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Assessment of Heavy Metal Assemblages in Coastal Sediments of the Cross River Estuary, Southeast Nigeria

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Abstract:*Surface sediment contamination by heavy metals poses significant ecological and human health risks in estuarine environments due to the persistence and bioaccumulative nature of these pollutants. This study assessed the concentrations, spatial distribution, contamination status, and ecological risks of heavy metals in bottom sediments of the Cross River estuary, Southeast Nigeria. Fifty-five surface sediment samples were collected along a 65 km stretch of the estuary and analyzed for Cu, Zn, Cd, Ni, Pb, and Fe using Atomic Absorption Spectrometry (AAS). Mean metal concentrations (mg/kg) were 0.241 for Cu, 0.356 for Zn, 0.027 for Cd, 0.439 for Ni, 0.003 for Pb, and 0.840 for Fe, following the order Fe > Ni > Zn > Cu > Cd > Pb. All measured concentrations were substantially lower than the world average shale values and the Department of Petroleum Resources (DPR) sediment quality guideline values. Geo-accumulation index (Igeo) values were ≤ 0 for all investigated metals, indicating unpolluted sediments, while contamination factor (CF) values were consistently < 1, reflecting low contamination. Degree of contamination (DC) values ranged from 0.007 to 0.254, and pollution load index (PLI) values ranged from 0.000 to 0.003, confirming the absence of overall sediment pollution. Ecological risk factor (ER) values varied between 0.000 and 7.000, whereas ecological risk index (RI) values ranged from 0.030 to 7.083, both indicating low ecological risk throughout the estuary. Hierarchical cluster analysis classified the investigated metals into two distinct assemblages, comprising Cu–Zn–Ni–Pb–Cd and Fe, suggesting mixed anthropogenic and lithogenic sources, with iron predominantly controlled by natural geological processes. Although the present contamination levels are low, continuous anthropogenic activities, including maritime transportation, urban runoff, dredging, and indiscriminate waste disposal, may progressively increase heavy metal accumulation. Continuous environmental monitoring is therefore recommended to ensure the long-term ecological sustainability of the Cross River estuary.*

Keywords: *Estuary. AAS. Sediments. Cross River estuary. Pollution indices.*

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1.0 Introduction

Heavy metals are among the most persistent environmental contaminants due to their toxicity, non-biodegradability, persistence, and tendency to bioaccumulate in aquatic organisms and sediments (Akpakpan *et al*., 2024; Bryan & Langston, 1992). Unlike many organic pollutants, heavy metals cannot be degraded through natural biological processes and may persist in sediments for extended periods, posing long-term ecological and human health risks (Udo *et al*., 2018). . Estuarine sediments are important sinks for anthropogenic pollutants (Xu *et al*., 2014; Wang *et al*., 2015; Emeka *et al*., 2026). Consequently, sediment quality is widely regarded as a reliable indicator for assessing the extent and historical accumulation of heavy

metal pollution in estuarine environments (Schröder-Adams, 2006; Li *et al*. 2007). Estuarine sediments are important sink for anthropogenic pollutants (Xu *et al*. 2014; Wang *et al*. 2015). Heavy metals in estuaries can be derived from anthropogenic and lithogenic sources. The relative contribution of these sources varies according to watershed characteristics, land-use practices, industrial development, and estuarine hydrodynamics Anthropogenic sources include oil exploration, dredging, mari-time transportation services, farming, industries and urban development. Lithogenic sources include weathering of rock materials, fresh water input and volcanic activities (Ahmadov *et al*., 2020). Heavy metal contamination in sediment can lead to deterioration of water quality and bioaccumulation of metals in aquatic organisms. Furthermore, contaminated sediments may act as secondary sources of pollution through the remobilization of metals into the water column under changing physicochemical conditions. This has an overall long-term health implication for humans and the aquatic ecosystem (Li *et al*. 2004; Ip *et al*. 2007; Zhao *et al*., 2017). Assessment of heavy metal pollution in coastal sediment is important for the effective management of coastal eco-systems and preservation of biodiversity. Against this background, the Cross River estuary represents an important tropical estuarine ecosystem where increasing anthropogenic activities may influence sediment quality and heavy metal distribution, thereby necessitating periodic environmental assessment.. The Cross River estuary is the largest estuary in the West African sub-region. It is located on the eastern flank of the oil rich Niger Delta region of Nigeria. The Cross River estuary takes its source from the Adamawa Mountain Range at over 1,000 m (1 km) above mean sea level, in Southwest Cameroon. The river flows through the Ikom-Mamfe embayment and around the Oban Massif, before cutting through the coastal plains of Southeast Nigeria, where it forms the estuary. Its total length, from source to sink is estimated to be over 500 km (Emeka *et al*., 2023a). The estuary has four major tributaries namely: Calabar, Great-Kwa, Akpa-Yafe and Mbo Rivers (Emeka *et al*., 2026). Cross River estuary is a major route for crude oil carrying vessels and other vessels entering into the Nigerian Ports Authority in Calabar. Socio-economic activities within the channel include commercial fisheries, boat transport services, sand mining, dredging, recreation and seafood trading. Farming Although these studies have provided valuable information on heavy metal contamination within the Cross River estuary and its tributaries, most investigations were conducted more than a decade ago or were limited to localized sections of the estuary. Moreover, few studies have integrated contamination indices with multivariate statistical techniques to comprehensively evaluate contamination levels, ecological risks, and potential pollution sources across the entire estuarine system. Given the increasing urbanization, maritime transportation, dredging, and industrial activities in the region, an updated assessment is necessary to determine the current status of heavy metal contamination.is common along the banks of the channel. Untreated effluents from domestic, industrial and agricultural sources are discharged through adjoining tributaries into the estuary. The growing human population, expanding urbanization, and increasing industrial and maritime activities have the potential to significantly affect aquatic biodiversity, sediment quality, and the overall ecological integrity of the estuary.Assessment of heavy metals in estuary and coastal sediments have received much attention (Zhang *et al*., 2009; Attia and Ghrefat 2013; Ewa *et al*., 2013; Wang *et al*., 2015; Zhao *et al*., 2017; Ahmadov *et al*., 2020; Odiongenyi, 2017; Dan *et al*., 2022). Globally, considerable research has focused on evaluating heavy metal contamination in estuarine sediments using

geochemical indices and multivariate statistical techniques to determine pollution levels, ecological risks, and contamination sources.

Accordingly, this study evaluates the spatial distribution of heavy metals in bottom sediments of the Cross River estuary, extending from the upper limits of tidal influence to the estuary mouth, using pollution indices and multivariate statistical analysis. Earlier investigations on the distribution of heavy metal levels in the Cross River estuary and its tributaries have been documented (e.g., Ntekim *et al*. 1993; Eddy *et al*. 2004; Essien *et al*., 2009; Ogri *et al*., 2011; Dan *et al*., 2022). Ntekim *et al*. (1993) studied heavy metal distribution in sediments from the Calabar River and related their occurrence to industrial sewages and untreated solid waste dumps. They associated elevated concentrations of heavy metals in Calabar River to industrial activities along the eastern banks of the channel. Eddy *et al*. (2004) analyzed sediment samples for heavy metals (V, Pb, Cu, Fe, Cr, Zn) in the Cross River estuary and reported that heavy metals in sediment were low and within background level. The authors attributed the sources of metals in estuarine sediments to domestic and agricultural wastes. Essien *et al*. (2009) reported that heavy metals in sediments of Cross River estuary showed concentrations indicative of anthropogenic sources and that high enrichment of V, Zn and Cr in sediments were related to industrial effluents discharged into the estuary. In this study, an attempt is made to investigate the distribution of heavy metals in the Cross River estuary from the upper limits of tidal penetration to the estuary mouth. The overall aim of this study was to evaluate the extent of heavy metal contamination and associated ecological risks in the bottom sediments of the Cross River estuary using established geochemical pollution indices and hierarchical cluster analysis. The main objectives of this work are (1) to assess heavy metal contamination in bottom sediments of the Cross River estuary using contamination indices (geo-accumulation index and contamination factor) (2) to determine the degree of pollution by heavy metals using degree of contamination (DC), pollution load index (PLI), and pollution ecological risk index (RI) (3) to classify heavy metals into different groups using hierarchical cluster analysis (HCA). The findings of this study provide updated baseline information on sediment quality in one of West Africa's largest estuarine systems. The results will enhance understanding of heavy metal contamination patterns, support long-term environmental monitoring programmes, assist regulatory agencies in pollution management, and contribute to the sustainable management and conservation of the Cross River estuarine ecosystem

2.0 Materials and method

2.1 Sediment Sampling

A total of fifty-five (55) surface sediment samples were collected from the Cross River estuary, Southeast Nigeria (Fig. 1), using a Van Veen grab sampler. The sampling stations extended over approximately 65 km of the estuarine channel, covering the upper limits of tidal penetration to the estuary mouth. The geographic coordinates of each sampling station were recorded using a Global Positioning System (GPS). To represent recently deposited sediments that are most susceptible to anthropogenic contamination, the upper 1–2 cm of sediment was carefully scooped from each grab sample. The collected sediments were immediately transferred into well-labelled polyethylene bags, preserved in an ice chest during transportation, and subsequently stored under frozen conditions until laboratory analysis.

2.2 Sample Preparation and Acid Digestion

In the laboratory, sediment samples were air-dried at room temperature and gently disaggregated using a clean mortar and pestle. The dried samples were sieved through a 2-mm stainless-steel mesh, and particles larger than 2

mm were discarded. The homogenized sediment fraction was transferred into labelled plastic containers and stored prior to chemical analysis.

Sediment digestion was carried out following the standard procedures recommended by the Association of Official Analytical Chemists (AOAC, 1990). Approximately 2.0 g of each sediment sample was accurately weighed into a round-bottom digestion flask and treated with 20 mL of a mixed acid solution consisting of concentrated nitric acid (65% HNO_3) and perchloric acid (35% $HClO_4$). The mixture was heated on an electrothermal heater at 80°C until near dryness and allowed to cool to room temperature. Subsequently, 50 mL of deionized water was added, and the contents were thoroughly mixed before filtration through Whatman No. 42 filter paper into a 100 mL volumetric flask. The filtrate was diluted to the calibration mark with deionized water and stored for elemental analysis.

