

Multi-Index Geochemical Evaluation of Cd, Pb, Cu, and Zn in Ketugar Island Marine Conservation Area, Indonesia

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Abstract

Ketugar Island, a coral reef conservation area on the eastern coast of Bangka Island, is potentially exposed to sedimentation and heavy metal inputs from tin mining. This research aims to evaluate the contamination levels and potential ecological risks associated with heavy metals in the sediments of the waters surrounding Ketugar Island. Heavy metal concentrations (Cd 0.09–0.16 mg/kg, Pb 0.80–3.04 mg/kg, Cu 0.07–0.10 mg/kg, and Zn 1.37–1.94 mg/kg) in surface sediments around Ketugar Island remain below the ANZECC/ARMCANZ SQGV thresholds, this is confirmed by SQG-Q, CF, Igeo, PLI, and RI indices, all of which indicate unpolluted conditions or low risk. This status is attributed to limited anthropogenic input of tin tailings due to the distance from the source and strong hydrodynamic dispersion in the open waters. Variations in sediment grain size with fine fractions dominating low energy stations on the southeastern side (KT-1, KT-2) and coarse fractions dominating the northwestern side exposed to strong monsoon currents (KT-3, KT-4) govern the distribution of organic matter. This is reflected in higher TOC content and C/N ratios in the fine fractions, resulting from terrestrial input from the Kurau River mangrove ecosystem. However, this pattern does not fully apply to heavy metal distribution, only Pb consistently follows the grain-size pattern, suggesting the influence of other factors such as local inputs and the hydrodynamic sorting of metal-bearing particles.

Keywords: Grain Size, Organic Matter, Heavy Metals, Ketugar Island

INTRODUCTION

Heavy metal contamination in sediments and aquatic ecosystems has emerged as a global environmental issue posing a serious threat in recent years (X. Liu *et al.*, 2023; Z. Wu *et al.*, 2023). Heavy metal concentrations in sediments reflect the overall environmental health of aquatic systems (Nugraha *et al.*, 2022). These metals may originate from geogenic processes (physical and chemical weathering of parent rock) or anthropogenic activities (N. *et al.*, 2018), such as industrial waste, motor vehicle emissions, fertilizer use, and mining operations. Compared to typical environmental pollutants, heavy metals possess unique characteristics, including toxicity, resistance to biodegradation (non-biodegradability), and the capacity to accumulate in organism tissues (bioaccumulation) (Huang *et al.*, 2018). Although some metals are biologically essential elements, exposure to concentrations exceeding threshold limits can cause toxic effects on aquatic biota. Extensive studies on metal contamination and potential ecological risks have been conducted worldwide, covering ecosystems such as lakes including Hussain Sagar Lake (India) (Ayyanar & Thatikonda, 2020), Bafa Lake (Turkey) (Algül & Beyhan, 2020), and Ozomu Lake (Southern Nigeria) (Olomukoro & Enabulele, 2024); rivers such as the Kelantan River (Malaysia) (A. jun Wang *et al.*, 2017), Tajan River (Iran) (Alahabadi & Malvandi, 2018), and Mangonbangon River (Philippines) (Decena *et al.*, 2018); estuarine regions such as the Densu Estuary, Ghana (Akita *et al.*, 2020), the Yellow River Estuary, China (Z. Wang *et al.*, 2022), and the Karnaphuli River Estuary, Bangladesh (Hossain *et al.*, 2022); as well as coastal and marine areas ranging from the Southern Corniche of Jeddah, Saudi Arabia (Bantan *et al.*, 2020), and Yueqing Bay, China (Yao *et al.*, 2021), to the northern Barents Sea and the Arctic Basin (Kohler *et al.*, 2022).

The Bangka Belitung Islands possess high marine biodiversity and constitute Indonesia's largest tin-producing region (Syari *et al.*, 2022), forming part of the Southeast Asia Granite Tin Belt (Cobbing *et al.*, 1986; Sampurno *et al.*, 2017). The presence of these tin reserves has established the tin mining

sector alongside agriculture as a primary livelihood within the local economy, with mining and extraction activities having taken place both onshore and offshore for a long period (Swastiwi *et al.*, 2017). Anthropogenic inputs from these mining activities drive increased sedimentation rates and the release of tailings containing carcinogenic and toxic heavy metals, thereby posing a threat to biota and environmental health (Bastami *et al.*, 2018; Irvani & Pitulima, 2016). Sedimentation modeling for Bangka Island resulting from tin mining activities (Pamungkas & Husrin, 2020) indicates the dispersal of sediment along the island's eastern coast. In terms of hydrological dynamics, sediment plays a crucial role as a carrier and sink for heavy metals (Antony *et al.*, 2022) which are associated with particulate matter or suspended solids and undergoes transport and deposition processes governed by hydrodynamic factors such as currents, waves, and tides (Z. Wu *et al.*, 2023).

