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Assessment of Heavy Metal Pollution and Ecological Risk In Bottom Sediments of the Qua-Iboe River Estuary, Southeast Nigeria

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Abstract: *The distribution, contamination status, and ecological risk of heavy metals in bottom sediments of the Qua-Iboe River Estuary, Southeast Nigeria, were investigated to evaluate the environmental quality of this tropical estuarine ecosystem. A total of 55 recent bottom sediment samples were collected from water depths ranging from 1 to 10 m and analyzed for Cu, Pb, Zn, Cd, Ni, and Fe using Atomic Absorption Spectrometry (AAS). Heavy metal concentrations ranged from 0.000–0.400 mg/kg (Cu), 0.000–0.030 mg/kg (Pb), 0.000–0.620 mg/kg (Zn), 0.000–0.171 mg/kg (Cd), 0.200–0.670 mg/kg (Ni), and 1.000–1.230 mg/kg (Fe), with mean concentrations of 0.180, 0.003, 0.341, 0.069, 0.476, and 1.090 mg/kg, respectively. The abundance of heavy metals followed the order Fe > Ni > Zn > Cu > Cd > Pb. All measured concentrations were considerably lower than the Average Shale Values and the Department of Petroleum Resources (DPR) sediment quality guidelines, indicating minimal contamination. The calculated geo-accumulation index (Igeo) values were all ≤ 0, classifying the sediments as unpolluted, while contamination factor (CF) values for all metals were < 1, indicating low contamination. The degree of contamination (DC) values ranged from 0.0049 to 0.5967, and pollution load index (PLI) values ranged from 0.0000 to 0.0048, confirming the absence of overall heavy metal pollution. Ecological risk assessment showed that ecological risk factor (Er) values for all metals were < 40, whereas the ecological risk index (RI) ranged from 0.0243 to 17.2072, indicating low ecological risk throughout the estuary. Hierarchical Cluster Analysis classified the investigated metals into two distinct groups, suggesting contributions from both natural geogenic sources and localized anthropogenic inputs. Although the sediments are presently of good environmental quality, increasing industrialization, oil-related activities, and domestic waste discharge within the Niger Delta necessitate continuous environmental monitoring to prevent future heavy metal accumulation and safeguard the ecological integrity of the Qua-Iboe River Estuary.*

Keywords: *Heavy metals; bottom sediments; Qua-Iboe River Estuary; geo-accumulation index; ecological risk assessment; pollution load index; hierarchical cluster analysis.*

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1.0 Introduction

Estuaries are dynamic transitional environments that form the interface between rivers and the oceans, serving as important sinks for river-borne sediments, nutrients, and anthropogenic pollutants. Owing to their high biological productivity and strategic economic importance, estuaries support diverse ecosystems and numerous socio-economic activities, including fisheries, navigation, agriculture, tourism, and industrial

development (Emeka *et al*., 2026; Wang *et al*., 2008). However, increasing urbanization and industrialization within coastal regions have intensified the discharge of contaminants into estuarine environments, making them among the most vulnerable aquatic ecosystems worldwide.

Heavy metals are among the most significant contaminants in estuarine ecosystems because they are non-biodegradable, environmentally persistent, and capable of bioaccumulating and biomagnifying through aquatic food webs (Akpakpan, *et* al., 2024; Omang *et al*., 2023; Seralathan *et al*., 2008; Udo *et* al., 2018; Waheed *et al*., 2013). Unlike many organic pollutants, heavy metals cannot be degraded into harmless products and may remain in sediments for extended periods, where they can be remobilized under changing physicochemical conditions. Heavy metals occurring in estuarine environments originate from both natural and anthropogenic sources. Natural inputs include rock weathering, erosion, riverine transport, and volcanic activities (Farkas *et al*., 2007), whereas anthropogenic inputs arise from mining, petroleum exploration, maritime transportation, industrial effluent discharge, agricultural runoff, municipal wastewater, and urban development. These metals accumulate in aquatic environments through complex geochemical and biological processes (Loska & Wiechuła, 2003) and cannot be eliminated through natural self-purification mechanisms. Consequently, toxic metals such as cadmium (Cd), lead (Pb), nickel (Ni), copper (Cu), zinc (Zn), chromium (Cr), mercury (Hg), and arsenic (As) may adversely affect aquatic organisms through bioaccumulation and biomagnification, thereby posing significant ecological and public health risks (Garai *et al*., 2021; Liu *et al*., 2004). Because bottom sediments function both as sinks and secondary sources of heavy metals, their assessment provides a reliable means of evaluating long-term environmental quality and potential ecological risks in estuarine ecosystems.

The Qua-Iboe River estuary is situated within the tropical humid rainforest belt of southeastern Nigeria and originates from the Umuahia Hills before flowing through alluvial deposits and Coastal Plain Sands into the Atlantic Ocean (Emeka *et al*., 2010; Antia *et al*., 2012; Emeka *et al*., 2023a, 2023b). The estuary is connected to several important tidal creeks, including Douglas, Stubbs, and Ukpenekang Creeks, while sediment transport and deposition are controlled by the combined effects of river discharge, tidal currents, and wave action (Antia *et al*., 2012). Because the estuary opens directly into the Gulf of Guinea, marine processes significantly influence its lower reaches, producing a highly dynamic sedimentary environment.

The Qua-Iboe River estuary is one of the most economically important estuaries in the Niger Delta region of Nigeria. The estuary is located adjacent to major petroleum production facilities, including crude oil processing and effluent treatment installations, while offshore petroleum exploration and production activities occur within its coastal waters. In addition, the estuary supports intensive maritime transportation, commercial fisheries, tourism, agriculture, and expanding urban settlements. These activities generate industrial effluents, agricultural runoff, domestic wastewater, petroleum-derived wastes, and other pollutants that are discharged directly or indirectly into the estuarine system. Consequently, increasing industrialization, urbanization, and petroleum-related activities may adversely affect sediment quality, aquatic biodiversity, and ecosystem health. Continuous monitoring of heavy metal contamination is therefore essential for protecting the ecological integrity and sustainable utilization of this economically important estuary.

Heavy metal contamination of estuarine and coastal sediments has received considerable scientific attention worldwide because

sediment provides a long-term record of contaminant accumulation and environmental change. Previous investigations have documented varying degrees of heavy metal enrichment in estuaries across Europe, Asia, Africa, and North America, with contamination generally linked to industrialization, urban development, maritime activities, and agricultural practices (Wen & Allen, 1999; Wang *et al*., 2008; Attia & Ghrefat, 2013; Zhao *et al*., 2015; Ahmadov *et al*., 2020; Dan *et al*., 2022). Most studies have employed pollution indices such as the geo-accumulation index (Igeo), contamination factor (CF), pollution load index (PLI), ecological risk index (RI), and multivariate statistical techniques to evaluate contamination status, identify pollution sources, and assess ecological risks associated with heavy metals.

Within Nigeria, several studies have examined heavy metal contamination in estuarine and coastal environments. Investigations conducted in Lagos Harbour, the Calabar River, Cross River Estuary, Ondo coastal waters, and other coastal ecosystems have generally reported low to moderate contamination levels, although localized enrichment has frequently been associated with industrial discharges, petroleum exploration, urban runoff, and maritime activities (Ihenyen, 1991; Ntekim *et al*., 1993; Adekola *et al*., 2000; Eddy *et al*., 2004; Tunde & Oluwagbenga, 2020; Solomon *et al*., 2021; Dan *et al*., 2022). For example, Ntekim *et al*. (1993) attributed elevated heavy metal concentrations in sediments of the Calabar River to industrial sewage and metal leaching from waste dumps, while Eddy *et al*. (2004) reported generally low heavy metal concentrations in sediments of the Cross River estuary. Similarly, Tunde and Oluwagbenga (2020) observed low contamination levels in the Ondo coastal marine environment but emphasized that continuous petroleum exploration, transportation activities, and indiscriminate waste disposal could progressively increase heavy metal accumulation in sediments.

Previous investigations within the Qua-Iboe River estuary have also demonstrated the occurrence of heavy metals in water and sediments (Ebong *et al*., 2004; Uwah *et al*., 2013; Dan *et al*., 2014; Vincent-Akpu & Offiong, 2015; Odiongenyi, 2017). Dan *et al*. (2014) reported moderate enrichment of Cd, Fe, and Zn in surface waters and attributed these enrichments to anthropogenic activities, atmospheric deposition, and remobilization of sediment-bound metals. Vincent-Akpu &Offiong (2015) found that concentrations of Fe, Zn, Pb, and Cd in surface water and sediments were generally below national and international guideline values, except for lead in water. These studies have significantly improved the understanding of heavy metal contamination within the estuary.

Despite these valuable contributions, important knowledge gaps remain. Most previous investigations focused on limited sections of the estuary, tidal banks, or surface waters and therefore do not adequately represent the spatial distribution of heavy metals throughout the entire estuarine system. Furthermore, relatively few studies have integrated contamination indices, ecological risk assessment, and multivariate statistical techniques such as hierarchical cluster analysis to simultaneously evaluate contamination levels, ecological risks, and potential sources of heavy metals. Consequently, comprehensive baseline information required for long-term environmental monitoring, pollution management, and sustainable ecosystem conservation within the Qua-Iboe River estuary remains limited.

The present study addresses these limitations by providing a comprehensive assessment of heavy metal contamination along the entire stretch of the Qua-Iboe River estuary using a combination of geochemical pollution indices and multivariate statistical analysis. Specifically, the study evaluates the

concentrations and spatial distribution of Cu, Zn, Pb, Cd, Ni, and Fe in bottom sediments; determines sediment contamination using the geo-accumulation index (Igeo) and contamination factor (CF); assesses pollution status using the degree of contamination (DC), pollution load index (PLI), and ecological risk index (RI); and applies hierarchical cluster analysis (HCA) to classify heavy metals according to their similarities and probable sources (Mehdi *et al*., 2018; Eug *et al*., 2019; Ahmadov *et al*., 2020).

The findings of this study will provide valuable baseline information for environmental monitoring and sustainable management of the Qua-Iboe River estuary. The results will contribute to understanding the influence of increasing industrialization, petroleum exploration, maritime transportation, and urban development on sediment quality while providing scientific evidence to support pollution control strategies, ecological conservation, and environmental policy formulation in the Niger Delta and other tropical estuarine systems.