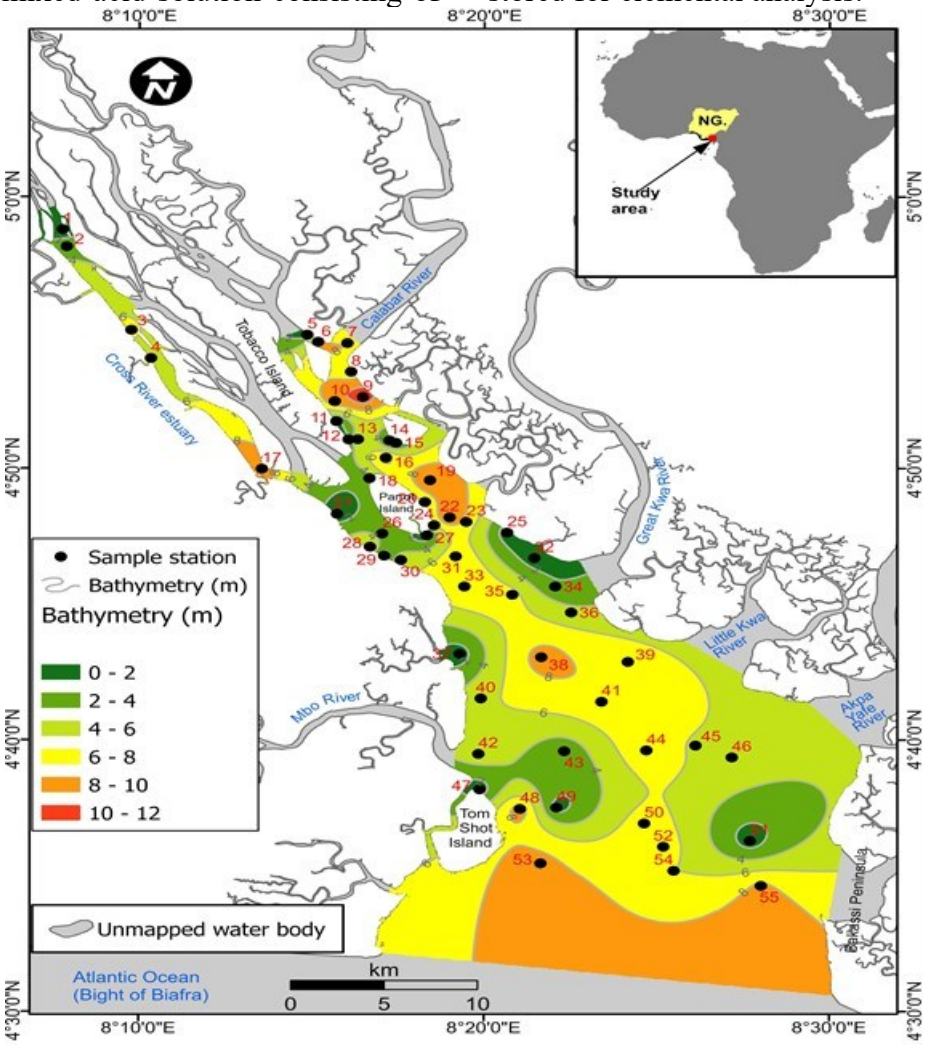

Fig. 1 Map of study area (Source: Emeka *et al*., 2023b)

2.3 Heavy Metal Analysis

The digested sediment solutions were analyzed for iron (Fe), lead (Pb), cadmium (Cd), zinc (Zn), nickel (Ni), and copper (Cu) using an Agilent 55AA Atomic Absorption Spectrometer (AAS). Instrument calibration was performed according to the manufacturer's recommendations using appropriate analytical standards prior to sample analysis.

2.4 Quality Assurance and Quality Control

Quality assurance and quality control (QA/QC) procedures were implemented throughout the analytical process to ensure the reliability and accuracy of the results. Analytical-grade reagents were used for all chemical analyses, while reagent blanks were prepared and analyzed alongside the sediment samples to monitor possible contamination. All samples were analyzed in duplicate, and the average values were used for subsequent data analysis. Instrument calibration was verified using standard solutions before and during sample analysis. The instrumental detection limits (mg kg^{-1}) for Cd, Cu, Fe, Zn, Ni, and Pb were 0.001, 0.001, 0.005, 0.001, 0.003, and 0.002, respectively.

4.0 Results and Discussion

4.1 Heavy Metal Concentrations in Surface Sediments

The concentrations of Cu, Pb, Zn, Cd, Ni, and Fe measured in the surface sediments of the Cross River estuary are presented in Table 1. The descriptive statistics indicate that the concentrations of all investigated heavy metals were generally low and exhibited spatial variability across the 55 sampling stations, reflecting differences in local geological characteristics, hydrodynamic processes, and anthropogenic inputs.

Iron (Fe) recorded the highest average concentration (0.84 ± 0.27 mg kg^{-1}), followed by Ni (0.44 ± 0.16 mg kg^{-1}), Zn (0.36 ± 0.14 mg kg^{-1}), Cu (0.24 ± 0.05 mg kg^{-1}), Cd (0.03 ± 0.02 mg kg^{-1}), and Pb (0.003 ± 0.005 mg kg^{-1}). The overall abundance of heavy metals followed the decreasing order, Fe > Ni > Zn > Cu > Cd > Pb

This distribution pattern is typical of tropical estuarine sediments where Fe commonly dominates because of its abundance in parent rocks and its strong affinity for fine-grained sediments and iron oxyhydroxides (Alloway, 2013; Förstner & Wittmann, 2012). Similar trends have been reported for other estuarine systems in southern Nigeria, including the Cross River estuary (Eddy *et al*., 2004), Calabar River (Ntekim *et al*., 1993), Qua Iboe River estuary (Emeka & Emeka, 2026), and Kolo Creek in the Niger Delta (Inengite *et al*., 2010).

Copper concentrations ranged from 0.19 to 0.35 mg kg^{-1}, with the highest concentration occurring at Station 46. Copper is commonly introduced into aquatic environments through industrial discharges, antifouling paints used on marine vessels, municipal wastewater, and agricultural runoff (Kabata-Pendias, 2011). However, the relatively low Cu concentrations observed in this study suggest limited anthropogenic enrichment and efficient dilution by estuarine mixing processes.

Lead exhibited the lowest concentrations among all investigated metals, ranging from below detection level to 0.035 mg kg^{-1}, with the highest value recorded at Station 8. The localized enrichment of Pb may reflect emissions from boat engines, accidental fuel spills, and urban runoff entering the estuary through the Calabar River. Although lead is generally associated with petroleum products, shipping activities, and industrial emissions, the measured concentrations remain substantially lower than internationally accepted sediment quality guideline values (Department of Petroleum Resources [DPR], 2002; Turekian & Wedepohl, 1961), indicating minimal contamination.

Zinc concentrations varied between 0.10 and 0.49 mg kg^{-1}, with an average concentration of 0.36 ± 0.14 mg kg^{-1}. Zinc is an essential trace element that is widely distributed in natural sediments but may also originate from industrial effluents, galvanized materials, domestic sewage, fertilizers, and corrosion of metallic infrastructure (Alloway, 2013). The relatively narrow concentration range suggests that Zn is largely controlled by natural sedimentary processes with minor anthropogenic influence.

Cadmium concentrations ranged from below detection level to 0.07 mg kg^{-1}, with the highest value observed at Station 51. Although Cd occurred at comparatively low concentrations, its environmental significance should not be underestimated because of its high toxicity, persistence, and tendency to bioaccumulate in aquatic organisms (Hakanson, 1980; Kabata-Pendias, 2011). Nevertheless, the measured concentrations remained well below the regulatory threshold recommended by the DPR (2002), indicating that Cd contamination is presently insignificant within the estuary.

Table 1: Measured concentration of heavy metals (in mg/kg) in sediment including descriptive statistics (mean, maximum, minimum and average shale value)

Sample stations	Cu	Pb	Zn	Cd	Ni	Fe
1	0.244	0.001	0.412	0.028	0.528	0.952
2	0.185	0.000	0.120	0.000	0.325	0.370
3	0.186	0.000	0.120	0.000	0.350	0.450
4	0.289	0.005	0.445	0.053	0.555	1.130
5	0.286	0.004	0.443	0.051	0.554	1.110
6	0.185	0.000	0.100	0.000	0.130	0.320
7	0.245	0.002	0.431	0.030	0.530	0.961
8	0.283	0.035	0.440	0.051	0.500	1.100
9	0.187	0.000	0.170	0.000	0.180	0.480
10	0.189	0.000	0.210	0.000	0.290	0.590
11	0.331	0.004	0.457	0.055	0.560	1.150
12	0.304	0.003	0.454	0.053	0.538	1.110
13	0.188	0.000	0.190	0.000	0.210	0.500
14	0.230	0.001	0.360	0.022	0.501	0.850
15	0.185	0.000	0.110	0.000	0.120	0.350
16	0.210	0.001	0.390	0.027	0.507	0.860
17	0.187	0.000	0.165	0.000	0.175	0.470
18	0.240	0.002	0.432	0.030	0.530	0.962
19	0.220	0.001	0.411	0.029	0.529	0.954
20	0.185	0.000	0.110	0.000	0.110	0.330
21	0.300	0.000	0.430	0.040	0.594	1.030
22	0.188	0.000	0.185	0.000	0.220	0.510
23	0.189	0.000	0.213	0.000	0.280	0.540
24	0.309	0.011	0.485	0.050	0.595	1.160
25	0.250	0.000	0.480	0.030	0.590	1.070
26	0.220	0.001	0.458	0.028	0.504	0.970
27	0.230	0.000	0.460	0.028	0.570	1.060
28	0.188	0.000	0.190	0.000	0.230	0.540
29	0.299	0.003	0.470	0.035	0.550	0.990
30	0.210	0.001	0.460	0.028	0.537	0.947
31	0.186	0.000	0.130	0.000	0.190	0.370
32	0.250	0.002	0.467	0.030	0.540	0.962
33	0.305	0.005	0.483	0.045	0.590	1.150

34	0.301	0.003	0.472	0.034	0.550	0.990
35	0.307	0.010	0.483	0.040	0.580	1.125
36	0.240	0.001	0.461	0.028	0.524	0.953
37	0.216	0.001	0.453	0.027	0.523	0.847
38	0.188	0.000	0.110	0.000	0.230	0.391
39	0.219	0.000	0.450	0.027	0.500	0.855
40	0.210	0.001	0.462	0.028	0.521	0.962
41	0.189	0.000	0.120	0.000	0.240	0.523
42	0.304	0.010	0.465	0.055	0.570	1.155
43	0.230	0.002	0.460	0.050	0.519	0.949
44	0.195	0.000	0.290	0.000	0.300	0.630
45	0.260	0.003	0.473	0.053	0.520	0.971
46	0.350	0.010	0.469	0.067	0.590	1.159
47	0.280	0.006	0.430	0.040	0.540	0.990
48	0.340	0.010	0.460	0.060	0.570	1.110
49	0.193	0.000	0.130	0.000	0.220	0.684
50	0.190	0.000	0.190	0.000	0.200	0.573
51	0.310	0.006	0.460	0.070	0.570	1.130
52	0.285	0.006	0.465	0.065	0.560	1.100
53	0.245	0.004	0.457	0.040	0.540	0.991
54	0.230	0.002	0.451	0.027	0.512	0.847
55	0.288	0.010	0.466	0.058	0.550	0.990
Mean	0.241	0.003	0.356	0.027	0.439	0.840
Minimum	0.185	0.000	0.100	0.000	0.110	0.320
Maximum	0.350	0.035	0.485	0.070	0.595	1.160
Standard deviation	0.049	0.005	0.142	0.022	0.158	0.271
Average Shale Value	45	20	95	0.3	68	47200
DPR (2002)	36	85	140	0.8	35	-

Nickel concentrations ranged from 0.11 to 0.595 mg kg^{-1}, averaging 0.44 ± 0.16 mg kg^{-1}. Nickel is commonly derived from weathering of ultramafic rocks, petroleum-related activities, and industrial discharges (Förstner & Wittmann, 2012). The relatively uniform distribution of Ni across the study area suggests that natural geological sources exert greater control than localized anthropogenic inputs.

Iron exhibited concentrations ranging from 0.32 to 1.16 mg kg^{-1}, with the highest value recorded at Station 24. The dominance of Fe is consistent with its natural abundance in tropical soils and sediments, particularly within the lateritic terrains of southeastern Nigeria. Elevated Fe concentrations have similarly been reported in sediments of the Cross River estuary (Eddy *et al*., 2004), Qua Iboe River estuary (Uwah *et al*., 2013), and Kolo Creek (Inengite *et al*., 2010), where they were attributed primarily to lithogenic contributions rather than pollution.