Ketugar Island is a small island located off the eastern coast of Bangka Island; it has been designated as a marine park conservation area (Decree of the Minister of Marine Affairs and Fisheries of the Republic of Indonesia Number 108, 2023). Its waters feature a coral reef ecosystem with unique natural characteristics and significant potential for the development of small-scale capture fisheries and sustainable tourism. The waters surrounding Ketugar Island fall within a limited-use zone where spatial usage has been agreed upon by various stakeholders and serve vital social, economic, and cultural functions for the local community. However, the distribution of sedimentation carrying accumulated heavy metals poses a potential threat to the sustainability of the coral reef ecosystem in the area. To date, research on heavy metal contamination in sediments has focused primarily on the waters of the main island (Bangka Island), covering locations such as the inner and outer Kelabat Bay (Puspitasari & Hindarti, 2009), inner Kelabat Bay (Komalasari *et al.*, 2019), outer Kelabat Bay (Tawa *et al.*, 2019), the Tanah Merah coast (Irvani *et al.*, 2021), Matras Beach (Nugraha *et al.*, 2022), Sampur Beach (Sastra *et al.*, 2023), and the Baturusa Estuary (Nugraha *et al.*, 2023). Conversely, studies concerning the waters of small islands remain very limited, covering only areas such as Putri Island (Nugraha *et al.*, 2021). The scarcity of data regarding metal contamination in the waters of small islands within the Bangka Belitung Islands Province specifically the waters of Ketugar Island serve as the primary basis for this study. This research aims to evaluate the contamination levels and potential ecological risks associated with heavy metals in the sediments of the waters surrounding Ketugar Island, Central Bangka Regency, Bangka Belitung Islands Province, Indonesia. A comprehensive evaluation was conducted using the Sediment Quality Guideline Quotient (SQG-Q), Contamination Factor (CF), Geo-accumulation Index (I_{geo}), Pollution Load Index (PLI), and Ecological Risk Index (RI). This assessment is expected to serve as an effective tool for understanding heavy metal deposition dynamics in sediments, thereby supporting sustainable aquatic conservation management for small islands.

MATERIALS AND METHODS

Sediment sampling was conducted in May 2022. The study was conducted in the waters of Ketugar Island, Central Bangka Regency, Bangka Belitung Islands Province. The surface sediment samples used in this study consisted of four stations (Figure 1). Stations KT-1 and KT-2 are located in the southern and eastern parts, while KT-3 and KT-4 are located in the northern and western parts of Ketugar Island. Surface sediment samples ($\pm 0-10$ cm) were collected using a grab tool. The surface sediment samples collected in the grab were then placed in polyethylene plastic containers and stored in a cold box filled with ice cubes. In the laboratory, surface sediment samples were stored at -20°C (Alahabadi & Malvandi, 2018; Elias *et al.*, 2018; Nugraha *et al.*, 2023).

Sediment grain size was analyzed using the sieve method (for coarse particles, namely sand) and the pipette method (for fine particles, namely silt and clay) (Badawi *et al.*, 2022; Dewanti *et al.*, 2016; Mohtar *et al.*, 2017; Surjono & Amijaya, 2017). TOC (Total Organic Carbon) of sediment was analyzed using the Walkley Black method (Gelman *et al.*, 2012). TN (Total Nitrogen) of sediment was tested using the Kjeldahl method (Indonesian National Standard (SNI) 4146:2013, 2013). For heavy

metal tests, Cd, Pb, Cu, and Zn used the Atomic Absorption Spectrophotometer/AAS method (Indonesian National Standard (SNI) 8910:2021, 2021).

The obtained sediment grain size values were classified based on the Wentworth classification. The grain size percentage was divided into three groups: $>63 \mu\text{m}$ / $<4 \phi$ (sand), $4-63 \mu\text{m}$ / $4-8 \phi$ (silt), and $<4 \mu\text{m}$ / $>8 \phi$ (clay) (M. sheng Gao *et al.*, 2020). The obtained sediment TOC and TN concentrations will be classified into two categories: values $>0.2\%$ are considered high, while values $<0.2\%$ are considered low (Silva *et al.*, 2011). The TOC-to-TN (C/N) ratio is used to assess whether the organic matter input is of terrestrial or aquatic origin. A C/N ratio between 4 and 10 indicates an aquatic source, a ratio >15 indicates terrestrial input, and a ratio between 10 and 15 indicates a mixed aquatic and terrestrial source (Abu-Zied *et al.*, 2024; Meyers, 1994).

