



Heavy Metal Contamination and Human Health Risk Assessment of Osin River, Ila-Orangun, Osun State.

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Abstract

The present study assessed certain heavy metals contamination in water, sediment, and fish samples from the Osin River in Ila-Orangun, Osun State, along with the ecological and human health risks linked to these concentrations across five locations (L1–L5). Samples were collected at these strategic locations along the flow of the River and were analyzed for thirteen heavy metals using the inductively coupled plasma mass spectrometry (ICP-MS) (Agilent 7700 series, Agilent Technologies, USA). To assess health implications of heavy metals contaminations several indices such as Environmental water quality index (EWQI), lifetime cancer risk (LCR) were calculated. Water samples typically showed low or non-detectable (ND) concentrations of contaminants, with only trace amounts of Mn (0.05–0.09 mg/L), Fe (0.07–0.33 mg/L), Cu (0.02–0.05 mg/L), and Zn (0.10–0.16 mg/L), all adhering to U.S. Environmental Protection Agency (USEPA) and World Health Organization (WHO) guidelines. The fish samples showed the higher concentration of certain metals (Mn 5.42 - 16.40mg/kg; Fe 4.75 - 11.7mg/kg, Zn 7.05 - 21.75 mg/kg, and Se 3.52 - 11.64mg/kg), exceeding the tolerable limit. The sediment sample revealed the highest concentrations of most metals relative to water and fish. EWQI demonstrated that the water quality was mostly good. Heavy metal pollution index (HMPI) and heavy metal toxicity index (HMTI) showed moderate to high contamination possibilities in sediments, with L5 as the most contaminated location. The hazard Index of adults ranged between 0.77 and 6.74, whereas that of children was between 0.03 and 0.72. LCR was within the acceptable range (10^{-6} - 10^{-4}), indicating a weak carcinogenic risk. However, the observed spatial variation in the sediment and fish concentration indicate the influence of localized anthropogenic activities which underscore the need for continuous environmental monitoring. Overall, the Osin River remains an important ecological and nutritional resource, however, regular risk assessments are essential to ensure its sustainable use.

Keywords: Ecological, Pollution, Sustainability, Water, Natural, Ecosystem

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Introduction

Water pollution is a major concern in many economies worldwide, developed and developing, compromising economic growth, socio-environmental sustainability, and the livelihoods of millions of human beings (Lin *et al.*, 2022). Natural sources of pollution

include microbial, geological, and naturally occurring pollutants in water bodies (Babuji *et al.*, 2023). Nevertheless, anthropogenic activities such as industrialization, agricultural activities, poor disposal of wastes, urban growth, and poor sewage management have contributed to environmental degradation and

pollution, damaging the water resources needed to support life (Li *et al.*, 2021). These activities pollute water resources, making them not suitable for use (Krishan *et al.*, 2023). Chemical pollutants in drinking water (arsenic, nitrate, bismuth, and fluoride) are potentially life-threatening, especially in low-income populations where water management systems are not effective (Jurczynski *et al.*, 2024). Consumption of water that contains toxic chemicals poses a great risk of contracting diseases such as cancer, endocrine disorders, and heart conditions (Al-Abdan *et al.*, 2021). Moreover, a lack of sufficient water and sanitation infrastructure plays a role in the spread of diseases like cholera, trachoma, schistosomiasis, and helminthiasis (Bose *et al.*, 2024). Gastrointestinal disorders can arise from unsafe drinking water and inadequate environmental hygiene, which can hinder nutrient acclimatization and lead to malnutrition among children (Lin *et al.*, 2022). Inorganic pollutants, including toxic metals such as arsenic, nitrate, chromium, lead, mercury, silver, and nickel, can enter the environment through agricultural runoff, industrial activities, mining operations, and natural events. Over time, exposure to these metals can affect water quality and pose serious health hazards to people and ecosystems. This can lead to acute toxicity, cancer, and numerous other health issues (Rashid *et al.*, 2023). Heavy metals are both naturally occurring elements found in the Earth's crust and persistent pollutants in the environment (Jomova *et al.*, 2025). Toxic metals are long-lasting contaminants and can accumulate in human tissues through the food chain (Singh *et al.*, 2025). Humans can be exposed to heavy metals through different routes, such as breathing in air or dust particles, consuming contaminated water or soil, or via the food chain (Jomova *et al.*, 2025). Due to the negative effect it is causing globally, environmental pollution by heavy metals is becoming an increasingly serious problem and a major concern (Briffa *et al.*, 2020; Tokatli, 2021). Heavy metals, as widely occurring contaminants, pose significant environmental issues owing to their toxic, persistent, and non-biodegradable

characteristics. These traits have grave ecological consequences for aquatic ecosystems (Sonkar & Kumar, 2013). These metals demonstrate a high degree of solubility in marine environments, which aids in their absorption by organisms; once they enter the food chain, they can accumulate in the human body (Kinuthia *et al.*, 2020). Human activity is responsible for the contamination of our waters, soils, and atmosphere with heavy metals (Mitra *et al.*, 2020). Most of these metals are vital for our everyday diet, but only in small quantities. Symptoms of heavy metal exposure can be reversible in larger doses, but they may also be irreversible and pose a threat to life (Briffa *et al.*, 2020). Ensuring a safe and renewable supply of groundwater for drinking is vital for a nation's sustainable development, as the presence of heavy metals can render water unsuitable for consumption and other purposes (Afolabi *et al.*, 2025; Li *et al.*, 2021). Groundwater is often found to contain chemical elements like metals (e.g., zinc, lead, mercury, chromium, and cadmium, and metalloids (e.g., selenium (Se) and arsenic (As). Although some of these elements are essential micronutrients at lower doses (Li *et al.*, 2021), exposures at high concentrations can lead to severe poisoning.

Rivers are valuable sources of fresh water, which aid domestic and industrial practices, especially in the rural areas, where people rely on surface water. However, increasing human activities have been a contributing factor to the build-up of heavy metals in the water system. Due to heavy metals persistence, they are capable of causing severe ecological and human health issues, toxicity, and bioaccumulative nature. Sediment may serve as a long-term reservoir of metals, and fish may absorb the contaminants and pass them on to humans via the food chain (Briffa *et al.*, 2020). Despite the socio-economic significance of the Osin River to the communities around it, there is a current dearth of scientific knowledge of data on its metal pollution level, and this study presents the first systematic assessment of heavy metal pollution in the river. Therefore, this study aims to evaluate the heavy metal concentrations in Osin River water, sediment,

and fish, and also evaluate the ecological and human health risks using established pollution indices to provide baseline data necessary for environmental monitoring, public health protection, and sustainable management of the river.

Materials and Methods

Site Description

Originating in Ila-Orangun in Osun State, Southwest Nigeria, Osin River is a tributary of

the River Niger. It runs through a number of cities and villages, including Arandun, Omido, Ajase-Ipo, Ilala and other Igbomina lands before reaching the Northern part of the country. The River is exposed to a variety of organic and inorganic pollution sources as it flows through a combination of industrialized areas and rural farming villages. The sampling locations are presented in the Figure 1.

