National Centre for Energy and Environment, Energy
Commission of Nigeria, University of Benin:
ISSN 2504-9593
DOI: 10.5281/zenodo.20220054
https://ijree.com/index.php/publications/article/view/46

Int. J. Renew. Energ & Environ Vol.4 (2), pp 98-120(2026)

MULTI-PATHWAY HUMAN EXPOSURE TO HEAVY METALS IN TWO URBAN RIVERS OF SOUTHERN NIGERIA: A DETERMINISTIC AND MONTE CARLO RISK ASSESSMENT

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ABSTRACT

Heavy metal contamination of freshwater systems poses significant public health concerns in urbanizing regions where rivers provide food and domestic water. This study assessed human health risks associated with Pb, Cd, Mn, Fe, Cu, Zn, and Ni in water, sediment, and fish from Ogba and Ikpoba Rivers, Nigeria, using integrated deterministic and probabilistic approaches. Exposure through fish consumption, water ingestion, and incidental sediment ingestion was evaluated for adults and children using Estimated Daily Intake (EDI), Hazard Quotient (HQ), Hazard Index (HI), and Monte Carlo simulation (10,000 iterations). Metal concentrations generally followed the pattern sediment > fish > water, indicating sediment retention with transfer into edible biota. Fish consumption was the dominant exposure pathway in both rivers, while sediment ingestion contributed minimally. Children consistently showed higher exposure and risk than adults due to lower body weight. All mean deterministic HI values were below 1, indicating no immediate non-carcinogenic risk under average exposure assumptions. However, upper-tail probabilistic estimates for child fish consumers approached levels of concern, particularly in Ogba River. Sensitivity analysis identified fish ingestion rate and metal concentration as the strongest drivers of risk variability. These findings show that average deterministic estimates may underestimate risk for high-exposure groups. Continuous monitoring, child-focused risk management, and fish consumption guidance are recommended for river-dependent communities.

***Keywords:** Heavy metals; Human health risk assessment; Monte Carlo simulation; Fish consumption*;

1. INTRODUCTION

Freshwater ecosystems are increasingly threatened by heavy metal contamination arising from urbanization, industrialization, transportation activities, waste disposal, agricultural runoff, and atmospheric deposition (Afzaal *et al.*, 2022; Hama Aziz *et al.*, 2023). Unlike many organic pollutants, heavy metals are non-biodegradable, environmentally persistent, and capable of cycling between water, sediment, and biota over long periods (Taiwo Adekanmi, 2021; Vukovi *et al.*, 2011). Once introduced into aquatic systems, they may accumulate in sediments, become remobilized under changing physicochemical conditions, and enter food webs through uptake by aquatic organisms (Chan *et al.*, 2021; Moiseenko and Gashkina, 2020; Sonone *et al.*, 2020; Tchounwou *et al.*, 2012). This persistence makes metal contamination a dual ecological and public health issue. Human exposure to aquatic metals occurs through multiple pathways, including ingestion of contaminated drinking water, consumption of fish and other aquatic foods, and incidental ingestion of sediment or suspended particles during occupational and recreational activities (Ajala *et al.*, 2025; Mititelu *et al.*, 2025). Among these pathways, fish consumption is often the most significant because fish can bioaccumulate metals from surrounding water, sediment, and diet, thereby integrating environmental contamination into a direct human exposure route (Ali *et al.*, 2019; Hossain *et al.*, 2022; Oros, 2025). The health implications of chronic exposure include neurotoxicity, nephrotoxicity, endocrine disruption, developmental impairment, carcinogenicity, and cardiovascular effects depending on the metal species, dose, and duration of exposure (Tchounwou *et al.*, 2012; Zhao *et al.*, 2024).

In many low- and middle-income countries, including Nigeria, rivers remain central to domestic water supply, artisanal fisheries, irrigation, transportation, and informal economic activity (Onyima *et al.*, 2024; Taiwo *et al.*, 2012). However, these benefits often coexist with weak wastewater control, unregulated discharge, urban runoff, dredging, and diffuse pollution sources. Several Nigerian studies have reported measurable heavy metal burdens in river water, sediment, and fish, indicating potential health concerns for exposed communities (Ehiemere *et al.*, 2022; Iyorah *et al.*, 2022; Obasohan *et al.*, 2007; Ogbeide and Ogbeide; Ogbonna *et al.*, 2021; Ojaniyi *et al.*, 2021), Despite this growing body of evidence, many assessments remain limited to concentration reporting, pollution indices, or deterministic screening approaches without explicitly quantifying uncertainty or identifying higher-risk population subgroups.

Ogba and Ikpoba Rivers in Benin City, southern Nigeria, are urban freshwater systems exposed to multiple anthropogenic pressures linked to expanding residential development, stormwater inputs, commercial activities, waste disposal, and catchment disturbance. Previous investigations in these systems have documented heavy metal contamination, ecological impairment, bioaccumulation in fish, and pathological alterations in aquatic organisms, indicating that contaminant transfer from the environment to biota is already occurring (Obasohan and Eguavoen, 2008; Ogbeide and Ogbeide, 2026; Ogbeide and Okoduwa, 2024). However, a comprehensive human health risk evaluation integrating water, sediment, and edible fish pathways has remained limited. Human health risk assessment (HHRA) is commonly implemented using deterministic models based on point estimates of exposure factors and contaminant concentrations. While useful for screening, deterministic methods may obscure real-world variability in consumption patterns, body weight, and environmental concentrations (Badeenezhad *et al.*, 2023; Maertens *et al.*, 2024). Probabilistic approaches, particularly Monte Carlo simulation, address this limitation by generating exposure distributions and estimating percentile risk or the probability of exceeding health benchmarks (Ataiesalami *et al.*, 2025; Craig *et al.*, 2020; Tudi *et al.*, 2022). These methods are increasingly recommended in environmental health studies because they provide a more realistic basis for decision-making than single-value estimates alone (Husejnović *et al.*, 2022; Wang *et al.*, 2023).

