Concentrations of Heavy Metals and Ecological Risks in Surface Water from Creeks Around Okrika Communities in Rivers State, Nigeria

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Abstract
This research assessed the levels of heavy metals in creeks around Okrika Communities, Rivers State. The study employed a spatial experimental, cross-sectional design and purposive sampling conducted across four strategic creek locations—Okochiri, Ekerekana, Okpoka-Toru, and Oba Ama—selected due to their proximity to major pollution point sources such as industrial effluent discharge points. Samples of water were collected during distinct wet and dry seasons to account for temporal variability. Laboratory analyses were performed in accordance with standardised international protocols, including those from the American Public Health Association and the American Society for Testing and Materials. Analytical techniques encompassed in-situ multi parameter probing, atomic absorption spectrophotometry for the heavy metals. The findings revealed the presence of heavy metals, including lead, cadmium, and chromium concentrations often surpassing permissible limits for seafood safety. The subsequent ecological and human health risk assessment yielded hazard indices and carcinogenic risk values that indicated significant potential for adverse health outcomes in the local population, particularly through the long-term consumption of contaminated fish. This study provides evidence that the creeks around Okrika communities are polluted by toxic metals. This contamination is directly linked to anthropogenic activities, resulting in an ecosystem under severe duress and posing danger to public health. It was recommended that policy frameworks should be strengthened to incorporate community-based monitoring and stricter penalties for environmental violations.

Keywords: Heavy Metals, Surface Water, Creeks, Ecological Risks, Okrika, Nigeria

Introduction

Global surface water and sediments are found in creek, rivers, wetlands, mangrove swamps, coral reefs, estuaries etc. (Onwugbuta *et al.,* 2022). These water bodies put together occupy seventy-one (71%) percent of the earth's surface, and is one of the most demanded and essentials of all-natural resources that are indispensable for human socio-economic activities and sustenance (United States Geologic Survey (USGS), 2021). Water is abundant everywhere on planet earth, but fresh potable water is not always available at the right time and place(s) for human use and ecosystem functioning (USGS, 2021). Surface water and sediments including

fishes are critical essential components of the earth's hydrological cycle, playing critical roles in shaping the marine ecological environment, supporting life and influencing human activities and well-being (Ogaga *et al.,* 2018). Surface water therefore refers to water that flows over the land surface, including rivers, streams, lakes, wetlands, and oceans (Green *et al.,* 2023). It is a vital component of the earth system accounting for about 2.5% of the planet total water resources (Green *et al.,* 2023). On the other hand, sediments are solid particles that settle at the bottom of surface water bodies, such as rivers, lakes, creeks and oceans, and they originate from various sources including erosion, weathering and human activities (Uzamere *et al.,* 2023a&b). Sediments play crucial roles in various ecological and human processes, including, habitat creation, water filtration, nutrient cycling, coastal protection and mineral resources laden. Fishes are living creatures that are found in the surface water and sediments of creeks, rivers, streams and oceans (Iyama *et al.,* 2020). Thus, understanding the nature and usefulness of surface water, sediments and fishes of water bodies is crucial for managing these resources sustainably, mitigating environmental impacts, and promoting ecological and ecosystem wellbeing as well as human survival (Green *et al.,* 2023). Furthermore, coastal areas have abundance of surface water, sediments and fishes, and are sites of discharge and accumulation of pollutants (Ideriah *et al.,* 2012). It has been shown by studies conducted on heavy metal discharges and accumulation in rivers, lakes, fish and sediments, that heavy metal contamination of coastal waters and sediments including fishes, has been identified as a serious threat to coastal surface water, sediments and fishes in Nigeria (Ideriah *et al.,* 2010a; Ideriah *et al.,* 2010b; Ideriah *et al.,* 2012). Water is a resource that has many uses, including recreation, transportation, hydroelectric power generation as well as domestic, industrial and commercial uses (Kumar & Putri, 2012). Kumar and Putri (2012), also asserted that water also supports all forms of lives and affects human health, life style and economic wellbeing. Although, more of the water available (71%), only about 2.8% of the earth's water is available for human consumption (Kumar & Putri, 2012). At present, approximately one-third of the world live in countries with moderate to high water stress, especially fresh potable water (Uzamere *et al.,* 2023a). Moreover, the world-wide fresh – water consumption had increased by six folds between 1900 and 1995, and between 2000 and 2020, as such more than twice the rate of the world are facing water scarcity problem due to limitation of the fresh water resources, considering the growing population trend globally (Kumar & Putri, 2012; Uzamere *et al.,* 2023b). Surface water qualities are poorer in rivers, streams, estuaries and creeks, than in reservoirs. This is because these sources of water play a major role in the assimilation of pollutants, carrying of municipal and industrial wastewater as they flow, and run off from agricultural land which constitute polluting point and non-point sources (Uzamere *et al.,* 2023a). It is worthy to note that with the rapid and increased rate of urbanization, industrialization and population increase couple with rapid rate of development in the various sectors of the economy, the rivers, creeks, streams and their surface water, sediments and fishes especially at the peripheral areas of urban centers are constantly and continuously contaminated with hazardous wastes, effluent discharges, sludges, heavy metals, and waste waters which have become a common phenomenon (Uzamere *et al.,* 2013b). Ogolo and Abam (2021) noted that as water sources for drinking and human use are contaminated, it is very difficult, costly and almost impossible to threat and restore it to its original state. However, till today, about eighty (80%) percent of our global wastes containing human wastes, toxic substances, heavy metals and xenobiotic are released into the water bodies (United Nation (UN), 2019). UN (2019), had also noted that measurable residues of persistent organics have been reported from fish and aquatic mammals.

In addition, heavy metals, xenobiotics and other pollutants have been widespread, and have caused significant threat to the human wellbeing and ecosystem stability due to changes in the

physicochemical parameters of water and sediments qualities and the bioaccumulation of xenobiotic in fishes and shell fish used as human food sources (UN, 2019). Studies by Iyama *et al.* (2020), Ogolo and Iyama (2021) and Uzamere *et al.* (2023a) have indicated that majority of the creeks, rivers and streams and their surface water, sediments and fishes are seriously polluted, due to rapid population increase, industrialisation, urbanisation and non-enforcement of existing environmental laws. Coupled with the above, is the uncontrollable release of untreated waste effluent and wastewaters into the water bodies, thereby negatively affecting the physicochemical parameters and increased the concentration levels of xenobiotics, thus, affecting the surface water quality, sediments and aquatic life (Uzamere *et al.,* 2023a).

Human economic activities have had untold impact on the surface water, sediments and fishes abundance and bioaccumulation effect in the creeks, streams and rivers around Okrika communities of Rivers State as seen in the deposition and concentration level of xenobiotics and changes in the levels of physicochemical parameters, thus, stimulating harmful algal blooms and destabilising the aquatic ecology (Uzamere *et al.,* 2023b). The contaminants released into the surface waters and sediments in the Niger Delta River, creeks and streams are of two types, and have a long-term impact on the aquatic systems natural equilibrium (USGS, 2021). The first category includes plant nutrients such as nitrate (NO_3^-), phosphate (PO_4^{3-}), and sulphate (SO_4^{2-}), which are not immediately damaging to plants or animals in water, but may dischareg an undesirable odour or flavor (Singh, 2013). This has the potential to dramatically disrupt the environment. The second category consists of chemical species that are environmentally refractory, such as heavy metals, radio-nuclides, chlorinated hydrocarbons, and polycylic aromatics, as well as sulphur (S) and nitrogen oxides (NO_x), which can produce acids in rainfall. This category has the potential to have direct harmful influence on the water ecosystem. It therefore, has long term negative impact on the marine ecosystem as it tends to bio-accumulate in the bottom sediments of aquatic systems and get concentrated by the biota, and they can reach humans, causing acute and chronic diseases (USGS, 2021).

The rivers, creeks and streams in Okrika Local Government Area have been polluted due to industrial effluents discharges, wastewater, sludges and other contaminants and pollution from the Refinery, Petrochemical Plants and the Fertiliser Company (Obire *et al.,* 2008a; Ideriah *et al.,* 2023). This has affected the littoral zone, the shallow surface, sediments and fishes in the creek along the shore, including the livelihood of the people of the area. Thus, the Okrika creek, rivers and streams in Rivers State, Nigeria are very important and vital component of the Niger Delta region's marine ecosystem that supports various aquatic lives and socioeconomic activities. However, this marine ecosystem is facing significant environmental challenges due to anthropogenic activities such as oil and gas exploration, production operations, chemical and fertiliser production operations including marine transportation which have led to the release of various pollutants including xenobiotics into the marine environment, thus, changing the physicochemical quality of the water ecosystem (Uzamere *et al.,* 2023a; Luo *et al.,* 2023). Xenobiotics, including Polycyclic Aromatic Hydrocarbons (PAHs), heavy metals, and pesticides, have been shown to have detrimental effect on aquatic life (fishes) and human health (Iyama *et al.,* 2020). These pollutants can accumulate in surface water, sediments, and fishes, leading to biomagnifications and potentially harmful effects on the marine ecosystem and human consumers.