Comparison of the measured concentrations with the average shale values proposed by Turekian & Wedepohl (1961) and the sediment quality limits established by the Department of Petroleum Resources (2002) indicates that all investigated metals occur at concentrations substantially below their respective background and regulatory threshold values

(Table 1). This finding demonstrates that the sediments of the Cross River estuary are presently characterized by low levels of heavy metal contamination.

The generally low concentrations observed in this study may be attributed to several interacting environmental processes. The Cross River estuary is characterized by strong tidal currents, continuous freshwater inflow, sediment resuspension, and effective flushing, all of which enhance dispersion and reduce localized accumulation of contaminants. Furthermore, the predominance of sandy sediment in many parts of the estuary likely limits heavy metal adsorption because coarse-grained sediments possess lower surface area and cation exchange capacity than fine-grained clay-rich deposits (Horowitz, 1991).

Despite the overall low concentrations, slight variations among sampling stations indicate localized anthropogenic influences. Areas situated close to major urban centres, industrial facilities, river tributaries, and navigation channels generally exhibited relatively higher metal concentrations than less disturbed sections of the estuary. These localized enrichments likely reflect inputs from municipal wastewater, agricultural runoff, boat traffic, dredging operations, sand mining, and petroleum-related activities. Similar observations have been reported for estuarine environments in the Niger Delta, where localized anthropogenic activities produce spatial heterogeneity in sediment quality despite generally low regional contamination levels (Dan *et al*., 2022; Essien *et al*., 2009).

Overall, the results suggest that the Cross River estuary remains relatively unpolluted with respect to Cu, Pb, Zn, Cd, Ni, and Fe. Nevertheless, increasing industrialization, urban expansion, and intensified maritime activities within the estuary underscore the importance of continuous environmental monitoring. Early detection of changes in sediment quality is essential for protecting aquatic ecosystems, maintaining fisheries productivity, and safeguarding public health.

4.2 Spatial Distribution of Heavy Metals

The spatial distribution patterns of Cu, Pb, Zn, Cd, Ni, and Fe across the Cross River estuary are illustrated in Fig. 2.

The distribution maps reveal that heavy metal concentrations are not uniformly distributed throughout the estuary but display distinct spatial variations that reflect the combined influence of hydrodynamic conditions, sediment transport, riverine inputs, and anthropogenic activities. Overall, Cu, Zn, Cd, Ni, and Fe exhibited a gradual increase in concentration toward the lower estuary and seaward section, whereas Pb remained consistently low throughout most of the study area.

The downstream enrichment of several metals is consistent with estuarine mixing processes, where suspended particles transported by river discharge undergo flocculation under increasing salinity and are subsequently deposited in lower-energy environments near the estuary mouth (Förstner & Wittmann, 2012). Fine-grained sediments in these depositional zones provide larger surface areas for adsorption of dissolved metals, thereby enhancing their accumulation.

Lead displayed a unique spatial pattern, with its highest concentration occurring upstream near Station 8, close to the mouth of the Calabar River. This localized enrichment is most likely associated with intensive boat traffic, fuel combustion, lubricating oil leakage, and urban runoff entering the estuary from Calabar metropolis. Similar localized Pb enrichment associated with navigation and urban activities has been documented in other estuarine environments (Alloway, 2013; Zhang *et al*., 2009).

Cadmium exhibited relatively minor spatial variation but showed slightly elevated concentrations near the eastern margin of the estuary, particularly around the Akpa-Yafe

River mouth and the entrance to the Bakassi Peninsula. These areas receive runoff from agricultural lands, settlements, and commercial activities, suggesting that diffuse anthropogenic inputs may contribute to Cd enrichment.

Zinc concentrations were relatively homogeneous throughout much of the estuary but increased slightly within the lower estuary and near the estuary mouth. This pattern may reflect the combined influence of riverine transport, marine processes, and localized anthropogenic discharges. Likewise, copper exhibited moderate spatial variability, with elevated concentrations observed around the Akpa-Yafe River and extending toward the Bakassi Peninsula. These areas are characterized by fishing activities, boat maintenance, and increasing coastal development, all of which can contribute trace amounts of Cu to the aquatic environment.

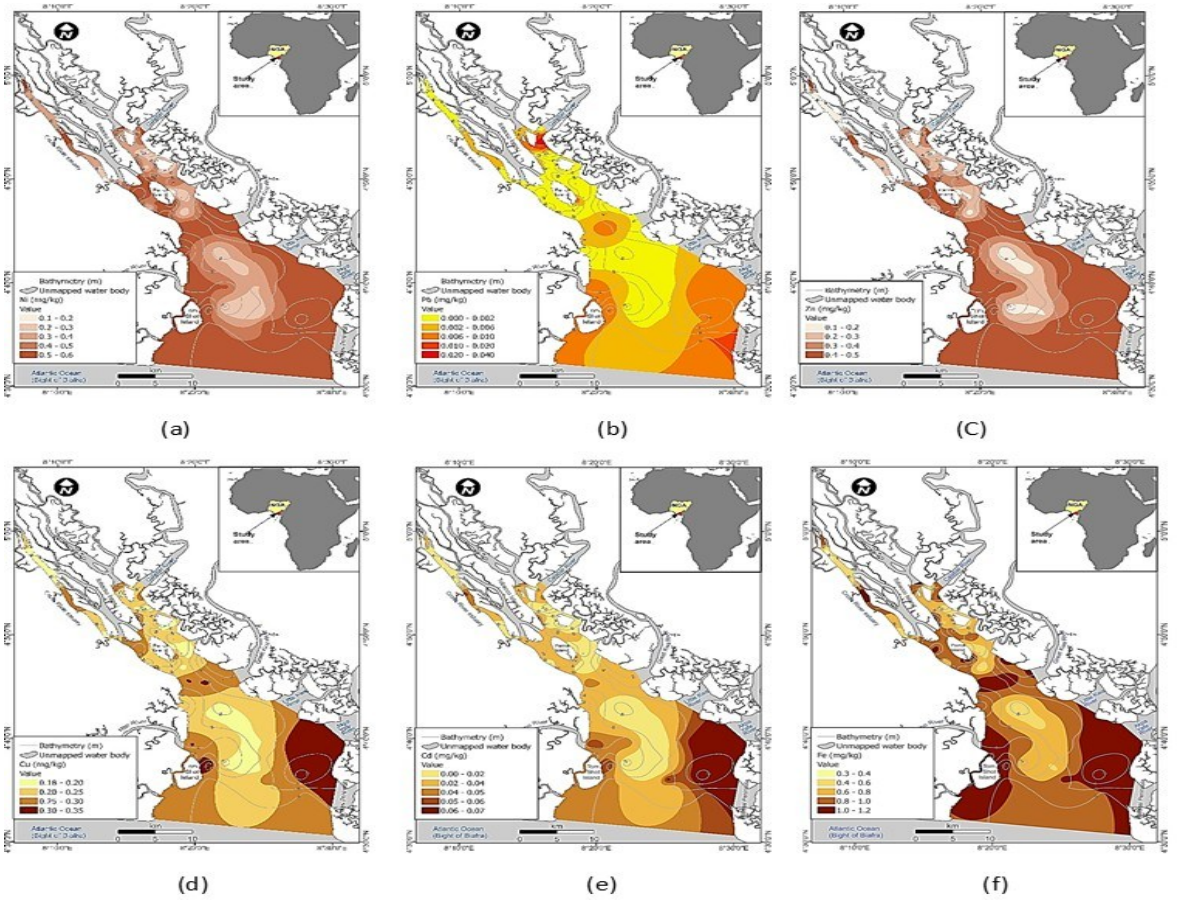

Fig. 2. Spatial distribution of (a) Ni (b) Pb (c) Zn (d) Cu (e) Cd (f) Fe in sediments of the Cross River estuary

Nickel displayed the most uniform spatial distribution among the investigated trace metals. Such uniformity suggests that Ni is predominantly controlled by natural lithogenic sources rather than localized pollution. The relatively consistent concentrations across the estuary further indicate efficient hydrodynamic mixing and sediment redistribution.

Iron showed the highest concentrations throughout the estuary and exhibited pronounced spatial variability. The elevated Fe concentrations reflect the natural mineralogical composition of sediments derived from weathering of Precambrian basement rocks and sedimentary formations within the Cross River Basin. Similar observations have been reported

for estuarine sediments in southeastern Nigeria (Eddy *et al*., 2004; Uwah *et al*., 2013).

Collectively, the spatial distribution maps indicate that the eastern margin of the Cross River estuary experiences slightly greater heavy metal enrichment than the western sector. This pattern coincides with areas of increased industrial development, urban expansion, shipping activities, and riverine discharge, suggesting that anthropogenic activities contribute to localized metal accumulation. Nevertheless, the magnitude of enrichment remains relatively low, indicating that natural sedimentary processes and estuarine hydrodynamics continue to exert the dominant control on heavy metal distribution within the estuary.

4.*3 Geo-Accumulation Index (Igeo)*

The geo-accumulation index (Igeo) is a widely accepted geochemical indicator used to evaluate the degree of heavy metal contamination in sediments by comparing present metal concentrations with pre-industrial background levels while accounting for natural lithological variations (Müller, 1969). The index was calculated using Equation (1), with average shale values proposed by Turekian & Wedepohl (1961) adopted as the geochemical background concentrations.

$$I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right) \quad (1)$$

where (C_n) is the measured concentration of the metal in the sediment, (B_n) is the background concentration of the metal, and the constant 1.5 accounts for natural variations in the background due to lithological heterogeneity.

Müller (1969) classified sediment contamination into seven categories based on Igeo values: Igeo ≤ 0 (unpolluted); 0 < Igeo ≤ 1 (unpolluted to moderately polluted); 1 < Igeo ≤ 2 (moderately polluted); 2 < Igeo ≤ 3 (moderately to heavily polluted); 3 < Igeo ≤ 4 (heavily polluted); 4 < Igeo ≤ 5 (heavily to extremely polluted); and Igeo > 5 (extremely polluted). The calculated Igeo values for Cu, Pb, Zn, Cd, Ni, and Fe are presented in Table 2, while the average Igeo values are illustrated in Fig. 3.

The calculated Igeo values were less than or equal to zero for virtually all investigated metals across the 55 sampling stations (Table 2). According to Müller's (1969) classification, these values indicate that the sediments of the Cross River estuary are unpolluted with respect to Cu, Pb, Zn, Cd, Ni, and Fe. Although slight variations occurred among sampling stations, none of the investigated metals attained values indicative of moderate or severe contamination. The mean Igeo values followed the order:Cd > Pb > Cu > Ni > Zn > Fe

Despite cadmium exhibiting the highest mean Igeo among the investigated metals, its values remained well below the pollution threshold. This observation suggests that although Cd possesses relatively greater enrichment compared with the other metals, its accumulation has not reached environmentally significant levels. Cadmium is generally regarded as one of the most ecotoxic heavy metals because of its high mobility, persistence, and ability to bioaccumulate within aquatic food chains (Hakanson, 1980; Kabata-Pendias, 2011). Consequently, even slight increases in Cd concentrations warrant continued environmental surveillance.

The extremely low Igeo values obtained for Fe indicate that its occurrence is overwhelmingly controlled by natural lithogenic sources rather than anthropogenic contamination. Iron is one of the principal constituents of tropical lateritic soils and sedimentary formations in southeastern Nigeria, and its abundance largely reflects weathering processes operating within the Cross River Basin (Eddy *et al*., 2004; Förstner & Wittmann, 2012).

Similarly, Cu, Zn, Ni, and Pb all exhibited strongly negative Igeo values, indicating negligible enrichment relative to average shale composition. These results demonstrate that

anthropogenic activities within the estuary, including shipping operations, dredging, urbanization, fishing activities, and agricultural practices, have not produced sufficient metal accumulation to significantly alter the natural geochemical composition of the sediments.