The present study therefore assessed the potential human health risks associated with Pb, Cd, Mn, Fe, Cu, Zn, and Ni in water, sediment, and fish from Ogba and Ikpoba Rivers using an integrated deterministic–probabilistic framework. Specifically, the study aimed to: (i) characterize metal distribution across environmental matrices; (ii) estimate exposure through fish consumption, water ingestion, and incidental sediment ingestion for adults and children; (iii) quantify non-carcinogenic and screening-level carcinogenic risks, including uncertainty, percentile risk, and exceedance probability through Monte Carlo simulation. (iv) identify dominant exposure drivers through sensitivity analysis. By combining multi-matrix monitoring with advanced risk modeling, the study provides evidence directly relevant to environmental management and public health protection in river-dependent communities.

3. MATERIALS AND METHODS

3.1 Study design and human health risk assessment framework

This study assessed the potential human health risks associated with exposure to heavy metals in water, sediment, and fish from Ogba and Ikpoba Rivers, Nigeria. The assessment integrated deterministic and probabilistic human health risk assessment (HHRA) methods to quantify screening-level risk, characterize population variability, and identify dominant exposure drivers.

The target metals were Pb, Cd, Mn, Fe, Cu, Zn, and Ni. Concentrations were determined in water, sediment, and fish muscle samples collected monthly from May to July. Fish muscle was emphasized because it represents the principal edible tissue and the most direct route of contaminant transfer to humans through aquatic food consumption.

The risk framework followed the conventional sequence:

Source → Environmental Medium
→ Exposure → Dose → Risk

This integrated approach is consistent with established environmental health methodologies applied to metal-contaminated aquatic systems (Authman *et al.*, 2015; Tchounwou *et al.*, 2012)

3.2 Study area, dataset structure, and data treatment

The study used measured concentrations from two tropical urban river systems: Ogba River and Ikpoba River. Monthly observations (May, June, and July) were available for three environmental matrices:

i. water (mg/L)
ii. sediment (mg/kg dry weight)
iii. fish muscle (mg/kg wet weight unless otherwise stated)

The dataset included Pb, Cd, Mn, Fe, Cu, Zn, and Ni. Values reported below detection limit were assigned a value of zero for screening-level exposure estimation. This substitution approach was adopted because non-detect values were infrequent and the objective was comparative risk ranking rather than trace-level censored data modeling.

Prior to analysis, all units were verified and harmonized by matrix. Concentration records were organized by river, month, matrix, and metal.

3.3 Exposure pathway characterization

Three oral exposure pathways were evaluated. Dietary exposure through fish consumption was considered the primary pathway because fish is widely consumed and can integrate contaminant uptake from water, sediment, and food webs. Direct water ingestion was included as a secondary pathway to represent domestic use, incidental intake, or untreated surface-water consumption.

Incidental sediment ingestion was included as a supplementary pathway relevant to occupational, shoreline, and recreational contact. Dermal absorption was not modeled because oral exposure generally contributes more substantially to total dose for the selected metals under community exposure scenarios.

3.4 Deterministic exposure assessment

3.4.1 Estimated daily intake for water and fish

Estimated Daily Intake (EDI) for water ingestion and fish consumption was calculated using Equation (1):

$$\mathrm{EDI} = \frac{C \times IR}{BW}$$

where (C) denotes the concentration of the metal in the respective matrix (mg/kg or mg/L), (IR) is the ingestion rate, and (BW) is the body weight of the exposed individual. This formulation has been widely applied in dietary and environmental exposure assessments involving aquatic contaminants ((Nędzarek and Czerniejewski, 2024)).

3.4.2 Estimated daily intake for sediment

For sediment ingestion, chronic exposure duration and frequency were incorporated using Equation (2): For sediment exposure, temporal factors were incorporated to reflect chronic exposure conditions, as expressed in Equation (2):

$$\mathrm{EDI}_{sed} = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

where (EF) represents exposure frequency, (ED) is exposure duration, and (AT) is the averaging time. This approach accounts for long-term cumulative exposure and is consistent with models applied in aquatic risk assessment studies (Panda *et al.*, 2023).

3.5 Deterministic non-carcinogenic risk assessment

3.5.1 Target Hazard Quotient

Non-carcinogenic risk was evaluated using the Target Hazard Quotient (THQ), defined as the ratio of estimated exposure to a reference dose, as shown in Equation (3):

$$THQ = \frac{\mathrm{EDI}}{\mathrm{RfD}}$$

where (RfD) represents the oral reference dose for each metal. A THQ value less than one indicates negligible risk, whereas values greater than one suggest the potential for adverse health effects. This approach is consistent with established methodologies in environmental risk assessment (Panda *et al.*, 2023; Tchounwou *et al.*, 2012).

3.5.2 Hazard Index

To account for combined exposure to multiple metals, the Hazard Index (HI) was calculated as the sum of individual THQs, as presented in Equation (4):

$$\mathrm{HI} = \sum_{i=1}^{n} \mathrm{THQ}_i$$

An HI value greater than one indicates potential cumulative health risk due to additive effects of multiple contaminants.

3.6 Deterministic carcinogenic risk assessment

Carcinogenic risk (CR) was estimated for metals with established carcinogenic potential using Equation (5):

$$\mathrm{CR} = \mathrm{EDI} \times \mathrm{SF}$$

where (SF) is the oral cancer slope factor. Risk values were interpreted using conventional regulatory benchmarks: < (10^{-6}) (negligible), (10^{-6})–(10^{-4}) (tolerable range), and > (10^{-4}) (potentially unacceptable).

For Pb, exposure was quantified and discussed separately within a screening framework because no universally accepted contemporary oral threshold exists, particularly for neurodevelopmental endpoints in children.

3.7 Probabilistic risk assessment

3.7.1 Monte Carlo simulation

To characterize uncertainty and inter-individual variability, probabilistic risk assessment was conducted using Monte Carlo simulation with 10,000 iterations. This iteration number is widely considered sufficient for convergence of central tendency and percentile estimates in environmental exposure models (Husejnović *et al.*, 2022; Ullah *et al.*, 2022).

Instead of fixed values, selected exposure variables were represented as probability distributions and randomly sampled during each iteration (Wei *et al.*, 2023). Resulting distributions of EDI, THQ, HI, and CR were used to estimate central tendency, upper-tail risk, and threshold exceedance probability (Li *et al.*, 2025a).