2.0 Materials and Methods

2.1 Study Area and Sediment Sampling

A total of 55 recent bottom sediment samples were collected from the Qua-Iboe River estuary, southeastern Nigeria (Fig. 1). Sampling stations were distributed from the upper tidal reaches to the estuary mouth to provide representative spatial coverage of the estuarine system. Water depths at the sampling locations ranged from 1 to 10 m.

Bottom sediments were collected using a Van Veen grab sampler, and only the upper layer of freshly deposited sediment was retained for analysis. The geographical coordinates of each sampling station were recorded using a Global Positioning System (GPS). Immediately after collection, samples were transferred into pre-labelled polyethylene bags, stored in an ice chest during transportation, and subsequently frozen until laboratory analysis to minimize physicochemical alteration.

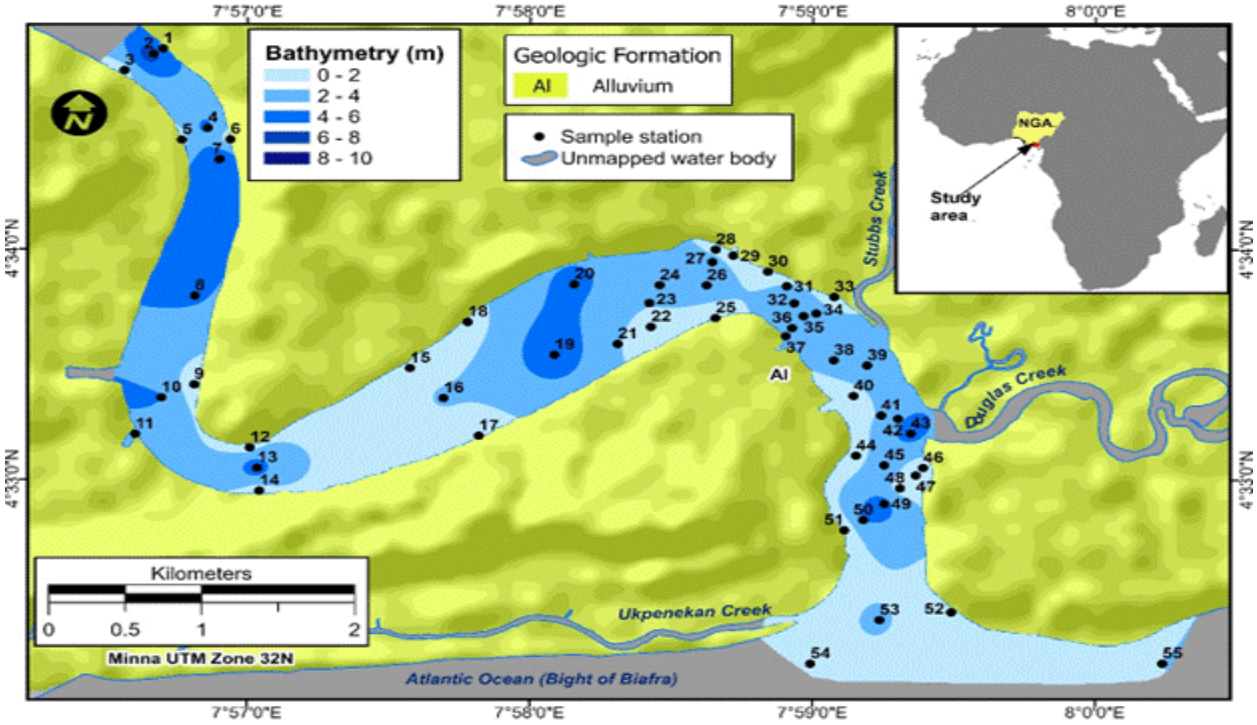

Fig. 1: Map of study area (Source: Emeka *et al*., 2023b)

2.2 Sample Preparation and Acid Digestion

In the laboratory, sediment samples were air-dried at room temperature and gently homogenized using a pre-cleaned porcelain mortar and pestle to avoid contamination. The dried sediments were sieved through a 2 mm stainless-steel mesh to remove coarse particles, shell fragments, and other debris. Sediment digestion was performed following the procedures recommended by the Association of Official Analytical Chemists (AOAC, 1990). Approximately 2.0 g of each homogenized sediment sample was weighed into a round-bottom digestion flask. A 20 mL acid mixture consisting of 65% nitric acid (HNO_3) and 35% perchloric acid ($HClO_4$) in a 3:1 (v/v) ratio was added to each sample. The mixture was heated on an electrothermal heater at 80°C until near dryness and then allowed to cool to room temperature.

Following digestion, 50 mL of deionized water was added to dissolve the residue. The digest was thoroughly mixed and filtered through Whatman No. 42 filter paper into a 100 mL volumetric flask, after which the solution was diluted to volume with deionized water. Similar digestion procedures have been reported for estuarine sediments by Tunde and Oluwagbenga (2020).

2.3 Heavy Metal Analysis

The digested sediment solutions were analysed for cadmium (Cd), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), and zinc (Zn) using an Agilent 55AA Atomic Absorption Spectrometer (AAS) following the manufacturer's recommended operating conditions. Metal concentrations were expressed as mg kg^{-1} dry weight.

2.4 Quality Assurance and Quality Control (QA/QC)

Strict quality assurance and quality control procedures were implemented throughout field sampling, sample preparation, digestion, and instrumental analysis to ensure the reliability and accuracy of analytical results.

All laboratory glassware and digestion vessels were thoroughly cleaned with dilute nitric acid and rinsed with deionized water before use. Analytical-grade reagents were used throughout the study. Instrument calibration was performed using certified standard solutions according to the manufacturer's recommendations before sample analysis.

Each sediment sample was analysed in duplicate, and the mean value was used for subsequent data analysis. Procedural blanks were prepared and analysed alongside the sediment samples to monitor laboratory contamination. No detectable contamination was observed in the blank analyses.

The instrumental detection limits for Cd, Cu, Fe, Zn, Ni, and Pb were 0.001, 0.001, 0.005, 0.001, 0.003, and 0.002 mg kg^{-1}, respectively

2.5 Statistical Analysis

Descriptive statistical parameters, including the minimum, maximum, mean, and standard deviation, were calculated using Microsoft Excel.

To investigate similarities in the distribution patterns of heavy metals and infer possible common sources, Hierarchical Cluster Analysis (HCA) was performed using Ward's linkage method and Euclidean distance as the similarity measure in Statistica Version 10 (StatSoft Inc., Tulsa, Oklahoma, USA).

2.6 Assessment of Heavy Metal Pollution

The degree of heavy metal contamination in bottom sediments was evaluated using several internationally accepted pollution indices. The geo-accumulation index (Igeo) proposed by Müller (1969) was used to determine the extent of sediment contamination relative to background concentrations. The contamination factor (CF) described by Hakanson (1980) was employed to assess contamination by individual metals.

3.0 Results and Discussion

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3.1 Spatial Distribution of Heavy Metals in Bottom Sediments

The concentrations of Cu, Pb, Zn, Cd, Ni, and Fe measured in fifty-five bottom sediment samples collected from the Qua-Iboe River estuary are presented in Table 1. Descriptive statistics, including the mean, minimum, maximum, standard deviation, average shale values (ASV), and the Department of Petroleum Resources (DPR) sediment quality guidelines, are also summarized in Table 1. The measured concentrations provide an overview of the present status of heavy metal accumulation within the estuarine sediments and serve as the basis for subsequent contamination and ecological risk assessments.

Table 1: Measured concentration of heavy metals in sediments, including descriptive statistics

Sample points	Cu (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Cd (mg/kg)	Ni (mg/kg)	Fe (mg/kg)
1	0.330	0.029	0.600	0.151	0.620	1.170
2	0.250	0.000	0.330	0.062	0.350	1.090
3	0.372	0.030	0.620	0.171	0.640	1.210
4	0.000	0.000	0.000	0.000	0.430	1.000
5	0.200	0.000	0.300	0.060	0.300	1.070
6	0.400	0.028	0.620	0.171	0.670	1.230
7	0.340	0.030	0.620	0.170	0.630	1.180
8	0.000	0.000	0.220	0.028	0.260	1.040
9	0.330	0.000	0.490	0.100	0.600	1.160
10	0.000	0.000	0.200	0.030	0.220	1.030
11	0.321	0.029	0.510	0.110	0.590	1.165
12	0.370	0.000	0.590	0.140	0.640	1.200
13	0.000	0.000	0.220	0.028	0.200	1.010
14	0.350	0.008	0.510	0.120	0.620	1.180
15	0.342	0.008	0.500	0.120	0.620	1.180
16	0.000	0.000	0.240	0.050	0.580	1.060
17	0.335	0.000	0.400	0.100	0.620	1.130
18	0.340	0.000	0.440	0.110	0.610	1.132
19	0.000	0.000	0.230	0.028	0.330	1.040
20	0.000	0.000	0.000	0.000	0.440	1.010
21	0.340	0.000	0.480	0.085	0.600	1.160
22	0.320	0.000	0.480	0.081	0.610	1.163
23	0.000	0.000	0.240	0.029	0.300	1.050
24	0.000	0.000	0.220	0.028	0.260	1.040
25	0.357	0.000	0.610	0.120	0.620	1.180
26	0.000	0.000	0.200	0.028	0.210	1.030
27	0.000	0.000	0.230	0.029	0.270	1.040
28	0.310	0.000	0.450	0.083	0.640	1.124
29	0.300	0.000	0.410	0.081	0.620	1.120
30	0.000	0.000	0.330	0.060	0.600	1.100
31	0.360	0.000	0.460	0.100	0.610	1.140
32	0.000	0.000	0.000	0.000	0.370	1.000

33	0.330	0.000	0.350	0.085	0.590	1.123
34	0.200	0.000	0.300	0.080	0.600	1.080
35	0.000	0.000	0.270	0.030	0.580	1.030
36	0.210	0.000	0.310	0.074	0.600	1.090
37	0.380	0.000	0.480	0.110	0.640	1.160
38	0.310	0.000	0.430	0.100	0.620	1.134
39	0.000	0.000	0.000	0.000	0.330	1.020
40	0.000	0.000	0.210	0.028	0.310	1.010
41	0.240	0.000	0.330	0.087	0.550	1.120
42	0.190	0.000	0.310	0.070	0.530	1.090
43	0.000	0.000	0.200	0.028	0.250	1.000
44	0.000	0.000	0.240	0.029	0.290	1.010
45	0.380	0.000	0.450	0.080	0.570	1.145
46	0.323	0.000	0.482	0.090	0.590	1.150
47	0.000	0.000	0.220	0.030	0.240	1.000
48	0.000	0.000	0.220	0.030	0.210	1.000
49	0.000	0.000	0.240	0.035	0.330	1.010
50	0.000	0.000	0.200	0.034	0.370	1.000
51	0.210	0.000	0.260	0.050	0.400	1.050
52	0.320	0.000	0.474	0.080	0.580	1.140
53	0.220	0.000	0.360	0.060	0.470	1.080
54	0.200	0.000	0.330	0.059	0.450	1.040
55	0.200	0.000	0.350	0.059	0.450	1.040
Mean	0.180	0.003	0.341	0.069	0.476	1.090
Maximum	0.400	0.030	0.620	0.171	0.670	1.230
Minimum	0.000	0.000	0.000	0.000	0.200	1.000
Standard deviation	0.156	0.008	0.16	0.044	0.153	0.067
Average Shale Value	45	20	95	0.3	68	47200
DPR (2002)	36	85	140	0.8	35	-

Table 1. Measured concentrations of heavy metals in bottom sediments of the Qua-Iboe River estuary and descriptive statistics.

