JJEES

JJEES (2026) 17 (1): 26-36
ISSN 1995-6681

Jordan Journal of Earth and Environmental Sciences

Ecological Risks of Toxic Metals in Contaminated Marine Sediments: A Case Study of Elechi Creek, Rivers State

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Received on 16 December 2024; Accepted on 16 July 2025

Abstract

Industrial activities and inadequate waste management in the Niger Delta have led to the accumulation of toxic metals in sediments, posing persistent ecological threats. This study assessed contamination and ecological risks at three sites in the region, focusing on six metals: cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), arsenic (As), and copper (Cu). Contamination was evaluated using several indices including the Contamination Factors (CF), Pollution Load Index (PLI), Geo-accumulation Index (Igeo), Enrichment Factor (EF), and Contamination Quantification (QoC). Among the sites, Site 3 exhibited the highest contamination levels, particularly for Cd, with a CF of 2.8, a PLI of 1.393, and a QoC of 46.43%. At this site, Cd also showed an Igeo of 0.562, indicating moderate pollution, and an EF of 6.36. At Site 2, Pb and Zn exhibited lower contamination levels, with CF values of 0.01476 and 0.01269, respectively, and a QoC of 35.48%. The Cd posed the most significant ecological risk at Site 3, with a potential Ecological Risk Index (PERI) of 16.18. These findings highlight industrial discharges as a major source of contamination. Immediate pollution control measures and improved waste management practices are essential to protect the sediment quality and maintain ecosystem health of the Niger Delta.

Keywords: *Metal contamination, Niger Delta, Sediment, Ecological risk, Pollution*

1. Introduction

Anthropogenic marine pollution and toxic metal poisoning have become major global environmental problems that continue to endanger ecosystems and public health. The persistence of these pollutants in the environment, their bioaccumulation in organisms, and their amplification through the food chain ultimately cause harmful effects across ecological and human systems, making them especially problematic (Sonone et al., 2020). These problems are exacerbated in coastal areas such as Nigeria's Niger Delta by heavy industry, poor waste disposal, and rapid urbanization, all of which increase the levels of Potentially Toxic Elements (PTEs) in sediments. In addition to disrupting the equilibrium of aquatic ecosystems, these hazardous metals pose serious risks to local populations, especially in areas with high pollution levels (Reckermann et al., 2022; Chris et al., 2024b). The results of this study align with those of related investigations conducted in the Niger Delta and other developed areas. Research in the Niger Delta has consistently shown that heavy metals, including Zn, Cd, and As, can persist and accumulate in aquatic systems, posing serious threats to the environment and human health (Chris et al., 2023a).

Furthermore, similar results have been found in research carried out in nations other than Nigeria, like China and India, indicating that industrial activities have elevated heavy metal in sediments, increasing the risk of cancer for the local population. These similarities show how widespread heavy metal contamination is, and they emphasize the need for concerted international action to combat it. The Hazard Index (HI) and Carcinogenic Risk Assessments (CRA) show that Elechi Creek's existing metal pollution levels, especially at Site 3, represent serious health hazards. The increased risks, linked to both non-cancerous and cancerous results, demand quick action to lessen these risks.

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Elechi Creek, situated in Rivers State, Nigeria, is a prime example of a region where toxic metal contamination and anthropogenic marine pollution present formidable environmental challenges. Fish and other aquatic life that are crucial to the local economy and way of life depend on the creek, a vital waterway that supports many biological processes and provide local inhabitants with the necessary supplies. However, the increasing industrial discharges and human encroachments into the creek have resulted in increased concentrations of metals in its sediments, raising significant concerns about the long-term ecological and health effects of these contaminants are in progress (Chris et al., 2024a; Seiyaboh and Izah, 2017).

Toxic metals are frequently associated with industrial and anthropogenic activities. For example, a study conducted by Sakina and et al. (2023) in Indonesia, stated that heavy metals are found in hospital wastewater, such as Cr (10 µg/L), Pb (9 µg/L), and Cd (0.8 µg/L). A study by Quist et al. (2022) found that there is an exposure of Mn, a predominantly heavy metals related to oil drilling site, in 29 pregnant women who live near the hydraulic fracturing. A study, conducted in Balqa, Jordan, found that Cr (CF= 11.82) and Ni (CF = 11.59) were the predominant contaminants in the soil (Tarawneh et al. 2021). Although these metals naturally occur in the environment, human activity may greatly increase their concentrations, resulting in pollution that seriously affects human health and aquatic environments. For example, the lead in human blood can increase the risk of blood pressure which is an increase in diastolic (0.013 mmHg) and systolic blood pressure (0.014 mmHg) with 1 µg/dL increase in blood lead levels (Bayat et al., 2016). Sakina (2021) stated that the blood lead levels in pregnant woman are 9 times higher (46.24 µg/L) than the threshold value (5 µg/L). In marine ecosystems, the heavy metals are accumulated in sediments and can lead to bioaccumulation in aquatic organisms, which, in turn, can be biomagnified through the food chain, disrupting ecological balance and causing harmful hazards to people and species eating polluted seafood (Vareda et al., 2019; Chris et al., 2023a; Ekperusi and Asiwa, 2024). For example, a study conducted in the Xiangshan Bay found that As found in seasnail, bivalve, oyster, crab, shrimp and other fish which exceeds the target hazard quotient (Liu et al., 2019). In Europe, Cd was found generally high in squid with close to the maximum residue level. Not only Cd, Hg is also found in tuna and mackerel.

