and Cd exhibited similar trends, with peak concentrations clustered in the central zone. Cu, Cr, As, and Hg also displayed elevated levels at mid-region stations, although their distributions were more spatially dispersed.

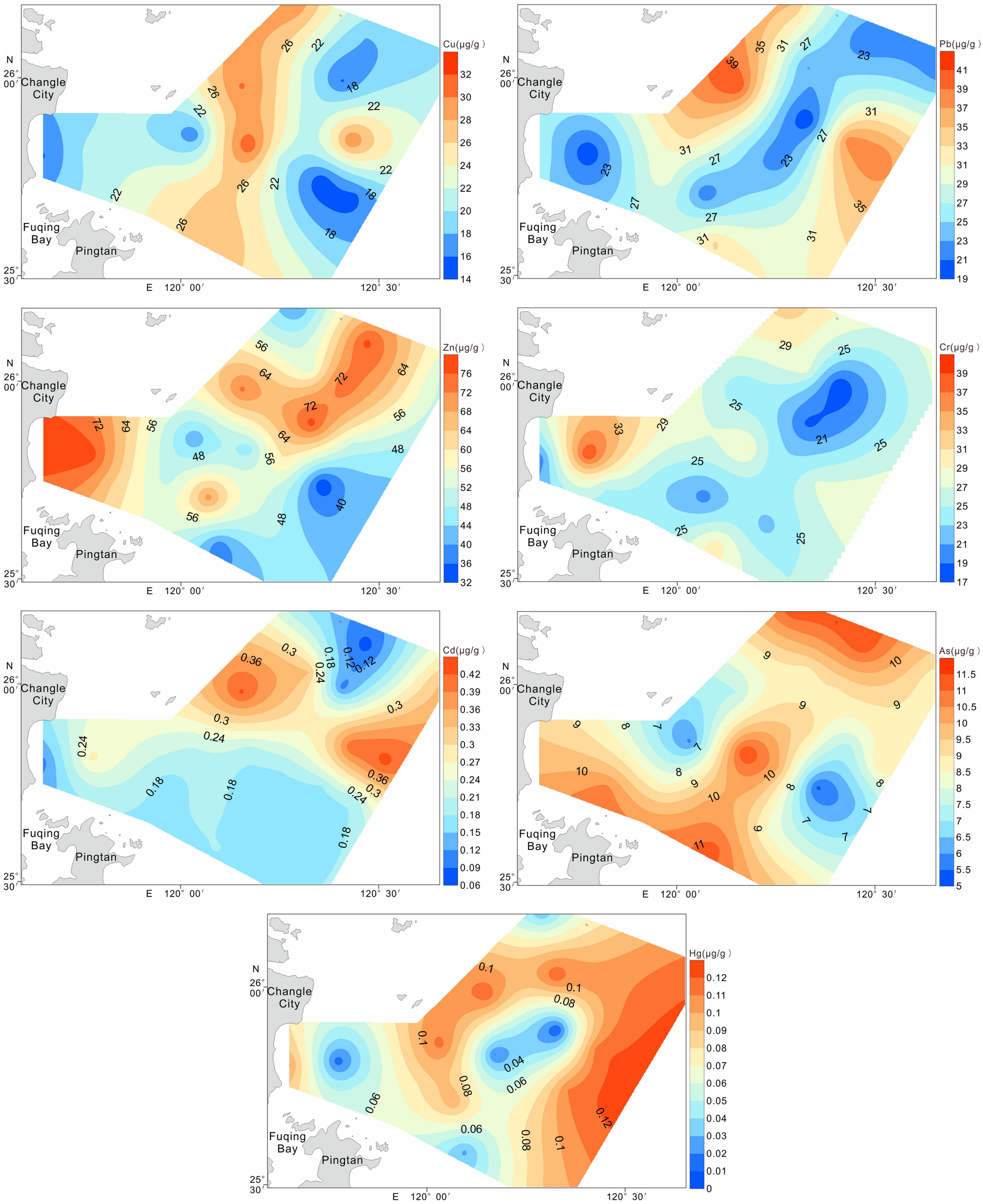

FIGURE 2
Spatial distributions of seven heavy metals in the surface sediments.