3.7.2 Distribution assignment

Metal concentration data were modeled using empirical distributions where sample size was limited, and lognormal distributions where distribution fitting was appropriate based on positive skewness commonly observed in environmental concentration data (Crabbe *et al.*, 2017).

Fish ingestion rate and sediment ingestion rate were modeled as lognormal variables. Water ingestion rate and body weight were modeled using normal distributions truncated at physiologically plausible lower bounds to prevent unrealistic values (Moloi *et al.*, 2020).

Table 1. Probabilistic model inputs

Variable	Distribution	Rationale
Metal concentration	Empirical / Lognormal	Environmental variability
Fish ingestion rate	Lognormal	Dietary heterogeneity
Water ingestion rate	Normal	Daily intake variability
Body weight	Normal	Population variability
Sediment ingestion rate	Lognormal	Behavioral variability

Exposure frequency and duration were retained as fixed parameters for chronic exposure scenarios.

3.7.3 Probabilistic outputs

The simulation produced:

i. mean risk estimate
ii. median (P50)
iii. 95th percentile (P95)
iv. probability that THQ > 1
v. probability that HI > 1
vi. probability density and cumulative exceedance plots

3.8 Sensitivity analysis

Sensitivity analysis was conducted using rank-based correlation between model inputs and output metrics (THQ and HI). Absolute coefficient magnitude was used to rank the relative influence of each variable. This procedure identified whether risk variability was driven primarily by concentration, ingestion behavior, body weight, or other exposure assumptions.

3.9 Exposure assumptions for deterministic modeling

Default receptor values were selected from established HHRA guidance and peer-reviewed aquatic exposure studies.

Table 2. Deterministic exposure parameters

Parameter	Adults	Children	Unit	Recommended Reference
Body weight (BW)	70	15	kg	(USEPA, 1989, 2011)
Fish ingestion rate	0.05	0.02	kg/day	(USEPA, 2011)
Water ingestion rate	2.0	1.0	L/day	(USEPA, 2011, 2018)
Sediment ingestion rate	0.0001	0.0002	kg/day	(ATSDR, 2020a; USEPA, 2011)
Exposure frequency (EF)	365	365	days/year	(USEPA, 1991b).
Exposure duration (ED)	30	6	years	(USEPA, 1991b)
Averaging time (AT)	ED × 365	ED × 365	days	(USEPA, 1989)

Children were modeled separately because lower body mass increases dose per unit weight and may increase vulnerability to toxic effects.

3.10 Toxicological reference values

Oral reference doses and slope factors were obtained from recognized toxicological databases and peer-reviewed sources.

Table 3. Toxicological parameters used in risk assessment Toxicological Parameters Used in Risk Assessment — With References

Metal	Oral RfD (mg/kg/day)	Oral Slope Factor $(mg/kg/day)^{-1}$	Reference(s)
Cd	0.001	6.1	(USEPA, 1994)
Ni	0.020	0.91	(USEPA, 1991a)
Cu	0.040	—	(USEPA, 2004e)
Zn	0.300	—	(USEPA, 2004c)
Fe	0.700	—	(USEPA, 2004a)
Mn	0.140	—	(USEPA, 2004b)
Pb	Screening via IEUBK/ALM	—	(ATSDR, 2020b; USEPA, 2004d)

Pb was not assigned a fixed safe threshold; instead, Pb exposure was interpreted conservatively using relative contribution to total hazard and pathway-specific intake.

3.11 Statistical analysis and computational implementation

All descriptive statistical analyses (means, medians, SDs, ranges, and distribution diagnostics) AND RISK ANALYSIS were performed using Python 3.11 (Python Software Foundation, 2023) with the pandas 2.2. (Reback *et al.*, 2020) and NumPy 1.26. libraries (Harris *et al.*, 2020)..

3.12 Quality assurance, model validation, and interpretation

All equations were applied consistently across rivers, months, matrices, and receptor groups. Outputs were screened for impossible values, dimensional inconsistencies, and simulation instability. Monte Carlo outputs were checked for convergence by comparing running summaries of mean and percentile estimates.

Deterministic results were interpreted as screening-level estimates based on central assumptions, whereas probabilistic outputs were used to characterize population variability and identify higher-risk subgroups. The combined framework provides a robust basis for prioritizing contaminants, exposure pathways, and public health interventions in river-dependent communities.

4. RESULTS

4.1 Heavy metal distribution across environmental matrices

The spatial and matrix-level distribution of Pb, Cd, Mn, Fe, Cu, Zn, and Ni is summarized in Figure 1. Across both rivers, metals were unevenly partitioned among environmental compartments, with the general loading pattern:

Sediment > Fish muscle > Water

Sediments consistently contained the highest burdens for all measured elements. Fish tissues contained appreciable concentrations of several metals, demonstrating bioavailable transfer from the aquatic environment, whereas dissolved concentrations in water were comparatively lower. Fe was the dominant element in all matrices. The highest single concentration recorded in the study was Fe in Ikpoba sediment during July (620.02 mg/kg), while Fe in fish muscle reached 46.31 mg/kg in Ogba during June. Zn and Cu also occurred at elevated levels in sediment and fish relative to water. Although Pb and Cd occurred at lower absolute concentrations, their toxicological relevance remained high because of lower health-based benchmark values. Temporal variation was more pronounced in water and fish than in sediment. Several aqueous and tissue concentrations declined by July relative to May or June,