The toxic effects of these metals include disruptions to reproductive and developmental processes, immune system impairments, and increased mortality rates in affected populations. Moreover, the persistence of these metals in the environment means that their impacts can be felt long after the initial contamination event, making them particularly insidious pollutants (Afzaal et al., 2022). Therefore, the evaluation of the potential negative consequences of toxic metal pollution on the environment depends critically on ecological risk assessments, which also consider their toxicity, bioavailability, and potential bioaccumulation. Understanding the severity of toxic metal contamination and anthropogenic marine pollution in Elechi Creek are particularly important, given the region's history of industrial activity and environmental degradation. The Niger Delta, where Elechi Creek is located, has long been recognized as a pollution hotspot, with numerous studies documenting the high levels of toxic metals and other contaminants in the region's water bodies (Kpee et al., 2014; Oritsemuelebi et al., 2021). These studies highlight the urgent need for comprehensive environmental assessments in key areas like Elechi Creek, where industrial activities and human encroachment continue to pose significant threats to the ecological health of the waterway. This study systematically evaluates the ecological risks posed by toxic metals in Elechi Creek's marine sediments, employing geochemical analysis and pollution indices to quantify their spatial distribution and threat to benthic ecosystems. The results identify severe contamination hotspots for metals, like Pb, Cd, Cu, Zn, As, and Fe, linked to anthropogenic sources, such as industrial effluents and urban runoff. The risk assessment underscores their potential to disrupt aquatic food webs, through bioaccumulation in benthic organisms and endanger human populations reliant on the creek for fisheries and water resources.

Given the global nature of toxic metal contamination and the specific challenges faced by regions like the Niger Delta, this study also aims to contribute to the broader understanding of how industrial and urban activities affect aquatic environments. The results from Elechi Creek can be compared with similar studies in other regions, providing a basis for developing more effective environmental policies and remediation strategies. In doing so, this research not only addresses local environmental issues in Rivers State but also contributes to the global discourse on managing and mitigating the impacts of toxic metal pollution on the marine coast.

The contamination of Elechi Creek with toxic metals from anthropogenic activities poses a significant environmental health challenge. This study's focus on sediment analysis and ecological risk assessment offers a comprehensive approach to understanding the scale and impact of this contamination. By highlighting the need for ongoing monitoring, stronger environmental regulations, and targeted public health interventions, this research underscores the importance of integrating scientific findings into policy and management practices aimed at preserving the environment and the communities that depend on it.

2. Materials and Methods

2.1 Study Stations

The research focuses on Elechi Creek in Port Harcourt, which contains both freshwater and saltwater due to tidal influences (Figure 1). The creek borders Eagle Island and reaches the Illoabuchi Street Riverbank. The creek's width varies, with some areas wider and others narrower. Station one (N04°47.15' and E006°58.96'), also known as Eagle Island, is a sand-fill area with hanging latrines, sharp sand, and vegetation dominated by Nipa palm and scattered white and red mangroves. Elephant grass surrounds the mangrove vegetation. Station two (N04°47.2' and E006°59.3'), the

Sawmill area, is downstream and features Nipa palm as the main vegetation, along with smaller numbers of white and red mangroves. Elephant grass is also present around the mangrove vegetation. Station three (Appa area, located at latitude N04°47.05' and longitude E006°59.36'), has Nipa palm vegetation with fewer white and red mangroves. Unfortunately, some Nipa palm trees have been cut down, and hanging latrines have been constructed along the waterway (Vincent-Akpu and Babatunde, 2013; Meregini-Ikechukwu et al., 2020).