The present findings are consistent with previous investigations conducted within the Cross River estuary. Eddy *et al*. (2004)similarly Yreported that heavy metal concentrations remained close to natural background levels and concluded that sediment quality was only minimally affected by human activities. Comparable observations have also been reported for the Calabar River (Ntekim *et al*., 1993), Qua Iboe River estuary (Emeka & Emea, 2026), and several tropical estuaries where efficient tidal flushing limits long-term accumulation of contaminants (Ahmadov *et al*., 2020; Attia & Ghrefat, 2013).

Table 2: Calculated I_{geo} values of heavy metals in sediment samples

Sample stations	Cu	Pb	Zn	Cd	Ni	Fe
1	-8.112	-14.873	-8.434	-4.017	-7.594	-16.182
2	-8.511	0.000	-10.214	0.000	-8.294	-17.546
3	-8.503	0.000	-10.214	0.000	-8.187	-17.263
4	-7.868	-12.551	-8.323	-3.086	-7.522	-15.935
5	-7.883	-12.873	-8.329	-3.141	-7.524	-15.961
6	-8.511	0.000	-10.477	0.000	-9.616	-17.755
7	-8.106	-13.873	-8.369	-3.907	-7.588	-16.169
8	-7.898	-9.743	-8.339	-3.141	-7.672	-15.974
9	-8.496	0.000	-9.711	0.000	-9.146	-17.170
10	-8.480	0.000	-9.406	0.000	-8.458	-16.873
11	-7.672	-12.873	-8.285	-3.032	-7.509	-15.910
12	-7.795	-13.288	-8.294	-3.086	-7.567	-15.961
13	-8.488	0.000	-9.551	0.000	-8.924	-17.111
14	-8.197	-14.873	-8.629	-4.354	-7.670	-16.346
15	-8.511	0.000	-10.339	0.000	-9.731	-17.626
16	-8.328	-14.873	-8.513	-4.059	-7.652	-16.329
17	-8.496	0.000	-9.754	0.000	-9.187	-17.201
18	-8.136	-13.873	-8.366	-3.907	-7.588	-16.167
19	-8.261	-14.873	-8.438	-3.956	-7.591	-16.179
20	-8.511	0.000	-10.339	0.000	-9.857	-17.711
21	-7.814	0.000	-8.372	-3.492	-7.424	-16.069
22	-8.488	0.000	-9.589	0.000	-8.857	-17.083
23	-8.480	0.000	-9.386	0.000	-8.509	-17.000
24	-7.771	-11.413	-8.199	-3.170	-7.421	-15.897
25	-8.077	0.000	-8.214	-3.907	-7.434	-16.014
26	-8.261	-14.873	-8.281	-4.017	-7.661	-16.155
27	-8.197	0.000	-8.275	-4.017	-7.483	-16.027
28	-8.488	0.000	-9.551	0.000	-8.793	-17.000
29	-7.819	-13.288	-8.244	-3.684	-7.535	-16.126
30	-8.328	-14.873	-8.275	-4.012	-7.569	-16.190
31	-8.503	0.000	-10.098	0.000	-9.068	-17.546

32	-8.077	-13.873	-8.253	-3.907	-7.561	-16.167
33	-7.790	-12.551	-8.205	-3.322	-7.434	-15.910
34	-7.809	-13.288	-8.238	-3.726	-7.535	-16.126
35	-7.781	-11.551	-8.205	-3.492	-7.458	-15.942
36	-8.136	-14.873	-8.272	-4.012	-7.605	-16.181
37	-8.288	-14.873	-8.297	-4.059	-7.608	-16.351
38	-8.488	0.000	-10.339	0.000	-8.793	-17.466
39	-8.268	0.000	-8.307	-4.059	-7.672	-16.337
40	-8.328	-14.873	-8.269	-4.017	-7.613	-16.167
41	-8.480	0.000	-10.214	0.000	-8.731	-17.047
42	-7.795	-11.551	-8.260	-3.032	-7.483	-15.904
43	-8.197	-13.873	-8.275	-3.170	-7.619	-16.187
44	-8.435	0.000	-8.941	0.000	-8.409	-16.778
45	-8.020	-13.288	-8.235	-3.086	-7.616	-16.154
46	-7.591	-11.551	-8.247	-2.748	-7.434	-15.899
47	-7.913	-12.288	-8.372	-3.492	-7.561	-16.126
48	-7.633	-11.551	-8.275	-2.907	-7.483	-15.961
49	-8.450	0.000	-10.098	0.000	-8.857	-16.659
50	-8.473	0.000	-9.551	0.000	-8.994	-16.915
51	-7.766	-12.288	-8.275	-2.684	-7.483	-15.935
52	-7.888	-12.362	-8.260	-2.791	-7.509	-15.974
53	-8.106	-12.873	-8.285	-3.492	-7.561	-16.125
54	-8.197	-13.873	-8.304	-4.059	-7.638	-16.351
55	-7.873	-11.551	-8.256	-2.956	-7.535	-16.126
Mean	-8.159	-7.926	-8.819	-2.382	-7.997	-16.459
Minimum	-8.511	-14.873	-10.477	-4.354	-9.857	-17.755
Maximum	-7.591	0.000	-8.199	0.000	-7.421	-15.897

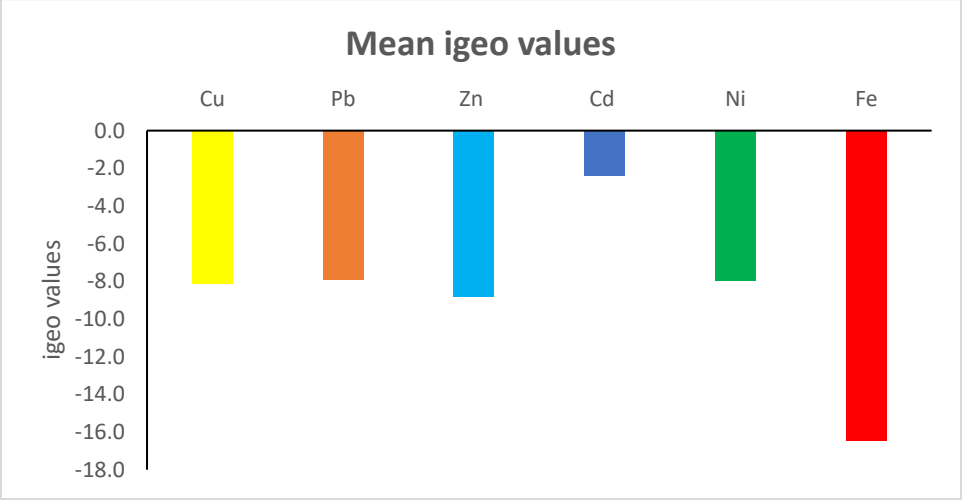

Fig. 3: Mean igeo values of investigated metals

The generally low Igeo values may be attributed to the highly dynamic hydrodynamic regime of the Cross River estuary. Strong tidal currents, seasonal freshwater discharge, continuous sediment resuspension, and active sediment transport reduce the residence time of

contaminants and minimize their accumulation within bottom sediments. Furthermore, the predominance of sandy sediments across much of the estuary limits heavy metal adsorption because coarse-grained sediments possess relatively low organic matter content and fewer adsorption sites compared with fine-grained clay-rich deposits (Horowitz, 1991).

Overall, the geo-accumulation index demonstrates that the sediments of the Cross River estuary remain geochemically stable and largely unaffected by significant heavy metal pollution. Nevertheless, continued monitoring is recommended because increasing industrialization, urban expansion, and maritime activities along the estuary could progressively elevate metal concentrations and alter sediment quality over time.

4.4 Contamination Factor (CF)

The contamination factor (CF) provides a quantitative measure of the degree of heavy metal contamination by comparing the concentration of each metal in sediment with its corresponding background concentration (Hakanson, 1980). The contamination factor was calculated using Equation (2):

$$CF = {C_m metal}/{C_m background} \quad (2)$$

where $C_m metal$ represents the measured concentration of the metal in the sediment and $C_m background$ is the corresponding average shale value proposed by Turekian & Wedepohl (1961).

According to Hakanson (1980), contamination levels are classified as follows: CF < 1: Low contamination, 1 ≤ CF < 3: Moderate contamination, 3 ≤ CF < 6: Considerable contamination and CF ≥ 6: Very high contamination. The calculated contamination factors for all investigated metals, together with the Degree of Contamination (DC) and Pollution Load Index (PLI), are presented in Table 3, while the mean CF values are illustrated in Fig. 4,

The contamination factor values obtained for Cu, Pb, Zn, Cd, Ni, and Fe were consistently less than unity across all sampling stations (Table 3). Mean CF values ranged from approximately 0.000 for Fe to 0.092 for Cd, with the overall trend: Cd > Ni > Cu > Zn > Pb > Fe

.Table 3: CF, DC and PLI values of sediment samples

Sample stations	CF						DC	PLI
	Cu	Pb	Zn	Cd	Ni	Fe		
1	0.005	0.000	0.004	0.093	0.008	0.000	0.110	0.002
2	0.004	0.000	0.001	0.000	0.005	0.000	0.010	0.000
3	0.004	0.000	0.001	0.000	0.005	0.000	0.011	0.000
4	0.006	0.000	0.005	0.177	0.008	0.000	0.196	0.003
5	0.006	0.000	0.005	0.170	0.008	0.000	0.189	0.002
6	0.004	0.000	0.001	0.000	0.002	0.000	0.007	0.000
7	0.005	0.000	0.005	0.100	0.008	0.000	0.118	0.002
8	0.006	0.002	0.005	0.170	0.007	0.000	0.190	0.003
9	0.004	0.000	0.002	0.000	0.003	0.000	0.009	0.000
10	0.004	0.000	0.002	0.000	0.004	0.000	0.011	0.000
11	0.007	0.000	0.005	0.183	0.008	0.000	0.204	0.003
12	0.007	0.000	0.005	0.177	0.008	0.000	0.196	0.002
13	0.004	0.000	0.002	0.000	0.003	0.000	0.009	0.000
14	0.005	0.000	0.004	0.073	0.007	0.000	0.090	0.001
15	0.004	0.000	0.001	0.000	0.002	0.000	0.007	0.000
16	0.005	0.000	0.004	0.090	0.007	0.000	0.106	0.002