The concentrations of copper (Cu) ranged from 0.00 to 0.40 mg kg^{-1}, with a mean concentration of 0.18 ± 0.16 mg kg^{-1}. The highest Cu concentration was recorded at Station 6, while several stations exhibited concentrations below the instrumental detection limit. Lead (Pb) concentrations varied between 0.00 and 0.03 mg kg^{-1}, with an average value of 0.003 ± 0.008 mg kg^{-1}, indicating extremely low levels throughout the study area. Zinc (Zn) concentrations ranged from 0.00 to 0.62 mg kg^{-1}, averaging 0.341 ± 0.16 mg kg^{-1}, whereas cadmium (Cd) concentrations varied between 0.00 and 0.171 mg kg^{-1}, with a mean value of 0.069 ± 0.044 mg kg^{-1}. Nickel (Ni) exhibited concentrations ranging from 0.20 to 0.67 mg kg^{-1}, with a mean concentration of 0.476 ± 0.153 mg kg^{-1}, while iron (Fe) showed the highest abundance among all investigated elements, ranging from 1.00 to 1.23 mg kg^{-1} with an average concentration of 1.09 ± 0.067 mg kg^{-1}. Overall, the mean concentrations of heavy metals followed the order, Fe > Ni > Zn > Cu > Cd > Pb

This distribution indicates that iron is the dominant metal in the estuarine sediments, whereas lead occurs only in trace quantities. The predominance of Fe is consistent with its natural abundance in the Earth's crust and reflects the ferruginous nature of the coastal plain sands and alluvial deposits that characterize the Qua-Iboe River catchment (Turekian & Wedepohl, 1961). Similar abundance patterns have been reported for other tropical estuaries in southeastern Nigeria, including the Cross River estuary (Eddy et al., 2004; Emeka & Emeka, 2006; Dan et al., 2022).

The relatively low standard deviations obtained for most metals suggest limited spatial variability across the estuary. Iron exhibited the lowest variability (SD = 0.067 mg kg^{-1}), indicating a relatively uniform spatial distribution that is primarily controlled by lithogenic processes. Conversely, cadmium displayed comparatively greater variability (SD = 0.044 mg kg^{-1} relative to its mean concentration), suggesting localized enrichment at specific sampling stations. Such localized increases may reflect anthropogenic inputs from industrial discharges, agricultural runoff, domestic wastes, and maritime activities occurring within the estuary.

Spatially, the highest concentrations of Cu, Ni, Cd, Zn, and Fe were consistently observed at Station 6, while the highest Pb concentration occurred at Station 3. The clustering of maximum concentrations around Station 6 suggests that this section of the estuary may function as a depositional sink for fine-grained sediments capable of adsorbing dissolved metals from the water column. Estuarine environments are characterized by reduced hydrodynamic energy, flocculation of suspended particles, and high organic matter accumulation, all of which promote the sequestration of trace metals within bottom sediments (Schröder-Adams, 2006). Similar sedimentary processes have been reported for the Pearl River Estuary, China (Ip et al., 2007; Li et al., 2007), and the western Caspian Sea (Ahmadov et al., 2020).

Although the Qua-Iboe River estuary is located within the oil-producing Niger Delta region, where petroleum exploration, navigation, industrial development, and urbanization constitute important sources of environmental contamination, the observed concentrations of all investigated metals remain remarkably low. Industrial facilities, crude oil export terminals, shipping operations, agricultural activities, and municipal waste disposal collectively represent potential anthropogenic sources of heavy metals within the estuarine ecosystem. Nevertheless, the present findings indicate that these activities have not yet resulted in significant heavy metal accumulation within the sediments.

To evaluate the extent of contamination, the measured concentrations were compared with internationally accepted geochemical background values proposed by Turekian and Wedepohl (1961) and sediment quality guidelines established by the Department of Petroleum Resources (DPR, 2002). The average concentrations of all investigated metals were substantially lower than their respective average shale values and regulatory guideline limits (Table 1). For example, the average Cu concentration (0.18 mg kg^{-1}) represents less than 0.5% of the average shale value (45 mg kg^{-1}), while the mean Zn concentration (0.341 mg kg^{-1}) corresponds to less than 0.4% of its average shale concentration (95 mg kg^{-1}). Similarly, the average Ni concentration (0.476 mg kg^{-1}) constitutes less than 1% of the background value of 68 mg kg^{-1}. These observations clearly demonstrate that the sediments remain largely unaffected by heavy metal enrichment.

The exceptionally low concentrations observed in the present study agree with previous investigations conducted in the Qua-Iboe River estuary and other estuarine systems along the Nigerian coastline. Ntekim et al. (1993) reported relatively low concentrations of Ni,

Co, Cd, and Fe in sediments from the Calabar River and concluded that metal concentrations were below levels capable of producing adverse ecological effects. Similarly, Eddy et al. (2004) observed that heavy metal concentrations in sediments of the Cross River estuary remained within natural background levels and reflected minimal anthropogenic contamination. Uwah et al. (2013) also reported relatively low concentrations of trace metals in sediments of the Qua-Iboe River estuary despite increasing industrial activities within the region.

Vincent-Akpu and Offiong (2015) investigated trace metal concentrations in water and sediments collected along the tidal banks of the Qua-Iboe River estuary and reported concentration ranges of 0.09–3.60 mg kg^{-1} for Fe, 0.01–1.27 mg kg^{-1} for Zn, 0.01–0.17 mg kg^{-1} for Pb, and 0.001–0.08 mg kg^{-1} for Cd. The Fe, Zn, and Pb concentrations obtained in the present study fall within comparable ranges, although the mean Cd concentration is slightly higher than previously reported values. Nevertheless, Cd concentrations remain well below internationally accepted sediment quality thresholds and therefore do not presently constitute a significant environmental concern.

Comparable observations have also been documented in other estuarine and coastal environments worldwide. Attia and Ghrefat (2013) reported generally low contamination of bottom sediments in Mabahiss Bay along the Red Sea coast of Egypt. Similarly, Ahmadov et al. (2020) concluded that coastal sediments of the western Caspian Sea exhibited low contamination levels despite increasing industrial development. Studies conducted in the Pearl River Estuary (Ip et al., 2007; Li et al., 2007), Dongping Lake, China (Wang et al., 2015), and the Yangtze River Delta (Xu et al., 2014) likewise demonstrated that metal accumulation in sediments is strongly influenced by both lithogenic inputs and localized anthropogenic activities. These similarities suggest that sediment geochemistry in estuarine environments is largely governed by the interaction between natural geological processes and human activities.

The relatively high abundance of iron observed in the present study is expected because Fe is one of the most abundant elements in the Earth's crust and is primarily derived from the weathering of ferromagnesian minerals and lateritic soils. Unlike more toxic trace metals such as cadmium and lead, iron generally exhibits low environmental mobility under oxic conditions and therefore serves as a useful indicator of natural sediment provenance rather than anthropogenic contamination (Turekian & Wedepohl, 1961). The distribution of trace metals in estuarine sediments is further influenced by grain size, mineralogical composition, organic matter content, redox conditions, and hydrodynamic processes that regulate sediment transport and deposition (Bryan & Langston, 1992; Zhang et al., 2009).

Overall, the heavy metal concentrations measured in the bottom sediments of the Qua-Iboe River estuary indicate that the estuary presently maintains good sediment quality with respect to Cu, Pb, Zn, Cd, Ni, and Fe. Nevertheless, the localized enrichment observed at several sampling stations, particularly Station 6, suggests that continuous anthropogenic activities—including oil exploration, maritime transportation, agricultural runoff, industrial effluent discharge, and domestic waste disposal—could progressively increase heavy metal accumulation if appropriate environmental management measures are not maintained. Consequently, periodic environmental monitoring remains essential to detect temporal changes in sediment quality and to ensure the long-term ecological sustainability of this economically important estuarine ecosystem.

3.2 Geo-Accumulation Index (Igeo)

The geo-accumulation index (Igeo) is a widely accepted geochemical indicator used to evaluate the extent of heavy metal

contamination in sediments by comparing present metal concentrations with pre-industrial or natural background concentrations while accounting for natural lithological variations (Müller, 1969). In this study, average shale values reported by Turekian and Wedepohl (1961) were adopted as the geochemical background concentrations for Zn (95 mg/kg), Ni (68 mg/kg), Fe (47,200 mg/kg), Cu (45 mg/kg), Pb (20 mg/kg), and Cd (0.3 mg/kg).

The geo-accumulation index was calculated using Equation (1):

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

where (C) is the measured concentration of the metal in the sediment, (Bn) 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). According to Müller (1969), Igeo values are classified as follows:

The calculated Igeo values for all investigated heavy metals are presented in Table 2, while the mean Igeo values are illustrated in Fig. 2.