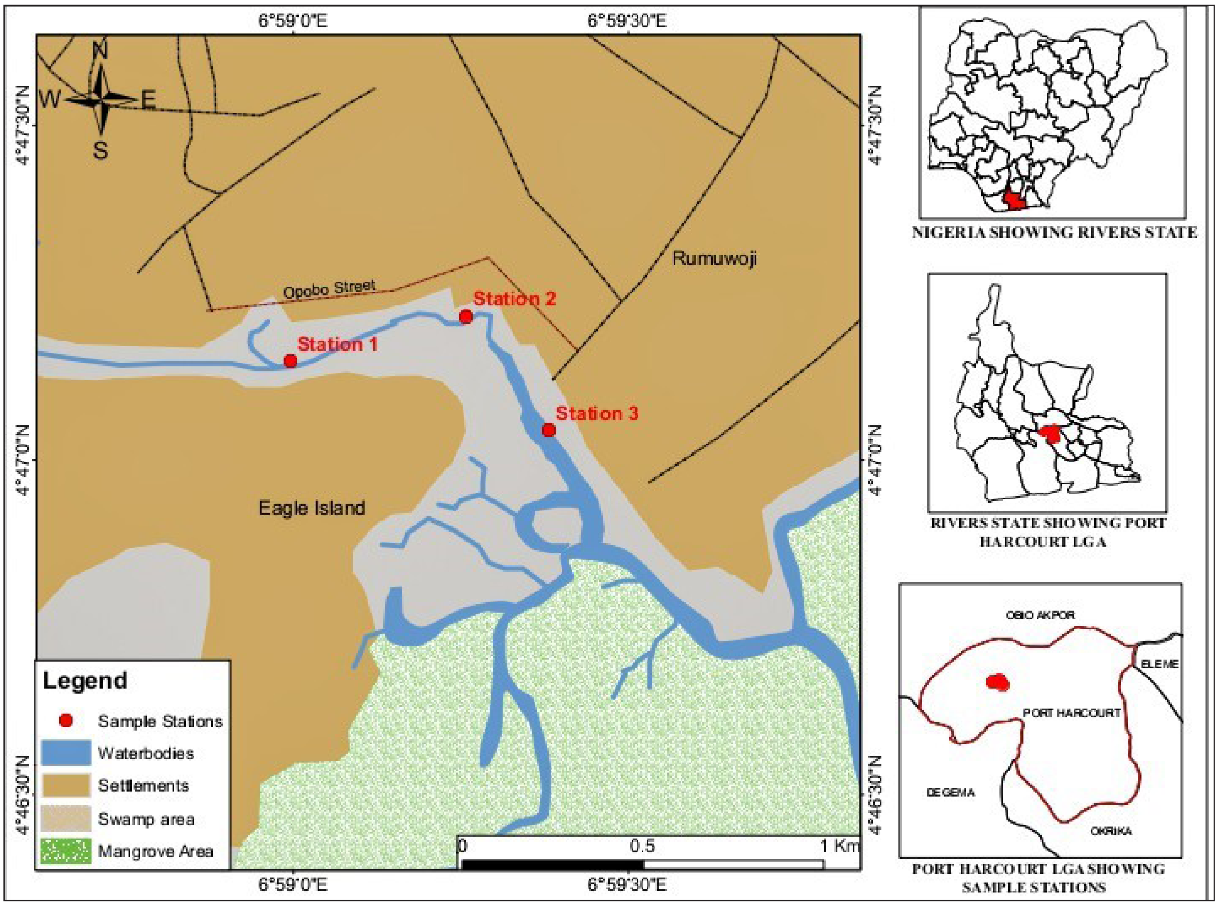

Figure 1. The map of the study area

2.2. Sample collection and preparation

Sediments of approximately 250 g each were collected in triplicate, monthly from three specified sites from January 2023 to July 2023. This sampling was consistently carried out during the first week of each designated month, with sample collection at 3 stations. The selection of the sampling distance from the bank was deliberate, ensuring that the collected sediment samples precisely represented the specific areas within the research site that experienced significant pollution impact. Sediment was collected from three different locations in the creek on a monthly basis for six months, utilizing an 'Ekman grab' sampler. A total of 54 samples, 9 per month and 3 at each station, were collected from the study sites (Moslen et al., 2018). After submersion in 10% nitric acid for 24 hours, the sediments were stored in plastic containers and, subsequently, washed with deionized water. The choice of sampling distance from the bank ensured that the sediment samples accurately represented the observable pollution hotspots within the research area. The frozen samples were then transported to the laboratory, where a UNICAM Solar 969 atomic absorption spectrometer (AAS) with model number API-RP 45 was employed to analyze them (Davies et al., 2024). The samples were maintained at 20°C in the laboratory.

2.3 Quality assurance and control

A calibration curve was generated, using atomic absorption for multiple heavy metals. The reagent blanks were performed after every 10 sample analyses to mitigate the effects of equipment drift. Using the Buck Scientific Model 210 VGP, an atomic absorption spectrophotometer, a range of recovery rates from 82% to 110% was observed for metal amounts in sediment samples.

2.4. Digestion and analysis of the sample

Following accepted procedures, acid digestion was carried out using the technique by Yi et al. (2011) and Chris and Anyanwu (2022), utilizing sediment samples. After four hours at 105°C, the samples were pulverized finely using an agate mortar and pestle. The 0.5 grams of powdered sediment samples were kept in a borosilicate beaker and then mixed with the Aqua regia concoction of HCl and HNO3. After two hours at 80°C, the samples were heated intermittently, adding 1% v/v HNO3 to stop drying. After cooling, the samples were filtered through Whatman 41 filter papers; the final volume was changed to 50 ml. Every stage of preparation used deionized water.

2.5. Analytical method

Sediment samples were analyzed for Pb, Cd, Cu, Zn, As, and Fe using an AAS (GBC Scientific Equipment, Sens AA-Pty Ltd, Australia) fitted with an air- acetylene flame (APHA, 2017). The device was calibrated using AAS standard solutions containing hazardous elements (Pb, Cd, Cu, Zn, As, and Fe) at a concentration of 1,000 mg/L. These solutions were appropriately diluted to generate calibration curves, from which the amounts of the metals were determined. For background reasons, the wavelength calibration was performed using a deuterium lamp. The preparation of standard and blank solutions involved the use of a 1 % (v/v) HNO3 solution. Three distinct concentrations were generated by combining an appropriate volume of a stock standard solution (1,000 mg/L) with a graduated flask of 100.0 mL capacity and subsequently filling it to the brim with deionized water.