3.2 Assessment of sediment pollution using ecological risk indices

The mean and range of the I_{geo} values for the seven HMs in the sediments in northeast Fuqing Bay are presented in Table 5. The mean degree of contamination was the highest for Cd, followed by As, Cu, Hg, Pb, Zn, and Cr. The I_{geo} values of Cd, As, and Hg were greater than zero in 95.5%, 63.6%, and 4.5% of the samples, respectively (Figure 4). More than half of the sediments in the middle of the study area were slightly contaminated (0–1) by As. Evidently, the majority of the area was slightly to strongly contaminated (0–3) by Cd (Muller, 1981).

The *PLI* analysis revealed considerable spatial variation across the study area, with values ranging from 0.03 to 1.73 (mean = 0.35) at the 22 sampling stations (Table 5). Spatial mapping (Figure 5) identified three northern stations (S4, S11, and S29) with *PLI* values > 1,

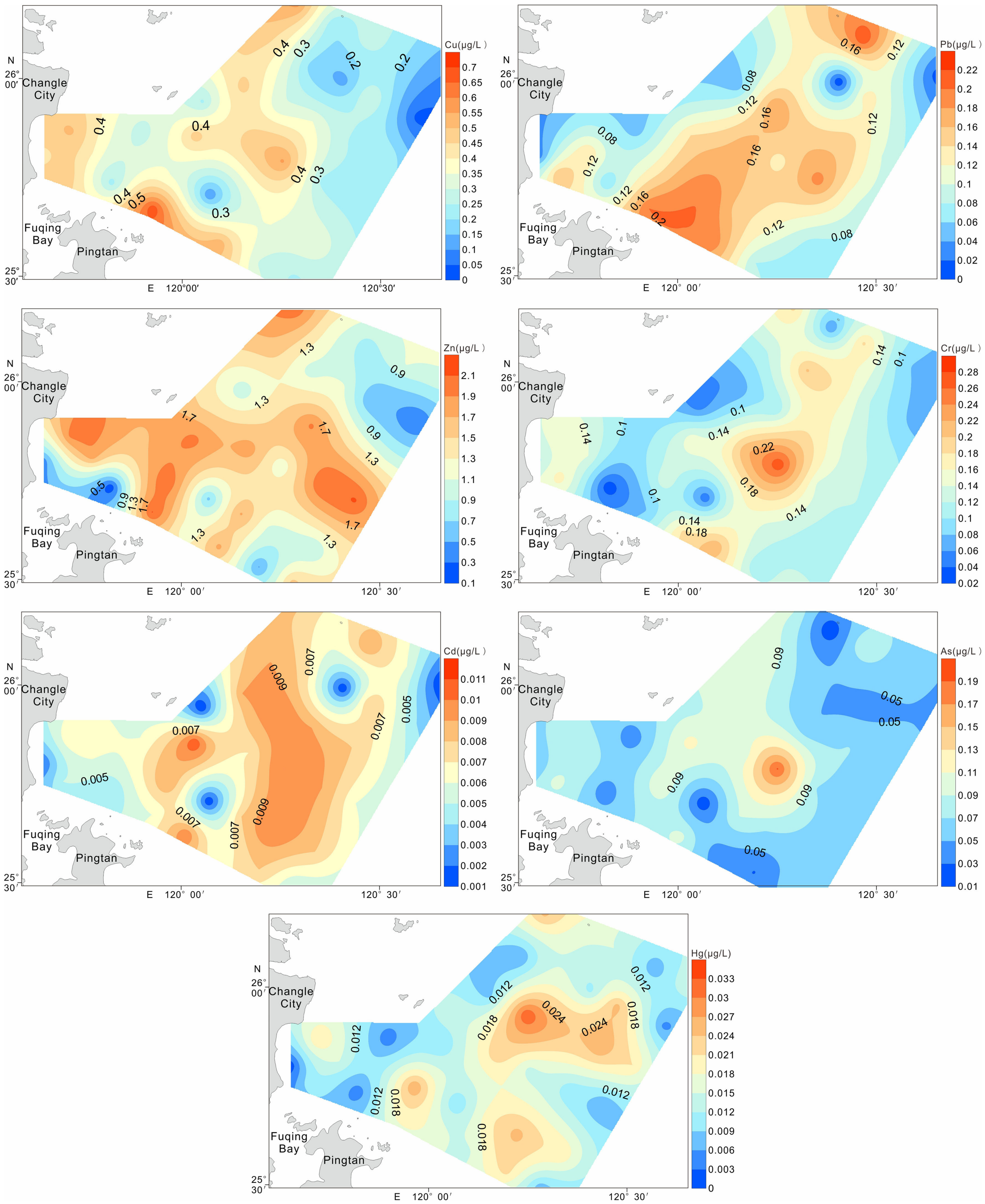

FIGURE 3
Spatial distributions of seven heavy metals in the surface seawaters.

suggesting a significant anthropogenic influence on HM accumulation at these locations.

The ecological risk assessment demonstrated distinct patterns among the measured metals. The risk coefficients followed the order: Cd (highest) > Hg > As > Cu > Pb > Cr > Zn (lowest) (Table 5). While most metals exhibited low ecological risk (average E_r^i< 40), Cd showed moderate–high risk potential (E_r^i range: 42.22-239.44). Hg is of particular concern, with 59.1% of the stations showing moderate ecological risk despite relatively low concentrations, reflecting its exceptionally high toxicity (Tam and Wong, 2000).