To assess the level of contamination, pollution, and ecological risk of the heavy metals Cd, Pb, Cu, and Zn, the mean Sediment Quality Guideline Quotient (SQG-Q), Contamination Factor (CF), Pollution Load Index (PLI), Geoaccumulation Index (I-Geo), and Potential Ecological Risk Index (RI) will be used. SQG is very useful for screening sediment contamination by comparing sediment contaminant concentrations with appropriate sediment quality guidelines (Caeiro *et al.*, 2005). SQG can also reflect ecological effects or risks to aquatic environments (J. Wang *et al.*, 2022). The formula used to calculate SQG-Q is as follows.

$$\text{SQG-Q} = \frac{\sum_{i=1}^n \text{PEL-Q}_i}{n}$$

$$\text{PEL-Q} = \frac{\text{contaminant}}{\text{PEL}}$$

PEL-Q is the quotient of the level of possible effects; PEL is the probable effect level for each contaminant. The PEL values (mg/kg) used for the heavy metals Cd, Pb, Cu, and Zn are 4.21; 112; 108; and 271. The impact levels of the SQG-Q value criteria are $\text{SQG-Q} \leq 0.1$ (unimpacted): the lowest potential for adverse biological effects; $0.1 < \text{SQG-Q} < 1$ (moderate impact): moderate potential for possible adverse biological effects; and $\text{SQG-Q} \geq 1$ (highly impacted): high potential for adverse biological effects.

The contamination factor is used to assess the level of anthropogenic heavy metal contamination and is calculated by measuring the ratio of the concentration of each element in the sediment to the background value (Ahmed *et al.*, 2018; Alahabadi & Malvandi, 2018; Bastami *et al.*, 2017; Hakanson, 1980; H. Li *et al.*, 2017; G. Wu *et al.*, 2014).

$$\text{CF} = C_n / C_{\text{Background}} (B_n)$$

Description: C_n = Concentration of element "n" in the sediment sample; $C_{\text{Background}} (B_n)$ = Concentration of element "n" in nature.

$C_{\text{Background}} (B_n)$ for metals Cd = 0.3 ppm; Pb = 20 ppm; Cu = 45 ppm; and Zn = 95 ppm (Turekian & Wedepohl, 1961). CF is divided into four classifications: Low Contamination Level ($\text{CF} < 1$), Moderate Contamination Level ($1 \leq \text{CF} < 3$), Considerable Contamination Level ($3 \leq \text{CF} < 6$), and Very High Contamination Level ($\text{CF} \geq 6$).

The Pollution Load Index (PLI) is a method for assessing the level of contamination for various elements and is calculated using the following formula (Ahmed *et al.*, 2018) (Alahabadi & Malvandi, 2018) (Bastami *et al.*, 2017).

$$\text{PLI} = [\text{CF}_1 \times \text{CF}_2 \times \text{CF}_3 \dots \times \text{CF}_n]^{1/n}$$

Description: CF = Contamination factor for each element; n = Number of metals

PLI value >1 indicates metal contamination, whereas a value <1 indicates no contamination.

The Geoaccumulation Index can also be used to determine the level of heavy metal contamination in sediment (Alahabadi & Malvandi, 2018; Z. Wang *et al.*, 2015; G. Wu *et al.*, 2014).

$$I_{geo} = \frac{\log_2(C_n)}{1.5 (B_n)}$$

Description: C_n = Concentration of element "n" in sediment sample; B_n = Background concentration of element "n".

The level of heavy metal contamination in the Geo-accumulation Index is divided into seven classes: Unpolluted ($I_{geo} \leq 0$), Unpolluted to moderately polluted ($0 < I_{geo} < 1$), moderately polluted ($1 < I_{geo} < 2$), moderately to severely polluted ($2 < I_{geo} < 3$), severely polluted ($3 < I_{geo} < 4$), severely to extremely polluted ($4 < I_{geo} < 5$), and extremely polluted ($I_{geo} > 5$).

Ecological risk assessment is a process that evaluates the likelihood that adverse ecological effects may occur or occur as a result of exposure to one or more stressors. The Ecological Risk Potential Index is an approach that represents the sensitivity of a biological community to the overall toxic substances present in sediments. The RI is calculated using the following formula (Ahmed *et al.*, 2018; Alahabadi & Malvandi, 2018; Elias *et al.*, 2018; Hakanson, 1980).