2.6. The degree of contamination [Cd]

The degree of contamination (C_d) represents the cumulative effect of several pollutants and serves as an indicator of the environmental hazards related to the presence of multiple toxic metals in sediment. The creation of the afore-mentioned tool was attributed to Hakanson (1980), while its subsequent utilization has been observed in the studies by Guan et al. (2014). Equation 1 presents a mathematical expression. Hakanson (1980) classified C_d as low, moderate, significant, or extremely high (C_d as < 6; 6 ≤ C_d < 12; 12 ≤ C_d < 24 = significant contamination, and C_d ≥ 24), with CF1 denoting the metal contamination factor.

$$C_d = \sum_{i=1}^{n} CF_1 \quad (1)$$

2.7. Contamination Factor (CF)

The concentration factor (CF) is defined by Hakanson (1980), as a ratio of THE metal content to the background value for each metal (Equation 2) where C_{metal} is the sample of mean metal content, while $C_{background}$ is the metal's mean natural value. The study categorizes emtal pollution into four grades: low, moderate, significant, and extremely high (CF > 1, 1 < CF < 3, 3 < CF < 6, CF > 6), using C_{metal} and $C_{background}$ values.

$$CF = \frac{C_{metal}}{C_{background}} \quad (2)$$

2.8. Metals Pollution Load Index (MPLI)

The PLI was assessed using the mathematical expression shown in Equation 3, as suggested by Chris and Anyanwu (2023b).

$$MPLI = (CF1 \times CF2 \times CF3 \ldots \times CFn)\frac{1}{n} \quad (3)$$

The variable n denotes the number of metals under evaluation. In contrast, the contamination factor, denoted as CF, represents the degree of contamination. An MPLI value greater than 1 indicates the presence of pollution, whereas a value less than 1 indicates the absence of pollution (Barakat et al., 2020). While n denotes the numerical value assigned to heavy metals in the specific context.

2.9 Potential Ecological Risk Index (PERI)

Hakanson introduced The Potential Ecological Risk Index (PERI) in 1980, and the Equation 4 is used to calculate it. In this context, n represents the number of heavy metals analyzed, and Er refers to the ecological risk index. According to Mwakisunga et al. (2021), the PERI is used to categorize the level of ecological risk linked to heavy metal contamination. The risk levels are defined as follows: a PERI value below 150 indicates low ecological risk, between 150 and 300 suggests moderate ecological risk, between 300 and 600 signifies high ecological risk, and a PERI value of 600 or more represents significantly high ecological risk. These categories help evaluate the severity of contamination and its potential impact on environmental health and ecosystem stability.

$$PERI = \sum_{i=1}^{N} E_r^i \quad (4)$$

2.10 Geo-accumulation index (Igeo)

The geo-accumulation index is a method for assessing the heavy metal content of sediment by comparing the current levels of contaminants with the historical levels (Qingjie et al., 2008). This approach has been implemented extensively in the evaluation of sediment contamination (Ahirvar et al., 2023; Islam et al., 2014). Müller's (1969) is employed to determine the Igeo (Equation 5).

$$Igeo = log_{2\frac{Cn}{1.5 \times Bn}} \quad (5)$$

The average content of toxic metals (C_n) in sediment samples is used to calculate the Igeo, with the reference background value (B_n) provided by Guan et al. (2014). In order to accommodate fluctuations in the baseline value, a 1.5-fold factor is implemented. The Igeo indices are classified into seven categories, as per Abdullah et al. (2020).

2.11 Ecological risk assessment

One or more contaminant or metals polluting the sediment are both evaluated in terms of their potential ecological danger using the risk factors evaluation (Er and PERI). The ecological risk factor (Er) is computed statistically using Equation 6.

$$Er = Tr \times C_f \quad (6)$$

The contamination factor (Cf) is employed in conjunction with the toxic-response factor (Tr) for each metal, including Cd, Pb, Zn, Ni, and Cu, to evaluate ecological risks according to how Mugoša et al. (2016) categorize the ecological risk factor (Er). Er signifies the single index used to quantify the ecological risk factor.

2.12 Enrichment Factor (EF)

The Enrichment Factor (EF) serves as a universal index, providing a straightforward and convenient approach to assessing enrichment and facilitating comparisons of contamination across various environmental media, as outlined by Nowrouzi and Pourkhabbaz (2014). Furthermore, it helps confirm whether heavy metal contamination originates from anthropogenic sources, as suggested by Jahan and Strezov (2018). The calculation for this index is specified in Equation 7.

$$EF = \frac{Cn\,/\,Crefsample}{Bn/Bref} \quad (7)$$

The EF is a measure of metal enrichment in samples, comparing the concentration of the analyzed metal to reference material (Bref) and background levels (B_n). EF values can be classified into five ranges: less than 2 indicates mineral enrichment, 2 to less than 5 indicates moderate enrichment, 5 to less than 20 signifies significant enrichment, 20 to less than 40 indicates very high enrichment, and greater than 40 indicates extremely high enrichment. Enrichment factors, close to or less than 1, indicate heavy metals from natural sources. In contrast, those factors greater than 1 indicate potential anthropogenic sources.