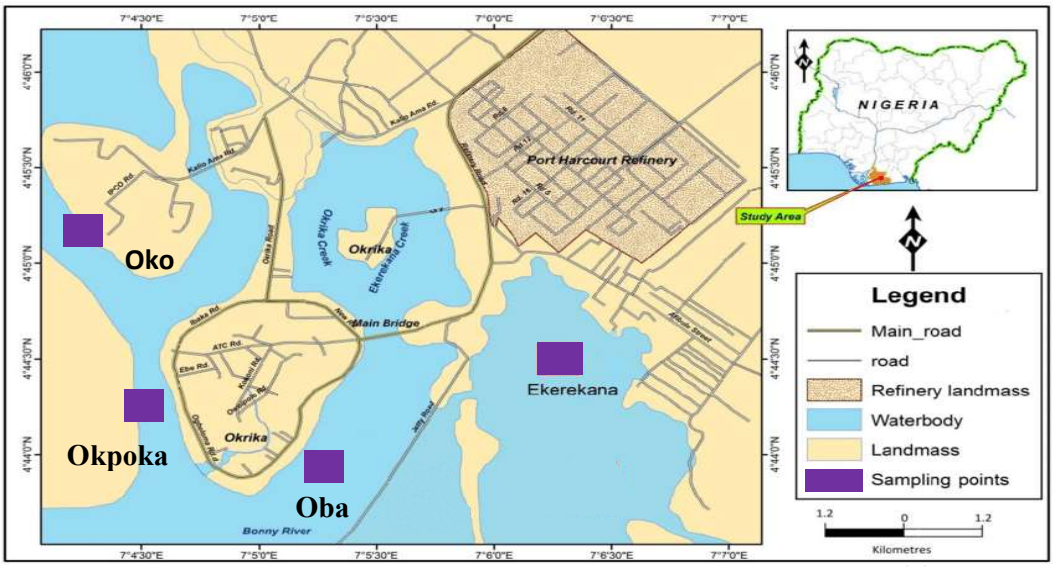


Figure Error! No text of specified style in document.**: Map of Nigeria showing Rivers State, and Creeks around Okrika Local Government Area**
Source: Adapted and Modified from Ogunola *et al.* (2017)

Materials and Methods

Sampling Technique

This study adopted the purposive sampling procedure. This is the sampling technique that allows the researcher to sample location/points/stations along creeks in Okrika LGA. The sampled point and their coordinate were determined using the Global Positioning System (GPS) Gainim Channel 78 Model. The samples were collected during wet and dry seasons at the same locations along the selected creeks for study. This sampling procedure helped the researcher collect samples that are logically assumed to be representative of the entire creeks selected for study stretch and that of entire creeks in Okrika LGA.

Surface Water Collection

All sample containers for water sample collection were rinsed with the water being sampled before the sample was placed into the containers. The water samples were collected with the aid of a stainless-steel surface water sampler. Samples were then transferred into amber bottles measuring 250 mL for analysis for biological oxygen demand, which were incubated for 5 days at 20 °C, for BOD_5 and Dissolved Oxygen (DO). Prior to laboratory analysis, the samples for BOD_5 analysis were fixed with 2 mL of Winkler I and II reagents. Samples for physicochemical parameters were collected in 2 L plastic containers. Water samples for heavy metals analyses were collected in plastic vials and fixed with 2% nitric acid to preserve the integrity of the samples before they were taken to the laboratory for analyses.

Samples for microbial analysis were collected in sterile vials. The samples and their points/locations/stations were selected using the purposive sampling procedure. Thus, the purposive sampling method allowed the researcher to sample locations/points/stations along creeks around Okrika community. The sampling procedure helped to produce samples that were logically assumed to be representative of the entire creeks of the communities in Okrika Local Government Area. All the laboratory tests were carried out at ambient laboratory temperature, while measurements were done in triplicates and the average values were recorded.

Spatial Variations in Data Collection

Samples/data were collected from multiple designated points across selected creeks to assess spatial variability in environmental conditions. The sampling locations include Okochiri Creek, Ekerekana Creek, Okpoka-Toru Creek, and Oba Ama Creek. At each site, samples were obtained from consistent, predefined coordinates to ensure comparability across space. This spatial approach allows for the identification of localised differences in water quality and potential impacts of nearby anthropogenic activities such as industrial effluent discharges. Data were collected during both wet and dry seasons to maintain temporal consistency across the spatial grid of sampling points. This harmonised method of data collection ensured consistency in sample collection and analysis across water, sediment, and fish, with referenced locations thereby enhancing the reliability and comparability of the results.

Materials for Samples Collection

The instrument for collecting data/samples for this study includes:

i. **Water Sampler:** The water sampler (stainless steel) was used to collect surface water samples and preserved in designated cans and vials for physicochemical and heavy metals parameters.

ii. **Amber Bottles (250 mL):** The water samples were collected and put in Amber bottles measuring 250 mL for analysis of Biological Oxygen Demand (BOD) in the laboratory for 5 days at 20 °C and Dissolved Oxygen (DO). The BOD_5 analysis were fixed with 2 mL of Winkler I and II reagents.

iii. **Multi-Parameter Probes (Model 430):** This was used to measure in-situ physicochemical parameters on the field such as pH, temperature, turbidity, conductivity, total dissolved solids, dissolved oxygen, and salinity.

iv. **Plastic Containers (2 L):** Employed for collecting water samples meant for general physicochemical parameters such as temperature, conductivity, pH, total dissolved solids, and salinity.

v. **Plastic Vials (pre-cleaned):** Used to collect water samples for heavy metals analysis and fixed with 2% nitric acid to preserve the integrity of the samples hence, preventing degradation before reaching the laboratory.



Figure 2: Map of Nigeria showing Rivers State, and Creeks around Okrika Local Government Area

Source: Adapted and Modified from Ogunola *et al.* (2017)

Samples Analysis

The samples collected were analysed for physical and chemical parameter using the standard laboratory analytical methods by (ASTM, 2005; APHA, 2017).

Laboratory Analysis

Filtered water samples (100 mL each) were subjected to acid digestion by adding 5 mL of concentrated HNO_3 and 15 mL of HCl. The mixture was heated gently until reduced to approximately 20 mL. After cooling, each digest was filtered if needed, and the final volume were made up to 50 mL with deionised water.

Heavy metal concentrations were determined using an Atomic Absorption Spectrophotometer (AAS), calibrated with certified standards and fitted with element-specific hollow cathode lamps. The wavelengths for each metal was:

Pb – 283.3 nm; Zn – 213.9 nm; Cu – 324.8 nm; Cd – 228.8 nm; and Cr – 357.9 nm

Quality assurance was ensured through the use of blanks, replicates, and reference materials to validate the accuracy and precision of the results.

The results was calculated using the formula (WHO, 2017):

$$Metal\ Concentration\left(\frac{\frac{mg}{L\ or\ mg}}{kg}\right) = \frac{AAS\ Reading \times Final\ Volume\ (mL)}{Sample\ Volume\ (mL)\ or\ Weight\ (g)} \quad (3.8)$$

The analysis provided baseline data on the levels of heavy metal contamination across the three sample types, offering insights into the potential bioaccumulation in aquatic organisms and contamination of aquatic environments. This information formed the basis for risk assessment and environmental management recommendations within the study area.

Ecological and Health Risk Assessment

The Human Health Risk Assessment of Heavy metals in the surface voter was done using framework as proposed by USEPA (2010).

Average Daily Dose (ADD): Average Daily Dose (ADD) for the heavy metal levels was calculated using Equations 3.14 and 3.15 for exposure via ingestion (ADD_{ing}) and dermol ($ADDd_{erm}$) pathways respectively.

$$ADD_{ing}\ (mg^{-1}\ L^{-1}\ day^{-1}) = \frac{(C_x \times Ir \times Ef \times Ed)}{(Bwt \times At)}$$

Where ADD_{ing} is the Average Daily Dose through ingestion per kilogram of body weight. C_x is the concentration of toxic metals in drinking water (mg/L), lr is the ingestion rate per unit time (L/day), Ed is the Exposure Duration (years), which is equal to the life expectancy of a resident Nigerian, Ef is the exposure frequency (days/ year), Bwt is body weight (kg), and A_t is the Averaging Time (Ed x Ef). For the conversion factor from years to days, 365 days is to be used.

$$ADD_{derm}\ (mg^{-1}\ L^{-1}\ day^{-1}) = \frac{(C_x \times Sa \times Pc \times Et \times Ef \times Ed \times Cf)}{(Bwt \times At)}$$

Where ADD_{derm}, is the Average Daily Dose through dermal exposure, Sa is the total Skin Surface Area (cm^3), Cf is the Volumetric Conversion Factor for water ($1L/1000cm^3$), Cf is the Exposure Time (h/day). Pc is the Chemical-Specific Dermal Permeability Constant (cm/h), Ef is the Exposure Frequency (days/years), Ed is the Exposure Duration (years), and Boil is Body Weight.

Hazard Assessment: The hazard level was assessed by comparing the calculated Contaminant dose from ingestion and dermal exposure routes with the Reference Dose (RfD) to develop the Hazard Quotient (HQ) using Equations 3.16 and 3.17 below.

$$HQ_{ing} = \frac{ADD_{ing}}{RfD_{ing}}$$

$$HQ_{derm} = \frac{ADD_{derm}}{RfD_{derm}}$$

HQ represents the Hazard Quotient via ingestion or dermal contact (no units) and RfD is the oral/ dermal reference dose (mg/L/day).
The Hazard Index (Hl) was calculated as the sum of hazard Quotients

$$HI = HQ_{ing} + HQ_{derm}$$

Carcinogenic Risk: Carcinogenic Risks or the metals was determined using Equation below:

$$CR_{ing} = \frac{ADD_{ing}}{SF_{ing}}$$

Where CR_{ing} represents the carcinogenic risk due to ingestion pathway, and SF is the slope factor (mg/L/day).
The slope factor (SF) is a toxicity value that quantitatively defines the relationship between dose and response' (USEPA, 2004). Standard exposure parameters and Slope Factor values or the various metals are found in Tables 1 and 2. The projected intakes and slope factor of heavy metals are used to estimate the potential carcinogenic risks over a lifetime exposure. The range for carcinogenic risk acceptable or tolerable by United States Environmental Protection Agency is l $x10^{-6}$ to l $x10^{-4}$ (USEPA, 2004).