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

Description: C_f^i is the concentration value of metal i divided by the background metal value, and T_r^i is the "toxic response factor" of metal i , which reflects the toxicity and sensitivity of bioorganisms to heavy metals. The toxic response factors are 30, 5, 5, and 1 for Cd, Pb, Cu, and Zn, respectively.

The RI value calculation can be divided into four classes: low ecological risk ($RI < 150$), moderate ecological risk ($150 \leq RI < 300$), considerable ecological risk ($300 \leq RI < 600$), and very high ecological risk ($RI \geq 600$).

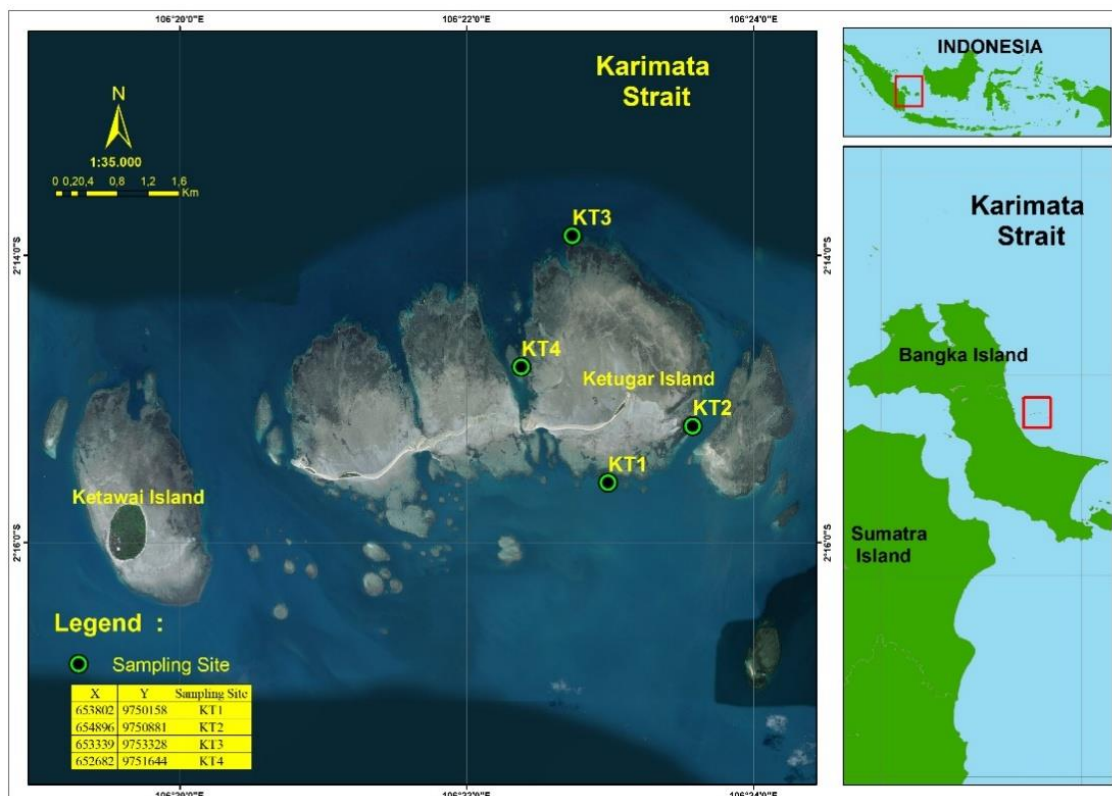


Figure 1. Research Location in the Waters of Ketugar Island (Red Square)

RESULTS AND DISCUSSION

The sediment textures observed in the waters of Ketugar Island vary (Table 1). The dominance of the sand fraction ($>63\ \mu\text{m}$) accounting for 74.84–92.77% of the total indicates that the area is generally characterized by a relatively high-energy depositional environment, a feature typical of shallow-water bottom sediments in the Karimata Strait and on the Sunda Shelf (Erawan *et al.*, 2018; Kolibongso *et al.*, 2017). This finding is consistent with Ketugar Island's location, which is exposed and faces directly toward the Karimata Strait.

Coarse sediment grain sizes at stations KT-3 (north of Ketugar Island) and KT-4 (west of Ketugar Island) show higher percentages compared to the southern (KT-1) and eastern (KT-2) sides of the island. Conversely, fine sediment fractions (silt + clay) accumulate more at stations KT-1 and KT-2 (up to 25.16%), reflecting a relatively low-energy depositional environment. This spatial variation indicates sediment sorting influenced by local hydrodynamic conditions, such as interactions between monsoon currents and waves (Gemilang *et al.*, 2018; Rahman *et al.*, 2022). Similar patterns of grain-size variation, driven by the configuration of island waters relative to local hydrodynamics, have also been observed in the waters off Sumba Island, East Nusa Tenggara (Putra & Nugroho, 2017) and the North Island in the South China Sea (Hu *et al.*, 2026).