2.13 Quantification of contamination (QoC)

The Quantification of contamination (QoC) index, a tool used to assess the main sources of metals, was assessed using Equation 8 in a study by Zarei et al. (2014). The mean metal content in sediment samples is *Ci*, with negative values indicating natural sources and positive values indicating anthropogenic sources, as per Guan et al. (2014) and Malvandi (2021).

$$\text{QoC}\ (\%) = \left[\frac{(Ci - Cin)}{Ci}\right] \times 100 \qquad \text{.......................................} \ (8)$$

2.14 Statistical analysis

The mean and standard deviation of all measured parameters across stations were calculated using descriptive statistics and months to summarize the data. Pearson correlation coefficients were used to assess relationships between the parameters. Furthermore, ANOVA was performed to test for statistical significance in differences between stations and months, applying a 95% confidence level with a significance level at $p < 0.05$.

3. Results and Discussion

In Table 1, the mean concentrations of six toxic metals (Cd, Pb, As, Cu, Zn, and Fe) were measured across three different stations in the surface sediment of Elechi Creek. However, the mean concentrations of toxic metals in surface sediments among the three stations were not significantly different ($p < 0.05$). These values are compared with the World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ), which serve as reference points for assessing the severity of sediment contamination.

The Cd concentrations at all stations significantly exceed the WHO and NSDWQ guideline values of 0.003 mg/kg, indicating substantial anthropogenic input, likely from industrial discharges and urban runoff. The high toxicity and persistence of Cd in the environment are concerning, as it can bioaccumulate in aquatic organisms, posing long-term health risks to both wildlife and humans (Abugu et al., 2023; Zhang et al., 2024).

Pb concentrations exceeded the WHO and NSDWQ guideline values of 0.01 mg/kg, indicating significant contamination, likely originating from sources such as leaded gasoline, industrial emissions, and improper waste disposal. Similarly, As levels also surpassed the WHO guideline of 0.01 mg/kg, with the highest concentration recorded at Station 3 (0.18 mg/kg) and the lowest at Station 2 (0.16 mg/kg). As is a potent carcinogen, and even at low concentrations, its presence in sediments poses substantial health risks due to potential bioaccumulation within the food chain, thereby necessitating continuous monitoring and possible remediation efforts (Ogbeide and Henry, 2024; Jiang et al., 2023; Okon et al., 2023; Shentu et al., 2023). Cu concentrations are well above the WHO and NSDWQ guideline of 0.02 mg/kg, with the highest levels at Station 2 (0.79 mg/kg) and the lowest at Station 3 (0.74 mg/kg). The variability in Cu levels suggests localized sources of contamination, likely related to industrial and agricultural activities in the region (Bhuyan et al., 2023; Chen et al., 2021).

The Zn level, although below the WHO and NSDWQ guideline of 3 mg/kg, indicates ongoing contamination with the highest concentration at Station 3 (0.83 mg/kg) and the lowest at Station 1 (0.72 mg/kg). High Fe concentrations in these sediments suggest substantial anthropogenic contributions (Ali et al., 2022; Li et al., 2023a; 2023b), likely from industrial discharges, impacting sediment chemistry and nutrient cycling, with potential downstream effects on aquatic life (Chris and Anyanwu, 2023b; Liu et al., 2023).

Table 1. Mean data for toxic metals in surface sediment

Sites	Cd	Pb	As	Cu	Zn	Fe
1	0.24±0.02[a]	0.29±0.01[a]	0.17±0.00[a]	0.78±0.02[a]	0.72±0.14[a]	6.21±0.27[a]
2	0.23±0.02[a]	0.31±0.02[a]	0.16±0.01[a]	0.79±0.03[a]	0.80±0.15[a]	5.75±0.38[a]
3	0.28±0.0[a]	0.29±0.02[a]	0.18±0.00[a]	0.74±0.04[a]	0.83±0.15[a]	6.00±0.24[a]
WHO	0.003	0.01	0.01	0.5	3.0	0.3
NSDWQ	0.003	0.01	0.05	0.02	3	0.3

Mean values with the same alphabet superscript are not significantly different ($p < 0.05$)
Mean values with different alphabet superscripts are significantly different ($p > 0.05$)

These findings in Table 2 align with similar studies in the Niger Delta, where elevated levels of toxic metals, particularly Cd and Pb, have been consistently reported due to industrial activities and oil exploration (Idowu, 2022; Ogbeide and Henry, 2024). Bwatanglang et al. (2021) found that Cd is the most abundant heavy metals in surface soils and sorrel plants, indicating moderate-to-considerable ecological risks ($40 < Er < 86$) in Adamawa State, Nigeria. Studies in industrialized regions, such as China's Yangtze River Delta, show high levels of heavy metals, such as Cd and Pb in sediments (Liu et al., 2023). Elechi Creek's surface sediment shows elevated levels of toxic metal, primarily due to human activities. These high concentrations of Cd, Pb, and As are of concern due to their toxicity and potential bioaccumulation, which could have severe consequences for aquatic ecosystems and human health. If these trends continue unchecked, there is a risk of long-term environmental degradation and public health crises.