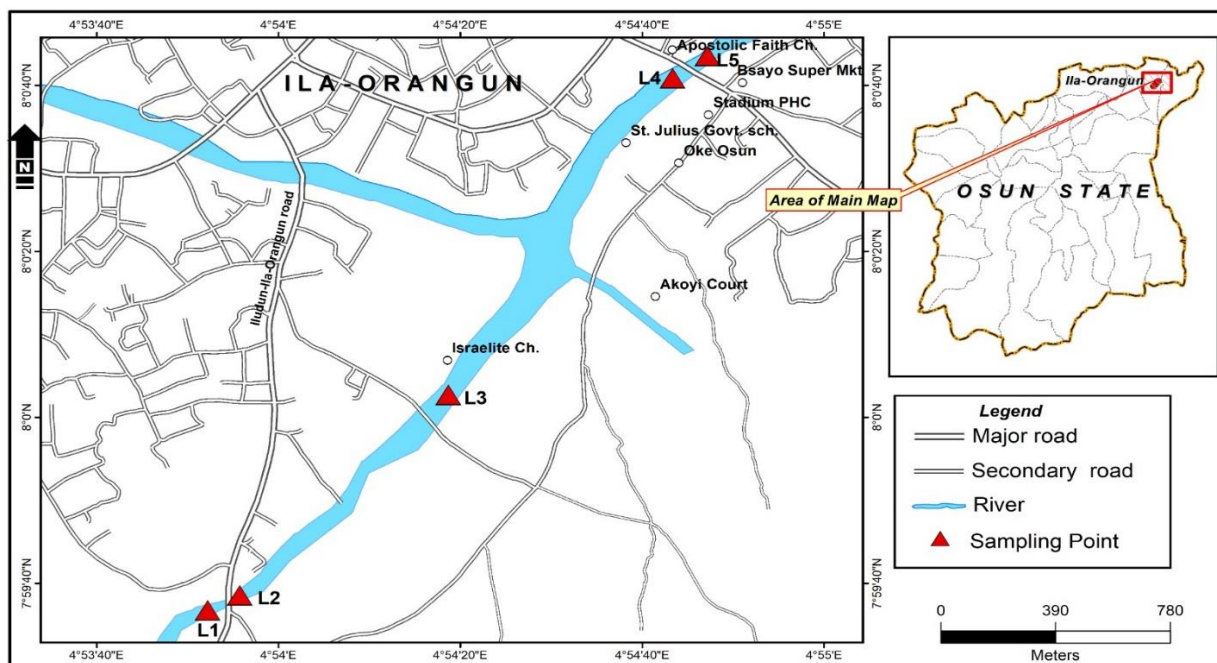


Figure 1: Map of the Osin River with designated sampling locations

Apart from its ecological importance, the Osin River plays a vital role in the local population's way of life and cultural customs. In many of the settlements along its path, it serves as the primary source of domestic water. In addition, the river provides irrigation for industrial discharges, livestock watering, and farmland. Additionally, because it is commonly used for religious ceremonies and customary cleansing practices, it has spiritual and cultural significance. The river's hydrochemical state and ecological health are significantly affected by these human activities.

Sample Collection and Preparation

Collection of water and sediment samples

To assess the impact of anthropogenic actions on the river in the study area, five locations

were identified as strategic along the river, and samples were collected in March 2025. The geographical distribution of the sampling points is presented in Figure 1. In every site, 1L of surface water was collected in pre-sterilized amber glass bottles with a screw cap. The samples were sampled at a depth of around 10-15 cm below the surface to reduce surface contamination and guarantee representative sampling. After collection, the water samples were immediately preserved in an ice-filled cooler at approximately 4 °C and transported to the Laboratory of the Department of Physical and Chemical Sciences, Federal University of Health Sciences, Ila-Orangun, for analysis within 24 hrs of sampling. Sediment samples were collected from the upper layer 5-10 cm, using

a stainless-steel sediment scoop following the procedure described by Adeyinka *et al.* (2025). At each sampling site, triplicate sediment samples and 1L water samples were collected and wrapped in pre-cleaned aluminum foil before being transferred into labelled sterile containers. All samples were appropriately labelled according to sampling site, sample type, date, and replicate number to ensure proper identification and traceability during laboratory analysis.

All samples were immediately placed in a cooler box to maintain a low temperature condition during transportation and subsequently conveyed to the laboratory of the Department of Physical and Chemical Sciences, Federal University of Health Sciences, Ila-Orangun, Osun State, Nigeria, for preservation and further analysis. Before analysis, the sediment samples were air-dried at ambient temperature, gradually dispersed using a wooden mallet, and sieved through a 2 mm mesh to remove coarse materials and then stored at 4 °C for subsequent analysis

Fish sample collection and processing

Sampling was conducted in March, 2025, following the procedure described by Ololade *et al.* (2025) with minor modifications. African catfish (*Clarias gariepinus*) were obtained from five studied locations along the river and well labeled. This species was selected because of its wide distribution, year-round availability, and ecological relevance which makes it suitable for biomonitoring studies. Local fishermen assisted in capturing the fish using conventional fishing techniques. At each sampling site, a minimum of twenty fish were randomly captured. From these, five individuals of comparable size-ranging in 450 to 550 g in weight and 28 - 35 cm in length-were selected for laboratory analysis to ensure sample uniformity. Immediately after captured, the specimen were rinsed with river water, to remove adhering debris, wrapped in aluminum foil pre-treated with hexane to prevent external contamination, and kept in open-glass containers stored in ice-filled coolers for temporary preservation during transportation. Upon arrival at the laboratory in the Department of Physical and Chemical Sciences, Federal University of Health

Sciences, Ila-Orangun, all samples were stored at -20°C until further analysis. During sample preparation, the partially frozen fish were dissected to remove the head, backbone, fins, and tail. The muscle tissue, the most widely and nutritionally important, is the only part of the body that is consumed. A portion was held back to be analyzed. The muscle tissues were then dissected into smaller sections, thoroughly homogenized, and pooled to create a representative composite sample of each sampling site. These composite samples were then stored and analyzed for heavy metals.

Digestion of samples

Water samples

Each water sample (100 mL) was transferred into acid-washed borosilicate beakers. Then, 3.0 mL of HNO₃ (65%) was added, and the mixture was heated on a hot plate at 95 °C (not boiled) until reduced to 15 mL. The digest was cooled and filtered through 0.45µm membrane filters, where needed, then quantitatively transferred to a 50 mL volumetric flask, and then diluted with ultrapure water to indicate according to the standard water digestion procedure (USEPA, 2017).

Sediment samples

The air-dried sediment samples were mixed in an agate mortar and pestle, and about 0.10 g of the aliquot was weighed into polytetrafluoroethylene (PTFE) digestion vessels. A tri-acid mixture consisting of 5 mL HNO₃ (65%), 1mL HCl (37%), and 1mL HF (40%) (5:1:1, v/v/v) was added to each sample. The sediment was digested in accordance with the protocol of Afolabi *et al.* (2025). A controlled heating block of digestion was used to perform digestion at 180 °C, over 4 hours, until full dissolution in accordance with the protocols of sediment digestion. The digest was then cooled to ambient temperature and transferred into a 50 mL volumetric flask and diluted to the mark with distilled water.

Fish samples

The homogenized fish samples (0.5 g) were accurately weighed into microwave digestion vessels. Subsequently, 5 ML of concentrated HNO₃ (65%) and 1 ML of H₂O₂ (30%) were added as the digestion mixture (5:1, v/v).

Microwave-assisted digestion was performed in a closed vessel system using the following program: ramping to 180 °C, holding for 20 min, and cooling for 15 min. The digestion was done to oxidize organic matrices efficiently. The obtained digest was filtered through 0.45 µm membrane filters and diluted to 50 mL using ultrapure water.

Instrumental analysis

The inductively coupled plasma mass spectrometry (ICP-MS) (Agilent 7700 series, Agilent Technologies, USA) was used to measure the heavy metal concentrations in all the digested samples of water, sediments and fish. The operating conditions of the instruments were optimized daily to guarantee maximum sensitivity and stability, and the calibration was done using multi-element standard solutions.

Calibration and quantification

A series of multi-element standard solutions at suitable concentration ranges were used to prepare calibration curves, usually with a range of calibration points of at least five. All the analyzed elements had a correlation coefficient (R^2) ≥ 0.999 and a great linearity of the calibration curves. To correct instrumental drift and matrix effects, an internal standard (rhodium) was used.

2.4 Quality Control/Quality Assurances

To certify the accuracy of the analytical process, stringent quality control (QC) and quality assurance (QA) were implemented. The validity of the analytical procedure with certified reference materials (CRMs) and matrix-spiked samples was evaluated to maintain accuracy and recovery rates within acceptable limits. Good laboratory practices (GLP) and safety measures were followed throughout the study. Glasses and equipment were thoroughly washed using an acid-wash process (10% HNO₃), deionized water, and allowed to dry in the air to avoid contamination. Moreover, laboratory blanks and reagent blanks were examined with the samples to confirm the validity of the results. All these measures ensured that the data generated was accurate, precise, and reproducible. The mean values of all the triplicate sample analyses were obtained and are presented as mean values with standard

deviations. The instrument was calibrated with multi-point calibration curves prepared with certified standards, and recalibration was periodically done to correct instrument drift. Detection limits and quantification limits were determined and verified before the analysis.