The high-energy depositional environments at KT-3 and KT-4 result from direct exposure to monsoon current circulation originating from the South China Sea and passing through the Karimata Strait (Apriansyah & Atmadipoera, 2020; Y. Wang *et al.*, 2019). During the first transitional season the period when samples for this study were collected direct exposure to water masses from the north continued to generate significant bottom shear stress and turbulence, despite a relative decrease in current velocity compared to the northwest monsoon season; this energy transported fine particles to calmer zones for further dispersal, while coarser grains settled rapidly (Cong *et al.*, 2022; Rachman *et al.*, 2023). Conversely, the low percentage of the sand fraction at KT-1 and KT-2 is attributed to the fact that these locations are sheltered from the primary flow of the northern monsoon current. Ketugar Island's protection significantly reduces current velocity and creates a low-energy depositional environment, allowing fine particles to flocculate and settle (Agusta *et al.*, 2023; George *et al.*, 2007; Winterwerp, 2002).

The TOC and TN values and C/N ratios (Table 2) obtained from the sediments of the waters around Ketugar Island ranged from 1.29–1.56%, 0.11–0.13%, and 11.76–13.00, respectively. TOC concentrations were higher at stations KT-1 and KT-2 compared to stations KT-3 and KT-4. TN concentrations were highest at station KT-2 and lowest at station KT-4. The highest C/N ratio was found at station KT-1, while the lowest was at station KT-4.

The TOC and TN values obtained from the sediments of the waters around Ketugar Island fall into the low category (TOC $< 1.6\%$; TN $< 0.2\%$) (Silva *et al.*, 2011). Organic matter input into these waters can originate from both natural (aquatic and terrestrial) and anthropogenic sources (X. Gao *et al.*, 2012; Gu *et al.*, 2017). In general, riverine and coastal sediments receive both exogenous contributions (terrestrial plant litter, soil, and domestic waste) and endogenous inputs (phytoplankton and aquatic plants), both of which play a crucial role in the carbon biogeochemical cycle (Cui *et al.*, 2025).

The C/N ratio is frequently used as an indicator to assess organic matter sources (the relative contribution of marine versus terrestrial organic matter) in aquatic systems (X. Gao *et al.*, 2012; Spano *et al.*, 2014). The C/N ratios in the waters of Ketugar Island fall within the 10–15 range, indicating that the organic matter originates from a mixture of terrestrial sources such as vascular plants and aquatic sources, including plankton, algae, and other aquatic microorganisms. Mangrove ecosystems are present in the Kurau River waters specifically in the East and West Kurau areas (Henri *et al.*, 2023; Randiansyah *et al.*, 2023; Saputra *et al.*, 2019) and are largely utilized for settlements, fisheries, and coastal infrastructure such as jetties (Fiolen *et al.*, 2023), creating a potential source of organic and

nutrient rich waste. These productive mangrove areas, which are also developed for ecotourism, contribute leaf litter and organic detritus with high carbon concentrations to the river system (Henri *et al.*, 2023; Randiansyah *et al.*, 2023). Additionally, unconventional tin mining activities in the upper reaches of the Kurau River contribute to high levels of sedimentation in the waters. This aligns with findings from Bangka Island, which indicate that illegal tin mining significantly alters river sedimentation patterns; notably, sediment grain-size distribution no longer follows the typical pattern of coarser material upstream and finer material downstream (Hambali *et al.*, 2024). These conditions support the hypothesis that fine sediment suspensions laden with terrestrial organic matter are dispersed by Kurau River flow toward the east coast of Bangka Island and as far as the waters surrounding Ketugar Island, particularly during periods of high discharge.

Mixed terrestrial and aquatic organic matter generally has a relatively high C/N ratio, allowing it to accumulate alongside the fine particle fraction (silt + clay) in the low-energy waters surrounding Ketugar Island. Figure 2 shows a very strong positive correlation (Suryapratama *et al.*, 2025) between the fine sediment fraction and the C/N ratio in these waters (i.e., the higher the percentage of fine sediment particles, the higher the surface sediment C/N ratio). This aligns with organo-mineral stabilization, in which the fine fraction (silt + clay), characterized by a large specific surface area and abundant negative charges, efficiently adsorbs and stabilizes organic carbon and nitrogen (Matus, 2021; Thabit *et al.*, 2023). As the proportion of the fine fraction increases, greater amounts of organic matter accumulate, and the C/N ratio measured in fine sediments tends to be higher than that in the coarse or sand fraction (Amorim *et al.*, 2023).