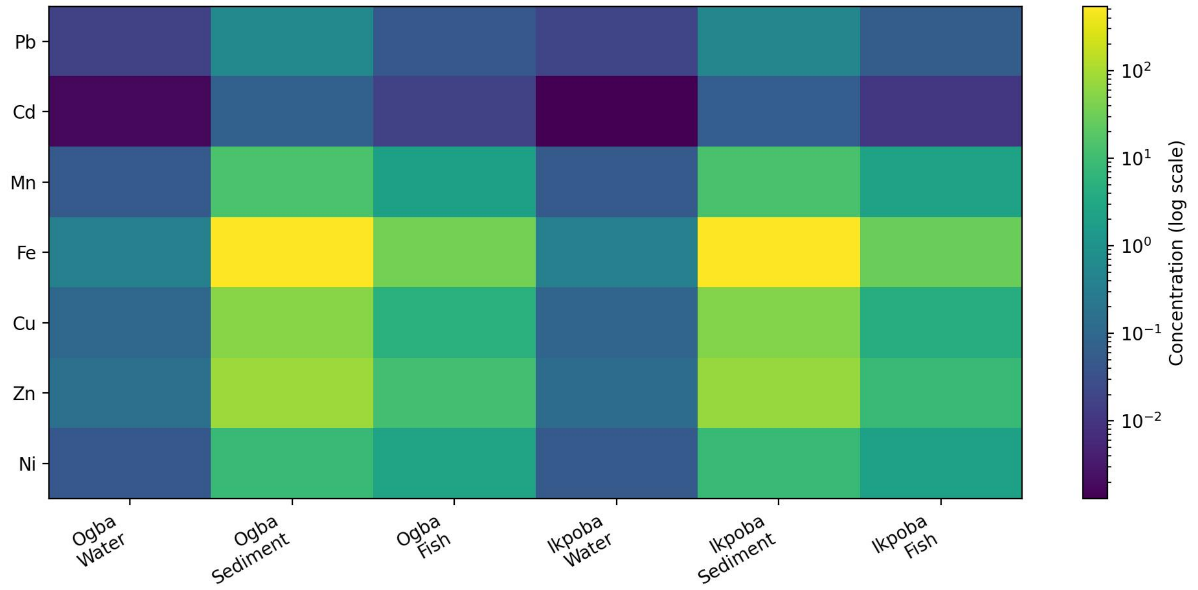

Figure 1. Heat Map of Mean Heavy Metal Concentrations Across Rivers and Matrices

4.2 Deterministic exposure assessment

Pathway-specific exposure estimates derived from the deterministic models are presented in Table 4. Across both rivers and receptor groups, exposure differed markedly by matrix. Fish consumption produced the highest Estimated Daily Intake (EDI) values for most metals, followed by direct water ingestion, whereas incidental sediment ingestion contributed the lowest doses.

For adults, fish-derived Fe intake reached 2.58E−02 mg/kg/day in Ogba and 2.16E−02 mg/kg/day in Ikpoba, exceeding corresponding water and sediment exposures. Similar pathway dominance was observed for Zn, Cu, and Ni. Water ingestion remained a meaningful secondary source of exposure, particularly for Fe, Zn, and Cu, but was consistently lower than dietary intake. Sediment ingestion produced minimal doses because of low ingestion rates assumed in the chronic exposure model. Children exhibited higher body weight-adjusted EDI values than adults under all scenarios. This was especially evident for fish consumption, where lower body mass amplified internal dose. For example, child fish-derived Fe intake was 4.82E−02 mg/kg/day in Ogba and 4.03E−02 mg/kg/day in Ikpoba.

Table 4. Estimated Daily Intake (EDI, mg/kg/day) by Exposure Pathway

River	Population	Highest Pathway	Dominant Metals
Ogba	Adult	Fish	Fe, Zn, Cu, Ni
Ogba	Child	Fish	Fe, Zn, Cu, Ni
Ikpoba	Adult	Fish	Fe, Zn, Cu, Ni
Ikpoba	Child	Fish	Fe, Zn, Cu, Ni

4.3 Deterministic non-carcinogenic risk

Metal-specific Hazard Quotients (HQ) and cumulative Hazard Index (HI) values are summarized in Table 5, while the comparative ranking of total risk scenarios is presented in Table 6 and visualized in Figure 2.

Across all modeled scenarios, cumulative HI values remained below the benchmark threshold of 1, Fish consumption produced the highest HI values in both rivers, followed by water ingestion, whereas sediment ingestion remained negligible to low. The maximum cumulative hazard occurred in the Ogba child fish scenario (HI = 0.499), followed by Ikpoba child fish (HI = 0.414), Ogba child water (HI = 0.428), and Ikpoba child water (HI = 0.400). Adult scenarios were consistently lower. Among individual metals, Ni and Cu were the largest contributors to total hazard, with Fe and Zn contributing moderate proportions because of higher concentrations but higher reference doses. Cd and Mn contributed smaller fractions of total HI.

The pathway hierarchy was therefore: $Fish >$ Water $> Sediment$ and the receptor hierarchy was: $Children >$ Adults

Table 5. Hazard Quotient (HQ/THQ) by Exposure Pathway

Pathway	Adults	Children	Relative Risk
Water	0.214–0.230	0.400–0.428	Moderate
Sediment	0.004	0.035–0.039	Low
Fish	0.222–0.268	0.414–0.499	Highest

Table 6. Hazard Index (HI) Ranking Across All Pathways

Rank	Scenario	HI
1	Ogba Child Fish	0.499
2	Ogba Child Water	0.428
3	Ikpoba Child Fish	0.414
4	Ikpoba Child Water	0.400
5	Ogba Adult Fish	0.268
6	Ogba Adult Water	0.230
7	Ikpoba Adult Fish	0.222
8	Ikpoba Adult Water	0.214