Table 1: Standard Values for Calculating Exposure Assessment in Groundwater Samples

Exposure Factors	Adult	Child
Concentration of Metals (mg/U)	-	-
Exposure Frequency (days/year)	365	365
Water Ingestion Rate (L/day)	2.2	11
Exposure Duration (years)	55	6
Average Body Weight (Kg)	70	15
Average Time (days)	20,075	2190
Exposed Skin Area (cm^2)	18,000	6,600
Exposure Time (h/day)	0.58	1
Unit Conversion Factor (L/cm^3)	$1x10^{-3}$	1×10^{-3}

Source: USEPA (2004)

Table 2: Standard Values of Health Risk Parameters for Heavy Metals

Parameter	Lead (Pb)	Zinc (Zn)	Copper (Cu)	Cadmium (Cd)	Chromium (Cr)
Dermal Permeability Coefficient (cm/h)	1×10^{-3}	6.3×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Slope Factor (oral) $(mg/kg/day)^{-1}$	8.51×10^{-3}	–	–	1.8×10^{-3}	6.12
Reference Dose (oral) (mg/kg/day)	1.4×10^{-3}	3.0×10^{-1}	4.0×10^{-2}	1.0×10^{-3}	5.0×10^{-2}
Reference Dose (dermal) (mg/kg/day)	4.2×10^{-3}	6.0×10^{-2}	1.2×10^{-2}	5.0×10^{-4}	2.5×10^{-5}

Source: USEPA, (2011); NESREA, (2011); WHO, (2017); ATSDR, (2020); USEPA, (2023)

Results and Discussion

Table 3 presents the mean concentrations (± standard deviation) of selected heavy metals and PAHs in water samples (WS1–WS3) collected from creeks around Okrika communities. Calcium (Ca) concentrations ranged from 18.692 ± 10.269 mg/L in WS3 to 55.127 ± 30.288 mg/L in WS1, indicating spatial variability likely influenced by geogenic sources such as limestone dissolution and anthropogenic inputs from industrial effluents. Magnesium (Mg) levels were relatively high in WS1 (18.564 ± 7.989 mg/L) and WS2 (20.775 ± 10.794 mg/L), but were below detectable limits in WS3, suggesting dilution effects or adsorption onto suspended particulates.

Iron (Fe) concentrations ranged from 1.184 ± 0.902 mg/L in WS2 to 1.444 ± 0.981 mg/L in WS3, remaining within tolerable limits for natural surface water but indicative of mild contamination possibly arising from corroded pipelines or industrial discharge. Copper (Cu) levels were low (0.028–0.056 mg/L) across all stations, consistent with trace anthropogenic influence, while Zinc (Zn) concentrations (0.162–0.186 mg/L) were slightly higher, reflecting its more mobile nature in aquatic systems. Lead (Pb) showed noTable variation, increasing sharply in WS2 (0.166 ± 0.598 mg/L) compared to WS1 (0.007 ± 0.013 mg/L) and WS3 (0.010 ± 0.016 mg/L), suggesting localised pollution hotspots possibly linked to petroleum-related activities or atmospheric deposition from vehicular emissions. Cadmium (Cd), Chromium (Cr), Manganese (Mn), and Nickel (Ni) were below detectable limits (0.000 ± 0.000 mg/L) across all stations, indicating minimal contamination from these metals, which may be due to low industrial discharges or strong sediment adsorption limiting their solubility. Polycyclic Aromatic Hydrocarbons (PAHs) were uniformly low (0.001 ± 0.000 mg/L) across all sites, implying either minimal hydrocarbon input or rapid degradation of these compounds under aerobic conditions. The biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were moderate, averaging 3.445 mg/L and 10.981 mg/L respectively, indicating slight organic loading, while the dissolved oxygen (DO) remained high (8.406 mg/L), suggesting healthy oxygenation capable of supporting aquatic life.

Table 4 summarises the analysis of variance (ANOVA) results for heavy metal concentrations across the three sampling stations. The ANOVA revealed significant variation among the parameters ($F = 10.778$, $p < 0.001$), indicating that the distribution of heavy metals differs significantly among the measured variables. However, differences between stations were not statistically significant ($F = 1.998$, $p = 0.158$), suggesting spatial homogeneity in contamination

levels across the creek system. The total sum of squares (SS = 5621.61) and high row variance indicate that variability is primarily driven by differences in metal type rather than sampling location. This pattern implies that certain metals, such as calcium and magnesium, dominate the ionic composition and contribute more to overall variability, while trace metals like cadmium and chromium exhibit negligible variation. The absence of significant spatial difference suggests that the pollution sources influencing the creeks—such as industrial discharges, urban runoff, and saltwater intrusion—are evenly distributed across sampling sites. The high F-value for parameters underscores the heterogeneous nature of ionic constituents in the water, reflecting complex geochemical and anthropogenic interactions in Okrika's aquatic ecosystem.

Table 5 presents the correlation matrix showing interrelationships among physicochemical parameters and heavy metals. A strong positive correlation was observed between calcium (Ca) and magnesium (Mg) (r = 0.955), indicating a common geologic origin such as carbonate dissolution. Dissolved oxygen (DO) also exhibited strong associations with both Ca (r = 0.948) and Mg (r = 0.9997), suggesting that oxygenation enhances metal solubility and stability in water. Copper (Cu), however, showed a strong negative correlation with Ca (r = –0.999) and Mg (r = –0.943), implying antagonistic behavior, possibly due to competition for adsorption sites or differing redox sensitivities. Lead (Pb) correlated negatively with iron (Fe, r = –0.967) but positively with Mg (r = 0.568), highlighting mixed anthropogenic and lithogenic sources. The positive relationship between biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (r = 0.973) indicates that organic pollution contributes substantially to oxygen depletion in the water column. Zinc (Zn) showed moderate positive correlations with Ca (r = 0.774) but negative with Cu (r = –0.797), suggesting differential solubility and mobility patterns. Overall, these correlations indicate that water quality in Okrika creeks is influenced by both natural geochemical processes and anthropogenic activities such as effluent discharge and petroleum contamination, resulting in complex ionic and metal interactions that govern aquatic chemistry.

Table Error! No text of specified style in document.**: Concentrations of Heavy Metals in Water Samples from Okrika Creeks**

S/N	Parameter	WS 1	WS 2	WS 3
1	Calcium (Ca)	55.127 ± 30.288	47.330 ± 29.988	18.692 ± 10.269
2	Magnesium (Mg)	18.564 ± 7.989	20.775 ± 10.794	0.000 ± 0.000
3	Manganese (Mn)	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
4	Cadmium (Cd)	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
5	Chromium (Cr)	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
6	Copper (Cu)	0.028 ± 0.021	0.035 ± 0.026	0.056 ± 0.104
7	Iron (Fe)	1.379 ± 0.959	1.184 ± 0.902	1.444 ± 0.981
8	Lead (Pb)	0.007 ± 0.013	0.166 ± 0.598	0.010 ± 0.016

9	Nickel (Ni)	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
10	Zinc (Zn)	0.186 ± 0.086	0.166 ± 0.110	0.162 ± 0.096

Table 1: ANOVA Results for Heavy Metal Concentrations in Water Samples

Summary	Count	Sum	Average	Variance
Calcium (Ca)	3	121.149	40.383	368.0729
Magnesium (Mg)	3	39.339	13.113	130.1852
Manganese (Mn)	3	0	0	0
Cadmium (Cd)	3	0	0	0
Chromium (Cr)	3	0	0	0
Copper (Cu)	3	0.119	0.039667	0.000212
Iron (Fe)	3	4.007	1.335667	0.018308
Lead (Pb)	3	0.183	0.061	0.008271
Nickel (Ni)	3	0	0	0
Zinc (Zn)	3	0.514	0.171333	0.000165
Total	5621.61	38		

Note: Undefined Correlations (0)

Table 2: Correlation Matrix of Heavy Metals in Water Samples

	Ca	Mg	Mn	Cd	Cr	Cu	Fe	Pb	Ni	Zn	BOD	Do	COD
Calcium (Ca)	1												
Magnesium (Mg)	0.9548	1											
Manganese (Mn)	0	0	1										
Cadmium (Cd)	0	0	0	1									
Chromium (Cr)	0	0	0	0	1								
Copper (Cu)	-0.9993	-0.9429	0	0	0	1							
Iron (Fe)	-0.5325	-0.7599	0	0	0	0.5	1						
Lead (Pb)	0.2979	0.5681	0	0	0	-0.2615	-0.9666	1					
Nickel (Ni)	0	0	0	0	0	0	0	0	1				
Zinc (Zn)	0.7735	0.5503	0	0	0	-0.7970	0.1245	-0.3746	0	1			

Key: Calcium (Ca), Magnesium (Mg), Manganese (Mn), Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe), Lead (Pb), Nickel (Ni), Zinc (Zn), Note: Undefined Correlations (0)

Geo-Accumulation Index (Igeo) Evaluation of Metal Contamination

The Igeo results in Table 7 and Figure 3 show that all metals have values well below zero, indicating that the study area is practically uncontaminated by these elements. Sodium, potassium, calcium, and magnesium have the highest mean concentrations among the metals, but their Igeo values remain strongly negative, reflecting their natural occurrence rather than anthropogenic enrichment. Trace metals such as cadmium, chromium, nickel, and lead also show extremely low Igeo values, confirming minimal pollution impact. Zinc and copper have slightly higher concentrations relative to some other trace metals, but their Igeo values still indicate negligible contamination. Overall, the data suggest that both major and trace metals are present at natural background levels. This implies that there is no significant human-induced metal contamination in the sampled area.