17	0.004	0.000	0.002	0.000	0.003	0.000	0.008	0.000
18	0.005	0.000	0.005	0.100	0.008	0.000	0.118	0.002
19	0.005	0.000	0.004	0.097	0.008	0.000	0.114	0.002
20	0.004	0.000	0.001	0.000	0.002	0.000	0.007	0.000
21	0.007	0.000	0.005	0.133	0.009	0.000	0.153	0.000
22	0.004	0.000	0.002	0.000	0.003	0.000	0.009	0.000
23	0.004	0.000	0.002	0.000	0.004	0.000	0.011	0.000
24	0.007	0.001	0.005	0.167	0.009	0.000	0.188	0.003
25	0.006	0.000	0.005	0.100	0.009	0.000	0.119	0.000
26	0.005	0.000	0.005	0.093	0.007	0.000	0.110	0.002
27	0.005	0.000	0.005	0.093	0.008	0.000	0.111	0.000
28	0.004	0.000	0.002	0.000	0.003	0.000	0.010	0.000
29	0.007	0.000	0.005	0.117	0.008	0.000	0.136	0.002
30	0.005	0.000	0.005	0.093	0.008	0.000	0.110	0.002
31	0.004	0.000	0.001	0.000	0.003	0.000	0.008	0.000
32	0.006	0.000	0.005	0.100	0.008	0.000	0.119	0.002
33	0.007	0.000	0.005	0.150	0.009	0.000	0.171	0.003
34	0.007	0.000	0.005	0.113	0.008	0.000	0.133	0.002
35	0.007	0.001	0.005	0.133	0.009	0.000	0.154	0.003
36	0.005	0.000	0.005	0.093	0.008	0.000	0.111	0.002
37	0.005	0.000	0.005	0.090	0.008	0.000	0.107	0.002
38	0.004	0.000	0.001	0.000	0.003	0.000	0.009	0.000
39	0.005	0.000	0.005	0.090	0.007	0.000	0.107	0.000
40	0.005	0.000	0.005	0.093	0.008	0.000	0.110	0.002
41	0.004	0.000	0.001	0.000	0.004	0.000	0.009	0.000
42	0.007	0.001	0.005	0.183	0.008	0.000	0.204	0.003
43	0.005	0.000	0.005	0.167	0.008	0.000	0.184	0.002
44	0.004	0.000	0.003	0.000	0.004	0.000	0.012	0.000
45	0.006	0.000	0.005	0.177	0.008	0.000	0.195	0.002
46	0.008	0.001	0.005	0.223	0.009	0.000	0.245	0.003
47	0.006	0.000	0.005	0.133	0.008	0.000	0.152	0.002
48	0.008	0.001	0.005	0.200	0.008	0.000	0.221	0.003
49	0.004	0.000	0.001	0.000	0.003	0.000	0.009	0.000
50	0.004	0.000	0.002	0.000	0.003	0.000	0.009	0.000
51	0.007	0.000	0.005	0.233	0.008	0.000	0.254	0.003
52	0.006	0.000	0.005	0.217	0.008	0.000	0.236	0.003
53	0.005	0.000	0.005	0.133	0.008	0.000	0.152	0.002
54	0.005	0.000	0.005	0.090	0.008	0.000	0.107	0.002
55	0.006	0.001	0.005	0.193	0.008	0.000	0.213	0.003
Mean	0.005	0.000	0.004	0.092	0.006	0.000	0.107	0.001
Minimum	0.004	0.000	0.001	0.000	0.002	0.000	0.007	0.000
Maximum	0.008	0.002	0.005	0.233	0.009	0.000	0.254	0.003

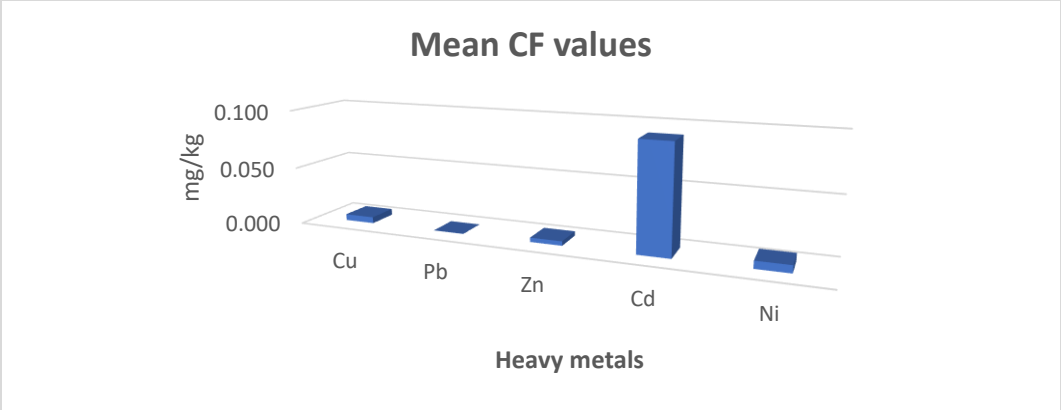

Fig. 4: Mean CF values of heavy metals

Although Cd exhibited the highest contamination factor among the investigated metals, its mean CF remained substantially below the threshold value of one, indicating low contamination. This observation reflects the relatively greater enrichment tendency of cadmium compared with the other metals but also confirms that Cd concentrations remain within acceptable environmental limits.

Copper, zinc, nickel, and lead similarly recorded very low contamination factors, indicating minimal anthropogenic enrichment. The uniformly low CF values suggest that the observed concentrations primarily reflect natural geological inputs derived from weathering of rocks and soils within the Cross River drainage basin rather than significant contamination from industrial or urban sources.

Iron exhibited the lowest contamination factor because of its exceptionally high background concentration in average shale. Its occurrence therefore reflects the natural mineralogical composition of sediments rather than pollution. Similar observations have been reported in estuarine sediments of southeastern Nigeria, where Fe concentrations are largely controlled by lithogenic processes (Eddy *et al*., 2004; Uwah *et al*., 2013).

Spatially, slightly elevated CF values were observed at stations located near the Akpa-Yafe River mouth, Calabar River, and the entrance to the Bakassi Peninsula. These locations coincide with areas characterized by increased shipping activities, coastal settlements, industrial establishments, agricultural runoff, and urban wastewater discharge. Although these localized increases suggest some degree of anthropogenic influence, the contamination factors remain sufficiently low to indicate that the overall sediment quality has not been adversely affected.

The present results agree closely with previous studies conducted within the Cross River estuary and other Niger Delta estuaries. Eddy *et al*. (2004) similarly reported contamination factor values below one for most investigated heavy metals and concluded that sediment contamination was insignificant. Comparable findings have also been reported by Attia & Ghrefat (2013), Ahmadov *et al*. (2020), and Emeka & Emeka (2026), who observed low contamination factors in relatively undisturbed estuarine systems.

The consistently low CF values indicate that the Cross River estuary presently experiences only minor anthropogenic inputs of heavy metals despite increasing urbanization and maritime activities. Nevertheless, the relatively higher contamination factor observed for cadmium suggests that this metal should receive particular attention during future environmental monitoring programmes because of its high toxicity and potential ecological significance even at relatively low concentrations (Hakanson, 1980; Kabata-Pendias, 2011).

4.5 Degree of Contamination (DC)

The Degree of Contamination (DC) is an integrated pollution index that provides a comprehensive assessment of the cumulative contamination of sediments by multiple heavy metals at each sampling location. Unlike the contamination factor, which evaluates individual metals separately, the DC combines the contamination factors of all investigated metals to quantify the overall contamination status of the sediment (Hakanson, 1980). The index was calculated using equation (3):

$$DC = \sum CF \quad (3)$$

where CF represents the contamination factor of each investigated metal. According to the classification proposed by Hakanson (1980), the Degree of Contamination is categorized as follows: DC < 6: Low degree of contamination, 6 ≤ DC < 12: Moderate degree of contamination, 12 ≤ DC < 24: Considerable degree of contamination and DC ≥ 24: Very high degree of contamination. The calculated DC values for all sediment sampling stations are presented in Table 3.

The Degree of Contamination values ranged from 0.007 to 0.254, with an average value of 0.107 (Table 3). All sampling stations recorded DC values far below the threshold value of 6, indicating a low degree of contamination throughout the Cross River estuary. These results demonstrate that the cumulative contribution of Cu, Pb, Zn, Cd, Ni, and Fe to sediment contamination is negligible and that no location within the study area exhibits evidence of significant heavy metal accumulation.

Although slight variations in DC values were observed among sampling stations, the highest values occurred at Stations 46, 48, 51, and 52. These stations correspond to areas characterized by relatively higher concentrations of Cu, Cd, Ni, and Zn (Table 1). Their proximity to active navigation routes, industrial facilities, coastal settlements, and river tributaries suggests that localized anthropogenic activities may contribute to minor increases in heavy metal inputs. Nevertheless, these localized enrichments remain insufficient to alter the overall contamination status of the estuary.

Conversely, the lowest DC values were recorded at Stations 6, 15, and 20, which are characterized by comparatively lower heavy metal concentrations. These stations are located within relatively less disturbed sections of the estuary where anthropogenic pressures are minimal, indicating that natural geochemical processes largely control sediment composition in these areas.

The consistently low DC values reflect the effectiveness of the estuary's hydrodynamic conditions in limiting contaminant accumulation. The Cross River estuary experiences strong tidal flushing, continuous freshwater inflow, and active sediment transport, all of which promote dispersion and dilution of contaminants before they can accumulate to environmentally significant concentrations. In addition, the predominance of sandy sediments with relatively low organic matter content reduces the adsorption and long-term retention of heavy metals (Horowitz, 1991; Förstner & Wittmann, 2012).

The present findings agree with previous investigations conducted within the Cross River estuary. Eddy *et al*. (2004) similarly reported low degrees of sediment contamination and concluded that heavy metal concentrations reflected predominantly natural geological sources. Comparable observations have also been reported for the Calabar River (Ntekim *et al*., 1993), Qua Iboe River estuary (Emeka & Emeka, 2026), and other tropical estuarine environments where efficient hydrodynamic mixing limits sediment contamination (Attia & Ghrefat, 2013; Ahmadov *et al*., 2020).

The low Degree of Contamination observed throughout the study area indicates that the combined influence of all investigated metals currently poses minimal environmental concern. However, increasing industrialization,

urban expansion, petroleum-related activities, and intensified maritime transport within the Cross River Basin may gradually elevate contamination levels if effective environmental management strategies are not maintained. Consequently, periodic sediment quality assessments are essential to detect early changes in contamination status before ecological degradation occurs.

4.6 Pollution Load Index (PLI)

The Pollution Load Index (PLI) is a comprehensive pollution indicator that evaluates the overall level of heavy metal contamination within sediments by integrating the contamination factors of all investigated metals into a single numerical value (Tomlinson *et al*., 1980). The index provides a convenient measure of the cumulative impact of anthropogenic activities on sediment quality and enables comparisons among different sampling locations and estuarine systems. The Pollution Load Index was calculated using equation (4):

$$PL1 = (CF1 \times CF2 \times CF3 \ldots . CFN)^{\frac{1}{n}} \quad (4)$$

where CF is the contamination factor of each investigated heavy metal and **n** represents the total number of metals considered.

According to Tomlinson *et al*. (1980), Attia and Ghrefat (2013), and Ahmadov *et al*. (2020): Accordinglu, PLI < 1 indicates an unpolluted environment. PLI = 1 indicates baseline pollution levels and PLI > 1 indicates sediment deterioration due to anthropogenic contamination. The calculated PLI values for the Cross River estuary are presented in Table 3.

The Pollution Load Index values ranged from 0.000 to 0.003, with an average value of approximately 0.001 (Table 3). All sampling stations recorded PLI values substantially below unity, indicating that the sediments of the Cross River estuary are unpolluted with respect to the investigated heavy metals.

Although slight spatial variations were observed, no sampling station exhibited a PLI value approaching the pollution threshold. Relatively higher PLI values occurred at Stations 46, 48, 51, and 55, reflecting localized increases in Cu, Cd, Zn, and Ni concentrations. These stations are situated near areas influenced by navigation activities, industrial operations, urban development, and riverine discharge. Nevertheless, the observed values remain several orders of magnitude below the critical value of one, demonstrating that these localized anthropogenic inputs have not significantly degraded sediment quality.

The extremely low PLI values obtained in this study indicate that natural geochemical processes continue to dominate the sediment chemistry of the Cross River estuary. Continuous tidal exchange between freshwater and marine environments enhances dilution and sediment redistribution, thereby minimizing the accumulation of contaminants. Furthermore, sediment transport associated with seasonal river discharge limits the long-term retention of heavy metals within depositional environments. The findings of this study are consistent with previous investigations in the Cross River estuary and adjacent coastal environments. Eddy *et al*. (2004) similarly concluded that the estuary remained largely free from heavy metal pollution based on contamination indices. Comparable results have also been reported for the Qua Iboe River estuary (Emeka & Emeka, 2026), Mediterranean coastal sediments (Attia & Ghrefat, 2013), and estuaries of the western Caspian Sea (Ahmadov *et al*., 2020), where Pollution Load Index values below one reflected minimal anthropogenic influence.