I_{geo} value	**Pollution class**
≤ 0	Unpolluted
0–1	Unpolluted to moderately polluted
1–2	Moderately polluted
2–3	Moderately to heavily polluted
3–4	Heavily polluted
4–5	Heavily to extremely polluted
>5	Extremely polluted

Table 2: Calculated Igeo values of heavy metals in sediment samples, including descriptive statistics

Stations	Cu (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Cd (mg/kg)	Ni (mg/kg)	Fe (mg/kg)
1	-7.676	-10.015	-7.892	-1.575	-7.362	-15.885
2	-8.077	0.000	-8.754	-2.860	-8.187	-15.987
3	-7.503	-9.966	-7.844	-1.396	-7.316	-15.836
4	0.000	0.000	0.000	0.000	-7.890	-16.111
5	-8.399	0.000	-8.892	-2.907	-8.409	-16.014
6	-7.399	-10.065	-7.844	-1.396	-7.250	-15.813
7	-7.633	-9.966	-7.844	-1.404	-7.339	-15.873
8	0.000	0.000	-9.339	-4.006	-8.616	-16.055
9	-7.676	0.000	-8.184	-2.170	-7.409	-15.897
10	0.000	0.000	-9.477	-3.907	-8.857	-16.069
11	-7.716	-10.015	-8.126	-2.032	-7.434	-15.891
12	-7.511	0.000	-7.916	-1.684	-7.316	-15.848
13	0.000	0.000	-9.339	-4.006	-8.994	-16.097
14	-7.591	-11.873	-8.126	-1.907	-7.362	-15.873
15	-7.625	-11.873	-8.155	-1.907	-7.362	-15.873
16	0.000	0.000	-9.214	-3.170	-7.458	-16.027
17	-7.655	0.000	-8.477	-2.170	-7.362	-15.935
18	-7.633	0.000	-8.339	-2.032	-7.386	-15.933
19	0.000	0.000	-9.275	-4.006	-8.272	-16.055
20	0.000	0.000	0.000	0.000	-7.857	-16.097
21	-7.633	0.000	-8.214	-2.404	-7.409	-15.897
22	-7.721	0.000	-8.214	-2.474	-7.386	-15.894
23	0.000	0.000	-9.214	-3.956	-8.409	-16.041

24	0.000	0.000	-9.339	-4.006	-8.616	-16.055
25	-7.563	0.000	-7.868	-1.907	-7.362	-15.873
26	0.000	0.000	-9.477	-4.006	-8.924	-16.069
27	0.000	0.000	-9.275	-3.956	-8.561	-16.055
28	-7.766	0.000	-8.307	-2.439	-7.316	-15.943
29	-7.814	0.000	-8.441	-2.474	-7.362	-15.948
30	0.000	0.000	-8.754	-2.907	-7.409	-15.974
31	-7.551	0.000	-8.275	-2.170	-7.386	-15.922
32	0.000	0.000	0.000	0.000	-8.107	-16.111
33	-7.676	0.000	-8.669	-2.404	-7.434	-15.944
34	-8.399	0.000	-8.892	-2.492	-7.409	-16.000
35	0.000	0.000	-9.044	-3.907	-7.458	-16.069
36	-8.328	0.000	-8.844	-2.604	-7.409	-15.987
37	-7.473	0.000	-8.214	-2.032	-7.316	-15.897
38	-7.766	0.000	-8.372	-2.170	-7.362	-15.930
39	0.000	0.000	0.000	0.000	-8.272	-16.083
40	0.000	0.000	-9.406	-4.006	-8.362	-16.097
41	-8.136	0.000	-8.754	-2.371	-7.535	-15.948
42	-8.473	0.000	-8.844	-2.684	-7.588	-15.987
43	0.000	0.000	-9.477	-4.012	-8.672	-16.111
44	0.000	0.000	-9.214	-3.956	-8.458	-16.097
45	-7.473	0.000	-8.307	-2.492	-7.483	-15.916
46	-7.707	0.000	-8.208	-2.322	-7.434	-15.910
47	0.000	0.000	-9.339	-3.907	-8.731	-16.111
48	0.000	0.000	-9.339	-3.907	-8.924	-16.111
49	0.000	0.000	-9.214	-3.684	-8.272	-16.097
50	0.000	0.000	-9.477	-3.726	-8.107	-16.111
51	-8.328	0.000	-9.098	-3.170	-7.994	-16.041
52	-7.721	0.000	-8.232	-2.492	-7.458	-15.922
53	-8.261	0.000	-8.629	-2.907	-7.762	-16.000
54	-8.399	0.000	-8.754	-2.931	-7.824	-16.055
55	-8.399	0.000	-8.669	-2.931	-7.824	-16.055
Minimum	-8.473	-11.873	-9.477	-4.012	-8.994	-16.111
Maximum	0.000	0.000	0.000	0.000	-7.250	-15.813
Average	-4.703	-1.341	-8.062	-2.624	-7.832	-15.990

Table 2. Calculated geo-accumulation index (Igeo) values for heavy metals in bottom sediments of the Qua-Iboe River Estuary.

The calculated Igeo values ranged from −8.473 to 0.000 for Cu, −11.873 to 0.000 for Pb, −9.477 to 0.000 for Zn, −4.012 to 0.000 for Cd, −8.994 to −7.250 for Ni, and −16.111 to −15.813 for Fe (Table 2). Mean Igeo values followed the order, Pb (−1.341) > Cd (−2.624) > Cu (−4.703) > Ni (−7.832) > Zn (−8.062) > Fe (−15.990). Although Pb exhibited the highest average Igeo value among the investigated metals, all mean values remained well below zero, indicating that none of the investigated metals has accumulated to levels above their natural background concentrations. The uniformly negative Igeo values obtained throughout the estuary clearly indicate that the sediments are unpolluted with respect to Cu, Pb, Zn, Cd, Ni, and Fe according to the

classification proposed by Müller (1969). These findings demonstrate that heavy metal concentrations remain close to their natural geochemical background levels and that anthropogenic enrichment is presently insignificant.

The exceptionally low Igeo values obtained for Fe reflect its predominantly lithogenic origin. Iron is one of the most abundant constituents of the Earth's crust and is generally controlled by mineral composition and weathering processes rather than localized anthropogenic inputs (Turekian & Wedepohl, 1961; Zhang et al., 2009). Likewise, the low Igeo values obtained for Cu, Zn, Ni, Pb, and Cd indicate that anthropogenic contributions from oil-related activities, navigation, domestic waste disposal, and agricultural runoff have not yet resulted in measurable sediment enrichment.

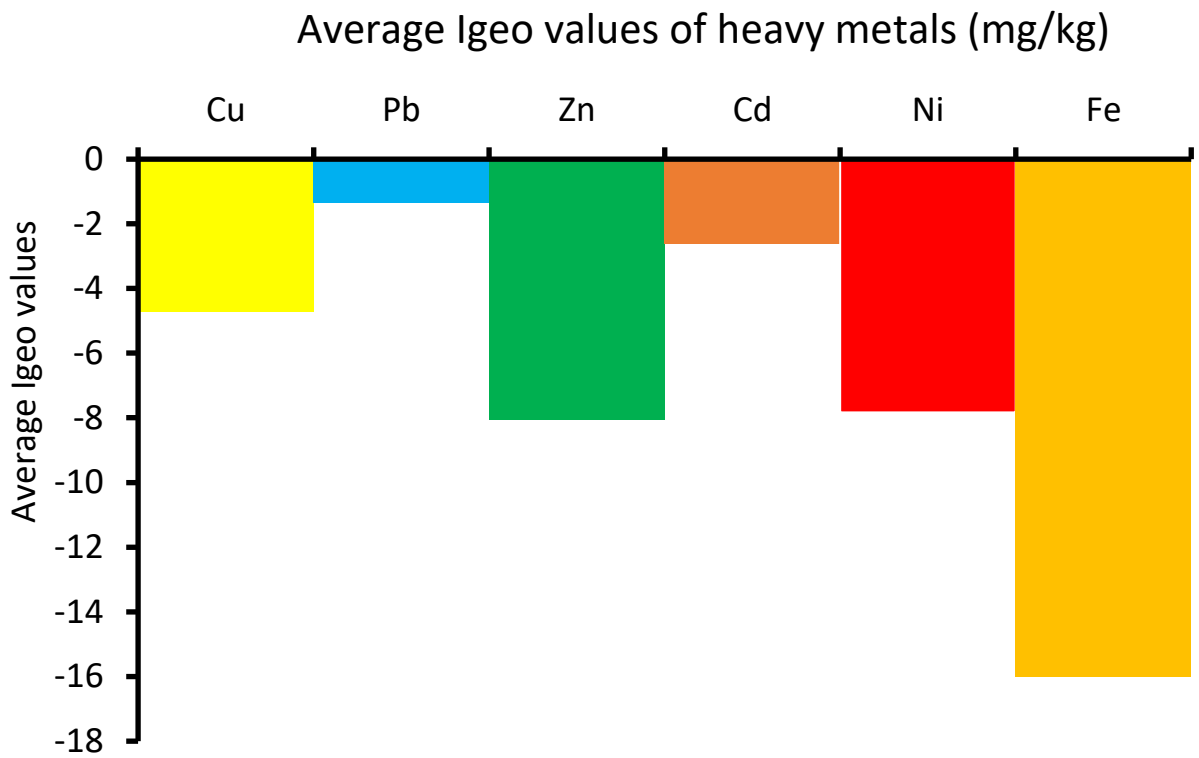

Fig. 2: Mean Igeo values of heavy metals

The present findings are consistent with previous studies conducted within southeastern Nigeria and other tropical estuaries. Uwah et al. (2013) reported that sediments from the Qua-Iboe River estuary exhibited low heavy metal enrichment despite increasing human activities. Similarly, Vincent-Akpu and Offiong (2015) observed that concentrations of Fe, Zn, Pb, and Cd in sediments of the same estuary were generally below internationally accepted sediment quality guidelines. Comparable observations of negligible geo-accumulation have also been reported for the western Caspian Sea (Ahmadov et al., 2020), the Red Sea coast (Attia & Ghrefat, 2013), and the Yangtze River intertidal zone (Zhang et al., 2009), where effective sediment dilution and continuous hydrodynamic flushing limited heavy metal accumulation.