The *RI* values ranged from118.77 to 328.1 (mean = 193.12), indicating a moderate ecological risk across the study area (Table 5). Five stations in the eastern and western sectors exceeded *RI* value of

TABLE 5 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 northeast Fuqing Bay.

Parameters		Cu	Pb	Zn	Cr	Cd	As	Hg
Surface sediments								
$M_{background}$[a](μg/g)		21.6	34.9	82.7	41.3	0.054	5.78	0.081
I_{geo}	Range	-1.15 to -0.03	-1.45 to -0.36	-1.93 to -0.67	-1.83 to -0.66	-0.09-2.41	-0.68-0.41	-3.75-0.01
	Average	-0.57	-0.92	-1.19	-1.30	1.35	0.03	-0.88
E_r^i	Range	3.38-7.36	2.74-5.86	0.39-0.94	0.84-1.9	42.22-239.44	9.34-19.9	4.44-60.25
	Average	5.18	4.06	0.68	1.24	126.36	15.64	39.96
RI (average)		118.77-328.10 (193.12)						
Contributions to *RI*		2.68%	2.10%	0.35%	0.64%	65.43%	8.10%	20.69%
PLI (average)		0.03-1.73 (0.35)						
Surface seawaters								
C_f	Range	0.006-0.14	0-0.22	0.01-0.11	0.001-0.006	0-0.01	0-0.01	0.02-0.66
	Average	0.07	0.12	0.07	0.003	0.01	0.004	0.31
WQI (average)		0.02-0.14 (0.108)						
E_r^i	Range	0.03-0.69	0-1.1	0.01-0.11	0-0.01	0.03-0.33	0.01-0.1	0.8-26
	Average	0.33	0.60	0.07	0.01	0.20	0.04	12.28
RI (average)		1.49-28.03 (13.52)						
Contributions to *RI*		2.45%	4.42%	0.49%	0.04%	1.48%	0.26%	90.87 %

[a]Background values of heavy metals are the elemental baseline in the soil of Fujian, China (Chen et al., 1992).