Table 7: Mean Metal Concentrations, Background Values, and Geo-accumulation Index (Igeo)

Parameter	Mean	Background	Igeo
Na	88.8116667	12000	-7.66303198
K	8.94533333	20000	-11.7115396
Ca	221.885	37000	-7.96653182
Mg	34.5503333	2200	-6.57762258
Mn	0.07966667	600	-13.4636612
Cd	0.00033333	0.06	-8.0768156
Cr	0.00033333	90	-18.6275624
Cu	0.14166667	55	-9.18574997
Fe	3.23666667	35000	-13.985521
Pb	0.03666667	20	-9.67627767
Ni	0.00033333	47	-17.6902981
Zn	0.56333333	70	-7.54218477

Background: Typical natural abundance of the metal in soil or sediment.
Igeo (Geo-accumulation Index): Indicates the degree of metal pollution.
Igeo $< 0 \rightarrow$ practically uncontaminated
$0 \leq$ Igeo $< 1 \rightarrow$ uncontaminated to moderately contaminated
Igeo $\geq 1 \rightarrow$ increasing levels of contamination

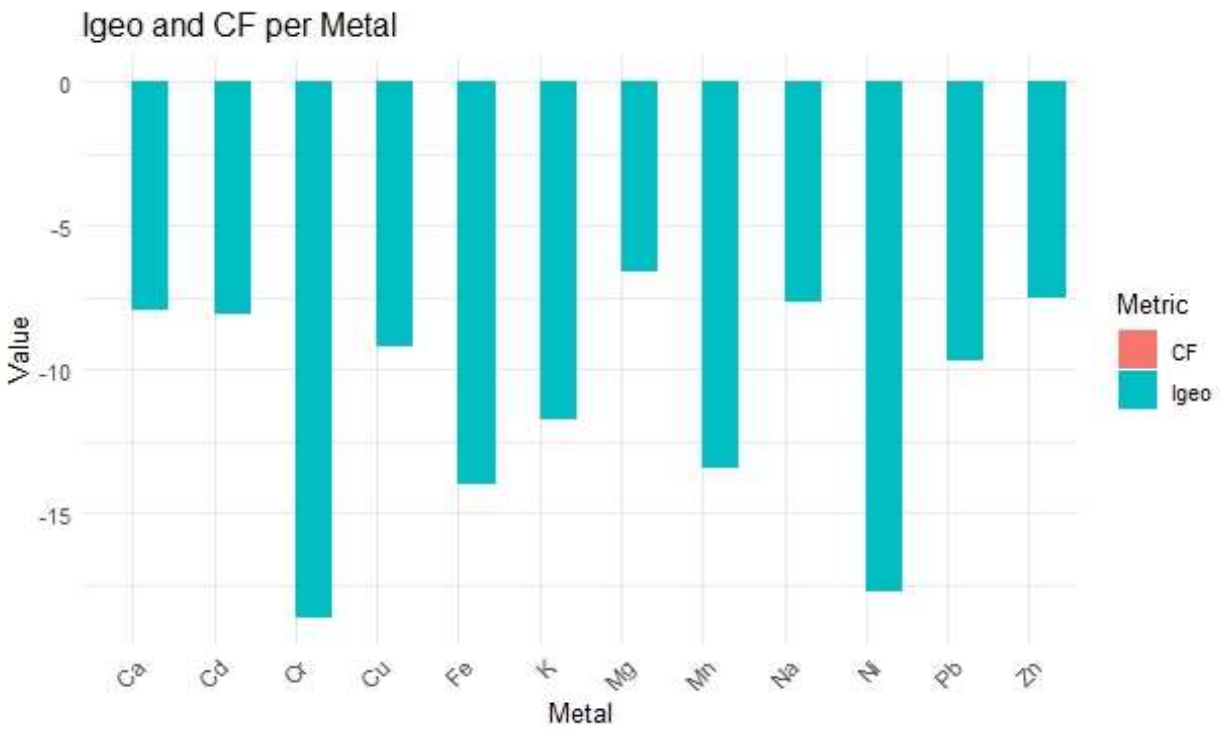


Figure 3: Geo-Accumulation Index (Igeo)

The Contamination Factor

The Contamination Factor (CF) results in Table 8 and Figure 4 indicate that all metals in the study area have values well below 1, suggesting low contamination levels. Magnesium shows the highest CF (0.0157) among the metals, but it still indicates minimal anthropogenic influence. Trace metals such as cadmium, chromium, nickel, and lead have extremely low CF values, confirming that they are present mostly at natural background levels. Zinc and copper have slightly higher CFs compared to other trace metals, but they remain in the low contamination category. Overall, the data suggest that both major and trace metals in the area are not significantly enriched due to human activities. This implies that the sampled environment is practically uncontaminated with respect to the measured metals.

Table 8: Mean Metal Concentrations, Background Values, and Contamination Factor (CF)

Parameter	Mean	Background	CF
Na	88.8116667	12000	0.00740097
K	8.94533333	20000	0.00044727
Ca	221.885	37000	0.00599689
Mg	34.5503333	2200	0.0157047
Mn	0.07966667	600	0.00013278
Cd	0.00033333	0.06	0.00555556
Cr	0.00033333	90	3.7037E-06
Cu	0.14166667	55	0.00257576
Fe	3.23666667	35000	9.2476E-05
Pb	0.03666667	20	0.00183333
Ni	0.00033333	47	7.0922E-06
Zn	0.56333333	70	0.00804762

CF (Contamination Factor) = Mean concentration ÷ Background concentration.
CF < 1 → low contamination
CF 1–3 → moderate contamination
CF 3–6 → considerable contamination
CF > 6 → very high contamination

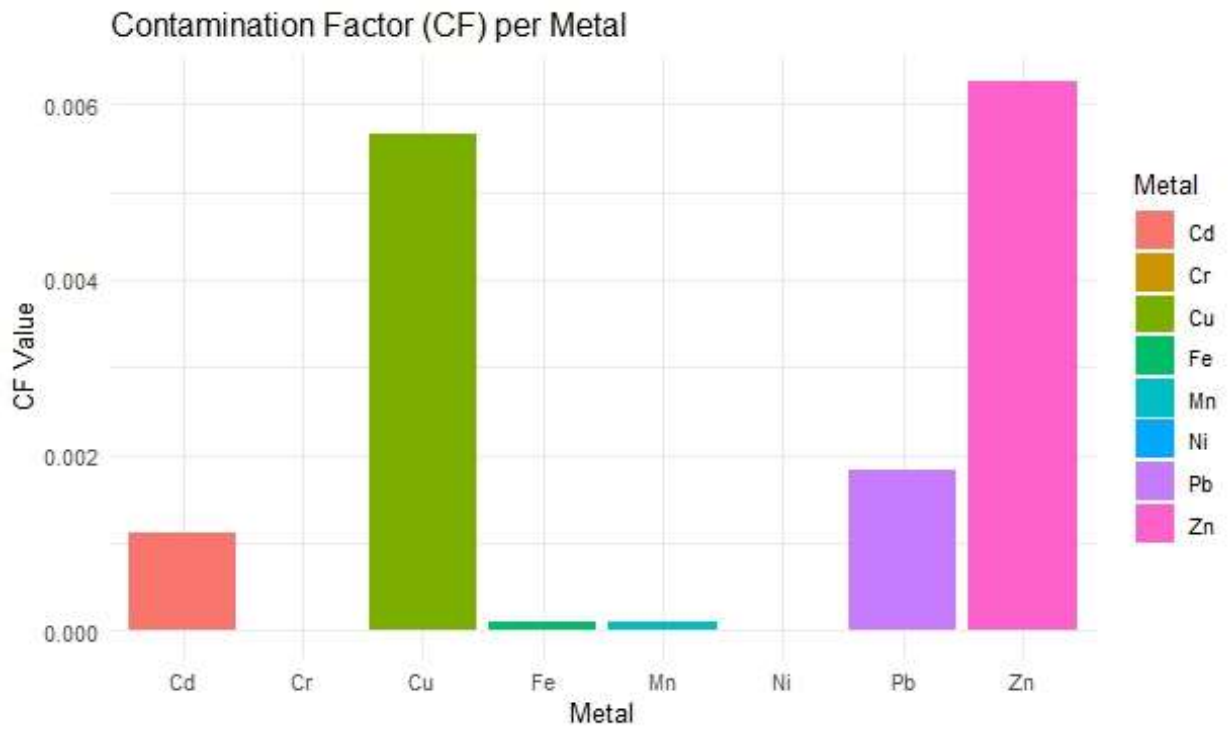


Figure Error! No text of specified style in document.**.: The Contamination Factor of Metals**

Pollution load Index

The Pollution Load Index (PLI) values for all three stations are well below 1, indicating that the sites are essentially unpolluted with respect to metals. Station S3 has a slightly higher PLI (0.000895) compared to S1 and S2, but this value is still extremely low, reflecting negligible contamination. Stations S1 and S2 have a PLI of 0, confirming that there is no detectable pollution at these locations. Overall, the results suggest that the study area is practically free from metal contamination. This aligns with the low Contamination Factor (CF) and Igeo values observed for the same metals, indicating a naturally clean environment.

Table *9*: Pollution Load Index (PLI) for the Sampled Stations

Station	PLI
S1	0
S2	0
S3	0.00089454

PLI (Pollution Load Index) provides an overall assessment of metal pollution at a site.
PLI = 1 → baseline level of pollution
PLI < 1 → no pollution
PLI > 1 → progressive site pollution

Ecological Risk Factor Assessment

The ecological risk assessment shows that most metals in the study area have very low Er_i values, indicating minimal potential ecological risk. Magnesium, sodium, potassium, and calcium have CF values slightly above zero, but their ecological risk remains negligible due to low toxic

response factors. Cadmium poses the highest risk at Station S3, with an Er_i of 0.5, reflecting its high toxic response factor, though it is still below the threshold of 1 for moderate risk. Other trace metals such as chromium, nickel, copper, lead, and zinc show extremely low Er_i values, suggesting they do not significantly threaten the ecosystem. Overall, the results indicate that the study area is largely uncontaminated and ecologically safe with respect to the measured metals. Continuous monitoring, especially for cadmium, is recommended to ensure the long-term ecological integrity of the site.