The low Pollution Load Index indicates that the cumulative effect of Cu, Pb, Zn, Cd, Ni, and Fe has not resulted in sediment degradation within the Cross River estuary. This finding is particularly significant considering the increasing levels of industrialization, petroleum exploration, commercial shipping, dredging, and urban expansion occurring within the estuarine catchment. The current

environmental condition therefore suggests that natural assimilative and self-purification processes remain effective in mitigating heavy metal accumulation.

However, because the estuary serves as a major transportation corridor and supports numerous industrial, agricultural, and domestic activities, continuous environmental monitoring should be maintained. Long-term surveillance will facilitate the early detection of changes in Pollution Load Index values and provide scientific evidence for sustainable management of the Cross River estuarine ecosystem.

4.7 Ecological Risk Factor (Er)

The Ecological Risk Factor (Er) is a widely used environmental index that evaluates the potential ecological threat posed by individual heavy metals in sediments by integrating the contamination level of each metal with its relative toxicity (Hakanson, 1980). Unlike contamination indices that consider only metal concentrations, the Er index accounts for the toxicological significance of each element, thereby providing a more realistic assessment of the environmental hazards associated with heavy metal contamination. The Ecological Risk Factor was calculated using Equation (5):

$$Er = Tr \times CF \quad (5)$$

where (E_r) is the ecological risk factor, (T_r) is the toxic-response coefficient of the metal, and (CF) is the contamination factor. Toxic-response coefficients adopted in this study were 30 for Cd, 5 for Cu, Pb and Ni, and 1 for Zn, following the recommendations of Hakanson (1980) and Sakan *et al*. (2009).

According to Hakanson (1980), ecological risk is classified as follows: Er < 40: Low ecological risk, 40 ≤ Er < 80: Moderate ecological risk, 80 ≤ Er < 160: Considerable ecological risk, 160 ≤ Er < 320: High ecological risk and Er ≥ 320: Very high ecological risk

The calculated ecological risk factors for all investigated metals are presented in Table 4, while the mean Er values are illustrated in Fig. 5.

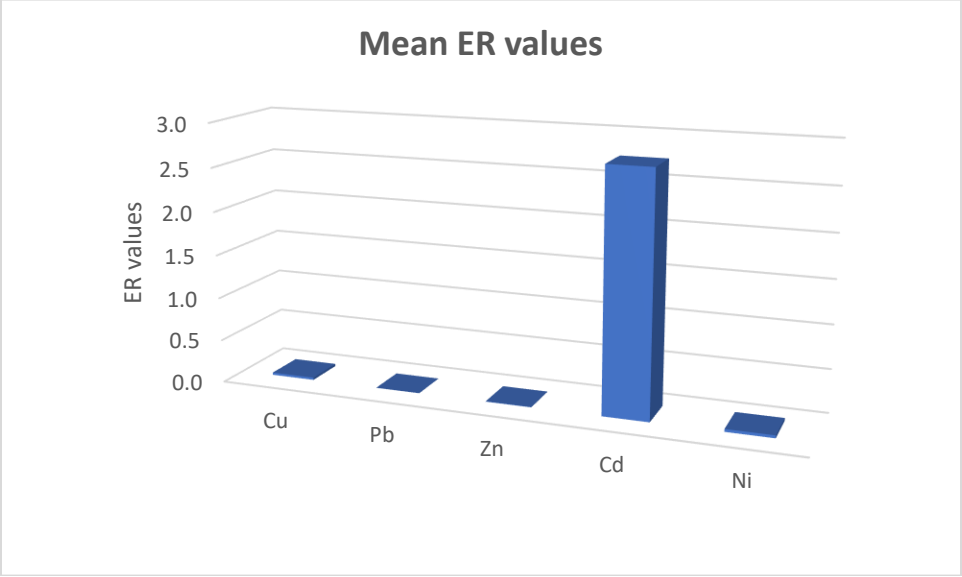

Fig. 5 Mean ER values of heavy metals

The calculated ecological risk factors indicate that all investigated metals pose low ecological risk to the sediments of the Cross River estuary. The Er values for Cu, Pb, Zn, Ni, and Cd were all substantially lower than the threshold value of 40, demonstrating that the concentrations of these metals are insufficient to produce significant adverse ecological effects under present environmental conditions.

Among the investigated metals, cadmium recorded the highest mean ecological risk factor (Er = 2.747), whereas zinc exhibited the lowest mean value (Er = 0.004) (Table 4; Fig. 5). Although cadmium occurred at relatively low concentrations in the sediment (Table 1), its higher Er value reflects its high toxic-response coefficient rather than elevated concentration. Cadmium is recognized as one of the most hazardous trace metals because of its high toxicity, persistence, mobility, and ability to bioaccumulate in aquatic organisms, even at relatively low environmental concentrations (Kabata-Pendias, 2011). Consequently, its ecological significance is proportionally greater than that of other investigated metals.

Copper and nickel exhibited mean Er values of 0.027 and 0.032, respectively, indicating negligible ecological risk despite their relatively higher concentrations compared to Pb and Cd. These low risk values result from their very low contamination factors, suggesting that their occurrence is predominantly controlled by natural geological sources rather than anthropogenic enrichment. Similarly, lead recorded a mean Er value of 0.001, confirming that Pb contamination within the estuary remains environmentally insignificant.

Spatial variations in Er values were relatively minor throughout the study area. Slightly elevated ecological risk factors were observed at Stations 46, 48, 51, and 52, corresponding to locations where cadmium and copper concentrations were relatively higher (Table 4). These stations are situated near areas characterized by increased navigation activities, urban settlements, industrial establishments, and riverine inputs. Although these localized increases suggest limited anthropogenic influence, the ecological risk remains well within the low-risk category.

The present findings are consistent with previous studies conducted in estuarine environments within southern Nigeria. Eddy *et al*. (2004) reported similarly low ecological risk factors for sediments of the Cross River estuary, while Uwah *et al*. (2013) and Emeka and Emeka (2026) also observed minimal ecological risks associated with heavy metals in the Qua Iboe River estuary. Comparable results have been reported in other coastal environments where effective tidal flushing and sediment mixing reduce heavy metal accumulation (Attia & Ghrefat, 2013; Ahmadov *et al*., 2020).

The generally low ecological risk observed in this study may be attributed to the relatively low concentrations of heavy metals, efficient sediment transport, continuous tidal exchange, and the absence of major industrial pollution sources capable of causing substantial metal enrichment. Furthermore, the predominance of sandy sediments within the estuary likely reduces the adsorption and retention of dissolved metals, thereby limiting their bioavailability to aquatic organisms (Horowitz, 1991). Overall, the Ecological Risk Factor demonstrates that individual heavy metals currently pose minimal ecological threats to the Cross River estuary. Nevertheless, cadmium deserves continued attention because of its comparatively higher toxicity and potential to bioaccumulate in aquatic food webs. Long-term monitoring of Cd concentrations should therefore form an integral component of future environmental assessment programmes.

4.8 Potential Ecological Risk Index (RI)

The Potential Ecological Risk Index (RI) provides a comprehensive assessment of the cumulative ecological risk posed by all investigated heavy metals within a sedimentary environment. Unlike the ecological risk factor, which evaluates each metal individually, the RI integrates the ecological risk factors of all metals to estimate the overall environmental threat at each sampling station (Hakanson, 1980). The index was calculated using equation 6:

$$RI = \sum Er = \sum (Tr \times CF) \qquad (6)$$

where (E_r) is the ecological risk factor of each heavy metal, (Tr) is the toxic-response coefficient, and (CF) is the contamination factor.

According to Hakanson (1980), the ecological risk index is classified as follows: RI < 95: Low ecological risk, 95 ≤ RI < 190: Moderate ecological risk, 190 ≤ RI < 380: Considerable ecological risk and RI ≥ 380: Very high ecological risk. The calculated RI values for all sampling stations are presented in Table 4, while their spatial variations are illustrated in Fig. 6.

Table 4: ER and RI values of sediment samples

Sampling stations	ER					RI
	Cu	Pb	Zn	Cd	Ni	
1	0.027	0.000	0.004	2.780	0.039	2.851
2	0.021	0.000	0.001	0.000	0.024	0.046
3	0.021	0.000	0.001	0.000	0.026	0.048
4	0.032	0.001	0.005	5.300	0.041	5.379
5	0.032	0.001	0.005	5.100	0.041	5.178
6	0.021	0.000	0.001	0.000	0.010	0.031
7	0.027	0.001	0.005	3.000	0.039	3.071
8	0.031	0.009	0.005	5.100	0.037	5.182
9	0.021	0.000	0.002	0.000	0.013	0.036
10	0.021	0.000	0.002	0.000	0.021	0.045
11	0.037	0.001	0.005	5.500	0.041	5.584
12	0.034	0.001	0.005	5.300	0.040	5.379
13	0.021	0.000	0.002	0.000	0.015	0.038
14	0.026	0.000	0.004	2.200	0.037	2.266
15	0.021	0.000	0.001	0.000	0.009	0.031
16	0.023	0.000	0.004	2.700	0.037	2.765
17	0.021	0.000	0.002	0.000	0.013	0.035
18	0.027	0.001	0.005	3.000	0.039	3.071
19	0.024	0.000	0.004	2.900	0.039	2.968
20	0.021	0.000	0.001	0.000	0.008	0.030
21	0.033	0.000	0.005	4.000	0.044	4.082
22	0.021	0.000	0.002	0.000	0.016	0.039
23	0.021	0.000	0.002	0.000	0.021	0.044
24	0.034	0.003	0.005	5.000	0.044	5.086
25	0.028	0.000	0.005	3.000	0.043	3.076
26	0.024	0.000	0.005	2.780	0.037	2.847
27	0.026	0.000	0.005	2.780	0.042	2.852
28	0.021	0.000	0.002	0.000	0.017	0.040
29	0.033	0.001	0.005	3.500	0.040	3.579
30	0.023	0.000	0.005	2.790	0.039	2.858
31	0.021	0.000	0.001	0.000	0.014	0.036
32	0.028	0.001	0.005	3.000	0.040	3.073
33	0.034	0.001	0.005	4.500	0.043	4.584
34	0.033	0.001	0.005	3.400	0.040	3.480
35	0.034	0.003	0.005	4.000	0.043	4.084

	36	0.027	0.000	0.005	2.790	0.039	2.860
	37	0.024	0.000	0.005	2.700	0.038	2.767
	38	0.021	0.000	0.001	0.000	0.017	0.039
	39	0.024	0.000	0.005	2.700	0.037	2.766
	40	**0.023**	**0.000**	**0.005**	**2.780**	**0.038**	**2.847**
	41	0.021	0.000	0.001	0.000	0.018	0.040
	42	0.034	0.003	0.005	5.500	0.042	5.583
	43	0.026	0.001	0.005	5.000	0.038	5.069
	44	0.022	0.000	0.003	0.000	0.022	0.047
	45	0.029	0.001	0.005	5.300	0.038	5.373
	46	**0.039**	**0.003**	**0.005**	**6.700**	**0.043**	**6.790**
	47	0.031	0.002	0.005	4.000	0.040	4.077
	48	0.038	0.003	0.005	6.000	0.042	6.087
	49	0.021	0.000	0.001	0.000	0.016	0.039
	50	0.021	0.000	0.002	0.000	0.015	0.038
	51	0.034	0.002	0.005	7.000	0.042	7.083
	52	0.032	0.001	0.005	6.500	0.041	6.579
	53	0.027	0.001	0.005	4.000	0.040	4.073
	54	0.026	0.001	0.005	2.700	0.038	2.768
	55	0.032	0.003	0.005	5.800	0.040	5.880
Mean		0.027	0.001	0.004	2.747	0.032	2.811
Minimum		0.021	0.000	0.001	0.000	0.008	0.030
Maximum		0.039	0.009	0.005	7.000	0.044	7.083