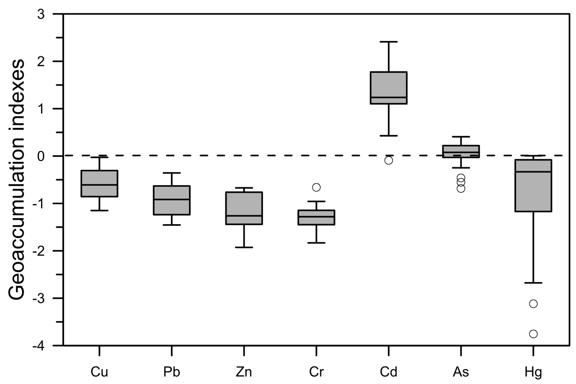

FIGURE 4
The I_{geo} of seven heavy metals in the sediments in northeast Fuqing Bay.

210, reaching the significant risk category (Figure 6). Source apportionment analysis identified Cd (65.43%) and Hg (20.69%) as the primary risk contributors (Table 5), highlighting their disproportionate ecological impact relative to their concentration levels (Di Bella et al., 2024). This phenomenon reflects the enhanced biological toxicity of these elements compared with that of the other measured metals. The *RI* values in Luoyuan Bay in northern eastern coast of Fujian Province ranged from 43.96 to 182.73, with mean level of 68 (Fan et al., 2022), which were lower than those in study area.

3.3 Assessment of HM contamination in surface waters

The C_f analysis revealed the following HM concentration ranges in the surface waters of northeastern Fuqing Bay: Cu (0.006–0.14), Pb (0–0.22), Zn (0.01–0.11), Cr (0.001–0.006), Cd (0–0.01), As (0–0.01), and Hg (0.02–0.66). The corresponding mean values were 0.07, 0.12, 0.07, 0.003, 0.01, 0.004, and 0.31, respectively (Table 5). *WQI* values across sampling stations varied between 0.02 and 0.14, consistently below the threshold value of 1. This demonstrated compliance with Class I seawater quality standards for all monitored HMs throughout the study period, reflecting good water quality conditions (Ramadan et al., 2021).

The ecological risk assessment results followed the order of single-element potential ecological risk coefficients as follows: Hg > Pd > Cu > Cd > Zn > As > Cr (Table 5). All individual risk coefficients remained below 40 at every sampling location, suggesting minimal ecological concern. The comprehensive potential ecological risk index (*RI*) values ranged from 1.49 to 28.03 (mean = 13.52, Table 5 and Figure 6), confirming an overall low ecological risk status in the study area (Küikrer and Mutlu, 2019).

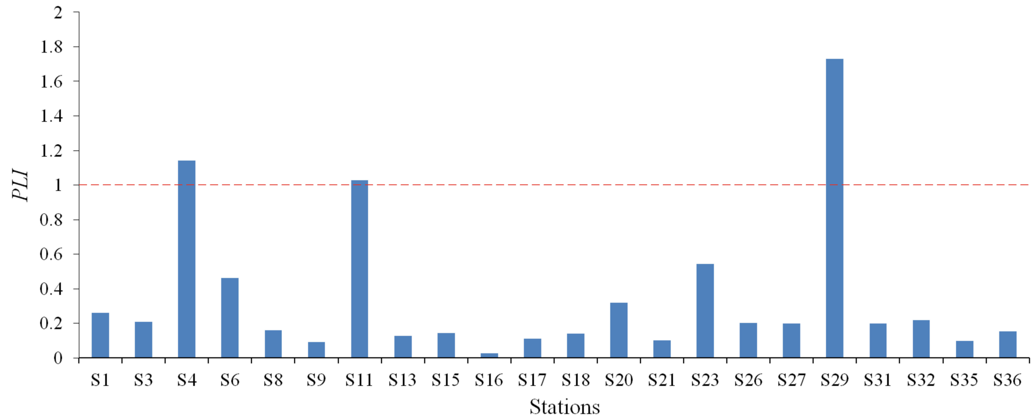

FIGURE 5
Spatial distribution of pollution load index (*PLI*) for heavy metals in surface sediments.