The CF values indicate that the highest Cd contamination occurs at Site 3 (2.8), suggesting a relatively higher anthropogenic impact at this location. Cd also shows the lowest CF at Site 2 (2.3), suggesting slightly less pollution than at other sites. For Pb, the CF values are very low across all sites, with the highest being at Site 2 (0.01476). This finding aligns with a study by Khudhur et al. (2018), which found Pb in soil (CF = 4.79) in the Sahdawa, Shamamal, and Sardasht areas of Erbil City. Zn shows a similar pattern, with the highest CF at Site 3 (0.01269). Fe, which typically indicates natural background levels, shows minimal variation across sites, with the highest value at Site 1 (0.00161). As has the highest CF at Site 3 (0.01385), and Cu is most concentrated at Site 2 (0.03511).

Similar studies in the Niger Delta have shown elevated CF for Cd, especially in areas near industrial activities and oil spill sites (Idowu, 2022). Pb contamination has also been reported, though generally at lower levels, similar to the findings in this study (Shentu et al., 2023). In other industrialized regions, like the Yangtze River in China, have reported comparable CF values for Cd and Pb, indicating similar contamination sources and industrial activities (Liu et al., 2023).

The higher Cd contamination factor at Site 3 suggests that this site is particularly vulnerable to industrial pollution, which could have long-term health implications for local populations. The consistent PLI values across the sites indicate a moderate pollution load, with Site 3 being the most polluted, warranting focused remediation efforts. The PLI is highest at Site 3 (1.393), indicating that this site experiences the most significant overall pollution. The PLI at Site 1 (1.219) and Site 2 (1.222) are lower, suggesting at these sites are less impacted by contamination but are still affected.

Table 2. Contamination Factor and Pollution Load Index

Metal	Studied Sites		
	1	2	3
Cd	2.4	2.3	2.8
Pb	0.01381	0.01476	0.01381
Zn	0.01101	0.01223	0.01269
Fe	0.00161	0.00149	0.00156
As	0.01308	0.01231	0.01385
Cu	0.03467	0.03511	0.03289
PLI	1.219	1.222	1.393

In Table 3, Cd exhibits the highest ecological risk at Site 3, with a value of 8.40. In contrast, the lowest risk is recorded at Site 2, with a value of 6.90. Pb, Zn, Ar, and Cu present their highest ecological risks at Site 2 and Site 3, albeit they appear with relatively minor differences. In Table 3, the PERI reaches its peak at Site 3, registering a value of 16.18, underscoring the heightened potential for ecological harm at this location. This site-specific increase in ecological risk aligns with findings from other studies in the Niger Delta, where industrial activities and oil exploration have significantly contaminated the environment (Iwegbue et al., 2018; Osayande and Nwokedi, 2019).

Similar patterns have been reported in the Niger Delta, where Cd is a significant contributor to ecological risk, particularly in areas impacted by oil spills and industrial discharges (Osayande and Nwokedi, 2019). In heavily industrialized regions such as India, elevated PERI values for Cd and lead are common, mirroring the results observed in this study (Kumar et al., 2020). The elevated PERI at Site 3, with a value of 16.18, indicates that this site is especially vulnerable, potentially leading to adverse effects on local biodiversity. While the consistent toxic response values for other metals suggest some level of ecological risk, Cd remains the most concerning pollutant in this context.

Table 3. Ecological risk factor and Potential Ecological Risk Index (PERI)

Metal	Studied Sites		
	1	2	3
Cd	7.20	6.90	8.40
Pb	1.45	1.55	1.45
Zn	0.72	0.80	0.83
As	1.70	1.60	1.80
Cu	3.90	3.95	3.70
PERI	14.97	14.80	16.18

In Figure 2, the degree of contamination (DC) is an aggregate measure of contamination across all metals. Site 1 has the highest DC (8.41), slightly higher than Site 3 (8.32), and Site 2 shows the lowest DC (8.04). These values indicate that all sites are experiencing a significant contamination, with Site 1 being the most affected. The high DC at these sites reflects the ongoing anthropogenic pressures in the Niger Delta, including oil spills and industrial waste discharge (Katz, 2012).

Site 1 has the highest contamination level (8.41), followed closely by Site 3 (8.32). Site 2 has the lowest DC (8.04), though still indicative of significant contamination. Similar DC values have been reported in studies from other parts of the Niger Delta, especially in areas with high industrial activity and oil exploration (Ugochukwu et al., 2022).