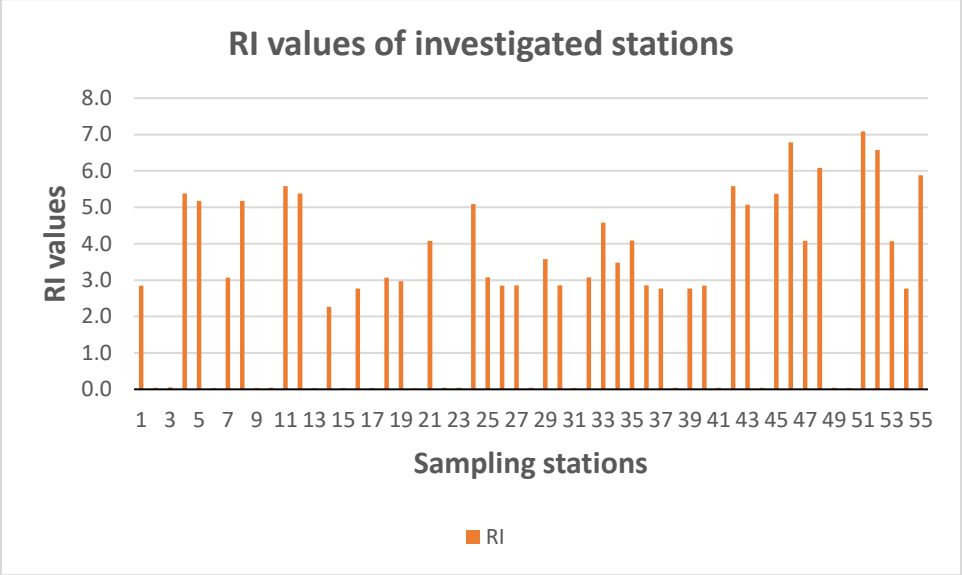

Fig. 6 RI values of investigated stations

The ecological risk index values ranged from 0.030 to 7.083, with a mean value of 2.811 (Table 4). All calculated RI values were substantially lower than the threshold value of

95, indicating that the sediments of the Cross River estuary pose low overall ecological risk with respect to Cu, Pb, Zn, Cd, and Ni.

Although slight variations were observed among sampling stations, the highest RI values occurred at Stations 46, 48, 51, and 52. These stations also recorded relatively elevated cadmium concentrations and corresponding ecological risk factors, demonstrating the strong influence of Cd on the overall ecological risk despite its comparatively low concentration. This finding highlights the importance of considering metal toxicity in ecological assessments rather than relying solely on concentration data.

The uniformly low RI values indicate that heavy metals have not accumulated to concentrations capable of causing significant ecological disturbances within the estuary. The results suggest that aquatic organisms inhabiting the estuary are presently exposed to relatively low toxicological stress arising from sediment-associated heavy metals. Consequently, the sediments can be regarded as environmentally safe under current conditions.

The observed low ecological risk may be attributed to several environmental factors, including effective tidal flushing, continuous freshwater inflow from the Cross River Basin, rapid sediment redistribution, and dilution through estuarine mixing. These hydrodynamic processes reduce contaminant residence time and minimize long-term accumulation of heavy metals within depositional environments. In addition, the relatively low levels of industrialization compared with heavily urbanized estuaries may further contribute to the favourable sediment quality observed in this study.

The present findings corroborate previous investigations within the Cross River estuary (Eddy *et al*., 2004), the Calabar River (Ntekim *et al*., 1993), and the Qua Iboe River estuary (Emeka & Emeka, 2026), all of which reported low ecological risk associated with sediment-bound heavy metals. Similar conclusions have been reached for estuarine environments in the Mediterranean region (Attia & Ghrefat, 2013), the Caspian Sea (Ahmadov *et al*., 2020), and several tropical coastal systems where natural hydrodynamic processes effectively limit heavy metal accumulation.

Although the present ecological risk is low, increasing anthropogenic activities within the Cross River estuary—including petroleum transportation, dredging, urban expansion, industrial development, agriculture, and commercial shipping—may progressively alter sediment quality over time. Continuous environmental monitoring and periodic ecological risk assessments are therefore essential to ensure the long-term protection of the estuarine ecosystem, preserve biodiversity, and safeguard fisheries and other ecosystem services.

4.7 Ecological Risk Factor (Er)

The Ecological Risk Factor (Er) is a widely used environmental index that evaluates the potential ecological threat posed by individual heavy metals in sediments by integrating the contamination level of each metal with its relative toxicity (Hakanson, 1980). Unlike contamination indices that consider only metal concentrations, the Er index accounts for the toxicological significance of each element, thereby providing a more realistic assessment of the environmental hazards associated with heavy metal contamination. The Ecological Risk Factor was calculated using equation (5):

$$Er = Tr \times CF \qquad (5)$$

where Er is the ecological risk factor, Tr is the toxic-response coefficient of the metal, and CFCFCF is the contamination factor. Toxic-response coefficients adopted in this study were 30 for Cd, 5 for Cu, Pb and Ni, and 1 for Zn, following the recommendations of Hakanson (1980) and Sakan *et al*. (2009). According to Hakanson (1980), ecological risk is classified as follows: Er < 40: Low ecological risk, 40 ≤ Er < 80: Moderate

ecological risk, 80 ≤ Er < 160: Considerable ecological risk, 160 ≤ Er < 320: High ecological risk and Er ≥ 320: Very high ecological risk. The calculated ecological risk factors for all investigated metals are presented in Table 4, while the mean Er values are illustrated in Fig. 5.

The calculated ecological risk factors indicate that all investigated metals pose low ecological risk to the sediments of the Cross River estuary. The Er values for Cu, Pb, Zn, Ni, and Cd were all substantially lower than the threshold value of 40, demonstrating that the concentrations of these metals are insufficient to produce significant adverse ecological effects under present environmental conditions.

Among the investigated metals, cadmium recorded the highest mean ecological risk factor (Er = 2.747), whereas zinc exhibited the lowest mean value (Er = 0.004) (Table 4; Fig. 5). Although cadmium occurred at relatively low concentrations in the sediment (Table 1), its higher Er value reflects its high toxic-response coefficient rather than elevated concentration. Cadmium is recognized as one of the most hazardous trace metals because of its high toxicity, persistence, mobility, and ability to bioaccumulate in aquatic organisms, even at relatively low environmental concentrations (Kabata-Pendias, 2011). Consequently, its ecological significance is proportionally greater than that of other investigated metals.

Copper and nickel exhibited mean Er values of 0.027 and 0.032, respectively, indicating negligible ecological risk despite their relatively higher concentrations compared to Pb and Cd. These low risk values result from their very low contamination factors, suggesting that their occurrence is predominantly controlled by natural geological sources rather than anthropogenic enrichment. Similarly, lead recorded a mean Er value of 0.001, confirming that Pb contamination within the estuary remains environmentally insignificant.

Spatial variations in Er values were relatively minor throughout the study area. Slightly elevated ecological risk factors were observed at Stations 46, 48, 51, and 52, corresponding to locations where cadmium and copper concentrations were relatively higher (Table 4). These stations are situated near areas characterized by increased navigation activities, urban settlements, industrial establishments, and riverine inputs. Although these localized increases suggest limited anthropogenic influence, the ecological risk remains well within the low-risk category.

The present findings are consistent with previous studies conducted in estuarine environments within southern Nigeria. Eddy *et al*. (2004) reported similarly low ecological risk factors for sediments of the Cross River estuary, while Uwah *et al*. (2013) and Emeka and Emeka (2026) also observed minimal ecological risks associated with heavy metals in the Qua Iboe River estuary. Comparable results have been reported in other coastal environments where effective tidal flushing and sediment mixing reduce heavy metal accumulation (Attia & Ghrefat, 2013; Ahmadov *et al*., 2020).

The generally low ecological risk observed in this study may be attributed to the relatively low concentrations of heavy metals, efficient sediment transport, continuous tidal exchange, and the absence of major industrial pollution sources capable of causing substantial metal enrichment. Furthermore, the predominance of sandy sediments within the estuary likely reduces the adsorption and retention of dissolved metals, thereby limiting their bioavailability to aquatic organisms (Horowitz, 1991).

Overall, the Ecological Risk Factor demonstrates that individual heavy metals currently pose minimal ecological threats to the Cross River estuary. Nevertheless, cadmium deserves continued attention because of its comparatively higher toxicity and potential to bioaccumulate in aquatic food webs. Long-

term monitoring of Cd concentrations should therefore form an integral component of future environmental assessment programmes.

4.8 Potential Ecological Risk Index (RI)

The Potential Ecological Risk Index (RI) provides a comprehensive assessment of the cumulative ecological risk posed by all investigated heavy metals within a sedimentary environment. Unlike the ecological risk factor, which evaluates each metal individually, the RI integrates the ecological risk factors of all metals to estimate the overall environmental threat at each sampling station (Hakanson, 1980). The index was calculated using Equation (6):

$$RI = \sum Er = \sum(Tr \times CF) \quad (6)$$

where Eris the ecological risk factor of each heavy metal, Tr is the toxic-response coefficient, and CF is the contamination factor. According to Hakanson (1980), the ecological risk index is classified as follows: RI < 95: Low ecological risk, 95 ≤ RI < 190: Moderate ecological risk, 190 ≤ RI < 380: Considerable ecological risk and RI ≥ 380: Very high ecological risk. The calculated RI values for all sampling stations are presented in Table 4, while their spatial variations are illustrated in Fig. 6.

The ecological risk index values ranged from 0.030 to 7.083, with a mean value of 2.811 (Table 4). All calculated RI values were substantially lower than the threshold value of 95, indicating that the sediments of the Cross River estuary pose low overall ecological risk with respect to Cu, Pb, Zn, Cd, and Ni.

Although slight variations were observed among sampling stations, the highest RI values occurred at Stations 46, 48, 51, and 52. These stations also recorded relatively elevated cadmium concentrations and corresponding ecological risk factors, demonstrating the strong influence of Cd on the overall ecological risk despite its comparatively low concentration. This finding highlights the importance of considering metal toxicity in ecological assessments rather than relying solely on concentration data.

The uniformly low RI values indicate that heavy metals have not accumulated to concentrations capable of causing significant ecological disturbances within the estuary. The results suggest that aquatic organisms inhabiting the estuary are presently exposed to relatively low toxicological stress arising from sediment-associated heavy metals. Consequently, the sediments can be regarded as environmentally safe under current conditions.

The observed low ecological risk may be attributed to several environmental factors, including effective tidal flushing, continuous freshwater inflow from the Cross River Basin, rapid sediment redistribution, and dilution through estuarine mixing. These hydrodynamic processes reduce contaminant residence time and minimize long-term accumulation of heavy metals within depositional environments. In addition, the relatively low levels of industrialization compared with heavily urbanized estuaries may further contribute to the favourable sediment quality observed in this study.