Table 10: Contamination Factor (CF) and Ecological Risk Factor (Er_i) for Metals at Sampled Stations

Parameter	Tr	CF_S1	CF_S2	CF_S3	Er_i_S1	Er_i_S2	Er_i_S3
Na		0.0076	0.0073	0.0073			
K		0.0005	0.0004	0.0005			
Ca		0.0060	0.0058	0.00612538			
Mg		0.0155	0.0160	0.0156			
Mn	1	0.0001	0.0002	0.0001	0.0001	0.0002	0.0001
Cd	30	0	0	0.0167	0	0	0.5
Cr	2	0	0	1.1111E-05	0	0	2.2222E-05
Cu	5	0.0027	0.0027	0.0024	0.0133	0.0133	0.0121
Fe	1	9.2086E-05	0.0001	9.3743E-05	9.2086E-05	0.0001	9.3743E-05
Pb	5	0.0019	0.0025	0.0011	0.0098	0.0125	0.0053
Ni	5	0	0	2.1277E-05	0	0	0.0001
Zn	1	0.0079	0.0081	0.0081	0.0079	0.0081	0.0081

Tr = Toxic response factor for each metal.
CF (Contamination Factor) = Mean metal concentration ÷ Background concentration.
Er_i (Ecological Risk Factor) = CF × Tr, represents the potential ecological risk posed by individual metals.
Metals with **$Er_i > 1$** indicate moderate to high ecological risk, while **$Er_i < 1$** suggests low risk.

The Potential Ecological Risk Index (PERI)

The Potential Ecological Risk Index (PERI) results indicate that all three stations are within the low ecological risk category. Stations S1 and S2 have very low PERI values (0.031 and 0.034), suggesting minimal cumulative ecological risk from the measured metals. Station S3 has a slightly higher PERI (0.526), largely due to the presence of cadmium, but it still falls well below the threshold for moderate risk. Overall, the results suggest that the study area is ecologically safe,

with negligible impact from metal contamination. Continuous monitoring is recommended, especially at S3, to ensure that no future accumulation of toxic metals elevates the ecological risk.

Table 11: Potential Ecological Risk Index (PERI) for Sampled Stations

Station	PERI
S1	0.03121362
S2	0.03408242
S3	0.52578754

PERI (Potential Ecological Risk Index) is the **sum of individual ecological risk factors (Er_i)** for all metals at a station.
PERI < 150 → low ecological risk
PERI 150–300 → moderate risk
PERI 300–600 → considerable risk
PERI > 600 → very high risk
The present study on heavy metals in water samples from creeks around Okrika communities reveals patterns of contamination that are comparable to several studies across Nigeria and other regions of the world, though some parameters display site-specific deviations attributable to industrial, anthropogenic, and geochemical factors. The findings suggest that while the concentrations of major cations and heavy metals such as calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), zinc (Zn), and lead (Pb) in Okrika creeks generally fall within expected ranges for coastal and industrially influenced waters, certain values point to localised environmental pressures, particularly those linked to oil-related activities typical of the Niger Delta.
The calcium and magnesium concentrations in Okrika creeks (Ca: 18.7–55.1 mg/L; Mg: 18.6–20.8 mg/L) are consistent with observations in various Nigerian freshwater systems, such as those in Osun State where Ca ranged from 6.4–232 mg/L and Mg from 2–71 mg/L, as reported by Titilawo *et al.* (2018). These similarities indicate that natural mineral dissolution and rock-water interactions largely control Ca and Mg levels, though anthropogenic inputs such as detergent and domestic waste effluents may contribute to elevated hardness. The slightly narrower range of Mg in Okrika compared to Osun State rivers suggests a more uniform geochemical background or limited variability in sediment mineralogy. However, the detectable difference in Ca levels across stations—higher at WS1 and lower at WS3—could be associated with differential runoff or proximity to industrial discharge points. This pattern aligns with Aluwong *et al.* (2024), who found spatial variation in Ca and Mg concentrations in northern Nigerian rivers influenced by agricultural and industrial inputs. In terms of iron, copper, and zinc, the Okrika values (Fe: 1.18–1.44 mg/L; Cu: 0.028–0.056 mg/L; Zn: 0.16–0.19 mg/L) generally fall within the moderate contamination range observed in similar aquatic environments. For instance, Wogu & Okaka (2011) reported Fe levels up to 1.93 mg/L in the Warri River, which is slightly higher than Okrika's concentrations, reflecting more intense industrial activity and petroleum waste discharge in that area. Similarly, Ocheni (2021) recorded comparable Fe concentrations in the Niger Delta creeks, indicating that iron, while naturally abundant in lateritic soils, can also be mobilised by oil pollution and corroded pipelines. Copper and zinc levels in Okrika are comparable to values found in other non-mining regions of Nigeria, supporting the notion that their presence may stem from domestic and urban runoff rather than direct industrial discharge. However, Cu and Zn concentrations are much lower than those recorded in heavily polluted water bodies near industrial zones or electroplating

industries, suggesting that Okrika's metal contamination is moderate and potentially manageable through better waste regulation. Lead (Pb) concentrations in Okrika creeks (up to 0.166 mg/L) exhibit localised elevation, particularly in WS2, which may be linked to petroleum-derived contaminants or the use of leaded materials in nearby industrial facilities. This finding aligns closely with those from Bakana River, where Okoro & Konyeme (2025) reported Pb at 0.132 mg/L and Cd at 0.014 mg/L. These similarities reinforce the idea that both areas, being within the same ecological and industrial region of the Niger Delta, are exposed to similar pollution pressures from oil exploration and artisanal refining activities. However, when compared to the Osun State rivers, where Pb and Cd were often undetectable (Titilawo *et al.*, 2018), Okrika's results clearly demonstrate the impact of industrialisation and hydrocarbon exploitation on trace metal accumulation. The below-detection levels of cadmium (Cd), chromium (Cr), manganese (Mn), and nickel (Ni) in Okrika creeks also contrast with elevated concentrations observed in mining regions such as parts of Plateau and Zamfara States, where these metals are mobilised by mineral extraction processes (Aluwong *et al.*, 2024; Obasi & Akudinobi, 2020). This contrast underscores the specificity of heavy metal signatures to dominant local activities: oil-related pollution in the Niger Delta tends to favor Pb and Fe enrichment, while mining areas show higher Cd, Cr, and Ni.

The correlation analysis in the Okrika study further supports well-established patterns in aquatic geochemistry. The strong positive relationship between calcium and magnesium ($r = 0.955$) indicates a shared geochemical source or similar mobilisation processes, a finding consistent with Aluwong *et al.* (2024), who also reported such interdependence in northern Nigerian rivers. Likewise, the high correlation between biochemical oxygen demand (BOD) and chemical oxygen demand (COD) ($r = 0.973$) reflects the influence of organic pollution from domestic and industrial effluents, similar to observations in Sedigheh *et al.* (2021) who noted analogous relationships in industrially influenced waters in Iran. The negative correlations, such as between copper and calcium ($r = –0.999$) and between lead and iron ($r = –0.967$), may suggest competitive adsorption or antagonistic interactions between these elements during transport and sedimentation. This pattern has been observed in several studies, where heavy metals with differing ionic potentials compete for binding sites on particulate matter, influencing their bioavailability and persistence.

When compared to other creeks in Nigeria, the PAH concentrations in Okrika waters (0.001 mg/L) appear significantly lower. For example, Ihunwo *et al.* (2019) recorded PAH levels between 6–29 mg/L in Woji Creek, another Niger Delta water body with intense hydrocarbon pollution and frequent artisanal refining. Similarly, Umeh *et al.* (2023) found PAH concentrations between 1.0–29.3 mg/L in Nigerian surface waters impacted by oil spills and industrial discharge, while Tongo *et al.* (2017) reported 0.002–0.026 mg/L in the Ovia River. The extremely low PAH concentration in Okrika may thus be attributed to seasonal variation, dilution by tidal inflow, or differences in sampling depth and timing. Furthermore, it is possible that local remediation or self-purification processes, such as microbial degradation, are more effective in this area, leading to lower hydrocarbon persistence. This interpretation aligns with global findings by Mojiri *et al.* (2019), who noted that PAH concentrations in some coastal waters can fall below detectable limits during periods of high rainfall or water exchange. However, considering Okrika's proximity to petroleum refineries and hydrocarbon-handling facilities, the low PAH levels contrast with expectations and suggest the need for longitudinal monitoring to account for temporal fluctuations.

The combined interpretation of the physicochemical parameters and xenobiotic concentrations in Okrika creeks indicates a water quality condition that is moderately impacted but not severely degraded. The BOD (3.445 mg/L), COD (10.981 mg/L), and DO (8.406 mg/L) values imply a balance between organic load and oxygenation, which is typical for semi-polluted but ecologically

functional aquatic systems. This profile aligns with findings from Amachree and Mon (2025), who reported similar oxygen-demand parameters in the Eleme–Onne industrial axis, noting that although organic pollution was evident, the waters retained sufficient oxygen to support aquatic life. The significant variation among parameters ($F = 10.778$, $p < 0.001$) but non-significant difference among stations ($F = 1.998$, $p = 0.158$) suggests uniform pollution pressure across the study area, a feature common in tidally influenced systems where mixing reduces spatial variability. This agrees with patterns reported by Umeh *et al.* (2023), where PAH and metal concentrations showed low spatial variation due to tidal flushing in coastal estuaries.