The low Igeo values observed in the present study can also be attributed to the dynamic hydrological characteristics of the Qua-Iboe River estuary. The estuary experiences continuous tidal flushing, sediment

resuspension, and sediment exchange with the adjacent Gulf of Guinea, processes that minimize the long-term retention of heavy metals in bottom sediments. These hydrodynamic processes reduce localized accumulation and promote redistribution of contaminants, thereby maintaining relatively low sediment contamination levels.

Overall, the geo-accumulation assessment indicates that bottom sediments of the Qua-Iboe River estuary presently remain in a natural or near-natural geochemical condition, with no evidence of significant heavy metal enrichment. Nevertheless, increasing industrialization, petroleum exploration, maritime transportation, and urban development within the estuarine catchment may elevate future contaminant inputs. Consequently, periodic monitoring of sediment quality remains essential for the early detection of environmental deterioration and sustainable management of this ecologically and economically important estuarine ecosystem.

3.3 Contamination Factor (CF)

The contamination factor (CF) is a widely used pollution index for evaluating the degree of contamination of sediments by comparing measured metal concentrations with their corresponding natural background concentrations. The index provides information on the magnitude of anthropogenic enrichment of individual metals and is particularly useful for distinguishing between natural geochemical variability and human-induced contamination (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). Hakanson (1980) classified contamination factor into four categories:

CF Value	**Degree of contamination**
CF < 1	Low contamination
1 ≤ CF < 3	Moderate contamination
3 ≤ CF < 6	Considerable contamination
CF ≥ 6	Very high contamination

The calculated contamination factors for Cu, Pb, Zn, Cd, Ni, and Fe are presented in Table 3. The calculated contamination factors varied from 0.0000–0.0089 for Cu, 0.0000–0.0015 for Pb, 0.0000–0.0065 for Zn, 0.0000–0.5700 for Cd, 0.0029–0.0099 for Ni, and approximately 0.0000 for Fe (Table 3). Mean contamination factors followed the order, Cd (0.2304) > Ni (0.0070) > Cu (0.0040) > Zn (0.0036) > Pb (0.0001) > Fe (≈0.0000).

Table 3: CF, DC and PLI values of sediment samples, including descriptive statistics

Stations	**CF**						**DC**	**PLI**
	Cu	Pb	Zn	Cd	Ni	Fe		
1	0.0073	0.0015	0.0063	0.5033	0.0091	0.0000	0.5276	0.0044
2	0.0056	0.0000	0.0035	0.2067	0.0051	0.0000	0.2209	0.0000
3	0.0083	0.0015	0.0065	0.5700	0.0094	0.0000	0.5957	0.0047
4	0.0000	0.0000	0.0000	0.0000	0.0063	0.0000	0.0063	0.0000
5	0.0044	0.0000	0.0032	0.2000	0.0044	0.0000	0.2120	0.0000
6	0.0089	0.0014	0.0065	0.5700	0.0099	0.0000	0.5967	0.0048
7	0.0076	0.0015	0.0065	0.5667	0.0093	0.0000	0.5915	0.0046
8	0.0000	0.0000	0.0023	0.0933	0.0038	0.0000	0.0995	0.0000
9	0.0073	0.0000	0.0052	0.3333	0.0088	0.0000	0.3547	0.0000
10	0.0000	0.0000	0.0021	0.1000	0.0032	0.0000	0.1054	0.0000
11	0.0071	0.0015	0.0054	0.3667	0.0087	0.0000	0.3893	0.0040
12	0.0082	0.0000	0.0062	0.4667	0.0094	0.0000	0.4905	0.0000

13	0.0000	0.0000	0.0023	0.0933	0.0029	0.0000	0.0986	0.0000
14	0.0078	0.0004	0.0054	0.4000	0.0091	0.0000	0.4227	0.0034
15	0.0076	0.0004	0.0053	0.4000	0.0091	0.0000	0.4224	0.0034
16	0.0000	0.0000	0.0025	0.1667	0.0085	0.0000	0.1777	0.0000
17	0.0074	0.0000	0.0042	0.3333	0.0091	0.0000	0.3541	0.0000
18	0.0076	0.0000	0.0046	0.3667	0.0090	0.0000	0.3878	0.0000
19	0.0000	0.0000	0.0024	0.0933	0.0049	0.0000	0.1006	0.0000
20	0.0000	0.0000	0.0000	0.0000	0.0065	0.0000	0.0065	0.0000
21	0.0076	0.0000	0.0051	0.2833	0.0088	0.0000	0.3048	0.0000
22	0.0071	0.0000	0.0051	0.2700	0.0090	0.0000	0.2912	0.0000
23	0.0000	0.0000	0.0025	0.0967	0.0044	0.0000	0.1036	0.0000
24	0.0000	0.0000	0.0023	0.0933	0.0038	0.0000	0.0995	0.0000
25	0.0079	0.0000	0.0064	0.4000	0.0091	0.0000	0.4235	0.0000
26	0.0000	0.0000	0.0021	0.0933	0.0031	0.0000	0.0985	0.0000
27	0.0000	0.0000	0.0024	0.0967	0.0040	0.0000	0.1031	0.0000
28	0.0069	0.0000	0.0047	0.2767	0.0094	0.0000	0.2977	0.0000
29	0.0067	0.0000	0.0043	0.2700	0.0091	0.0000	0.2901	0.0000
30	0.0000	0.0000	0.0035	0.2000	0.0088	0.0000	0.2123	0.0000
31	0.0080	0.0000	0.0048	0.3333	0.0090	0.0000	0.3552	0.0000
32	0.0000	0.0000	0.0000	0.0000	0.0054	0.0000	0.0055	0.0000
33	0.0073	0.0000	0.0037	0.2833	0.0087	0.0000	0.3031	0.0000
34	0.0044	0.0000	0.0032	0.2667	0.0088	0.0000	0.2831	0.0000
35	0.0000	0.0000	0.0028	0.1000	0.0085	0.0000	0.1114	0.0000
36	0.0047	0.0000	0.0033	0.2467	0.0088	0.0000	0.2634	0.0000
37	0.0084	0.0000	0.0051	0.3667	0.0094	0.0000	0.3896	0.0000
38	0.0069	0.0000	0.0045	0.3333	0.0091	0.0000	0.3539	0.0000
39	0.0000	0.0000	0.0000	0.0000	0.0049	0.0000	0.0049	0.0000
40	0.0000	0.0000	0.0022	0.0933	0.0046	0.0000	0.1001	0.0000
41	0.0053	0.0000	0.0035	0.2900	0.0081	0.0000	0.3069	0.0000
42	0.0042	0.0000	0.0033	0.2333	0.0078	0.0000	0.2486	0.0000
43	0.0000	0.0000	0.0021	0.0930	0.0037	0.0000	0.0988	0.0000
44	0.0000	0.0000	0.0025	0.0967	0.0043	0.0000	0.1035	0.0000
45	0.0084	0.0000	0.0047	0.2667	0.0084	0.0000	0.2883	0.0000
46	0.0072	0.0000	0.0051	0.3000	0.0087	0.0000	0.3210	0.0000
47	0.0000	0.0000	0.0023	0.1000	0.0035	0.0000	0.1059	0.0000
48	0.0000	0.0000	0.0023	0.1000	0.0031	0.0000	0.1054	0.0000
49	0.0000	0.0000	0.0025	0.1167	0.0049	0.0000	0.1241	0.0000
50	0.0000	0.0000	0.0021	0.1133	0.0054	0.0000	0.1209	0.0000
51	0.0047	0.0000	0.0027	0.1667	0.0059	0.0000	0.1800	0.0000
52	0.0071	0.0000	0.0050	0.2667	0.0085	0.0000	0.2873	0.0000
53	0.0049	0.0000	0.0038	0.2000	0.0069	0.0000	0.2156	0.0000
54	0.0044	0.0000	0.0035	0.1967	0.0066	0.0000	0.2112	0.0000
55	0.0044	0.0000	0.0037	0.1967	0.0066	0.0000	0.2114	0.0000
Min	0.0000	0.0000	0.0000	0.0000	0.0029	0.0000	0.0049	0.0000
Max	0.0089	0.0015	0.0065	0.5700	0.0099	0.0000	0.5967	0.0048
Mean	0.0040	0.0001	0.0036	0.2304	0.0070	0.0000	0.2452	0.0005

SD	0.0035	0.0004	0.0017	0.1470	0.0023	0.0000	0.1537	0.0014

Cadmium exhibited the highest mean contamination factor among all investigated metals, although its value remained substantially below the threshold of 1.0. Conversely, Fe recorded the lowest contamination factor because its measured concentrations were extremely small relative to its average shale background concentration of 47,200 mg/kg (Turekian & Wedepohl, 1961).

All sampling stations recorded CF values less than 1, indicating that the sediments are characterized by low contamination with respect to every investigated heavy metal according to the classification of Hakanson (1980). These results indicate that the concentrations of Cu, Pb, Zn, Cd, Ni, and Fe largely reflect their natural geochemical abundance rather than significant anthropogenic enrichment.

Although cadmium recorded the highest contamination factor, its mean value of 0.2304 is still considerably lower than the threshold for moderate contamination. Cadmium is recognized as one of the most toxic trace metals because of its high mobility, persistence, and bioaccumulation potential (Hakanson, 1980; Qing et al., 2015). The relatively higher CF values observed for Cd compared with the other metals may therefore reflect minor anthropogenic inputs from petroleum-related activities, agricultural runoff, domestic waste disposal, and boat maintenance operations occurring within the estuary. However, the present levels remain environmentally insignificant.

Nickel exhibited the second highest contamination factor (mean = 0.0070), followed by Cu and Zn. The slightly elevated Ni values may be associated with weathering of parent rocks within the Niger Delta basin as well as diffuse industrial and petroleum-related inputs. Similar observations have been reported for sediments from the Cross River Estuary (Dan et al., 2022), the Qua-Iboe River Estuary (Uwah et al., 2013), and coastal environments of southeastern Nigeria (Vincent-Akpu & Offiong, 2015). Nevertheless, the extremely low CF values indicate that these metals have not accumulated to concentrations capable of causing significant ecological degradation.