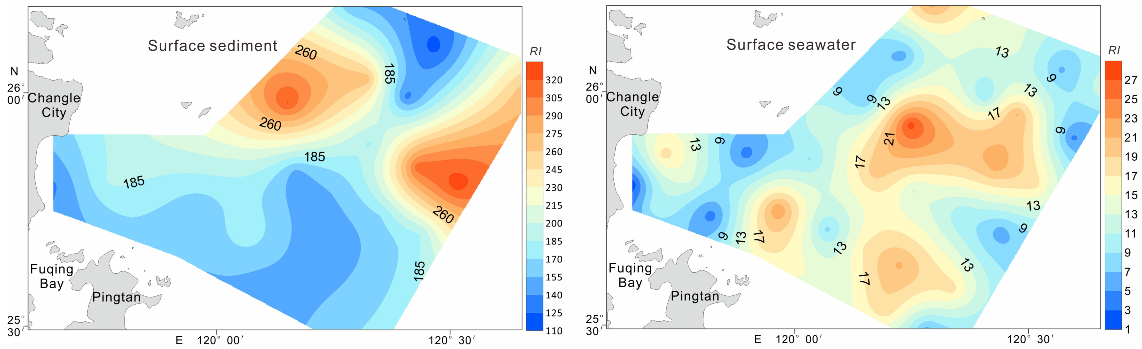

FIGURE 6
Spatial distributions of *RI* values in the surface sediment and surface seawater.

3.4 Accumulation of HMs in organisms

Statistical analysis revealed distinct distribution patterns of HM concentrations in the two marine organism groups in northeastern Fuqing Bay. The descending order of metal concentrations in fish was Cr > Hg > Pb > Cu > Cd > Zn > As, with crustaceans also showing a similar pattern. Notably, elevated levels of Cr and Hg in both groups suggest potential environmental contamination. When evaluated against the biological quality criteria established in China's Coastal Zone and Marine Resource Comprehensive Survey Guidelines, the standardized indices presented in Table 6 demonstrate that Cr concentrations exceeded the permissible limits at four sampling locations. Among the measured metals, Cr exhibited the highest standardized indices in both fish (6.74) and crustaceans (3.23). Other HMs remained within the acceptable thresholds according to the national standards. Cr, particularly in its hexavalent form (Cr(VI)), is highly toxic to aquatic organisms. Studies have indicated that chromium exposure can induce various adverse physiological effects in aquatic invertebrates and fish, including but not limited to: triggering oxidative stress, causing damage to tissues such as gills and hepatopancreas, inhibiting growth and development, and impairing immune and reproductive functions.

The bioaccumulation potential was assessed using two key indicators: *BWAF* and *BSAF*. Values exceeding unity for *BSAF* signify significant metal accumulation capacity, whereas *BWAF* > 1 indicates pronounced bioaccumulation in aqueous environments. As shown in Table 7, all *BSAF* measurements remained below 1, suggesting limited HM uptake from sedimentary sources (Dean et al., 2007). This finding contrasts with the aqueous bioaccumulation pattern, where despite generally low dissolved metal concentrations in seawater, most *BWAF* values exceeded 1 (excluding Cr at S35 and Hg at S4/S6). This demonstrates the efficient biological concentration of metals from the aqueous phase through trophic transfer, which is consistent with the findings of previous studies (Harada, 2016; Hoai et al., 2020; Islam and Tanaka, 2004). The observed differential accumulation patterns between the sedimentary and aqueous sources highlight the complex dynamics of metal transfer in marine ecosystems.