The present findings corroborate previous investigations within the Cross River estuary (Eddy *et al*., 2004), the Calabar River (Ntekim *et al*., 1993), and the Qua Iboe River estuary (Emeka & Emeka, 2026), all of which reported low ecological risk associated with sediment-bound heavy metals. Similar conclusions have been reached for estuarine environments in the Mediterranean region (Attia & Ghrefat, 2013), the Caspian Sea (Ahmadov *et al*., 2020), and several tropical coastal systems where natural hydrodynamic processes effectively limit heavy metal accumulation.

Although the present ecological risk is low, increasing anthropogenic activities within the Cross River estuary—including petroleum transportation, dredging, urban expansion, industrial development, agriculture, and commercial shipping—may progressively alter

sediment quality over time. Continuous environmental monitoring and periodic ecological risk assessments are therefore essential to ensure the long-term protection of the estuarine ecosystem, preserve biodiversity, and safeguard fisheries and other ecosystem services.

4.9 Hierarchical Cluster Analysis (HCA)

Hierarchical Cluster Analysis (HCA) is a multivariate statistical technique widely employed to identify similarities among variables and infer potential sources of heavy metals in environmental media. In this study, Q-mode hierarchical cluster analysis based on Single Linkage Euclidean Distance was applied to evaluate the relationships among the investigated heavy metals and to identify possible similarities in their sources and geochemical behavior. The resulting dendrogram is presented in Fig. 7.

The dendrogram revealed two distinct clusters, indicating differences in the origin and environmental behavior of the investigated heavy metals. Cluster I, formed at a Euclidean distance of approximately 1.6, comprised Cu, Zn, Ni, Pb, and Cd, whereas Cluster II, formed at a Euclidean distance of approximately 3.2, consisted solely of Fe (Fig. 7). The separation of Fe from the other metals suggests that it possesses a different geochemical affinity and source compared with the remaining trace metals.

The grouping of Cu, Zn, Ni, Pb, and Cd into Cluster I indicates that these metals exhibit similar spatial distribution patterns throughout the estuary and are likely influenced by comparable environmental processes. Such clustering generally implies a common origin or similar transport and depositional mechanisms (Reimann *et al*., 2008). Although the concentrations of these metals were low, their association suggests that they may originate from diffuse anthropogenic activities superimposed on natural geological inputs.

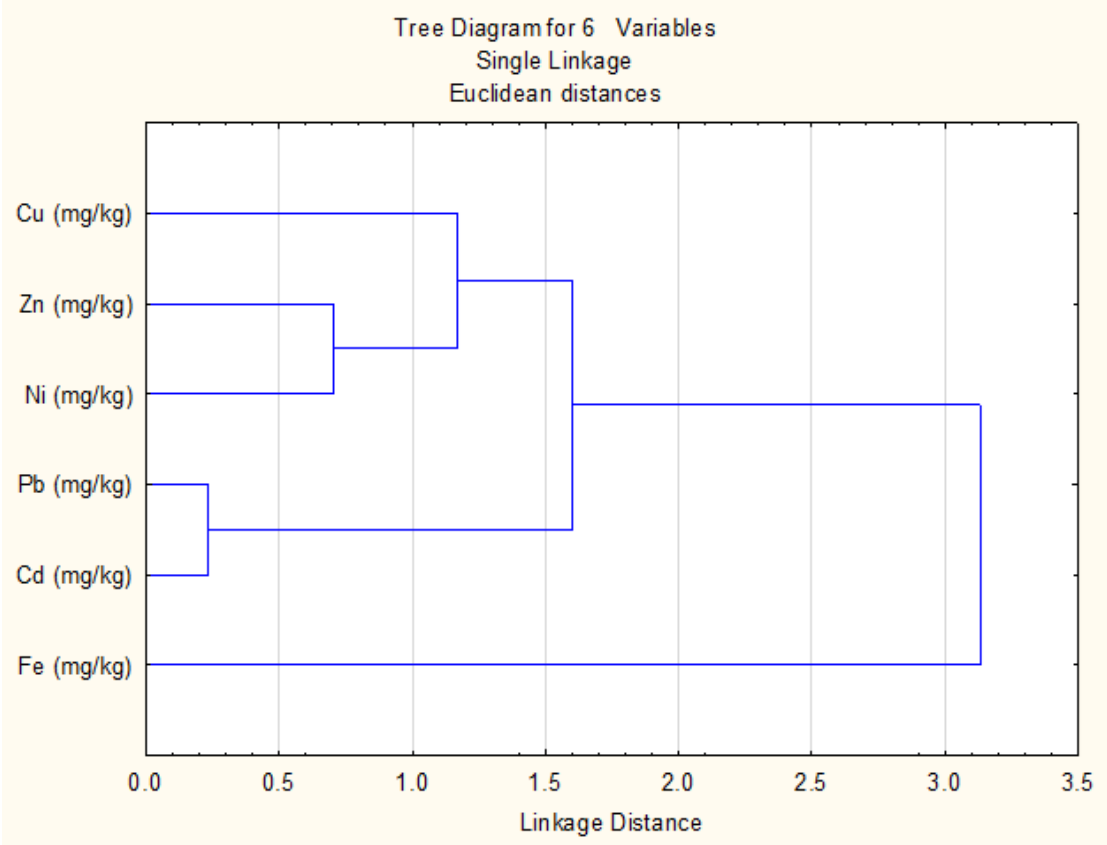

Fig. 7 :Dendrogram shows clustering of heavy metals in the study area

Potential anthropogenic sources include urban runoff, domestic wastewater discharge, agricultural runoff, maritime transportation, dredging activities, fishing operations, and petroleum-related activities occurring within the Cross River estuary. These activities release trace quantities of heavy metals into the aquatic environment, where they are subsequently transported and redistributed by estuarine hydrodynamic processes. The clustering pattern therefore reflects the combined influence of multiple low-intensity anthropogenic sources rather than contamination from a single dominant pollution source.

The close association between Cu and Zn is consistent with findings from numerous estuarine and coastal studies, where both metals are commonly linked to boat maintenance activities, corrosion of metallic structures, antifouling paints, municipal wastewater, and industrial discharges (Alloway, 2013; Förstner & Wittmann, 2012). Similarly, the association of Cd with Pb and Ni suggests that these metals may share common pathways through urban runoff, agricultural inputs, atmospheric deposition, and petroleum-related activities. However, the uniformly low concentrations and contamination indices indicate that these sources currently exert only a minor influence on sediment quality.

In contrast, Fe formed an independent cluster (Cluster II), clearly separated from the remaining heavy metals. This distinct grouping suggests that iron is primarily derived from natural lithogenic processes rather than anthropogenic contamination. Iron is one of the most abundant elements in the Earth's crust and is a major constituent of tropical soils, lateritic profiles, and sedimentary rocks within the Cross River Basin. Consequently, its distribution is largely controlled by weathering, erosion, and sediment transport rather than human activities (Kabata-Pendias, 2011; Turekian & Wedepohl, 1961).

The independent clustering of Fe corroborates the results obtained from the geo-accumulation index, contamination factor, pollution load index, and ecological risk assessment, all of which indicate that Fe concentrations are predominantly controlled by natural geological processes. Similar clustering patterns have been reported in estuarine sediments of the Niger Delta (Dan *et al*., 2022; Eddy *et al*., 2004) and other coastal environments, where Fe commonly forms a separate cluster because of its dominant lithogenic origin.

The hierarchical clustering results also support the spatial distribution patterns observed in Fig. 2. Stations located along the eastern sector of the estuary exhibited relatively higher concentrations of Cu, Zn, Cd, Pb, and Ni, corresponding to areas characterized by greater anthropogenic activities, including industrial establishments, urban development, commercial navigation, and riverine discharge. Nevertheless, the differences between the eastern and western sectors were relatively small, indicating that tidal mixing and continuous sediment redistribution effectively reduce localized accumulation of heavy metals within the estuary. Overall, the HCA results demonstrate that the investigated heavy metals originate from both natural and anthropogenic sources, with lithogenic processes exerting the dominant influence on sediment geochemistry. The clustering pattern confirms that, although localized human activities contribute to trace metal inputs, these contributions remain insufficient to significantly alter the natural geochemical composition of the estuarine sediments. These findings are in agreement with the pollution indices discussed in the preceding sections, which consistently indicate that the Cross River estuary is currently characterized by low heavy metal contamination and minimal ecological risk.

5.0 Conclusion

This study assessed the occurrence, distribution, contamination status, and

ecological risks associated with six heavy metals (Cu, Zn, Ni, Fe, Cd, and Pb) in surface sediments of the Cross River estuary, southeastern Nigeria. The results demonstrate that the estuary remains relatively unpolluted, with all investigated metals occurring at concentrations substantially below the average shale values (Turekian & Wedepohl, 1961) and the sediment quality guideline values established by the Department of Petroleum Resources (2002). The mean concentrations followed the order Fe > Ni > Zn > Cu > Cd > Pb, reflecting the predominance of naturally occurring iron-bearing minerals within the estuarine sediments.

Spatial distribution patterns revealed slight enrichment of Cu, Zn, Cd, Pb, and Ni in sections of the eastern estuary associated with greater anthropogenic activities, including urban development, industrial establishments, navigation, and petroleum-related operations. However, the observed increases were localized and remained considerably below internationally accepted pollution thresholds. The overall distribution of heavy metals appears to be strongly controlled by estuarine hydrodynamics, tidal mixing, sediment transport, and natural geological processes, which collectively limit contaminant accumulation.

The various pollution indices consistently demonstrated excellent sediment quality throughout the study area. Geo-accumulation index values indicated that the sediments are unpolluted, contamination factor values confirmed low contamination for all investigated metals, and Degree of Contamination values demonstrated that none of the sampling stations experienced significant cumulative pollution. Likewise, Pollution Load Index values remained well below unity, confirming the absence of overall sediment deterioration due to heavy metal contamination.

Ecological risk assessment further revealed that all investigated metals pose low ecological risk to the estuarine ecosystem. Although cadmium exhibited relatively higher ecological risk values because of its high toxic-response coefficient, its concentrations remained sufficiently low to preclude significant ecological effects. Consequently, the overall Potential Ecological Risk Index indicated that the sediments presently constitute a safe environment for aquatic organisms.

Hierarchical Cluster Analysis distinguished two principal metal assemblages, separating Fe from Cu, Zn, Ni, Pb, and Cd. This clustering suggests that Fe is predominantly derived from lithogenic sources, whereas the remaining metals reflect a combination of natural weathering processes and diffuse anthropogenic inputs associated with urbanization, agriculture, maritime transportation, and industrial activities. Nevertheless, natural geological processes remain the dominant control on sediment geochemistry within the Cross River estuary.

Although the present study indicates favourable sediment quality, increasing industrialization, coastal urbanization, petroleum transportation, dredging activities, and expanding maritime operations have the potential to increase heavy metal loading in the future. Therefore, continuous environmental monitoring, coupled with periodic assessment of sediments, water, and aquatic biota, is recommended to detect early changes in contamination levels and support sustainable management of the Cross River estuarine ecosystem. Future investigations should also incorporate heavy metal speciation, seasonal variability, sediment characteristics, and biological accumulation studies to provide a more comprehensive understanding of contaminant dynamics and ecological health within this important tropical estuary.

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6.0 References

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Statement and Declarations

Competing Interests

The authors hereby declare that there is no known conflict of interest either financial or personal relationships which may have appeared to influence the work as reported in the manuscript.

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Authorship contribution statement

Victoria Inyang Emeka: Conceptualization, methodology, resources, writing – original draft, writing – review & editing.

Chimezie Ndunagum Emeka: Methodology, Fig.s preparation, Writing – review & editing.

Availability of data and material

All data used in this manuscript are original except those duly acknowledged and cited by the author.