Comparatively, global studies reveal that Okrika's water quality is moderate. For instance, PAH levels in some European rivers fall within the nanogram per liter (ng/L) range, reflecting stringent pollution controls, while in parts of Asia and the Middle East, especially industrial zones, concentrations can exceed several micrograms per liter (Mojiri *et al.*, 2019). Similarly, the levels of Fe, Pb, and Zn in Okrika waters are lower than those reported in heavily industrialised regions of China or India but higher than pristine rivers in Europe or North America. These comparisons highlight the transitional pollution status of Okrika—neither unpolluted nor severely contaminated, but exhibiting anthropogenic influence that warrants continued monitoring and management. In synthesis, the present study aligns broadly with national and international patterns regarding heavy metal and PAH contamination in aquatic ecosystems, though it exhibits distinct local characteristics. The heavy metals measured correspond closely with concentrations found in other Niger Delta water bodies, affirming the influence of oil-related and industrial activities. The low PAH levels, in contrast, deviate from expectations and may signify localised dilution or temporal reduction in hydrocarbon discharge. Correlation analyses further reinforce known geochemical and pollution dynamics, with metal-metal and organic-organic associations reflecting both natural processes and anthropogenic inputs. Thus, while the findings are largely consistent with previous research, they also introduce nuances that expand understanding of pollutant behavior in coastal and oil-influenced aquatic environments of southern Nigeria.

Health Risks Associated with Heavy Metals in Water Samples

The present study on heavy metal-associated health risks in creek waters from Okrika communities provides an important understanding of the toxicological implications of environmental exposure to trace metals in a highly industrialised coastal region. The results reveal that the Hazard Quotient (HQ) values for both ingestion and dermal exposure were below 1 for all metals, and the overall Hazard Index (HI) and Carcinogenic Risk (CR) values were below critical thresholds for both children and adults. These outcomes indicate that, at the time of sampling, non-carcinogenic and carcinogenic risks from exposure to heavy metals such as Fe, Cu, Zn, Mn, Ni, Cd, Cr, and Pb are minimal, suggesting low potential for adverse health effects. When compared with findings from other Nigerian and global studies, the results from Okrika show both strong alignment with regions of low contamination and clear contrast with highly polluted sites where heavy metal risks often exceed safe limits. The Hazard Quotient (HQ) values in the Okrika creeks reflect a consistent pattern of low exposure risk. For ingestion, Cu recorded the highest HQ (0.0506 for children and 0.0217 for adults), followed by Fe (0.0229; 0.0098) and Zn (0.0225; 0.0096), while Ni, Mn, Cd, and Cr showed negligible contributions. Similarly, dermal HQ values were also low, with Fe and Cu again contributing most significantly, yet still below unity. This trend is characteristic of low-risk aquatic systems, where metal concentrations are either naturally regulated or sufficiently diluted to prevent toxic accumulation. The pattern observed in Okrika aligns closely with that reported in Gombe State, northern Nigeria, where Balogun *et al.* (2023) found HQ values for all

metals below 1 for both adults and children. Likewise, studies conducted in less industrialised environments in Iran and Tunisia (Mohammadi *et al.*, 2019; Troudi *et al.*, 2022) reported similar results, where HQ and HI values were below critical limits, signifying negligible non-carcinogenic health risks. This agreement indicates that despite Okrika's proximity to industrial and oil-related activities, the bioavailability of metals in the sampled environment remains relatively low, possibly due to sediment sequestration or limited anthropogenic discharge during the study period.

However, when compared to several other studies across Nigeria, a notable contrast emerges. In industrial and oil-impacted regions such as Nnewi, Awka, Aleto-Eleme, and Burutu, HQ and HI values frequently exceed 1, suggesting significant health risks, particularly for children. For example, Ayejoto and Egbueri (2023) reported HQ and HI values greater than unity for Cd and Pb in Nnewi and Awka groundwater, indicating potential non-carcinogenic hazards due to extensive industrial discharges and poor waste management. Similarly, Oni *et al.* (2022) and Bawa-Allah (2023) observed elevated HQ values in surface waters of the Benin River and the Aleto-Eleme axis of the Niger Delta, primarily attributed to refinery emissions, metal scrap recycling, and effluent from petrochemical industries. In these studies, children exhibited higher HQ and HI values than adults, reflecting greater vulnerability due to higher intake rates per body weight. This contrasts sharply with Okrika, where HQ values were substantially lower, suggesting that despite the industrial setting, metal concentrations have not yet reached toxic thresholds capable of inducing significant health effects. The Hazard Index (HI) values in Okrika creeks also reflect minimal cumulative non-carcinogenic risk. The total HI values were 0.51 for children and 0.0797 for adults, both far below the critical limit of 1. This indicates that combined exposure to all metals through both ingestion and dermal contact does not pose a significant threat to human health. This finding is consistent with results from Balogun *et al.* (2023), who reported similar HI values below 1 in Gombe State waters. Studies in Tunisia and Iran (Mohammadi *et al.*, 2019; Troudi *et al.*, 2022) have also recorded HI values below unity, signifying that populations exposed to such low metal concentrations are not at risk of cumulative non-carcinogenic effects. Conversely, studies in Aleto-Eleme and Benin River systems (Ezemonye *et al.*, 2018; Eruke *et al.*, 2025) documented HI values exceeding 1, indicating potential chronic health implications, particularly for children exposed to Cd, Pb, and Ni. This discrepancy highlights the spatial variability of pollution intensity across regions, with Okrika currently representing a comparatively low-risk zone within the Niger Delta's complex pollution landscape. The Carcinogenic Risk (CR) assessment provides further insight into potential long-term effects. In the Okrika study, Cd exhibited CR values of 6.44×10^{-6} for children and 2.85×10^{-6} for adults, while Cr showed CR values below 1×10^{-6}. These results indicate negligible cancer risk since the acceptable limit for lifetime cancer risk typically falls between 1×10^{-6} and 1×10^{-4}. This finding aligns with observations from Gombe State (Balogun *et al.*, 2023) and studies in less polluted regions of Iran and Tunisia (Mohammadi *et al.*, 2019; Troudi *et al.*, 2022), where CR values for Cd, Cr, and Pb remained below 1×10^{-6}, reflecting low carcinogenic potential. However, the results from Okrika contrast sharply with those from other heavily impacted regions such as Benin River (Ezemonye *et al.*, 2018), Nnewi (Ayejoto & Egbueri, 2023), and Aleto-Eleme (Eruke *et al.*, 2025), where CR values for Cd and Pb often exceed 1×10^{-4}, implying a significant lifetime cancer risk. In these high-risk sites, industrial effluents, waste dumps, and hydrocarbon emissions contribute to persistent metal accumulation, particularly of Cd, Cr, Pb, and Ni. Therefore, while the CR values from Okrika align with safer regions, they contrast with the alarming conditions in more polluted parts of Nigeria and globally contaminated sites.

The rank order of metal contribution to health risk in Okrika—Fe > Cu > Zn > Cd > Mn > Ni > Cr > Pb—further reinforces the dominance of essential trace elements such as Fe, Cu, and Zn, which,

though biologically important, may contribute most to non-carcinogenic risk when concentrations are slightly elevated. This pattern mirrors findings from Mohammadi *et al.* (2019) in Iran and Balogun *et al.* (2023) in Gombe, where Fe, Cu, and Zn were identified as the major contributors to HQ and HI values, albeit still below critical limits. Conversely, in more contaminated settings like Aleto-Eleme and Nnewi, non-essential and toxic metals such as Cd, Cr, and Pb dominate risk profiles, leading to higher CR values and health concerns (Ayejoto & Egbueri, 2023; Eruke *et al.*, 2025). The Okrika trend, therefore, indicates an environment influenced more by natural mineral leaching and low-level anthropogenic inputs than by acute industrial contamination.

Geographically, Okrika's proximity to industrial operations, including refineries and oil facilities, would typically predict higher metal contamination and risk levels. Yet, the results reveal otherwise. This may be due to localised containment measures, sediment sequestration of metals, or dilution effects from tidal exchange and rainfall influx. Comparatively, inland urban centers like Nnewi and Awka, where drainage and hydrological dilution are limited, exhibit more severe metal accumulation in surface waters and sediments, leading to elevated HQ and HI values. Similarly, Aleto-Eleme, located near petrochemical and refinery operations with direct effluent discharge, shows much higher risk indices (Eruke *et al.*, 2025). Globally, studies from Tunisia (Troudi *et al.*, 2022) and Egypt (Eid *et al.*, 2024) demonstrate that CR and HI values tend to increase in semi-arid and industrial zones where evaporation intensifies metal concentration. Thus, Okrika's lower risk profile may be partly explained by its coastal hydrodynamics and environmental flushing capacity.

Another important contrast between the Okrika study and other regions lies in the vulnerability of children compared to adults. While Okrika results show higher HQ and HI values for children, they still remain below 1, indicating minimal risk. This pattern is consistent with almost all health risk assessments globally, where children typically exhibit higher risk due to greater exposure rates relative to body weight. In studies such as those conducted by Mohammadi *et al.* (2019) in Iran, and Oni *et al.* (2022) and Emmanuel *et al.* (2022) in Nigeria, children consistently presented higher HQ, HI, and CR values than adults, sometimes surpassing safety thresholds. Therefore, while Okrika aligns with global exposure trends in demographic vulnerability, it contrasts in magnitude since even the higher child values remain within safe limits.