TABLE 6 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	4	Range	0.01-0.14	0.08-0.45	0.003-0.02	2.93-8.67	0.01-0.08	0.001-0.004	0.33-1.33
		Average	0.05	0.25	0.01	4.98	0.04	0.002	0.87
Crustaceans	2	Range	0.01-0.02	0.08-0.13	0.003-0.01	2.93-3.53	0.01-0.03	0.001-0.001	0.5-1.3
		Average	0.02	0.11	0.01	3.23	0.02	0.001	0.90
Fish	2	Range	0.02-0.14	0.32-0.45	0.01-0.02	4.8-8.67	0.03-0.08	0.002-0.004	0.33-1.33
		Average	0.08	0.39	0.02	6.74	0.06	0.003	0.83

TABLE 7 *BAF* of heavy metals in northeast Fuqing Bay.

Species	Station	*BSAF*							*BWAF*						
		Cu	Pb	Zn	Cr	Cd	As	Hg	Cu	Pb	Zn	Cr	Cd	As	Hg
Fish	S4	0.01	0.024	0.28	0.015	0.05	0.1	0.16	1.25	5.00	6.25	3.54	3.33	1.55	0.95
	S6	0.13	0.024	0.14	0.004	0.15	0.07	0.08	1.50	5.40	6.92	1.45	5.00	1.26	0.67
Crustaceans	S27	0.04	0.046	0.11	0.01	0.23	0.03	0.09	1.25	4.00	2.24	1.70	4.55	1.28	1.11
	S35	0.09	0.027	0.07	0.003	0.04	0.03	0.71	4.19	1.70	5.89	0.85	5.00	5.10	1.01

3.5 Source identification of HMs

To identify the potential HM sources in the environment, PCA was performed using SPSS software. For surface sediments, three principal components (PCs) with eigenvalues >1 were extracted, which collectively explained 77.94% of the total variance (Table 8), thereby capturing most of the variability in the dataset (Waykar and Petare, 2016).

PC1 accounted for 34.29% of the variance and exhibited strong loadings for Pb (0.81), Cd (0.56), and Hg (0.70), thereby implying a shared origin for these elements. The spatial distribution of Cd indicates slight to moderate contamination (0–3) across most of the study area (Table 5 and Figure 6). Potential anthropogenic sources include industrial effluents from chemical plants that often discharge wastewater containing Cd and Hg into rivers and coastal waters. Additionally, port operations, machinery maintenance, and related industrial activities generate metal-laden dust and wastewater, and Pb is a notable contaminant in these maintenance processes.

PC2 explained 27.03% of the variance, and was dominated by Cu (0.83), Cr (0.60), and As (0.43). These metals may originate from the natural weathering of local geological formations, such as granite and basalt, which release Cu, Cr, and Zn into aquatic systems via surface runoff and atmospheric deposition. Furthermore, metal smelting activities in Fuqing contribute to Cu and Zn emissions from industrial wastewater and airborne particulates.

PC3 contributed 16.62% of the variance with notable loadings for Zn (0.57) and Cd (0.52). Agricultural runoff is another plausible source, as pesticides (containing As) and fertilizers (containing Zn) can be introduced into marine sediments via rainwater erosion and riverine transport.

For surface seawater in northeastern Fuqing Bay, two principal components were extracted, which explained 62.79% of the total variance (Table 8).

PC1 (46.5% variance) showed high positive loadings (>0.7) for Cu, Cr, Cd, and As, suggesting a natural origin because their concentrations remained below background levels and showed minimal anthropogenic influence. However, Pb, Zn, and Hg also exhibited moderate loadings on PC1, indicating partial contributions from these components.

TABLE 8 Extracted three principal components in surface sediments and two principal components for surface seawater.