Table 1. Percentage of Sediment Grain Size (%) in the waters of Ketugar Island

Station	Sediment Fraction (%)			
	Sand	Silt	Clay	Silt + Clay
KT-1	74.84	12.82	12.34	25.16
KT-2	86.79	5.17	8.04	13.21
KT-3	92.77	0.04	7.19	7.23
KT-4	92.48	4.75	2.77	7.52

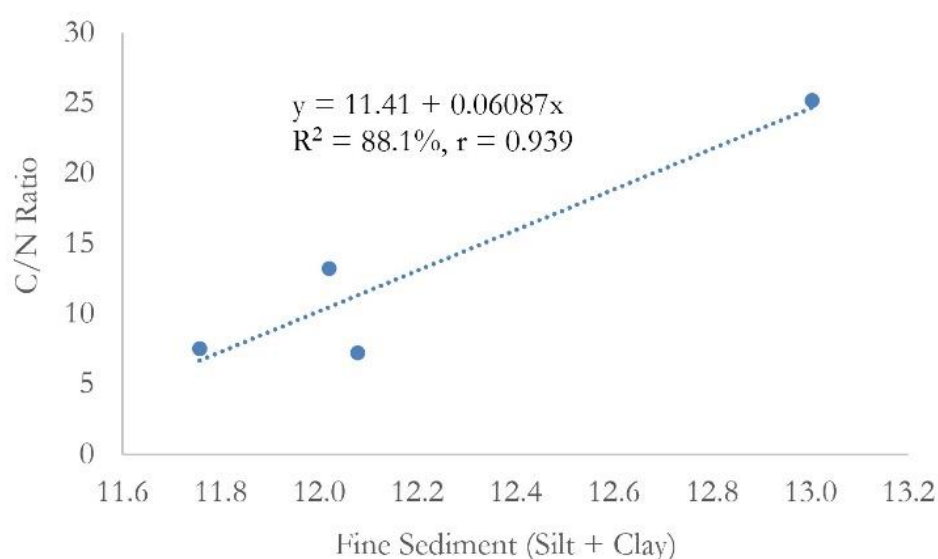


Figure 2. The relationship between the C/N ratio and the fine fraction of sediment in the waters of Ketugar Island

Table 2. TOC Concentration (%), TN (%), and C/N Ratio in the waters of Ketugar Island

Station	TOC (%)	TN (%)	C/N Ratio
KT-1	1.56	0.12	13.00
KT-2	1.56	0.13	12.02
KT-3	1.45	0.12	12.08
KT-4	1.29	0.11	11.76

Table 3 shows the total concentrations of the heavy metals Cd, Pb, Cu, and Zn in the surface sediments of Ketugar Island waters. The concentrations of Cd, Pb, Cu, and Zn elements obtained ranged from 0.09-0.16 mg/kg (average 0.13 mg/kg); 0.80-3.04 mg/kg (average 1.60 mg/kg); 0.07-0.10 mg/kg (average 0.09 mg/kg); and 1.37-1.94 mg/kg (average 1.69 mg/kg). The concentrations of heavy metals Cd, Pb, Cu, and Zn in the surface sediments of Ketugar Island, Central Bangka Regency, did not exceed the sediment quality limits based on ANZECC/ARMCANZ (total concentration <SQGV). In general, sediments in Ketugar Island can be classified as having a low risk to biota (Simpson *et al.*, 2013). The same status of heavy metals Cd, Pb, Cu, and Zn was also found in the coastal waters of Matras, Bangka Regency (Nugraha *et al.*, 2022). However, the concentration of heavy metals Cd, Pb, Cu, and Zn in the sediments of Ketugar Island waters was relatively higher when compared to the heavy metals Cd, Pb, Cu, and Zn found in Matras waters, Bangka Regency, which ranged from 0.02-0.06 mg/kg (average 0.04 mg/kg), 0.12-0.18 mg/kg (average 0.15 mg/kg), 0.01 mg/kg, and 0.54-1.34 mg/kg (average 0.92 mg/kg). The concentration values of heavy metals Pb, Cu, and Zn in the sediments of Ketugar Island waters are relatively lower when compared to the heavy metals Pb, Cu, and Zn found in the waters of Kelabat Bay, Bangka Island (Nugraha *et al.*, 2019) which range from 8.86-29.21 mg/kg, 0.16-9.54 mg/kg, and 25.58-237.24 mg/kg. Furthermore, the concentrations of Cd, Cu, and Zn metals in Ketugar Island waters when compared to Baturusa Estuary, Pangkalpinang City (ranging from 0.68-0.85 mg/kg, 10.49-25.68 mg/kg, and 7.69-46.18 mg/kg) are still relatively lower in the waters of Ketugar Island (Nugraha *et al.*, 2023). The sediment quality status of the Baturusa Estuary, including Zn, is the same as that of the waters off Ketugar Island, meaning it has not exceeded sediment quality standards. Meanwhile, Cd and Cu levels in the Baturusa Estuary have exceeded sediment quality guidelines at several observation stations. Differences in concentrations of the heavy metals Cd, Pb, Cu, and Zn between the Matras coast, Kelabat Bay, the Baturusa Estuary, and the waters off Ketugar Island are primarily due to the intensity and type of anthropogenic sources, hydrodynamic characteristics, and the sediment and geochemical characteristics of the depositional environment. In general, locations closer to and connected to tin mining, urban areas, and polluted rivers exhibit higher metal concentrations in sediment than open ocean locations such as the waters off Ketugar Island (J. Li *et al.*, 2024; Z. Liu *et al.*, 2024; Ma *et al.*, 2025; Yap & Al-Mutairi, 2022; Zhao *et al.*, 2023).