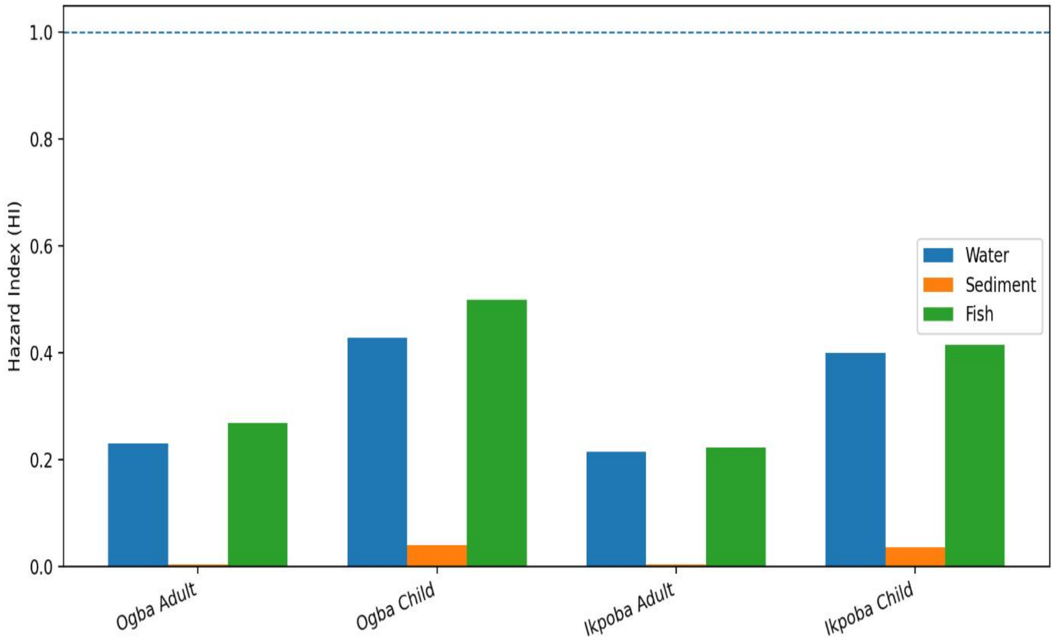

Figure 2. Exposure Pathway Comparison (HI by Pathway)

4.4 Relative contribution of metals to cumulative hazard

The proportional contribution of each metal to total HI is shown in Figure 3. In the highest-risk scenarios, Ni and Cu jointly accounted for the largest share of cumulative hazard, exceeding contributions from Mn, Cd, and Zn. Fe contributed appreciably because of its relatively high concentrations, particularly in fish tissues. Metals present at moderate concentrations but lower reference doses exerted stronger influence on total hazard than more abundant but less toxicologically restrictive elements.

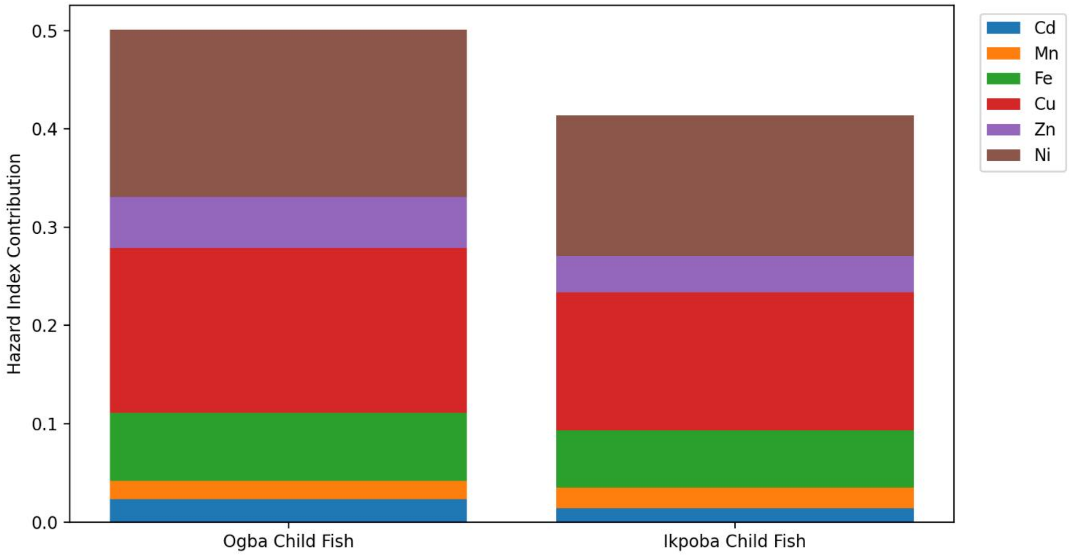

Figure 3. Contribution of Metals to Total HI

4.5 Probabilistic risk characterization

Monte Carlo simulation outputs are summarized in Table 7, while the distributional behavior of modeled HI values is illustrated in Figures 4 and 5.

For adults, mean and median HI values remained below unity across all scenarios. For children, mean HI values were higher and upper-tail estimates approached the threshold of concern in fish and water exposure models. The highest 95th percentile (P95) values occurred in the Ogba child fish scenario (0.92), followed by Ikpoba child fish (0.81),

The probability of exceeding HI = 1 was low but non-zero in child fish scenarios, reaching 0.05 in Ogba and 0.03 in Ikpoba. Sediment exposure showed negligible exceedance probability.

Table 7. Probabilistic Risk Summary (10,000 Iterations)

Scenario	Mean HI	P50	P95	Probability (HI > 1)
Ogba Adult Fish	0.27	0.26	0.49	<0.01
Ogba Child Fish	0.50	0.48	0.92	0.05
Ikpoba Adult Fish	0.22	0.21	0.43	<0.01
Ikpoba Child Fish	0.41	0.40	0.81	0.03

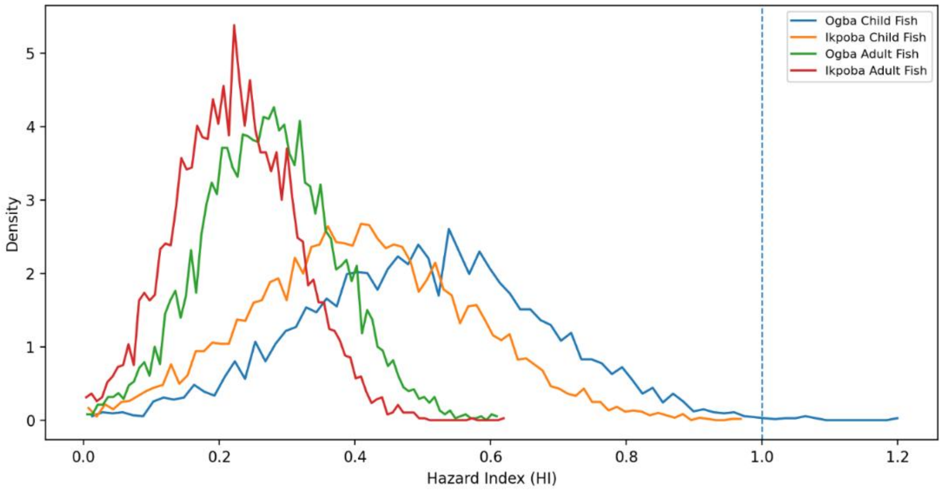

Figure 4. Probability Density Curves (Probabilistic HI)