The present findings agree with previous investigations conducted in Nigerian estuaries. Uwah et al. (2013) reported low contamination factors for most heavy metals in sediments of the Qua-Iboe River Estuary despite increasing anthropogenic activities within the watershed. Similarly, Odiongenyi (2017) observed that heavy metal concentrations in sediments of the same estuary remained below internationally accepted sediment quality guidelines. Comparable results have also been reported for the western Caspian Sea (Ahmadov et al., 2020), the Pearl River Estuary, China (Li et al., 2007), and Dongping Lake, eastern China (Wang et al., 2015), where contamination factors indicated low levels of sediment contamination despite rapid industrialization.

The generally low contamination factors observed in this study are consistent with the efficient hydrodynamic flushing characteristics of the Qua-Iboe River Estuary. Continuous tidal exchange with the Gulf of Guinea promotes sediment resuspension, dispersion, and dilution of contaminants, thereby limiting heavy metal accumulation within bottom sediments. In addition, the relatively coarse nature of estuarine sediments in parts of the channel may reduce the adsorption capacity for trace metals, thereby contributing to the low contamination levels observed.

3.4 Degree of Contamination (DC)

The degree of contamination (DC) is an integrated pollution index proposed by Hakanson (1980) for evaluating the cumulative contamination of sediments by multiple heavy metals. Unlike the contamination factor, which evaluates individual metals independently, the degree of contamination provides an overall

assessment of the combined influence of all investigated metals within a sampling location. Consequently, DC is widely applied in sediment quality assessments because it reflects the collective impact of anthropogenic inputs on the aquatic environment.

The degree of contamination 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 sampling stations were presented in Table 3.

The calculated degree of contamination ranged from 0.0049 at Station 39 to 0.5967 at Station 6, with an overall mean value of 0.2452 ± 0.1537 (Table 3). These values are substantially lower than the threshold value of DC = 6, indicating that every sampling station within the estuary falls within the low contamination category proposed by Hakanson (1980). Spatially, the highest DC values were recorded at Stations 6 (0.5967), 3 (0.5957), and 7 (0.5915). These stations also exhibited relatively higher concentrations of Cu, Cd, Zn, Ni, and Fe (Table 1), suggesting localized enrichment of heavy metals. The slightly elevated contamination observed at these locations may be attributed to increased anthropogenic activities, including navigation, petroleum-related operations, industrial effluent discharge, and runoff from nearby settlements. Nevertheless, the observed DC values remain well below levels associated with moderate ecological concern.

Conversely, the lowest contamination levels occurred at Stations 39 (0.0049), 32 (0.0055), 4 (0.0063), and 20 (0.0065), indicating minimal accumulation of heavy metals. These stations are likely characterized by reduced anthropogenic influence and more efficient sediment flushing, resulting in lower retention of trace metals within bottom sediments.

The generally low DC values observed throughout the estuary indicate that the cumulative contribution of all investigated metals is insignificant. Although cadmium contributed the largest proportion to the overall contamination because of its relatively higher contamination factor, its contribution remained sufficiently small to maintain low cumulative contamination across all sampling stations.

The present findings agree with previous investigations conducted within Nigerian coastal environments. Uwah et al. (2013) similarly reported low cumulative contamination in sediments of the Qua-Iboe River Estuary, while Odiongenyi (2017) concluded that heavy metal pollution in the estuary remained below critical ecological thresholds. Comparable studies conducted in the western Caspian Sea (Ahmadov et al., 2020), the Pearl River Estuary (Li et al., 2007), and Dongping Lake, China (Wang et al., 2015) also reported low degrees of contamination despite increasing industrial and urban activities.

The low degree of contamination observed in this study can largely be attributed to the hydrodynamic nature of the Qua-Iboe River Estuary. Continuous tidal exchange with the Gulf of Guinea promotes dilution, sediment resuspension, and export of contaminants from the estuarine environment. Furthermore, the relatively low concentrations of all investigated heavy metals compared with average shale values indicate that natural geological inputs remain the dominant source of sediment chemistry.

3.5 Pollution Load Index (PLI)

The Pollution Load Index (PLI) is a comprehensive pollution assessment tool developed by Tomlinson et al. (1980) to evaluate the overall level of heavy metal

contamination at individual sampling locations. Unlike the contamination factor, which assesses individual metals separately, the PLI integrates the contamination factors of all investigated metals into a single numerical value, thereby providing a comprehensive measure of sediment quality and environmental status. The index is particularly useful for comparing pollution levels among sampling stations and determining the overall health of aquatic ecosystems.

The Pollution Load Index was calculated using Equation (4):

$$L1 = (CF1 \times CF2 \times CF3 \ldots . CFN)^{\frac{1}{n}} \quad (4)$$

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 Pollution Load Index values for all sampling stations were also presented in Table 3.

The calculated PLI values ranged from 0.0000 to 0.0048, with a mean value of 0.0005 ± 0.0014 (Table 3). The highest PLI value (0.0048) was recorded at Station 6, followed closely by Stations 3 (0.0047) and 7 (0.0046), whereas many sampling stations recorded values approaching zero because one or more investigated metals were either absent or occurred at extremely low concentrations.

Importantly, all calculated PLI values were significantly less than unity (PLI < 1), indicating that every sampling station within the Qua-Iboe River Estuary can be classified as unpolluted according to the criteria established by Tomlinson et al. (1980). These results confirm that the combined effects of Cu, Pb, Zn, Cd, Ni, and Fe have not resulted in measurable deterioration of sediment quality within the study area.

The relatively higher PLI values observed at Stations 3, 6, and 7 correspond closely with stations exhibiting comparatively elevated concentrations of Cd, Ni, Cu, and Zn (Table 1). These localized increases may reflect the influence of nearby anthropogenic activities, including petroleum exploration, marine transportation, industrial discharges, and domestic waste disposal. Nevertheless, because the calculated PLI values remain far below the pollution threshold, these localized inputs have not produced significant environmental degradation.

The extremely low PLI values recorded throughout the estuary further suggest that the natural geochemical composition of the sediments remains largely unaffected by anthropogenic contamination. The efficient tidal circulation and continuous sediment exchange between the estuary and the Gulf of Guinea promote dilution, dispersion, and removal of contaminants, thereby limiting heavy metal accumulation within bottom sediments. Similar hydrodynamic controls on sediment quality have been reported for other tropical estuarine environments (Schröder-Adams, 2006).

The present findings agree with previous investigations conducted in Nigerian and international estuaries. Attia and Ghrefat (2013) reported PLI values below unity in sediments of Mabahiss Bay along the Red Sea coast, indicating low levels of heavy metal pollution. Similarly, Ahmadov et al. (2020) observed low pollution load indices in coastal sediments of the western Caspian Sea despite increasing industrial development. Comparable observations have also been reported for the Dongping Lake sediments of eastern China (Wang et al., 2015), the Yangtze River intertidal zone (Zhang et al., 2009), and coastal wetlands of the Pearl River Estuary (Li et al., 2007), where low PLI values reflected limited anthropogenic enrichment.

The Pollution Load Index results are also consistent with the geo-accumulation index

and contamination factor assessments discussed in the preceding sections. All three pollution indices consistently demonstrate that heavy metal concentrations remain well below internationally accepted sediment quality thresholds and that the sediments of the Qua-Iboe River Estuary presently exhibit excellent environmental quality.

Overall, the Pollution Load Index confirms that the bottom sediments of the Qua-Iboe River Estuary are unpolluted with respect to the investigated heavy metals. Although current contamination levels are negligible, increasing petroleum exploitation, industrialization, urban expansion, and maritime activities within the estuarine catchment could alter sediment quality over time. Therefore, continuous environmental surveillance and periodic sediment quality assessments are recommended to ensure the long-term ecological sustainability of this economically and environmentally important tropical estuary.

3.6 Ecological Risk Factor (Er)

The ecological risk factor (Er) is a quantitative index developed by Hakanson (1980) to evaluate the potential ecological hazard posed by individual heavy metals in aquatic sediments. Unlike contamination indices that only measure enrichment, the ecological risk factor incorporates both the contamination level of each metal and its relative toxicity, thereby providing a more realistic assessment of potential environmental impacts. Metals with high toxicity coefficients contribute more significantly to ecological risk, even when their concentrations are relatively low.

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 the investigated heavy metals are presented in Table 4, while the mean ecological risk values are illustrated in Fig. 3.

Table 4: ER and RI values of sediment samples, including descriptive statistics

Stations	ER					RI
	Cu	Pb	Zn	Cd	Ni	
1	0.0367	0.0073	0.0063	15.1000	0.0456	15.1958
2	0.0278	0.0000	0.0035	6.2000	0.0257	6.2570
3	0.0413	0.0075	0.0065	17.1000	0.0471	17.2024
4	0.0000	0.0000	0.0000	0.0000	0.0316	0.0316
5	0.0222	0.0000	0.0032	6.0000	0.0221	6.0474
6	0.0444	0.0070	0.0065	17.1000	0.0493	17.2072
7	0.0378	0.0075	0.0065	17.0000	0.0463	17.0981
8	0.0000	0.0000	0.0023	2.8000	0.0191	2.8214
9	0.0367	0.0000	0.0052	10.0000	0.0441	10.0859
10	0.0000	0.0000	0.0021	3.0000	0.0162	3.0183
11	0.0357	0.0073	0.0054	11.0000	0.0434	11.0917
12	0.0411	0.0000	0.0062	14.0000	0.0471	14.0944