2.5 Bioaccumulation Factor (BAF), and biota-sediment accumulation factor (BSAF)

$$BAF = C_f / C_w \quad (1)$$

$$BSAF = \frac{C_f}{C_s} \quad (2)$$

Where:

BAF = bioaccumulation factor; BSAF = the biota sediment accumulation factor; C_f = the concentration of metal in fish (mg/kg); C_s = the concentration of PCBs in sediment (mg/kg); and C_w = concentration of PCBs in water (mg/L)

Heavy Metal Pollution Index (HMPI) Calculations

The HMPI was employed for measuring and summarizing the cumulative impact of a range of metals in water. An HPI was implemented to determine the extent of heavy metal induced pollution in a water body on a common scale. The HMPI assesses water quality ranging between 0 and 100, with 0 indicating the absence of heavy metals and 100 signifying extreme danger where all heavy metals exceed the national standards' acceptable limits. The identified heavy metals were evaluated according to their importance for human health when consumed, and their toxicity level (Arora *et al.*, 2025).

The HMPI was calculated as follows:

$$HMPI = \frac{\sum_{i=1}^n W_i \times Q_i}{\sum_{i=1}^n W_i} \quad (3)$$

Where;

HMPI = the Heavy Metal Pollution Index; W_i = the Unit weight assigned to the i -th parameter; and Q_i = the value of the sub-index of the i th parameter.

Heavy Metal Toxicity Index (HMTI) Calculations

The Heavy Metal Toxicity Index (HMTI) was used to determine the cumulative toxicity of heavy metals in surface water. The measurement of the Heavy Metal Toxicity Index (HMTI) in surface water is crucial because it provides a composite index of the overall toxicological impact of different metals on the quality of water. This is essential

in regions that experience various human activities, including industrial discharge, mining, agricultural runoff, and urbanization, thereby acting as a source of heavy metals to rivers. Unlike the analysis of individual metal concentrations, HMTI combines the measured concentration of each metal with its relative weight (determined by its toxicity and permissible limit), thus providing a more thorough insight into possible threats to human health and the environment.

The HMTI was calculated using the expression:

$$HMTI = \sum_{i=1}^n (Hconc \times TSHM) \quad (4)$$

Where, HMTI = total heavy metal toxicity index, n= the total number of heavy metals analyzed, Hconc = measured concentration of each heavy metal measured in the sample (mg/L). TS_{HM} = Toxicity score of each heavy metal, derived from the ATSDR priority list and toxicological profiles.

Heavy Metal Evaluation Index (HMEI) Calculations

$$HMEI = \sum_{i=1}^n \frac{Hconc_i}{MPC_i} \quad (5)$$

Where, HMEI = Health Metal Evaluation Index; HMPC, i = Maximum permissible concentration of the i-th heavy metal, Hconc, i = Measured concentration of the i-th heavy metal in the water sample (mg/L) according to the WHO and the EPA.

Hazards Quotient (HQ) and Hazards Index (HI) Calculations

The HI and HQ are employed to estimate the prospective non-carcinogenic health effects of cumulative exposure to heavy metals, which can vary widely. It evaluates the risk management, which examines the possible health impacts associated with the environmental risk factors on animals and humans. The non-carcinogenic hazards resulting from exposure are quantified using the hazard quotient (HQ) and the hazard index (HI). When the HQ or HI value is below 1, there are no significant non-carcinogenic threats to human health (Adeyinka *et al.*, 2024; Afolabi *et al.*, 2025). The HQ or HI value exceeding the threshold limit of 1.0 indicates significant non-carcinogenic hazards. The HQ for each heavy metal was determined as stated below:

$$HQ = \frac{CDI}{RFD} \quad (6)$$

Where, HQ = Hazard Quotient RfD = is the USEPA standard value called reference dose ($\mu\text{g}/(\text{kg}\cdot\text{day})$) for inhalation for each heavy metal. CDI = chronic daily intake for inhalation (CDI); for the selected heavy metals, the CDI values, which are represented in milligrams per kilogram per day, or mg/kg/day, are computed taking into account the ingestion route.

$$CDI_{in} = \frac{CA \times IR \times EF \times ED}{BW \times AT} \quad (7)$$

Where, CA is the measured concentration of each heavy metal; IR is ingestion rate (l/day); EF is exposure frequency (day/year); ED is exposure duration (year); BW is average body weight (kg); AT is average time (day). The total of each heavy metal's unique HQ determines the HI.

Carcinogenic Risk Index (CRI) and Lifetime Cancer Risk (LCR) Calculation

The purpose of exposure assessment is to measure or estimate the intensity, frequency, and duration of human exposures to an environmental contaminant (Kamunda *et al.*, 2016). Exposure to toxic metals can lead to neurological disorders, various cancers, and, in extreme cases, death. The risk of human cancer rises with extended exposure to water contaminated with heavy metals. The risks are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to the potential carcinogen. Potential carcinogenic risk was computed by the following equation: (Kamunda *et al.*, 2016; Tong *et al.*, 2021; Afolabi *et al.*, 2025).

$$CRI = CDI \times SF \quad (8)$$

Where, CRI = carcinogenic risk index; CDI is chronic daily intake ($\mu\text{g}/\text{kgday}$); SF_{in} is the slope factor ($\text{kgday}/\mu\text{g}$) which was derived from the reference value of USEPA for each heavy metal. The chronic daily intake for dermal contact (CDI_{der}) was calculated as follows.

$$CDI = \frac{CA \times SA \times ABS \times EF \times SAF \times ED}{BW \times AT} \quad (9)$$

Where, CA is the measured concentration of each heavy metal; EF is exposure frequency (day/year); ED is exposure duration (year); BW is average body weight (kg); AT is the average time (day); SA is exposed skin area

(dm²); SAF is the dermal adherence factor; ET is exposure time during bathing and showering (h/day). ABS is the dermal absorption factor. The lifetime carcinogenic risk (LCR) of the heavy metals was computed by the summation of the carcinogenic risk index of each heavy metal (CRI).

$$LCR = \sum_{i=0}^n (CRI)_i \quad (10)$$

Statistical Analyses

Analysis of variance (ANOVA) and Duncan's multiple range test were carried out to compare the concentration of heavy metals in these media among the five sampling points. Pearson correlation was used to analyse the relationship between the heavy metals in water, soil, and sediment samples. We also examined cluster analysis to cluster the different sites or sampling points according to

the heavy metal contamination. The major sources of heavy metals in water, soil, and sediment samples were obtained using principal component analysis (PCA). The data were analyzed using statistical package for social sciences (SPSS version 27.0).

Results and Discussion

The concentration of heavy metals in water, sediment, and fish samples from the Osin River as shown in Table 1, revealed distinct distribution patterns across the five sampling locations (L1-L5). Water samples showed non-detectable levels for most of the metals, while only trace amounts of Mn, Fe, Cu, Zn, and As were detected. Iron was the most abundant of all the heavy metals measured, ranging from 0.19 to 0.3335 mg/L, with the highest concentration at L2 (0.3335 mg/L).