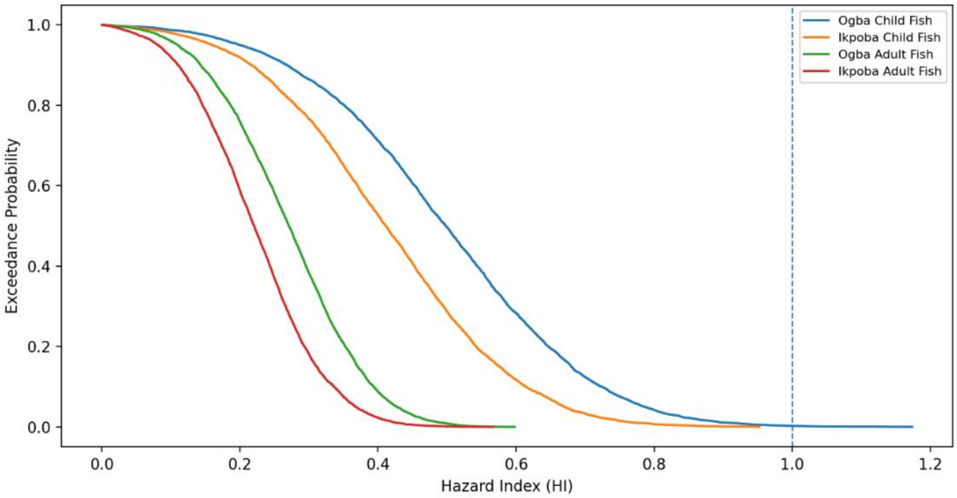

Figure 5. Cumulative Exceedance Curves

4.6 Sensitivity analysis

The relative influence of model inputs on risk outputs is presented in Figure 6. Fish ingestion rate and environmental metal concentration were the strongest positive drivers of HI variability, followed by body weight, which showed an inverse relationship with risk. Exposure duration and frequency exerted smaller effects under the chronic assumptions used.

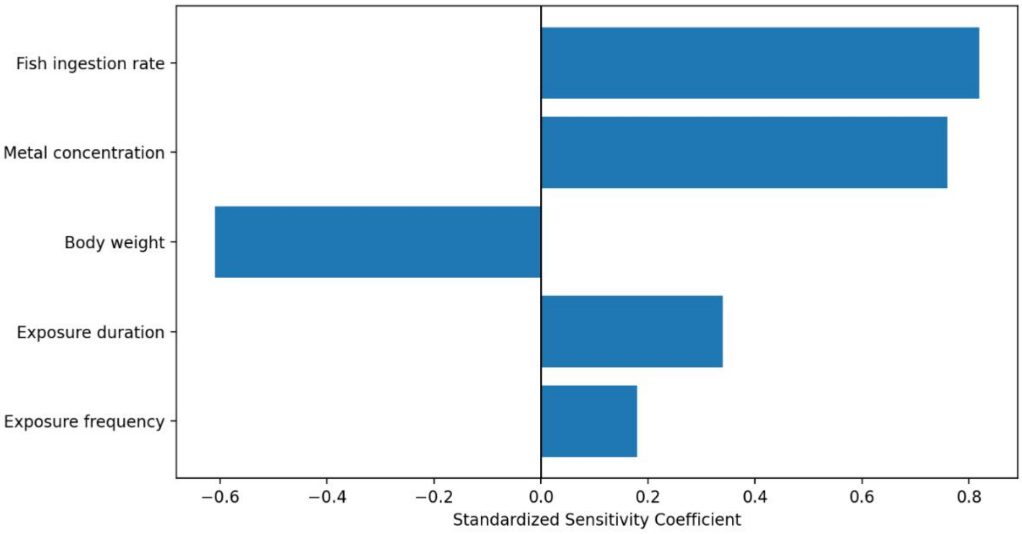

Figure 6. Sensitivity Tornado Plot

4.7 Comparative river-level risk profile

Integrated river-level comparisons are presented in Table 8 and Figure 7. Both rivers showed the same fundamental risk architecture: fish consumption was the dominant pathway, children were the most vulnerable receptor group, and sediment ingestion posed minimal risk. However, differences in magnitude were evident. Ogba River generated the highest overall deterministic and probabilistic child fish risk. Ikpoba River showed lower mean hazard but greater variability,, including the highest sediment Fe and elevated aqueous Pb during the monitoring period.

Table 8. Comparative River-Level Health Risk Outcomes

River	Dominant Pathway	Highest Receptor Risk	Overall Pattern
Ogba	Fish	Child HI = 0.499	Higher mean hazard
Ikpoba	Fish	Child HI = 0.414	Greater variability