13	0.0000	0.0000	0.0023	2.8000	0.0147	2.8170
14	0.0389	0.0020	0.0054	12.0000	0.0456	12.0918
15	0.0380	0.0020	0.0053	12.0000	0.0456	12.0909
16	0.0000	0.0000	0.0025	5.0000	0.0426	5.0452
17	0.0372	0.0000	0.0042	10.0000	0.0456	10.0870
18	0.0378	0.0000	0.0046	11.0000	0.0449	11.0873
19	0.0000	0.0000	0.0024	2.8000	0.0243	2.8267
20	0.0000	0.0000	0.0000	0.0000	0.0324	0.0324
21	0.0378	0.0000	0.0051	8.5000	0.0441	8.5869
22	0.0356	0.0000	0.0051	8.1000	0.0449	8.1855
23	0.0000	0.0000	0.0025	2.9000	0.0221	2.9246
24	0.0000	0.0000	0.0023	2.8000	0.0191	2.8214
25	0.0397	0.0000	0.0064	12.0000	0.0456	12.0917
26	0.0000	0.0000	0.0021	2.8000	0.0154	2.8175
27	0.0000	0.0000	0.0024	2.9000	0.0199	2.9223
28	0.0344	0.0000	0.0047	8.3000	0.0471	8.3862
29	0.0333	0.0000	0.0043	8.1000	0.0456	8.1832
30	0.0000	0.0000	0.0035	6.0000	0.0441	6.0476
31	0.0400	0.0000	0.0048	10.0000	0.0449	10.0897
32	0.0000	0.0000	0.0000	0.0000	0.0272	0.0272
33	0.0367	0.0000	0.0037	8.5000	0.0434	8.5837
34	0.0222	0.0000	0.0032	8.0000	0.0441	8.0695
35	0.0000	0.0000	0.0028	3.0000	0.0426	3.0455
36	0.0233	0.0000	0.0033	7.4000	0.0441	7.4707
37	0.0422	0.0000	0.0051	11.0000	0.0471	11.0943
38	0.0344	0.0000	0.0045	10.0000	0.0456	10.0846
39	0.0000	0.0000	0.0000	0.0000	0.0243	0.0243
40	0.0000	0.0000	0.0022	2.8000	0.0228	2.8250
41	0.0267	0.0000	0.0035	8.7000	0.0404	8.7706
42	0.0211	0.0000	0.0033	7.0000	0.0390	7.0633
43	0.0000	0.0000	0.0021	2.7900	0.0184	2.8105
44	0.0000	0.0000	0.0025	2.9000	0.0213	2.9238
45	0.0422	0.0000	0.0047	8.0000	0.0419	8.0889
46	0.0359	0.0000	0.0051	9.0000	0.0434	9.0843
47	0.0000	0.0000	0.0023	3.0000	0.0176	3.0200
48	0.0000	0.0000	0.0023	3.0000	0.0154	3.0178
49	0.0000	0.0000	0.0025	3.5000	0.0243	3.5268
50	0.0000	0.0000	0.0021	3.4000	0.0272	3.4293
51	0.0233	0.0000	0.0027	5.0000	0.0294	5.0555
52	0.0356	0.0000	0.0050	8.0000	0.0426	8.0832
53	0.0244	0.0000	0.0038	6.0000	0.0346	6.0628
54	0.0222	0.0000	0.0035	5.9000	0.0331	5.9588
55	0.0222	0.0000	0.0037	5.9000	0.0331	5.9590
Min	0.0000	0.0000	0.0000	0.0000	0.0147	0.0243
Max	0.0444	0.0075	0.0065	17.1000	0.0493	17.2072
Mean	0.0202	0.0007	0.0036	6.9107	0.0351	6.9703

SD	0.0174	0.0021	0.0017	4.4089	0.0113	4.4361

The calculated ecological risk factors varied from 0.0000–0.0444 for Cu, 0.0000–0.0075 for Pb, 0.0000–0.0065 for Zn, 0.0000–17.1000 for Cd, and 0.0147–0.0493 for Ni (Table 4). The corresponding mean values were 0.0202 for Cu, 0.0007 for Pb, 0.0036 for Zn, 6.9107 for Cd, and 0.0351 for Ni. The mean ecological risk values followed the order, Cd > Ni > Cu > Pb > Zn.

Cadmium exhibited the highest ecological risk among all investigated metals, with Er values ranging from 0.0000 to 17.1000 and a mean value of 6.9107. This observation is expected because cadmium possesses the highest toxic-response coefficient (Tr = 30), making it one of the most environmentally hazardous trace metals even at relatively low concentrations (Hakanson, 1980). Nevertheless, all cadmium Er values remained well below the threshold value of 40, indicating low ecological risk throughout the study area.

Copper and nickel recorded comparatively low ecological risk values despite having toxic-response coefficients of five. Their low contamination factors resulted in correspondingly small ecological risk values, with maximum Er values of 0.0444 for Cu and 0.0493 for Ni. Zinc exhibited the lowest ecological risk because of its relatively low contamination factor and toxic-response coefficient (Tr = 1). Lead similarly contributed negligibly to ecological risk owing to its extremely low sediment concentrations.

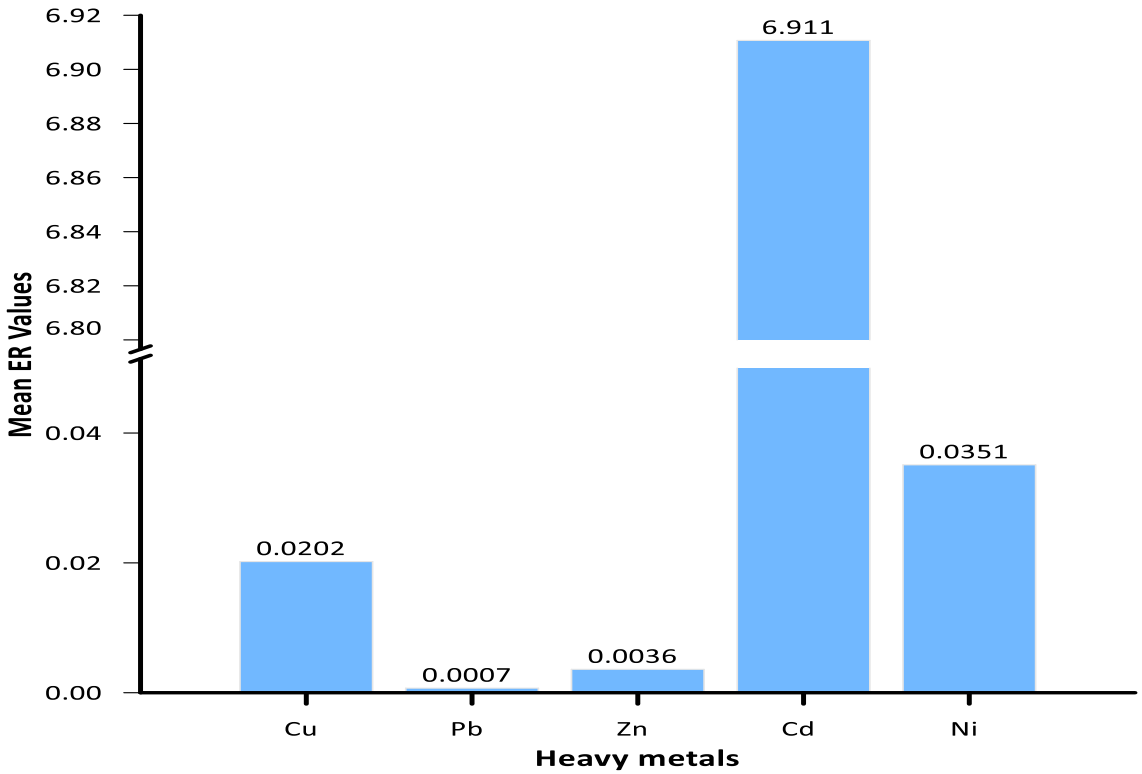

Fig. 3: ER values of investigated metals

Fig. 3 clearly demonstrates that cadmium contributes the largest proportion of the total ecological risk despite its relatively low sediment concentration. This reflects the importance of considering metal toxicity in ecological assessments rather than relying solely on concentration values. Similar observations have been reported in numerous

estuarine environments where cadmium constitutes the principal contributor to ecological risk because of its high biological toxicity (Attia & Ghrefat, 2013; Qing et al., 2015; Wang et al., 2015).

Spatially, the highest ecological risk values were recorded at Stations 3 and 6, where cadmium reached a maximum Er value of 17.10. These stations also correspond to locations with relatively elevated contamination factors and heavy metal concentrations (Tables 1 and 3), suggesting localized anthropogenic inputs. Possible sources include petroleum exploration and production activities, industrial effluent discharge, maritime transportation, agricultural runoff, and domestic waste disposal within the estuarine catchment. However, even at these locations, ecological risk remained well within the low-risk category.

The present findings are consistent with previous studies conducted in southeastern Nigeria. Uwah et al. (2013) reported similarly low ecological risks for heavy metals in sediments of the Qua-Iboe River Estuary, while Odiongenyi (2017) concluded that sediment quality within the estuary posed minimal ecological concern. Comparable studies from the western Caspian Sea (Ahmadov et al., 2020), Mabahiss Bay in the Red Sea (Attia & Ghrefat, 2013), Dongping Lake (Wang et al., 2015), and the Pearl River Estuary (Li et al., 2007) likewise reported that ecological risk factors for most heavy metals remained within the low-risk category despite increasing anthropogenic activities.

The uniformly low ecological risk factors observed in this study indicate that heavy metals currently pose little threat to benthic organisms inhabiting the Qua-Iboe River Estuary. The low contamination levels, combined with continuous tidal flushing and sediment exchange with the Gulf of Guinea, likely reduce the residence time of contaminants and limit their accumulation within bottom sediments. Furthermore, the predominance of lithogenic over anthropogenic sources for most metals contributes to the favorable ecological condition observed.

3.7 Ecological Risk Index (RI)

The Ecological Risk Index (RI) is a comprehensive ecological assessment proposed by Hakanson (1980) for evaluating the cumulative ecological risk posed by multiple heavy metals in aquatic sediments. Unlike the ecological risk factor (Er), which assesses the potential risk of individual metals, the RI integrates the risks associated with all investigated metals into a single index, thereby providing an overall measure of the ecological status of the sediment environment. This index considers both the contamination level and the toxic response of each metal and is widely used in environmental pollution studies to evaluate the potential impact of heavy metals on aquatic ecosystems.

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

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 ecological risk index values for the Qua-Iboe River Estuary were presented in Table 4, while their spatial distribution is illustrated in Fig. 5

The calculated RI values ranged from 0.0243 at Station 39 to 17.2072 at Station 6, with a mean value of 6.9703 ± 4.4361 (Table 4). The highest ecological risk indices were observed at Stations 6 (17.2072), 3 (17.2024), and 7 (17.0981), whereas the lowest values occurred at Stations 39 (0.0243), 32 (0.0272), 20 (0.0324), and 4 (0.0316).