The SQG-Q, CF, I-Geo, PLI, and RI index values in the waters of Ketugar Island indicate that sediment conditions remain unpolluted to low ecological risk for the metal elements Cd, Pb, Cu, and Zn. SQG-Q (Sediment Quality Guideline Quotient) is a sediment toxicity index calculated by normalizing the concentration of each contaminant to the sediment quality guideline (SQG) value, for example PEL/Probable Effect Level or ERM/Effects Range Median), then averaging all quotients to describe the toxic risk of pollutant mixtures on benthic organisms (Tunde & Oluwagbenga, 2020; J. Wang *et al.*, 2022). This index is widely used to classify the level of ecological risk of sediments contaminated with heavy metals and organic compounds in various aquatic ecosystems. The SQG-Q value (0.009-0.016) in the waters of Ketugar Island (Table 4) is included in the unimpacted category ($SQG-Q \leq 0.1$), which is a low potential for adverse biological effects. SQG-Q values with the same category, namely unimpacted (0.00-0.006) or low impacted (with a focus on heavy metal Pb) were also found on the east side of the Panjang Island coast, Banten Bay, Indonesia (Nurhidayati *et al.*,

2023). In addition, in Lampung Bay, Indonesia, SQG-Q values (metals Cd, Pb, Cu, and Zn) were found with the same category, namely unimpacted, but several stations were found in the moderate impact category with values ranging from 0.06-0.22 (Budiyanto & Lestari, 2015). SQG-Q values (Cd, Pb, Cu, and Zn) with a dominant moderate impact category were found in the Kramat Kebo Estuary, West Java, Indonesia (Puspitasari & Lestari, 2018).

CF values (Table 5) for Cd (0.2993-0.5470), Pb (0.0399-0.1521), Cu (0.0016-0.0022), and Zn (0.0144-0.0205) obtained in the waters of Ketugar Island, Central Bangka Regency, were at a low contamination level ($CF < 1$). CF values with low contamination levels were also found in the waters of Morotai Island, North Maluku, Indonesia (Pb, Cd, Cu, Zn, Ni, and Cr) (Edward, 2015). In the Musi River estuary sediments, CF values for Pb, Cu, and Zn also showed low contamination (Putri *et al.*, 2022). Very high levels of contamination ($CF \geq 6$) with an average of 10.8 for the heavy metal Cd were found in sediments in the waters of Segara Anakan, Cilacap, Indonesia (Hidayati *et al.*, 2014).

The I-Geo values (Table 5) for Cd (-2.33 to -1.46), Pb (-5.23 to -3.30), Cu (-9.84 to -9.39), and Zn (-6.70 to -6.20) obtained in the waters of Ketugar Island were classified as unpolluted ($I\text{-Geo} \leq 0$). I-Geo with unpolluted status was also found in the waters of Morotai Island, North Maluku, Indonesia (metals Pb, Cd, Cu, Zn, Ni, and Cr) (Edward, 2015). The I-Geo value for the heavy metal Pb found in the waters of Ketugar Island is lower than that of Pasaran Island, Lampung Bay, Indonesia, which is 4.025-4.516 (severely to very heavily polluted) (Hamid *et al.*, 2023).