Table 1: Concentrations of metals in Water, Sediment, and Fish in the selected locations of the Osin River

	Metals	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Pb	Ag	Cd
L1	Water	ND	ND	0.098	0.24	ND	ND	0.023	0.164	ND	ND	ND	ND	0.003
	Sediment	18.81	11.77	144.05	816.39	19.83	ND	0.21	10.20	ND	ND	ND	ND	0.14
	Fish	ND	3.57	6.74	4.75	ND	ND	2.44	9.68	ND	ND	ND	ND	0.36
L2	Water	ND	ND	0.0618	0.3335	ND	ND	0.0525	0.1285	ND	0.0608	ND	ND	0.004
	Sediment	63.96	40.13	96.17	1271.24	19.03	ND	5.4	10.11	ND	3.52	ND	ND	0.65
	Fish	ND	3.12	5.42	6.06	ND	ND	ND	7.05	ND	11.64	ND	ND	0.4317
L3	Water	ND	ND	0.0503	0.2348	ND	ND	0.0186	0.1007	ND	ND	ND	ND	ND
	Sediment	41.73	35.02	83.33	910.07	17.45	ND	1.50	3.95	ND	ND	ND	ND	0.61
	Fish	ND	4.12	11.7	9.79	ND	ND	ND	9.57	ND	7.82	ND	ND	ND
L4	Water	ND	ND	0.07	0.19	ND	ND	0.03	0.23	0.05				
	ND	ND	ND	0.04										
	Sediment	37.20	31.48	161.15	1056.96	18.78	2.44	7.78	56.14	ND	4.35	ND	ND	0.47
L5	Fish	ND	0.89	5.99	6.11	ND	ND	0.95	7.79	ND	ND	ND	ND	ND
	Water	ND	ND	0.07	0.23	ND	ND	0.05	0.33	ND	0.06	ND	ND	0.02
	Sediment	76.05	29.49	344.71	2039.75	37.95	16.53	16.31	36.22	ND	ND	ND	ND	0.89
	Fish	ND	ND	6.81	16.40	ND	ND	ND	21.75	ND	6.16	ND	ND	0.79

The high iron concentration in the river at L2 could be due to agricultural inputs, such as palm oil processing at the study location. Iron is the major component of palm fruit and oil (Bustamam *et al.*, 2020). The observed values

were within the permissible limits of the WHO (0.300 mg/L) and US EPA (0.300 mg/L) standards for drinking water, whereas the observed values are lower than 1.060-2.100 mg/L reported by Afolabi *et al.* (2025).

Manganese is crucial for ensuring ideal bone health and a lack of manganese can negatively impact skeletal development (Taskozhina *et al.*, 2024). The concentration of manganese is in the range of 0.0503 and 0.098 mg/L across the sites. The dissolution of minerals in the soils, rocks and the use of agrochemicals by the farmers could be a major source of manganese in the river. The values obtained for Mn in this study were found to be higher than 0.0012 mg/L reported by Odunaike *et al.*, (2022) and lower than 0.45 -0.85 mg/L reported by Azeez *et al.* (2020). The concentration of copper varied between 0.0018 mg/L at L1 and 0.0525 mg/L at L2. The use of agrochemicals such as fungicides, pesticides and fertilizer could be possible source of copper in the river. The values of Cu were lower than 0.22-0.26 mg/L reported by Anifowose *et al.*, 2019 and 0.58-18.30 mg/L reported by Agbaje *et al.*, 2023. The concentration of zinc varied across all locations from 0.1007 mg/L at L3 to 0.33 mg/L at L5. Zinc forms an integral part of soils and rocks. The source of zinc in this river could be attributed to both natural and anthropogenic process. The leaching and weathering of rocks could be the source of zinc concentration in the river. The concentration of cadmium at L1 (0.003 mg/L) and L2 (0.004 mg/L) were within the permissible limit while the elevated level of cadmium was observed in L4 (0.04 mg/L) and L5 (0.02 mg/L). The values of Cd obtained at location 4 and 5 (0.04 and 0.02 mg/L) are higher than the permissible limit of WHO (0.003 mg/L), FEPA (0.003 mg/L), NAFDAC (0.003 mg/L), and US EPA (0.005 mg/L). Although the values are consistent with the previous study reported by Odunaike *et al.*, (2022) (0.016-0.02 mg/L) and Azeez *et al.* (2020) (0.0005-0.013 mg/L) while toxic metals such as Pb, and Ag were not detected. Although the measured metal concentrations in this phase were below levels associated with immediate toxic effect, continuous monitoring remains essential due to the potential for bioaccumulation and long-term adverse effects resulting from chronic exposure to these metals. Trace metals like zinc, iron, copper, and manganese are crucial

for human health and the functioning of ecosystems when present within permissible limits. These metals are essential micronutrients necessary for the physiological and biochemical processes of humans and aquatic organisms. Moreso, iron is another vital trace element necessary for transporting oxygen, cellular respiration, and enzyme activity. According to Obeagu (2025), the Fe concentration in water from the Osin River being within permissible limits indicates that there is no immediate ecological threat.

Sediment acts as a long-term reservoir for contaminants, which can be remobilized when physicochemical conditions change, thereby posing ecological risks (Cui *et al.*, 2025). The sediment samples showed the highest metal concentrations compared to water and fish, indicating sediments as sinks for heavy metal pollution. The highest metal concentrations, especially those of Fe and Mn, were significantly elevated. The concentration of iron varied from 816 mg/kg to 2039.75 mg/kg, and the concentration of manganese ranged from 83.33 mg/kg to 344.71 mg/kg. Human exposure to elevated levels of manganese can lead to negative effects such as hypotension, manganism, adverse effects on the nervous system, behavioral changes, lethargy, and weakness (Briffa *et al.*, 2020). Vanadium, chromium, cobalt, and nickel were consistently detected in the sediment with the highest value of 76.05mg/kg (V), 35.02mg/kg (Cr), 37.95mg/kg (Co), and 18.78mg/kg (Ni), respectively. According to Nazmul *et al.* (2025), exposure to chromium causes damage to live tissue and DNA mutations, induces pathological alterations in the gill, liver, and kidney tissues of fish, and hampers photosynthesis in various aquatic plants, including phytoplankton. Vanadium has effects that include damage to the nervous system, liver, and kidneys; tremors; paralysis; changes in behavior; heart disease; and inflammation of the gastrointestinal organs (Briffa *et al.*, 2020). Individuals who are exposed to nickel inhalation have a heightened risk of developing lung and nasal cancers, as well as lung embolisms, respiratory failure, cardiovascular issues, dizziness, asthma, and an increased likelihood of other cancers

(Briffa *et al.*, 2020). Skin and respiratory issues can arise from exposure to cobalt, with acute effects including congestion, edema, and lung hemorrhage upon inhalation. Chronic inhalation may lead to wheezing, asthma, respiratory irritation, reduced lung function, pneumonia, and fibrosis (Briffa *et al.*, 2020). Selenium was detected at L2 (3.52 mg/L) and L4 (4.35mg/L). The elevated concentrations in sediment suggest inputs from anthropogenic activities such as mining. Selenium is a vital nutrient for both humans and animals, serving as a component of glutathione peroxidase to help shield tissues from oxidative damage. while selenium is a vital nutrient, high-level exposure through inhalation or ingestion can lead to negative health consequences, including respiratory, cardiovascular, gastrointestinal, hepatic, and neurological effects (Genchi *et al.*, 2023).

The Fish samples showed the highest concentration of certain metals (Mn, Fe, Zn, and Se), exceeding the tolerable limit, offered by WHO (3.000 mg/L, 0.400 mg/L, 2.000 mg/L), NAFDAC (3.000 mg/L, 0.200 mg/L, 2.000 mg/L), FEPA (3.000 mg/L, 0.200 mg/L, 1.000 mg/L), and US EPA (3.000 mg/L, 0.050 mg/L, 1.300 mg/L). The concentration of Mn ranged from 5.42 mg/kg to 16.40 mg/kg, and Iron varied between 4.75 mg/kg and 11.7 mg/kg. Zinc was markedly high in the fish sample, ranging between 7.05 mg/kg and 21.75 kg/mg, selenium was detected in L2, L3, and L5, with the highest concentration of 11.64 mg/kg. The values obtained were higher

than those reported by Remi & Olajubu (2025). (Mn 0.322-0.453 mg/kg; Zn 0.995-1.433 kg/mg); lower than the report of Tongo & Ezemonye 2019 (Mn 9.61-17.37 mg/kg; Fe 175.95-255.52; Zn 78.65-109.38 mg/kg). This indicates that the bioavailability of these metals in the aquatic environment is high, and the bioaccumulation of these metals in fish tissues points to the possible ecological and human health risks. Although needed in low amounts, a high intake of it in the form of fish may lead to oxidative stress, organ toxicity, and neurological impairment (Abera *et al.*, 2024). Spatially, at L5, the sediment and fish samples had the highest levels of most of the metals, particularly Fe, Mn, Zn, and V, implying contamination sources. Anthropogenic activities like washing, waste disposal, and agricultural activities, e.g., L5 is placed near a poultry farm, fish pounds, and a car wash workshop, might affect the site more. Conversely, the L1 sample had relatively lower concentrations in sediment and fish samples, which can be attributed to a gradient contamination of the river course. Therefore, the findings highlight the importance of risk evaluation of fish consumption in local communities that rely on the Osin River as a source of protein.