The comparative evaluation of Okrika's findings within the broader Nigerian and global context suggests that while the region shares hydrochemical and exposure characteristics with other industrialised settings, its overall contamination level is lower. The absence of significant Cd, Cr, and Pb accumulation in Okrika, as reflected by HQ and CR values near zero, stands in contrast to numerous studies across Nigeria's oil-producing regions where these metals are major contributors to health risks. In Benin River (Ezemonye *et al.*, 2018) and Eleme (Eruke *et al.*, 2025), Cd and Pb were primary carcinogens, with CR values exceeding 1×10^{-4}, reflecting chronic pollution from industrial effluents. The Okrika study, therefore, reveals a more favorable environmental and public health status compared to many other parts of the Niger Delta.

In summary, the health risk assessment results from the Okrika creeks align closely with findings from low-contamination regions such as Gombe, Iran, and Tunisia, where HQ, HI, and CR values remain below regulatory limits. However, they contrast sharply with high-risk industrial and urban zones like Aleto-Eleme, Nnewi, and Benin River, where metal levels and health risks are significantly higher. The relatively low risk in Okrika suggests limited anthropogenic metal input or effective natural attenuation processes within the creeks. The dominance of Fe, Cu, and Zn in non-carcinogenic risk profiles reflects the natural geochemical composition rather than industrial contamination, while the absence of significant Cd, Cr, and Pb impact confirms minimal

carcinogenic potential. Nevertheless, the findings underscore the need for continuous monitoring, as Okrika's industrial setting and tidal dynamics could shift metal bioavailability over time. Overall, the present study aligns with low-risk global trends but contrasts with the high-risk profile typical of many Nigerian and international industrial environments, reaffirming that, at present, Okrika creek waters and sediments pose negligible health risks to surrounding communities.

Carcinogenic Risk of Cadmium (Cd) and Chromium (Cr) in Okrika Creeks

The present study from Okrika Creeks revealed that the carcinogenic risk (CR) values for cadmium (Cd) and chromium (Cr) were relatively low, falling within or slightly above the negligible range as defined by USEPA standards (1×10^{-6} to 1×10^{-4}). Specifically, Cd showed a CR value of 6.44×10^{-6} for children and 2.85×10^{-6} for adults, while Cr exhibited CR values below 1×10^{-6} for both population groups, signifying a minimal cancer risk. These values suggest that while Cd presents a slightly elevated potential for long-term carcinogenic effects, particularly among children, the overall health implications remain within acceptable regulatory limits. When placed in the national and global context, these findings align with several studies conducted in regions of moderate contamination, though they contrast sharply with results from heavily industrialised or mining-impacted areas where the risks are far higher.

In Nigeria, studies across various states have provided a broad spectrum of results regarding the carcinogenic risks of Cd and Cr, depending on the degree of environmental pollution. The findings from Okrika Creeks correspond closely with those of Akakuru *et al.* (2024) in Ebonyi State, where Cd and Cr CR values for both children and adults ranged between 10^{-6} and 10^{-5}, indicating low to moderate cancer risks. The water bodies studied by Akakuru and colleagues were located in agricultural and semi-industrial areas where metal contamination arises primarily from natural weathering processes and minor anthropogenic inputs, rather than from large-scale industrial discharges. Similarly, Titilawo *et al.* (2018) in Osun State reported CR values for Cd and Cr within the 10^{-6} range, particularly in groundwater sources used for domestic and agricultural purposes. These values correspond with those obtained in Okrika Creeks, reinforcing the interpretation that slightly elevated Cd CR levels for children are not uncommon in Nigerian water systems that experience diffuse pollution rather than concentrated industrial discharge. Both studies thus support the conclusion that Okrika's Cd and Cr levels represent a low carcinogenic threat under current conditions, though continued monitoring remains vital.

Further evidence supporting this alignment can be drawn from Bello *et al.* (2019), who investigated carcinogenic and non-carcinogenic risks associated with heavy metals in surface waters within artisanal mining communities. The researchers reported total excess lifetime cancer risks for Cd and Cr in the range of 10^{-6}, a level consistent with Okrika's results and considered below major health concern thresholds. Despite the presence of small-scale mining activities in Bello's study area, dilution effects and natural attenuation processes helped maintain metal concentrations at levels that posed only minimal cancer risk. This scenario is similar to that of Okrika, where, despite the proximity to industrial and shipping activities, the dilution capacity of the creek system likely contributes to maintaining overall low carcinogenic risk levels.

In contrast, several other Nigerian studies document markedly higher CR values for Cd and Cr, especially in locations where industrial, waste disposal, or mining operations have intensified environmental contamination. For instance, Emmanuel *et al.* (2022) in Anambra State recorded Cd CR values ranging from 1.8×10^{-1} to 2.5×10^{-1} for children and 3.96×10^{-2} to 5×10^{-2} for adults, far exceeding the acceptable risk threshold of 1×10^{-4}. Chromium also presented elevated risks, with CR values reaching up to 1.75×10^{-4} for children and 5×10^{-2} for adults. These exceptionally

high Figures reflect severe pollution, primarily due to industrial waste discharges, open dumpsite leachates, and improper waste management practices that contribute to elevated concentrations of toxic metals. When compared with Okrika's CR values, it becomes evident that while Okrika's aquatic environment may be moderately impacted by anthropogenic activity, it has not yet reached the critical contamination levels seen in Anambra's industrial regions. Thus, while both environments are influenced by human activities, the intensity and nature of these activities account for the observed differences in carcinogenic risks.

Similarly, Oni *et al.* (2022), in their study of water and sediment samples from a junk market in Ibadan, reported Cd CR values ranging between 9.9×10^{-3} and 1×10^{-2} for children, and up to 1.09×10^{-5} for adults. Chromium presented CR values as high as 3.3×10^{-4} for children and 1.55×10^{-4} for adults, levels that are considerably higher than those observed in Okrika. These Figures suggest that individuals, particularly children, residing near such heavily industrialised and waste-handling zones face significantly elevated cancer risks. The elevated CR values in Ibadan are attributable to the direct leaching of metals from discarded electronic components, vehicular parts, and metal scraps, which often contain Cd and Cr in high concentrations. The contrast between the Okrika results and those from Ibadan thus underscores how differences in waste management, industrial density, and hydrological characteristics influence carcinogenic exposure risks. Okrika's relatively lower CR values may be attributed to effective dilution and dispersion processes facilitated by tidal mixing in the creeks, which are absent in stagnant or landlocked environments such as the Ibadan junk market.

Another contrasting example can be found in Ayejoto *et al.* (2022), who reported high carcinogenic risks associated with heavy metal contamination in Anambra's peri-urban surface waters. The CR values for Cd and Cr frequently exceeded 1×10^{-3}, indicating severe health implications. Such elevated risks are linked to runoff from nearby industrial estates and improper discharge of untreated effluents, suggesting that site-specific activities play a defining role in determining carcinogenic exposure levels. Compared to Okrika, where Cd and Cr concentrations remain within or near permissible limits, Anambra's surface waters demonstrate the impacts of unregulated industrialization.

The findings from Eruke *et al.* (2025) in Aleto-Eleme, Rivers State, further illustrate this pattern. The study reported carcinogenic risks for Cd and Cr exceeding safe limits for both children and adults, attributed to heavy industrialisation from petrochemical operations and refinery effluents. Aleto-Eleme, situated within the same state as Okrika, represents a region where industrial contamination is more direct and intense, primarily due to effluent discharge from nearby industries. The lower CR values observed in Okrika therefore suggest that while both locations share industrial proximity, Okrika's coastal and estuarine characteristics promote better dilution and metal dispersion. Thus, the findings in Okrika partially align with Eruke *et al.* (2025) in terms of metal presence but contrast sharply regarding risk magnitude, highlighting the moderating role of environmental dynamics.

Comparatively, studies conducted outside Nigeria also provide valuable perspectives that help situate Okrika's results within a broader global framework. Mohammadi *et al.* (2019), examining heavy metals in Iranian surface waters, found Cd and Cr CR values ranging between 10^{-6} and 10^{-5}, indicating negligible to low cancer risks similar to Okrika. Likewise, Troudi *et al.* (2022) in Tunisia reported CR values within the 10^{-6} to 10^{-5} range, especially for children, in non-industrialised regions, while polluted urban areas showed higher CRs approaching 10^{-4}. These results demonstrate that Okrika's carcinogenic risk levels are consistent with global findings from

moderately impacted sites, emphasising that environmental management, industrial zoning, and water body type largely determine carcinogenic exposure potential.

In regions of heavy industrialisation, however, global studies report markedly higher CR values. Georgaki *et al.* (2023) reviewed carcinogenic risks associated with Cr(VI) contamination in industrial and mining regions globally and noted that CR values often exceed 1×10^{-4} in highly polluted sites. For example, studies from India, China, and Greece have reported Cd and Cr CR values surpassing acceptable thresholds, particularly in water bodies receiving untreated industrial waste. In these contexts, children are consistently at greater risk than adults due to higher exposure rates relative to body weight and increased physiological sensitivity. The Okrika findings align with these observations regarding age-based vulnerability, as children recorded slightly higher CR values than adults, reflecting consistent global risk patterns. However, Okrika's lower overall CR levels signify that while the creeks are exposed to anthropogenic influence, they are not yet experiencing the severe contamination levels characteristic of major industrial basins elsewhere.

It is important to emphasise that Okrika's slightly elevated Cd CR value for children (6.44×10^{-6}) compared to adults (2.85×10^{-6}) demonstrates the universal trend of higher vulnerability among younger populations. This age-related variation mirrors the results of Bello *et al.* (2019) and Titilawo *et al.* (2018), who both reported that children face higher carcinogenic risks from Cd and Cr exposure due to greater ingestion rates per unit body weight and longer potential exposure periods. Thus, even in environments with overall low contamination, as in Okrika, children remain a sensitive demographic requiring specific monitoring and preventive health measures.