Parameter	Surface sediments			Surface seawaters	
	PC1	PC2	PC3	PC1	PC2
Cu	0.05	0.83	0.45	0.74	-0.36
Pb	0.81	0.30	0.07	0.58	0.53
Zn	-0.57	-0.38	0.57	0.60	0.05
Cr	0.03	0.60	-0.57	0.79	-0.16
Cd	0.56	0.35	0.52	0.77	0.12
As	-0.78	0.43	0.14	0.72	-0.51
Hg	0.70	-0.54	0.14	0.52	0.65
Eigenvalues	2.4	1.89	1.16	3.26	1.14
Percentage of variance	34.29	27.03	16.62	46.5	16.29
Cumulative % eigenvector	34.29	61.32	77.94	46.5	62.79

PC2 (21.44% variance) was strongly associated with Pb (0.53) and Hg (0.65), likely reflecting anthropogenic input. Domestic wastewater, particularly that from urban and rural sewage systems, often contains Hg (from cosmetics, batteries, and electronic waste) and Pb (from industrial and household sources). Inadequate wastewater treatment may lead to the discharge of residual HMs into coastal waters, ultimately accumulating in sediments.

While PCA provides valuable insights into potential pollution sources, several limitations should be considered. Firstly, the results are dependent on the initial selection of variables and data normalization techniques. Secondly, the extracted factors require subjective interpretation based on loading patterns and ancillary knowledge of the study area, which introduces an element of expert judgment. Furthermore, PCA assumes linear relationships among variables and may not fully capture complex interactions or minor sources. Lastly, unlike absolute receptor models, PCA does not directly quantify the mass contribution from each identified source. Therefore, the findings presented here should be viewed as a preliminary identification of major source categories rather than an exact quantification of their contributions.

4 Conclusion

This study focused on the evaluation of surface sediments, seawater, and HMs in organisms in northeastern Fuqing Bay, Fujian Province. Results revealed that the concentrations of HMs in surface sediments and seawater in the area were consistent with the relevant standard classes. However, spatial variations in the distributions of certain HMs were also observed. In the sediments, Cd, As, and Hg were present in some samples, posing potential moderate ecological risk primarily due to Cd and Hg. The ecological risk posed by seawater was determined to be low, with fairly uncontaminated water quality. Regarding marine organisms, Cr levels exceeded the standard at some stations, and organisms exhibited a significant enrichment capacity for most HMs in seawater. PCA indicated wastewater discharge from chemical enterprises, port operations, rock weathering, metal smelting, and agricultural activities as the principal sources of HMs in the sediments. Notably, a proportion of the HMs detected in seawater has a natural origin, whereas others are attributable to anthropogenic activities, including urban and rural domestic sewage discharge. This study provides a fundamental foundation for research on regional ecological environments. To effectively mitigate the identified pollution, future efforts should translate these findings into concrete actions. For key anthropogenic sources identified by PCA, such as chemical industries and ports, we recommend implementing technology-based effluent standards that mandate the installation of advanced wastewater treatment systems (e.g., electrocoagulation, membrane filtration) and establishing a real-time online monitoring network for their discharges to ensure continuous compliance.

Regarding agricultural non-point source pollution, the promotion of Best Management Practices (BMPs) is essential, including precision farming to reduce pesticide and fertilizer use, the construction of riparian buffer zones to intercept runoff, and incentives for adopting organic alternatives.

Furthermore, policy makers should consider enacting stricter discharge limits for heavy metals, imposing stronger penalties for violations, and incorporating heavy metal pollution control metrics into the environmental performance assessments of local authorities. Continued monitoring, coupled with these targeted regulatory and management measures, will provide essential scientific support for the effective restoration and protection of the ecological environment in Fuqing Bay.

Data availability statement

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

Author contributions

EW: Conceptualization, Formal Analysis, Funding acquisition, Writing – original draft. YY: Investigation, Project administration, Writing – original draft. YS: Software, Supervision, Writing – original draft. JW: Resources, Visualization, Writing – original draft. XC: Methodology, Project administration, Writing – original draft. JY: Data curation, Formal Analysis, Writing – original draft. JQW: Investigation, Validation, Writing – original draft. CD: Data curation, Resources, Writing – original draft. JQ: Conceptualization, Formal Analysis, Methodology, Writing – original draft. ZW: Methodology, Resources, Writing – original draft.

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Author YY was employed by the company Fuzhou Haixia Electricity Generation Co., Ltd.

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