Statistical analysis

Tables 2, 3, and 4 present the correlation analysis among heavy metals in water (Table 2), sediment (Table 3), and fish samples (Table 4).

Table 2: Correlations among heavy metals in water samples

	Mn	Fe	Cu	Zn	Se	Cd
Mn	1					
Fe	-0.219	1				
Cu	-0.175	0.628*	1			
Zn	0.241	-0.466	0.369	1		
Se	1.000**	-1.000**	-1.000**	1.000**	1	
Cd	-0.265	-0.752**	-0.288	0.553	1.000**	1

*Correlation is significant at 1% ($p < .05$).

**Correlation is significant at 1% ($p < .01$).

Table 3: Correlations among heavy metals in sediment samples

	V	Cr	Mn	Fe	Co	Cu	Zn	Se	Cd
V	1								
Cr	0.647**	1							
Mn	0.539*	-0.182	1						
Fe	0.887**	0.269	0.866**	1					
Co	0.678**	-0.068	0.966**	0.932**	1				
Cu	0.793**	0.272	0.884**	0.947**	0.875**	1			
Zn	0.151	0.053	0.532*	0.365	0.335	0.640*	1		
Se	-1.000**	-1.000**	1.000**	-1.000**	-1.000**	1.000**	1.000**	1	
Cd	0.943**	0.720**	0.497	0.817**	0.625*	0.762**	0.186	-0.972**	1

*Correlation is significant at 1% ($p < .05$).

**Correlation is significant at 1% ($p < .01$).

Table 4: Correlations among heavy metals in fish samples

	Cr	Mn	Fe	Cu	Zn	Se	Cd
Cr	1						
Mn	0.572	1					
Fe	0.375	0.243	1				
Cu	0.997**	0.998**	-0.997**	1			
Zn	0.554	0.009	0.922**	0.995**	1		
Se	-0.987**	-0.416	-0.930**	00.02	-0.835**	1	
Cd	-0.925**	0.420	0.999**	0.120	0.955**	-1.000**	1

*Correlation is significant at 1% ($p < .05$).

**Correlation is significant at 1% ($p < .01$).

In the water samples, Cu showed a significant positive correlation with Fe ($r = 0.628$, $p < 0.05$). Selenium (Se) revealed perfect positive correlations with manganese (Mn) and zinc (Zn), and a perfect negative correlation with Fe. Cadmium (Cd) on the other hand revealed a significant negative correlation with Fe ($r = -0.752$, $p < 0.01$) and a perfect significant positive correlation with Se ($r = 1.000$, $p < 0.01$). For sediment samples, Cu and Cd exhibited strong positive correlations with most of the heavy metals, indicating a high tendency of co-contamination and possible common contamination pathway. In contrast, Zn exhibited generally weak correlations with other heavy metals, suggesting relatively distinct sources of contamination. Generally, the majority of heavy metals in sediments were found to be strongly interrelated, indicating that some of these heavy metals shared similar pollution pathways, while only a few metals appeared to have independent sources.

In fish samples, Cu exhibited strong and significant positive correlations with Cr ($r = 0.997$, $p < 0.01$) and Mn ($r = 0.998$, $p < 0.01$), indicating common accumulation sources within fish tissues. Additionally, Fe showed strong positive correlations with Cd ($r = 0.999$, $p < 0.01$) and Zn ($r = 0.922$, $p < 0.01$), but a significant negative correlation with Cr ($r = -0.925$, $p < 0.01$). Collectively, these findings indicate that most of the heavy metals particularly Cr, Mn, Cu, Fe, Zn, and Cd are significantly correlated, indicating that they may originate from similar contamination sources or follow comparable environmental pollution pathways.

The results in Table 5 indicated no significant differences in the concentrations of Mn and Cu between water and fish samples. However, the concentrations of these metals in sediment were significantly higher than those observed in both water and fish samples ($p < 0.05$).

Table 5: Statistical Correlation of heavy metals in water, fish and sediment samples

Heavy metals	Water	Sediment	Fish
V	ND	47.583 ± 21.003	ND
Cr	ND	29.578 ± 9.947	2.937 ± 1.296
Mn	0.071 ± 0.016 ^a	165.876 ± 97.273 ^b	7.342 ± 2.337 ^a
Fe	0.245 ± 0.049 ^a	1218.855 ± 453.591 ^b	8.619 ± 4.380 ^a
Co	ND	22.605 ± 7.981	ND
Ni	ND	9.485 ± 7.713	ND
Cu	0.033 ± 0.014 ^a	6.240 ± 5.915 ^b	1.714 ± 0.807 ^a
Zn	0.190 ± 0.084 ^a	23.322 ± 20.523 ^c	11.164 ± 5.576 ^b
As	0.051 ± 0.000	ND	ND
Se	0.061 ± 0.000 ^a	3.931 ± 0.459 ^b	8.550 ± 2.436 ^c
Pb	ND	ND	ND
Ag	ND	ND	ND
Cd	0.017 ± 0.017 ^a	0.553 ± 0.255 ^b	0.525 ± 0.197 ^b

Similar superscript letter means not significantly different ($p > .05$), different superscript letters means significantly different ($p < .05$).

Zinc (Zn) concentration was significantly higher in fish compared to water, while sediment samples exhibited significantly higher Zn levels than fish ($p < .05$). In the case of selenium (Se), significantly higher concentrations were recorded in fish samples compared with both water and sediment. Furthermore, cadmium (Cd) concentrations

did not differ significantly between sediment and fish samples but were significantly lower in water than in both fish and sediment ($p < .05$). The PCA for sediment, water and fish are presented in Figures 2, 3 and 4 respectively with PC 1 accounting for the majority of the total variance of 69.1.0% for sediment, 46.2% for fish and 73.1% for water.

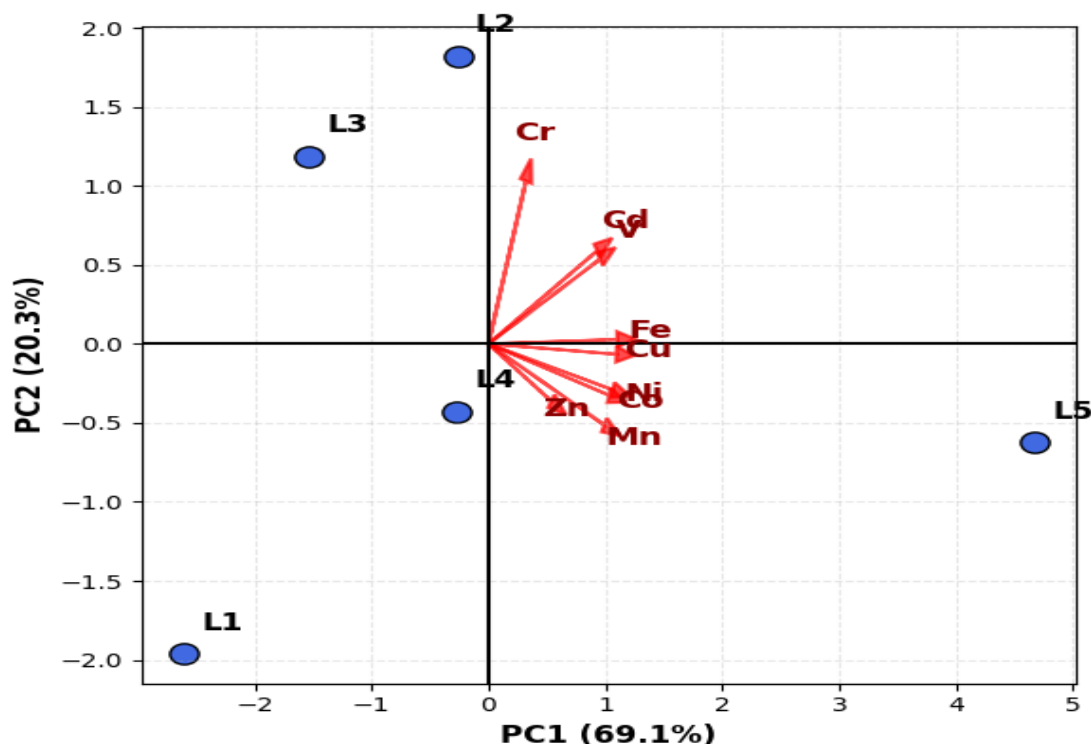


Fig 2: PCA Biplot identifying possible sources of heavy metal contamination in sediment.