Globally, regions with similar industrial profiles, such as parts of South America, have reported DC values comparable to those observed here, indicating that the contamination levels observed here are not unique to Nigeria (Sangeetha et al., 2021; Romero-Murillo et al., 2023). The high DC values across all sites underscore the need for comprehensive remediation strategies to reduce cumulative contamination. Site 1, particularly high DC, suggests nearby industrial activities may more heavily impact it.

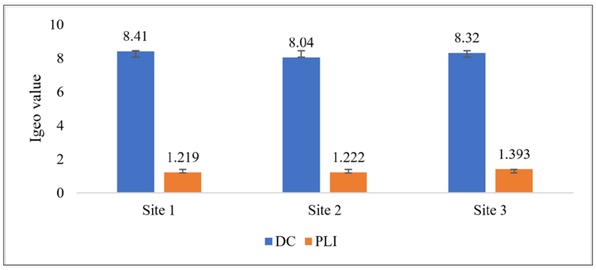

Figure 2. Degree of Contamination (DC)

The Igeo is highest for Cd at Site 3 (0.562), indicating moderate pollution levels. The Igeo values for Cu, Zn, Pb, As, and Fe are very low across the sites, reflecting minimal to no pollution from these metals. These findings align with previous studies in the Niger Delta that have identified Cd as a significant sediment pollutant from industrial and agricultural runoff (Attah et al., 2021). Igeo values for Cd have been reported as moderately high in other studies conducted in the Niger Delta, particularly near oil production sites (Iwegbue et al., 2018). The low Igeo values for other metals align with findings in less impacted areas. In industrial regions, such as southeast asia, similar Igeo trends have been observed, with Cd showing higher Igeo values than other metals, reflecting its widespread use and persistence (Banerjee, 2022).

In Table 4, the moderate Igeo for Cd at Site 3 emphasizes the need for targeted pollution control measures to prevent further environmental degradation. The low Igeo values for other metals suggest that natural background levels are more influential in these cases, reducing the urgency for immediate intervention for these specific contaminants.

Table 4. Geo-accumulation index (Igeo) for the three sites

Metal	Studied Sites		
	1	2	3
Cd	0.482	0.462	0.562
Pb	0.003	0.003	0.003
Zn	0.002	0.002	0.003
Fe	0.000	0.000	0.000
As	0.003	0.002	0.003
Cu	0.007	0.007	0.007

In Table 5, the EF indicates the degree of anthropogenic influence on sediment metal concentrations. Cd shows significant enrichment at Site 3 (6.36), which is categorized as moderate to a considerable enrichment according to Al-Jaberi et al. (2020). The other metals, including Pb, Zn, As, and Cu, exhibit very low EF values across all sites, suggesting that these metals are primarily of natural origin. Similar findings have been reported in studies focusing on areas affected by industrial waste and oil spills, consistent with the elevated Cd enrichment at Site 3 (Nriagu et al., 2016). Low enrichment factors for other metals are consistent with less impacted sites in the region. This pattern has also been observed in European rivers, where Cd is often enriched by industrial discharges. At the same time, other metals tend to reflect natural background levels (Schulte et al., 2024). The significant enrichment of Cd at Site 3 indicates a strong anthropogenic influence, which could have serious ecological and health implications if not addressed. The low enrichment of other metals indicates that they are less likely to be of immediate concern, though continued monitoring is recommended.

Table 5. Enrichment factor for toxic metals in sediment

Metal	Studied Sites		
	1	2	3
Cd	5.45	5.22	6.36
Pb	0.03	0.03	0.03
Zn	0.02	0.03	0.03
As	0.03	0.03	0.03
Cu	0.08	0.08	0.07

In Figure 3, the QoC shows that Cd shows the highest contamination level at Site 3 (46.43%). In comparison, Site 2 shows the highest QoC for Pb (35.48%) and Cu (36.71%). These results highlight the variability in metal contamination across the sites, with different metals being more prominent in various areas. The high QoC for Cd at Site 3 is particularly concerning, as Cd is known to have toxic effects even at low concentrations (Ogbeide and Henry, 2024).

High QoC values for Cd and Pb are consistent with findings in other contaminated sites in the Niger Delta, where industrial and urban runoff are major contributors (Iwegbue et al., 2018). Similar patterns have been observed in other studies of highly industrialized areas. Globally, areas with heavy industrialization and poor waste management, such as in some parts of India, report similar QoC values, highlighting the widespread nature of this issue (Gupta and Gupta, 2023). The high QoC for Cd and Pb, particularly at Sites 2 and 3, suggests an urgent need for intervention to prevent further contamination and mitigate potential health risks. These results emphasize the importance of implementing stricter pollution controls and remediation efforts.