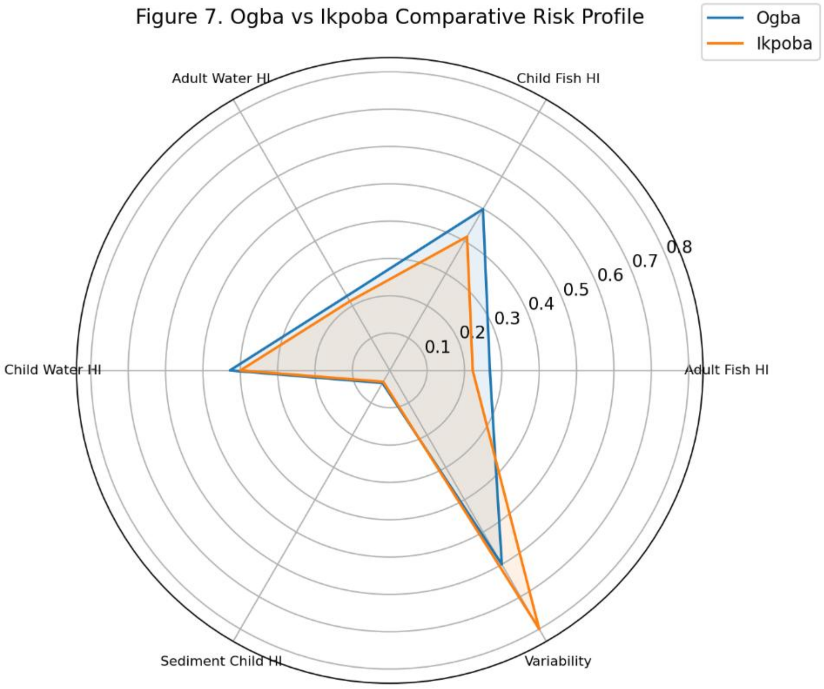

Figure 7. Ogba vs Ikpoba Comparative Risk Profile

5. DISCUSSION

5.1 Metal distribution and environmental partitioning

The observed distribution pattern (sediment > fish > water, Figure 1) reflects classical geochemical behavior of trace metals in aquatic systems, where sediments act as long-term sinks while water represents the mobile phase. This partitioning has been widely reported in contaminated freshwater systems, particularly in urban-influenced catchments where metals adsorb onto suspended particles and accumulate in benthic substrates (Authman *et al.*, 2015; Tchounwou *et al.*, 2012). This trend indicates preferential association of metals with particulate matter and subsequent transfer into aquatic biota

The high sediment Fe concentrations recorded in both rivers, especially the peak value in Ikpoba, align with findings from tropical river systems where iron oxides play a dominant role in binding and co-precipitating other trace metals. Similar patterns have been documented in African and Asian rivers, where Fe-rich sediments act as both sinks and secondary sources of contamination under changing redox conditions (Duncan *et al.*, 2018; Gupta *et al.*, 2024; Hsu *et al.*, 2016; Muhaya *et al.*, 2017; Netshiongolwe *et al.*, 2020; Okorondu *et al.*, 2021; Pelede *et al.*, 2018; Sarkar *et al.*, 2014)

Fish tissue concentrations observed in this study confirm active bioavailability of metals from environmental compartments into aquatic organisms. This is consistent with previous work demonstrating that fish integrate exposure from water, sediment, and diet, making them reliable bioindicators of ecosystem contamination (Khawar *et al.*, 2024; Ogbonna *et al.*, 2021; Saputri *et al.*, 2023). The relatively lower concentrations in water compared to sediment and fish further support the concept that dissolved concentrations alone underestimate ecological and human exposure risk.

However, not all studies report this clear partitioning. Some investigations in highly polluted systems have shown comparable or even higher aqueous concentrations, particularly where continuous industrial discharge maintains elevated dissolved metal levels (Deshmukh *et al.*, 2025; Iloms *et al.*, 2020; Rodrigo Sanz *et al.*, 2021). The lower aqueous concentrations observed in the present study suggest episodic rather than continuous contamination inputs.

The decline in aqueous and tissue concentrations by July suggests seasonal dilution, altered mobility, or changing bioavailability during the sampling period.

5.2 Dominance of dietary exposure pathway

The deterministic exposure results (Table 4) clearly identify fish consumption as the dominant exposure pathway, a finding strongly supported by both HQ/HI outcomes (Tables 5–6) and visualized in Figure 2. This pattern is consistent with numerous studies reporting that dietary intake of contaminated fish is the primary route of human exposure to metals in aquatic environments (Laoye *et al.*, 2025; Oros, 2025; Storelli *et al.*, 2005). These results identify fish consumption as the dominant human exposure route and confirm greater dose vulnerability in child receptors.

The magnitude of fish-derived EDI relative to water and sediment pathways reflects two key factors: higher metal concentrations in fish tissues and the efficiency of trophic transfer. Metals such as Ni and Cu, which showed strong contributions to total hazard (Figure 3), are known to bioaccumulate in fish tissues through both dietary uptake and physiological regulation mechanisms.

Comparable findings have been reported in Nigerian and other tropical systems, where fish consumption consistently drives human health risk more than direct water ingestion (Davies *et al.*, 2024; Doherty *et al.*, 2024; Laoye *et al.*, 2025; Obasohan *et al.*, 2007; Oros, 2025). This reinforces the importance of considering food pathways in environmental health assessments rather than relying solely on water quality metrics. However, some studies have reported contrasting results, particularly in regions where drinking water is heavily contaminated. For instance, research in parts of South Asia has shown that water ingestion can exceed dietary exposure when groundwater or surface water contains high levels of arsenic or heavy metals (Rahman *et al.*, 2012). The present study differs in those aqueous concentrations remained relatively low, limiting the contribution of water ingestion to total exposure.

5.3 non-carcinogenic risk patterns and threshold interpretation

Although all deterministic HI values remained below the critical threshold of 1 (Table 5), this indicates no immediate non-carcinogenic risk under the moderate exposure assumptions used. The results indicate clear pathway and receptor-specific differences in risk. Clear differences in pathway importance and receptor sensitivity were observed. The highest values observed in child fish consumption scenarios (HI = 0.499 in Ogba) approach moderate concern levels, particularly when considered alongside probabilistic upper-bound estimates (Table 7).

The dominance of Ni and Cu in total hazard contribution (Figure 3) is consistent with their relatively lower reference doses compared to Fe and Zn. This reinforces a key principle in risk assessment: hazard is governed not only by concentration but also by toxicological potency (Borgert *et al.*, 2021). Similar findings have been reported in aquatic risk studies where metals with moderate concentrations but low RfDs disproportionately drive risk outcomes (Liu *et al.*, 2022; Saputri *et al.*, 2023; Viana *et al.*, 2022). The observed hierarchy: $Fish >$ Water ≫ Sediment is consistent with previous environmental health studies and reflects realistic exposure dynamics in river-dependent communities. Sediment ingestion contributed minimally to risk, which agrees with studies indicating that incidental sediment exposure is typically negligible compared to dietary pathways (Lauper *et al.*, 2021; Wang *et al.*, 2021).