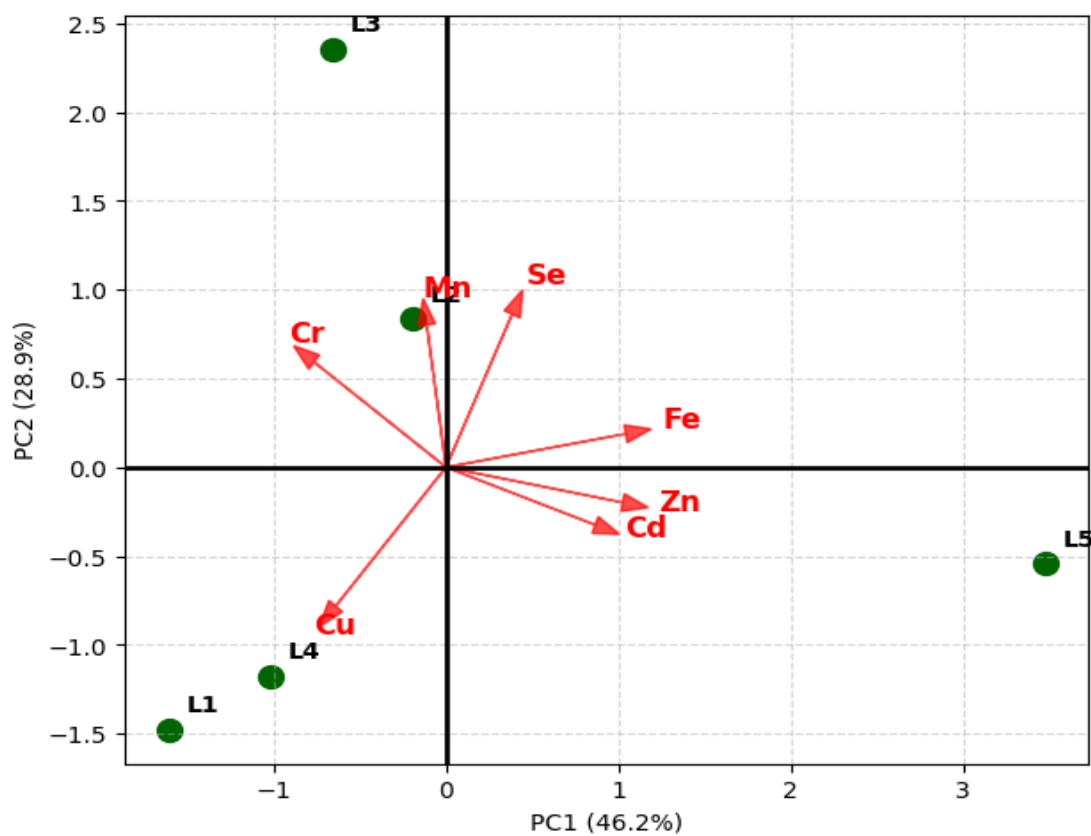


Fig 3: PCA Biplot identifying possible sources of heavy metals contamination in fish.

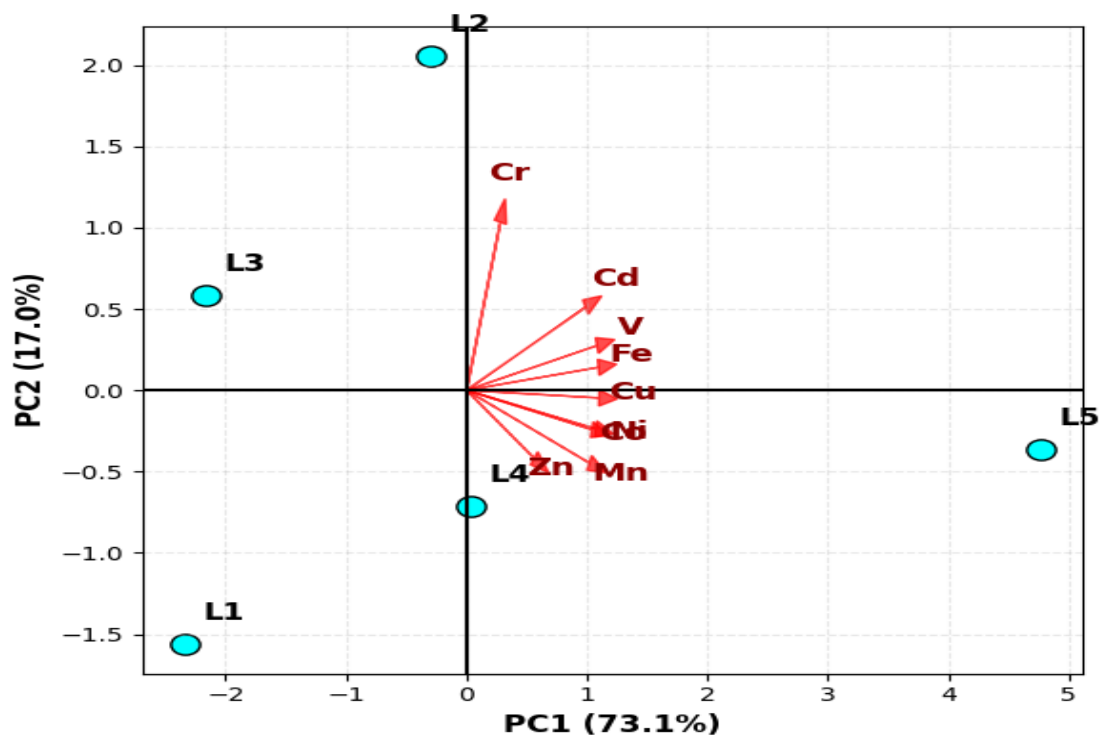


Fig 4: PCA Biplot identifying possible sources of heavy metals contamination in water

For sediment, the PCA plot as shown in Figure 2 reveals that L1-L5 are separated by PCA 1 suggesting differences in their contamination profile with L5 appearing to be the most contaminated with a high influenced by Fe, Ni, Co, Zn and Mn while L1 was found to be the least contaminated site. This implies that Fe, Ni, Co, Zn and Mn share similar source of contamination which different from other heavy metals. Also in the Fish, PC1 was found to account for 46.2% of the variation with high contribution from Zn, Cd, and Fe. The sample position confirmed L5 to be the most contaminated site with L1 being the least. The PCA reveals distinct contamination patterns across the fish samples, with L5 indicating potential

industrial metal input, L2 and L3 showing other metal influences, and L1 and L4 being comparatively lower in metal contamination compared to other sites. For the water sample, PC1 was dominated by Zn, Cd, Fe, and V with L5 having contamination from Zn, Cd, Fe, and V, L2 and L3 show higher Cr influence, and L1 and L4 appear comparatively less contaminated with L5 also showing to be most contaminated.

The cluster heatmap in Figure 5 in fish identified L5 has a major hotspot for most of the heavily metals Cd, Fe, and Zn with L3 standing out due to its high level of contamination with Mn and Cr compared with other sites. Sites L4 and L5 were found to have similar level of contamination.