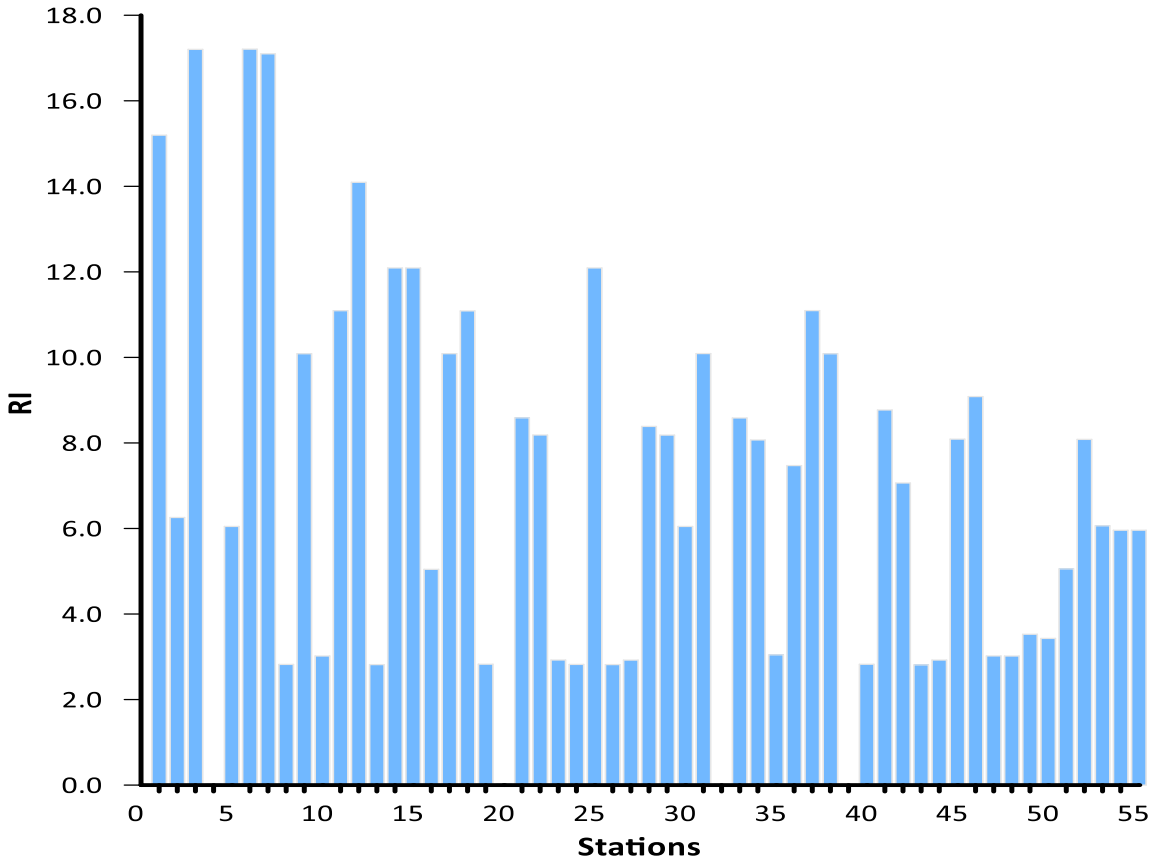

Fig. 4: RI values of investigated stations

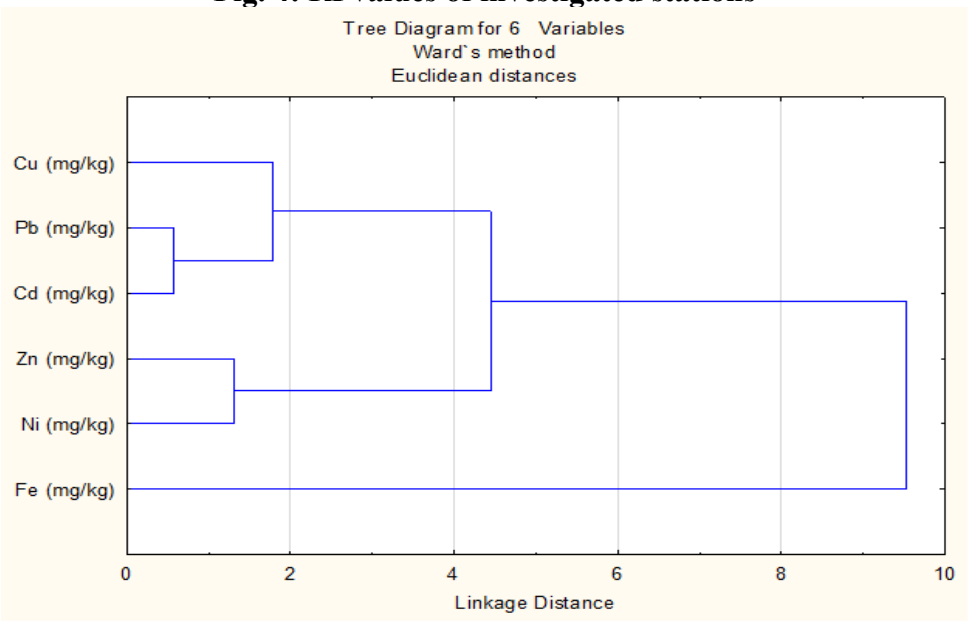

Fig. 5: Dendrogram shows clustering of heavy metals in the study area

Despite these spatial variations, all RI values were substantially lower than the threshold value of 95, indicating that every sampling station within the Qua-Iboe River Estuary falls within the low ecological risk category according to Hakanson (1980). These results

demonstrate that the combined effects of Cu, Pb, Zn, Cd, and Ni currently pose minimal ecological threats to the estuarine environment. The spatial pattern of RI closely follows the distribution of cadmium, which contributed most significantly to the cumulative ecological risk because of its relatively high toxic-response coefficient (Tr = 30). Although Cd concentrations were low, its toxicity resulted in greater contributions to the overall RI compared with Cu, Ni, Zn, and Pb. Nevertheless, the cumulative ecological risk remained well below internationally accepted threshold values, indicating that the present levels of heavy metals are unlikely to produce adverse ecological effects on benthic organisms and other components of the estuarine ecosystem.

Stations 3, 6, and 7 consistently recorded the highest RI values, corresponding to locations where elevated concentrations of Cu, Cd, Zn, Ni, and Fe were observed (Table 1). These localized increases are likely associated with anthropogenic activities occurring within the estuary, including petroleum exploration and production, marine transportation, industrial effluent discharge, agricultural runoff, and domestic waste disposal. However, the low RI values indicate that these activities have not yet resulted in ecological degradation of the sediment environment.

Conversely, the very low RI values recorded at Stations 4, 20, 32, and 39 suggest that these areas remain largely unaffected by anthropogenic contamination. Efficient tidal flushing, sediment resuspension, and continuous exchange of sediments with the Gulf of Guinea probably contribute to the dilution and redistribution of contaminants, thereby preventing long-term accumulation of heavy metals within bottom sediments.

The present findings are consistent with previous investigations conducted in southeastern Nigeria and elsewhere. Uwah et al. (2013) similarly reported low ecological risk indices for sediments of the Qua-Iboe River Estuary, while Odiongenyi (2017) concluded that heavy metal contamination within the estuary posed minimal ecological concern. Comparable studies from the western Caspian Sea (Ahmadov et al., 2020), the Red Sea coast (Attia & Ghrefat, 2013), Dongping Lake, China (Wang et al., 2015), and the Yangtze River intertidal zone (Zhang et al., 2009) likewise reported ecological risk indices below critical ecological thresholds despite increasing industrial and urban activities.

The consistency between the ecological risk index and the other pollution indices (Igeo, CF, DC, and PLI) further strengthens the conclusion that heavy metal contamination within the Qua-Iboe River Estuary is currently minimal. All indices consistently indicate that heavy metal concentrations remain close to natural background levels and that anthropogenic enrichment has not reached levels capable of causing ecological impairment.

4.0 Conclusion

This study assessed the spatial distribution, contamination status, and ecological risk of selected heavy metals (Cu, Pb, Zn, Cd, Ni, and Fe) in recent bottom sediments of the Qua-Iboe River Estuary, Southeast Nigeria, using geochemical indices and multivariate statistical techniques. Analysis of 55 sediment samples showed that the mean concentrations of heavy metals followed the order Fe (1.09 mg/kg) > Ni (0.476 mg/kg) > Zn (0.341 mg/kg) > Cu (0.180 mg/kg) > Cd (0.069 mg/kg) > Pb (0.003 mg/kg). All measured concentrations were substantially lower than the Average Shale Values (Turekian & Wedepohl, 1961) and the sediment quality guidelines of the Department of Petroleum Resources (DPR, 2002), indicating that the sediments are presently uncontaminated by the investigated metals.

The calculated geo-accumulation index (Igeo) values were all ≤ 0, classifying the sediments as unpolluted with respect to Cu, Pb, Zn, Cd, Ni, and Fe. Similarly, contamination factor (CF) values for all metals were less than 1,

indicating low contamination, while degree of contamination (DC) values at all sampling stations remained below the threshold of 6, confirming a low overall contamination status. Pollution Load Index (PLI) values were consistently below unity, demonstrating the absence of significant anthropogenic metal pollution throughout the estuary.

Ecological risk assessment further revealed that all ecological risk factor (Er) values were below 40, and the ecological risk index (RI) values for every sampling station were less than 95, indicating low potential ecological risk to the aquatic ecosystem. Hierarchical Cluster Analysis (HCA) separated the investigated metals into two distinct groups, with Fe forming an independent cluster while Cu, Pb, Cd, Zn, and Ni constituted a second cluster, suggesting that metal distribution is controlled by a combination of natural geological processes and localized anthropogenic inputs.

Overall, the sediments of the Qua-Iboe River Estuary remain in a relatively pristine environmental condition with respect to heavy metal contamination. Nevertheless, the estuary is located within the rapidly developing Niger Delta region, where increasing industrialization, oil and gas activities, maritime transportation, agricultural practices, and domestic waste discharge may progressively elevate heavy metal inputs. Therefore, continuous environmental monitoring, effective pollution control measures, and sustainable watershed management are recommended to preserve the ecological integrity of the estuary and prevent future deterioration of sediment quality.

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Declaration

Competing Interests

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

Ethical Consideration

Not applicable

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Victoria Inyang Emeka: Conceptualization, methodology, Resources, writing – original draft, writing – review & editing. Chimezie Ndunagum Emeka: Methodology, figures preparation, writing – review & editing, corresponding author

Availability of data and material

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