Overall, the carcinogenic risk profile in Okrika aligns more closely with studies conducted in regions of low to moderate pollution—such as those reported by Akakuru *et al.* (2024) in Ebonyi State, Titilawo *et al.* (2018) in Osun State, Bello *et al.* (2019) in artisanal mining areas, and Mohammadi *et al.* (2019) and Troudi *et al.* (2022) internationally—than with those from highly polluted industrial or waste-handling zones like Emmanuel *et al.* (2022) in Anambra, Oni *et al.* (2022) in Ibadan, and Eruke *et al.* (2025) in Aleto-Eleme. The consistency across low-risk sites supports the validity of Okrika's results, while the contrasts with high-risk locations highlight the importance of environmental management practices in shaping carcinogenic exposure outcomes.

In conclusion, the present study's findings indicate that the carcinogenic risks associated with Cd and Cr in Okrika Creeks remain within acceptable regulatory limits and are lower than those observed in heavily polluted Nigerian and global locations. The results align closely with studies from regions of moderate contamination, confirming that Okrika's aquatic environment currently poses minimal cancer risks to both children and adults. However, the slightly elevated Cd CR value for children underscores the importance of sustained monitoring, particularly given the area's industrial backdrop and potential for future contamination. Should industrial activity intensify or pollution controls weaken, the carcinogenic risk profile could escalate toward levels observed in more contaminated regions such as Anambra, Ibadan, or Aleto-Eleme. Therefore, proactive management, continuous surveillance, and environmental education remain crucial for maintaining the current low-risk status of Okrika Creeks.

Potential Ecological Risk Index (PERI) from Creeks around Okrika Communities

The results of the present study show that the Potential Ecological Risk Index (PERI) values for all stations in Okrika Creek are very low, ranging from 0.031 to 0.526. These values indicate that the creek is within the low ecological risk category and that the metals measured pose minimal cumulative ecological threat to the aquatic environment. Stations S1 and S2 recorded extremely low PERI values of 0.031 and 0.034, while station S3 showed a slightly higher PERI of 0.526,

mainly due to the influence of cadmium (Cd). However, this value still falls well below the moderate risk threshold, confirming that overall ecological conditions in the study area remain unpolluted. This section presents a comparative discussion between the present findings and other studies conducted nationally and globally to determine whether the Okrika Creek results align or contrast with existing research. In Nigeria, several studies have documented similar findings, showing low ecological risk indices across creeks and rivers. For instance, Uzamere *et al.* (2023) assessed the ecological condition of Okrika and other creeks in Rivers State and reported a low risk index (RI = 135.31), which, despite being numerically higher due to methodological variations, still indicates low ecological risk. This aligns with the present study, which also found negligible contamination and risk from heavy metals in Okrika Creek sediments. Both studies point to limited anthropogenic influence, minimal industrial discharges, and the possible dominance of natural background sources of metals in the sediments. The consistency between these two findings reinforces the idea that Okrika's aquatic environment is not heavily impacted by heavy metal pollution at present. Similarly, Ikhuoriah & Igheghe (2024) studied the Amagba-Okoroma River and reported that PERI values for all metals were within the low-risk category. They found that all metal concentrations were below international guideline thresholds, except for isolated moderate risks at specific points, which were attributed to local domestic and agricultural runoff. These results agree with the present study, confirming that most Nigerian inland water bodies that are not directly exposed to industrial effluents tend to exhibit low ecological risk levels. The similarity further suggests that regional environmental management and the absence of large-scale industrial activities contribute to the preservation of sediment quality in these water systems. Ajeh & Frederick (2020) also reported low PERI values in the Ikpoba River, with all metals falling below guideline thresholds. However, they observed moderate ecological risk for copper (Cu) at one sampling station, attributed to municipal waste discharge. This observation provides a contrast to the present study, where no metals exhibited moderate or high risk, even at the most impacted site (S3). This difference implies that the Okrika Creek environment may currently experience less anthropogenic pressure compared to the Ikpoba River, possibly due to differences in population density, industrialisation level, or the effectiveness of local waste management practices.

Furthermore, Okafor *et al.* (2024b) examined metal contamination and ecological risk in streams around Ifite Ogwari, Nigeria. Their findings revealed that most sampling sites had low PERI values, consistent with the results of the present study. However, they also noted some streams that exhibited moderate to high risk due to localised contamination, mainly from agricultural and domestic sources. This contrast highlights the spatial variability of contamination in freshwater systems, suggesting that while general ecological conditions in Nigerian rivers and creeks remain low-risk, specific locations can become hotspots depending on human activities. In comparison, the Okrika Creek system appears relatively stable and less impacted, possibly benefiting from hydrological dilution and sediment flushing that reduce metal accumulation.

On a global scale, the findings from this present study also align with results from several international studies in unpolluted or minimally impacted aquatic systems. In Vietnam, Huynh *et al.* (2025) assessed the Dong Nai River and found PERI values ranging from 5.23 to 6.73, all classified as low ecological risk. Although the numerical range of PERI values in the Dong Nai River is slightly higher than those found in the Okrika Creek (0.031–0.526), both studies indicate minimal cumulative ecological risk. The slight variation could result from differences in metal concentration units, regional geology, or anthropogenic influence. Nonetheless, both studies converge on the conclusion that low PERI values signify safe ecological conditions and limited metal toxicity in sediments. In Bangladesh, Bhuyan *et al.* (2023) investigated sediments from

Eastern St. Martin's Island and found PERI values ranging from 0.28 to 2.18, suggesting no significant ecological risk. This finding aligns closely with the present study's results, especially the low PERI values at all Okrika stations. Both locations are coastal or near-coastal systems influenced by marine water exchange, which often promotes metal dilution and prevents excessive accumulation in sediments. The agreement between these two environments, despite being in different geographic regions, supports the conclusion that where industrial inputs are limited, sediments tend to maintain low contamination and ecological risk levels.

Similarly, Gholisadeh & Patimar (2018) studied the Gorgan Bay in the Caspian Sea and reported low PERI values across all sampling sites, indicating that heavy metal contamination was minimal and ecological risk negligible. This is in perfect alignment with the present study. Both Okrika Creek and Gorgan Bay display low ecological risk characteristics, underscoring the global pattern that unindustrialised or moderately impacted water systems show minimal heavy metal risk levels. These environments are likely governed by natural processes such as weathering, sedimentation, and nutrient cycling rather than heavy industrial pollution. Another comparative example is found in the work of Beltrán-Dávalos *et al.* (2025), who examined Andean lakes in Ecuador. Their findings showed that PERI values remained low across all sites, confirming limited ecological risk from heavy metals. This aligns with the Okrika Creek results and suggests that both tropical and high-altitude aquatic systems can exhibit similarly low contamination profiles when anthropogenic disturbances are minimal. The comparable outcomes between such geographically distinct systems imply that natural geochemical controls may play a stronger role than localised anthropogenic inputs in determining background metal levels.

Despite these widespread similarities, contrasts also exist between Okrika Creek and other reported systems, mainly in areas with greater industrial and agricultural activity. For instance, Okafor *et al.* (2024a) and Ajeh and Frederick (2020) reported isolated moderate risk levels for metals such as Cd and Cu in Nigerian streams and rivers affected by human activity. Likewise, some international studies, although not discussed extensively here, show elevated PERI values in urbanised regions where industrial effluents or mining residues enter aquatic environments. The absence of such elevated risk in the present study highlights the relatively pristine condition of the Okrika Creek, at least in terms of heavy metal contamination. The uniformity of low PERI values across Nigerian and international studies reflects a shared environmental condition where metal inputs are primarily natural rather than anthropogenic. It also reinforces the accuracy of the present study's methodology, as the findings are consistent with global standards of low ecological risk in unpolluted sediments. Furthermore, the slightly higher PERI observed at station S3 (0.526) could be attributed to minor localised sources such as runoff from domestic waste or boat traffic, yet even this remains within the safe limit. This suggests effective natural attenuation and sedimentary self-purification mechanisms in Okrika Creek.

Overall, the present study's results align closely with national and global research findings. In Nigeria, studies by Uzamere *et al.* (2023), Ikhuoriah & Igheghe (2024), and Ajeh & Frederick (2020) collectively show that aquatic systems with limited industrial exposure, like Okrika Creek, generally present low ecological risk. Internationally, research by Huynh *et al.* (2025) in Vietnam, Bhuyan *et al.* (2023) in Bangladesh, Gholisadeh & Patimar (2018) in the Caspian Sea, and Beltrán-Dávalos *et al.* (2025) in Ecuador all report similar patterns, reinforcing the conclusion that unpolluted environments typically exhibit PERI values within the low-risk range.

In conclusion, the Potential Ecological Risk Index (PERI) results from Okrika Creek sediments demonstrate clear alignment with both national and international findings from comparable low-risk aquatic systems. The consistent pattern of low PERI values indicates that Okrika Creek

sediments are minimally contaminated and that ecological risks from metals are negligible. This conformity with other studies emphasises that the region's sediments reflect background concentrations of metals rather than pollution-derived enrichment. The overall comparison confirms that the ecological integrity of Okrika Creek remains intact and that its metal load poses no significant threat to the aquatic ecosystem.

Conclusion

The health risk assessment for heavy metals demonstrated that both the Hazard Quotient (HQ) and Hazard Index (HI) values for ingestion and dermal exposure were below 1 for children and adults, indicating no immediate non-carcinogenic health risk. Carcinogenic risk (CR) values for cadmium and chromium were also below the threshold, suggesting negligible lifetime cancer risk. The order of metal contribution to risk (Fe > Cu > Zn > Cd > Mn > Ni > Cr > Pb) reflects natural geochemical patterns rather than pollution-derived exposure. The study generally showed evidence of health risk associated with heavy metal exposure in Okrika creeks.

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