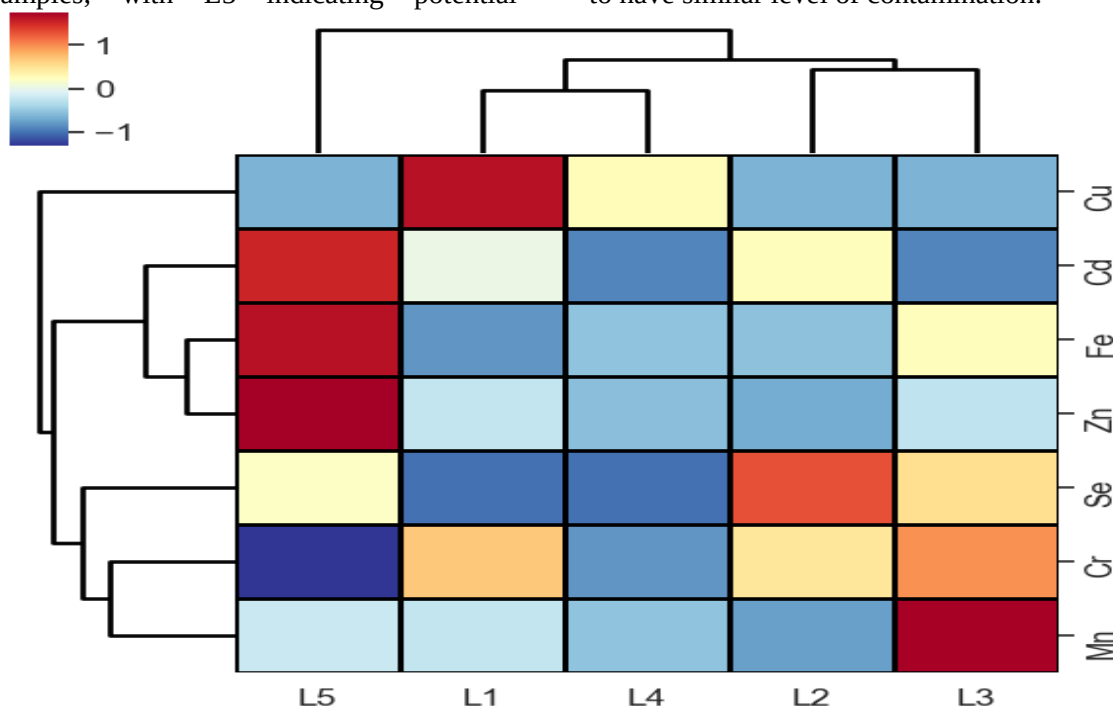


Fig 5: Hierarchical cluster heatmap showing the spatial distribution of heavy metals in fish samples.

The distribution of heavy metals in L2 and L3 were also uniquely different with L5 being most affected followed by L3, L2 while L1 and L4 share similar pattern. Similar result was obtained in the sediment where L5 was also found to have a uniquely different

distribution of heavy metals and L1 and L3 sharing similar pattern of contamination (Figure 6). For water, L5 was found to be in different cluster, L4 in the second, L2 in the third, L3 in the fourth and L1 is the first cluster making site L1 has the site with least distribution of heavy metal contamination (Figure 7).

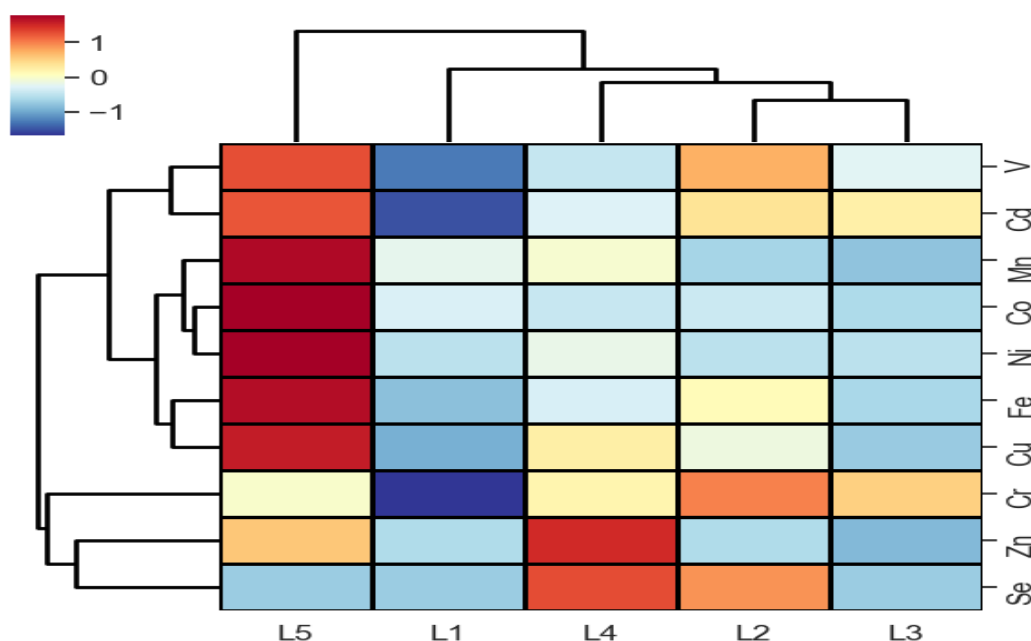


Fig 6: Hierarchical cluster heatmap showing the spatial distribution of heavy metals in sediment.

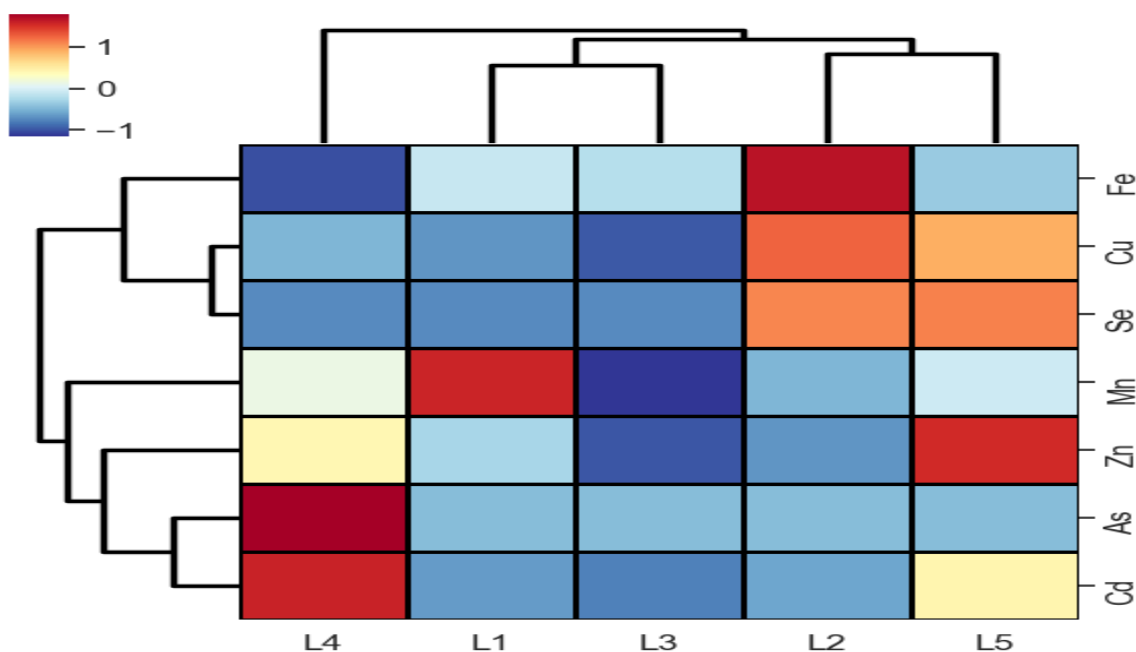


Fig 7: Hierarchical cluster heat map showing the spatial distribution of heavy metals in water.

Bioaccumulation (BAF) and Biota-Sediment accumulation factor (BSAF)

The bioaccumulation factors (BAF) and Biota-Sediment Accumulation Factor (BSAF) were evaluated to assess the bioaccumulation potential of heavy metals in aquatic organisms

from the Osin River. The estimated bioaccumulation factors (BAF) and biota-sediment accumulation factors (BSAF) in Table 6 showed the extent to which fish absorb metals in relation to their surrounding environmental compartments.