However, disagreement exists in the literature regarding sediment exposure relevance. Some studies in heavily contaminated floodplain environments have reported significant sediment-related risk, particularly for children engaging in recreational activities (Adewoye *et al.*, 2021; Gearhart-Serna *et al.*, 2018). The low sediment contribution in the present study is therefore context-dependent and influenced by both exposure assumptions and local behavior patterns.

5.4 Elevated vulnerability of children

Children consistently exhibited higher EDI and HI values across all pathways (Tables 4–6), reflecting lower body weight and higher dose per unit mass. This finding is well established in environmental toxicology and aligns with global risk assessment frameworks that recognize children as a sensitive receptor group (Felter *et al.*, 2015; Landrigan *et al.*, 2003; Tchounwou *et al.*, 2012).

The probabilistic results further reinforce this vulnerability. The 95th percentile HI values for child fish exposure approached unity (Table 7), and the probability of exceedance, although low, was non-negligible. These findings are consistent with previous probabilistic risk assessments showing that children often occupy the upper tail of exposure distributions due to physiological and behavioral factors (Landrigan *et al.*, 2003; Mastorci *et al.*, 2021).

In addition, metals such as Pb and Cd, even at low concentrations, are of particular concern in children due to neurodevelopmental and cumulative toxicity effects. Although Pb was not included in quantitative HI calculations, its presence in fish and water underscores potential additional risk not fully captured by threshold-based metrics (Ngo *et al.*, 2021).

5.5 Probabilistic insights and risk variability

The probabilistic analysis (Table 7; Figures 4–5) provides important refinement beyond deterministic estimates. Probabilistic analysis confirmed the deterministic ranking of pathways and receptors. While mean HI values suggest acceptable risk levels, the distributional outputs reveal that a subset of the population may experience elevated exposure. Elevated risk is observed among high-end consumers or more sensitive subgroups.

The positively skewed distributions observed indicate that risk is not uniformly distributed, a finding consistent with probabilistic HHRA studies in aquatic systems (Kismelyeva *et al.*, 2021; Ku *et al.*, 2021). Most of the population falls within low to moderate risk ranges, while high-end risk is concentrated in child dietary exposure scenarios. The exceedance curves (Figure 5) demonstrate that risk becomes concentrated in high-consumption scenarios, particularly for children consuming fish from Ogba River. This highlights a key limitation of deterministic approaches: reliance on average values may underestimate risk for high-exposure individuals. The integration of Monte Carlo simulation therefore strengthens the robustness of the assessment and aligns with best practices in environmental risk modeling (Li *et al.*, 2025b; Pakzad *et al.*, 2023).

5.6 Sensitivity analysis and dominant risk drivers

The sensitivity analysis (Figure 6) identified ingestion rate and metal concentration as the most influential variables controlling risk variability. This finding is consistent with prior studies demonstrating that dietary habits and environmental contamination levels are primary determinants of exposure (Manea *et al.*, 2020; Wang *et al.*, 2023; Zhao *et al.*, 2024). Changes in dietary behavior and contaminant concentration would produce the greatest shifts in population risk. Lower body mass explains the higher vulnerability of children. The inverse relationship between body weight and risk further explains the higher vulnerability of children. Exposure duration and frequency showed comparatively lower influence under the fixed chronic assumptions used, indicating that short-term variability in concentration and behavior may be more critical than long-term exposure parameters in shaping risk outcomes (Johns *et al.*, 2022). These results have direct management implications. Interventions targeting reduction in fish contamination or moderating consumption rates are likely to produce the most significant reductions in human health risk (Akash *et al.*, 2024; Binnington *et al.*, 2013).

5.7 River-specific differences and environmental implications

Although both rivers exhibited similar risk structures, differences in magnitude and variability were evident (Table 8; Figure 7). Higher risk in Ogba reflects stronger combined contributions of Ni, Cu, and Fe in edible tissues. Ogba River showed higher mean hazard values, particularly for child fish exposure, while Ikpoba River exhibited greater variability and higher peak concentrations in certain matrices.

This contrast suggests differences in contamination dynamics. Ogba may be subject to more consistent, chronic inputs (Obasohan and Eguavoen, 2008; Ogbeide and Ogbeide, 2026), while Ikpoba may experience episodic or pulse contamination events (Igibah and Ihimekpen, 2022; Ogbeide and Ogbeide, 2026). Similar patterns have been reported in urban river systems influenced by intermittent discharge and runoff events (Berg *et al.*, 2024; Croghan *et al.*, 2020; Ogbeide and Okoduwa, 2024).

The higher variability observed in Ikpoba is particularly important from a risk perspective, as it increases the likelihood of high-end exposure scenarios despite lower mean values. Greater variability in Ikpoba is consistent with episodic peaks observed in measured concentrations.

5.8 Implications for environmental health and risk management

The findings of this study underscore the importance of integrating multi-pathway and probabilistic approaches in human health risk assessment of aquatic systems. Sediments function as the principal environmental sink for heavy metals. Fish consumption represents the dominant pathway of human exposure. Children experience substantially higher risk than adults. Upper-tail exposure scenarios approach levels of concern despite acceptable mean risk values. The dominance of fish consumption as an exposure pathway indicates that public health interventions should prioritize food safety monitoring and community awareness regarding fish consumption patterns (Alam *et al.*, 2021; Tarekegn *et al.*, 2025).

The elevated vulnerability of children highlights the need for child-specific risk management strategies, including dietary advisories and targeted monitoring of metals with high toxicological significance. While average risk levels were below critical thresholds, the presence of upper-tail exceedance in probabilistic scenarios suggests that precautionary approaches are warranted. This aligns with recommendations from global health frameworks emphasizing protection of sensitive subpopulations even when mean risk appears acceptable.

5.9 Study limitations and uncertainties

Several limitations should be acknowledged. The assignment of zero to non-detect values may underestimate true exposure for some metals. The use of fixed exposure parameters in deterministic models may not fully capture local consumption variability. Additionally, the absence of a quantitative threshold for Pb limits direct integration into cumulative risk metrics.

Despite these limitations, the combined deterministic and probabilistic framework provides a robust and comprehensive assessment of human health risk, consistent with contemporary environmental risk assessment practice.

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