The PLI value (0.0262-0.0375) for Cd, Pb, Cu, and Zn obtained in the waters of Ketugar Island (Table 5) indicates an unpolluted status ($PLI < 1$). A PLI with an unpolluted status was also found in the waters of Morotai Island, North Maluku, Indonesia (Pb, Cd, Cu, Zn, Ni, and Cr) (Edward, 2015). The PLI value in the Musi River Estuary sediment (Pb, Cu, and Zn) also indicates an unpolluted status (Putri *et al.*, 2022). The PLI for Pb and Zn in coastal sediments off Sungsang was also found to be uncontaminated (Yudhistira *et al.*, 2025). The RI values (9.24-16.85) for Cd, Pb, Cu, and Zn in the waters of Ketugar Island (Table 5) indicate a low ecological risk status ($RI < 150$). Similarly, a low ecological risk status (Cd, Pb, Cu, and Zn) was also found in the waters off Matras, Bangka Island, Indonesia (Nugraha *et al.*, 2022). Low ecological risk (As, Cd, Cr, Cu, and Pb) was also found in the Madura Strait, East Java, Indonesia (Afifudin *et al.*, 2025).

Table 3. Total concentration of heavy metals Cd, Pb, Cu, and Zn (mg/kg) in the waters of Ketugar Island

Station	Cd	Pb	Cu	Zn
KT-1	0.13	3.04	0.09	1.37
KT-2	0.09	0.91	0.09	1.94
KT-3	0.16	1.65	0.10	1.86
KT-4	0.13	0.80	0.07	1.58
Average	0.13	1.60	0.09	1.69
ANZECC/ ARMCANZ (Simpson <i>et al.</i> , 2013)				
SQGV	1.5	50	65	200
SQG-High	10	220	270	410

Description: SQGV (Sediment Quality Guideline Values); SQG-High (Sediment Quality Guideline-High); Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ).

Table 4. SQG-Q index in the waters of Ketugar Island

Station	PEL-Q				SQG-Q
	Cd	Pb	Cu	Zn	
KT-1	0.0298	0.0272	0.0009	0.0051	0.016
KT-2	0.0214	0.0081	0.0008	0.0072	0.009
KT-3	0.0391	0.0148	0.0009	0.0069	0.015
KT-4	0.0308	0.0071	0.0007	0.0058	0.011

Table 5. CF, I-Geo, PLI, and RI values in the waters of Ketugar Island

Geochemical Proxies		Station			
		KT-1	KT-2	KT-3	KT-4
CF	Cd	0.4174	0.2993	0.5470	0.4311
	Pb	0.1521	0.0455	0.0826	0.0399
	Cu	0.0021	0.0019	0.0022	0.0016
	Zn	0.0144	0.0205	0.0196	0.0167
I-Geo	Cd	-1.85	-2.33	-1.46	-1.80
	Pb	-3.30	-5.04	-4.18	-5.23
	Cu	-9.49	-9.60	-9.39	-9.84
	Zn	-6.70	-6.20	-6.26	-6.49
PLI		0.0372	0.0271	0.0375	0.0262
RI		13.31	9.24	16.85	13.16

CONCLUSION

This study shows that heavy metal concentrations of Cd, Pb, Cu, and Zn (0.09–0.16, 0.80–3.04, 0.07–0.10, and 1.37–1.94 mg/kg, respectively) in the surface sediments of Ketugar Island remain below the ANZECC/ARMCANZ SQGV, reinforced by the unimpacted SQG-Q multi-geochemical index (0.009–0.016), CF <1 (low), Igeo <0 (unpolluted), PLI <1 (unpolluted), and low RI (9.24–16.85), consistently indicating limited anthropogenic input from tin tailings due to the distance of the conservation site and the hydrodynamic dispersion of open waters. This low-risk status is best understood alongside variations in sediment grain size, which govern the distribution of organic matter in surface sediments: the fine fraction (silt + clay) dominates at stations KT-1 (25.16%) and KT-2 (13.21%) on the south-east side with low depositional environmental energy, while the energy is higher at KT-3 (7.23%) and KT-4 (7.52%) in the north-west, exposed to the strong tropical monsoon currents of the Karimata Strait. This fine fraction, with large specific surface area and high negative charge, facilitated the adsorption of TOC (1.29–1.56%, highest in KT-1/KT-2) and a relatively high C/N ratio (11.76–13.00) from terrestrial input of Kurau River mangrove, consistent with the strong positive correlation observed between the fine fraction and the C/N ratio. In contrast, the distribution of heavy metals did not consistently follow this grain-size pattern: only Pb was clearly highest at the fine fraction dominated KT-1, suggesting that factors beyond grain size, such as localized inputs or hydrodynamic sorting of metal-bearing particles, also shape their spatial distribution. Given this, continuous monitoring is needed considering the threat of sedimentation from anthropogenic activities around Bangka Island to maintain the sustainability of this marine park area.

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