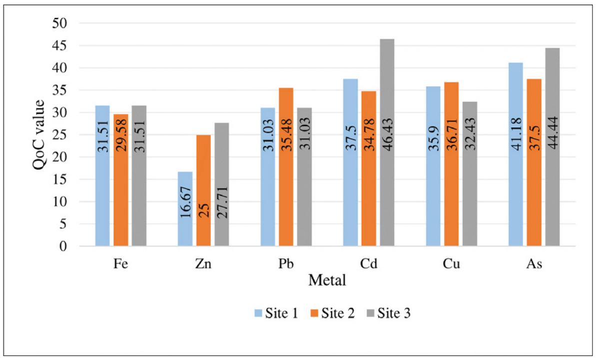

Figure 3. Quantification of contamination (QoC) in Sites 1, 2, and 3

The study reveals that Site 3 in the Niger Delta is experiencing the highest levels of contamination, particularly for Cd, indicating a high ecological risk and enrichment factor. This finding is concerning due to the toxic nature of Cd and its potential to cause adverse health effects in wildlife and humans (Osayande and Nwokedi, 2019). The elevated PLI and PERI at Site 3 underscore the need for urgent remediation. Similar patterns of heavy metal contamination have been observed in the Niger Delta, particularly concerning Cd and Pb, often linked to oil spills and industrial activities (Iwegbue et al., 2018). International studies, such as those in China and India, also report significant ecological risks associated with Cd and Pb contamination (Kumar et al., 2020; Liu et al., 2023). The study highlights the need for targeted environmental management strategies to mitigate further pollution and protect the ecological integrity of the Niger Delta.

The correlation in Table 6 shows the associations between heavy metals (Cd, Pb, As, Cu, Zn, Fe) in sediment samples. The table shows Pearson's r values and their significance ($p < 0.05$). The matrix analysis, presented in Table 6, revealed significant relationships among heavy metals in the sediment samples. Cd and Pb showed a strong positive correlation ($r = 0.96$), suggesting a common anthropogenic source, such as oil spills or industrial effluents, which have been documented in similarly polluted deltaic regions (Onyena et al., 2024). As and Cu also exhibited a strong positive correlation ($r = 0.95$), consistent with findings in agricultural and mining- impacted sediments where these metals co-occur due to pesticide use and ore processing (Ratnakar et al., 2018). Cu and Zn were positively correlated ($r = 0.91$), a pattern frequently observed in urbanized coastal areas where corroded infrastructure and stormwater runoff contribute to metal deposition (Onyena, A. P. and Nwaogbe, 2024).

Notably, strong negative correlations were observed between Cd and As ($r = -0.94$), Cd and Cu ($r = -0.99$), and Pb and As ($r = -0.99$). The inverse relationships observed among certain metals likely result from competition for binding sites in the sediment. This phenomenon has been well documented in estuarine environments, where similar competitive interactions between metals have been observed (Zhang et al., 2022). Interestingly, iron showed almost no correlation with the other metals studied. This makes sense because the iron in these sediments likely comes mostly from naturalrock weathering rather than human activities, as other researchers working in the Niger Delta have found (Ogbeide et al., 2024).

The close connection between Cd and Pb is particularly concerning because both metals are toxic and often originate from the same pollution sources, such as oil spills and factory waste. Recent studies have confirmed that these metals pose serious threats to both ecosystems and human health in contaminated areas (Afolabi et al., 2024). The strong link between Cu and Zn points to urban runoff as a major contributor, something coastal cities need to address through better stormwater management (Adimalla and Taloor, 2020).

What's really interesting is how some metals seem to "push each other out" of the sediment. This behavior, especially between Cd, Cu, and As, shows a need to pay close attention to sediment chemistry-factors like acidity and organic content can dramatically affect how these metals move through the environment (Bao et al., 2024). Our results add to growing evidence from around the world that industrialized river deltas need comprehensive pollution control plans that address both cleanup and prevention (Akpa et al., 2025).

Table 6. Pearson Correlation Matrix for Heavy Metals

Metals	Cd	Pb	As	Cu	Zn	Fe
Cd	1.00					
Pb	0.96*	1.00				
As	−0.94*	−0.99*	1.00			
Cu	−0.99*	−0.94*	0.95*	1.00		
Zn	−0.87	−0.80	0.82	0.91*	1.00	
Fe	0.12	0.08	−0.10	−0.15	−0.33	1.00

Bold = Strong correlation.
** = Significant (p < 0.05).*
Negative values = Inverse relationships.

4. Conclusion

The study reveals significant contamination across all sites, with Site 3 exhibiting the highest levels, particularly for Cd, which poses the most substantial ecological risk. The CF and PLI highlight the greater anthropogenic impact at Site 3, where Cd contamination is notably higher than at other sites. The ecological risk factor and PERI indicate that Site 3 has the highest potential for ecological harm. The DC indicates widespread contamination, with Site 1 showing the highest cumulative contamination due to industrial proximity. Igeo indicates moderate Cd pollution levels, indicating the need for pollution control measures. The enrichment factor analysis confirms significant anthropogenic influence, particularly for Cd, aligning with similar findings in the Niger Delta and other industrialized regions globally. The quantification of contamination indicates that Cd and Pb are the most concerning contaminants, particularly at Sites 2 and 3. Immediate action is required to reduce industrial discharges and implement sustainable waste management practices to safeguard both the environment and public health in the region.

Competing Interests and Funding

There is no conflict of interest to declare, and no funding for the proposed project.

Ethical Approval

No specific ethical approval was required for this study.

Data Availability Statement

All relevant data supporting the study are in the article, and the raw data are also available upon request from readers.

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