Table 6: Bioaccumulation and Biota sediment accumulation factor

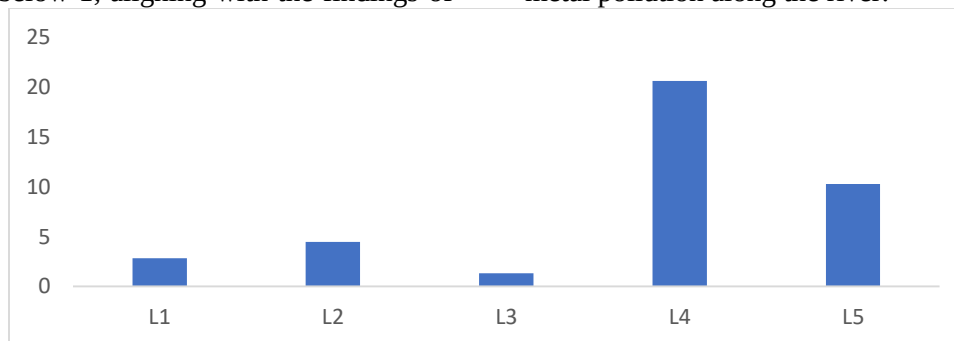
Metals	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Pb	Ag	Cd
Fish	ND	2.92	7.332	8.622	ND	ND	1.69	11.168	ND	8.54	ND	ND	0.527
		5					5						2
Water	ND	ND	0.07	0.2456	ND	ND	0.03	0.1906	0.0	0.0604	ND	ND	0.016
				6			5	4	5				8
Sediment	47.5	29.5	165.8	1218.8	22.6	9.48	6.24	23.324	ND	3.935	ND	ND	0.552
	5	8	8	8	1	5							
BAF	ND	ND	104.7	35.097	ND	ND	48.6	58.581	ND	141.39	ND	ND	31.47
			1	3			8	6		1			7
BSAF	ND	0.09	0.044	0.0070	ND	ND	0.27	0.4788	ND	2.1702	ND	ND	0.955
		9	2	7			2	2		7			1

The values of BAF exceeding 1 signal considerable accumulation from water, whereas a BSAF above 1 indicates that the metal is bioavailable. This shows an increased risk of bioaccumulation across trophic levels. This research suggested that the fish species efficiently bioaccumulated selenium, manganese, zinc, and copper from water, as evidenced by their elevated BAF values. The highest BAF values were recorded for selenium and manganese (104.71), at 141.39, followed by zinc (58.58) and copper (48.67). Conversely, the lowest values of BAF were iron (35.09) and cadmium (31.47). The results may be compared with those of Melaka *et al.* (2023) in Ethiopian waters, which showed that these metals may or may not be bioavailable or excreted efficiently. The BSAF value in the present study shows that selenium (2.17) is above 1, as reported by Kobkeathawin *et al.* (2021), which implies that it is accumulating significantly in comparison to sediment concentration; cadmium (0.95) is close to 1, which implies moderate bioavailability of cadmium through sediment. On the other hand, iron (0.007), manganese (0.044), copper (0.272), and zinc (0.478) exhibited BSAF values below 1, aligning with the findings of

Melaka *et al.* (2023) and Islam *et al.* (2017). This implies that there is low efficiency of the transfer of sediments to fish, which is most likely due to the strong geochemical affinity of sediments to fish. These findings indicate that the fish in the sampled sites are more prone to the build-up of selenium, manganese, copper, and cadmium, which can potentially be hazardous to ecology and human health. The rise in the values of the BAF and BSAF emphasizes the need to continuously monitor these trace metals and assess the risks to consumers.

Heavy Metal Evaluation Index

The Heavy Metal Evaluation Index (HMEI) is a widely used tool to assess the overall condition of pollution of water bodies due to metal pollution. It sums up the concentrations of other heavy metals into a single index value, which provides a quantitative measure of the level of pollution. High values of HMEI are associated with increased contamination and associated environmental and health risks. Values of the HMEI of the Osin River in five sampling positions (L1 to L5) ranged between 1.315107 at L3 and 20.63297 at L4 (Figure 8), indicating a great range in the levels of heavy metal pollution along the river.

**Figure 8: Heavy Metal Evaluation Index**

L3 showed the lowest HMEI value, indicating a moderate contamination of heavy metals in the River. Possibly, the water quality of L3 might not be impacted by the pollution sources because it is upstream or far away from the sources of industrial, agricultural, and urban discharge. Moreover, L1 (2.8243) and L2 (4.468283) present moderate values of HMEI, implying a low to moderate amount of heavy metal pollution. These can be signs of both diffuse sources of pollution, such as agricultural runoff containing some traces of heavy metals in fertilizer, and localized small-scale pollution. At L5 (10.28093) is, rather elevated, which means that the concentration of heavy metals increased significantly. This may be due to the cumulative impacts of downstream pollution or closeness to a particular source of pollution, like industrial waste or urban runoff. The highest value was observed in L4 (20.63297), higher than L5 by a factor of more than two, and L3 by more than 15 times. This value indicates a severe case of heavy metal contamination, which is likely due to the existence of a major source of pollution in the area, such as an industrial

release, mining, or the entry of untreated wastewater in the vicinity of L4. The heavy metal contamination of river systems presents serious environmental and human health hazards because of the persistence, bioaccumulation, and toxicity of metals like lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr). The HMEI values observed might have ecological, human health, and socio-economic implications. The heavy metal levels may pile up in locations where HMEI is higher, like L4 (20.63297) and L5 (10.28093), which interfere with aquatic life. Heavy metals are toxic to aquatic organisms, such as fish, invertebrates, and phytoplankton, by bioaccumulating in the food chain. This can lead to a reduction in biodiversity and alterations in the dynamics of the ecosystems. Chronic exposure to heavy metals may impair the rates of

Heavy Metal Pollution Index

The HMPI values obtained in this study at five different locations range from 1.58 to 508.02 (Figure 9). L3 showed the lowest HMPI value of 1.58, indicating L3 has the most favorable water quality conditions.

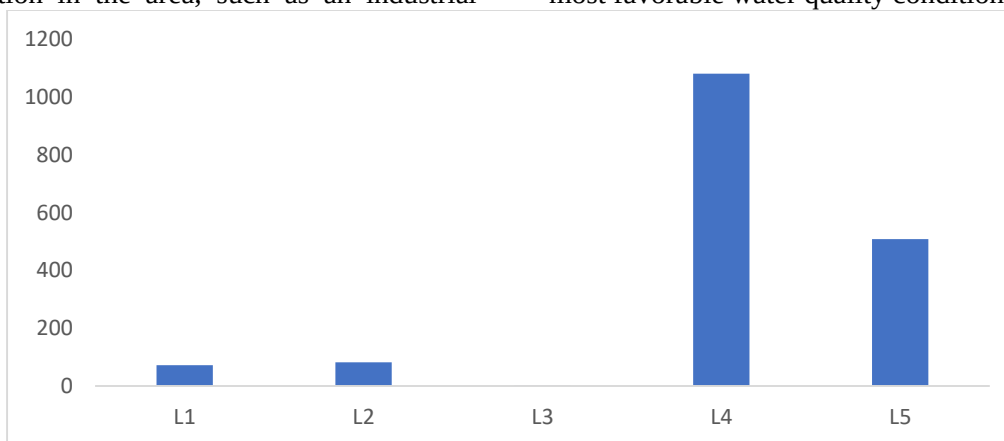


Figure 9: Heavy Metal Pollution Index (HMPI)

This could indicate a part of the Osin River that has not been significantly polluted, perhaps somewhere above the greatest human activity, or a place where natural dilution and self-purification processes are especially effective. HMPI values at L1 (71.66) and L2 (82.64) were fairly high, indicating some degree of water quality degradation or an increased pollutant load when compared to L3. The values show that the river at these points is stressed, possibly by diffuse pollution (as in agricultural runoff)

or localized point sources, which are not yet overstressed. L5 (508.02) and L4 (1080.84) showed the highest levels of HMPI, with the latter showing the strongest outcome. The high indices are a strong indication of a high level of water degradation. This can be due to the summation of a number of pollution sources, release of industrial or municipal wastewater (treated or not), agricultural runoff, or a rise in the concentration of the pollutant due to a reduction in water flow. The increase in the

HMPI value between L3 upstream and L4 and L5 downstream highlights the fact that there could be a significant accumulation of pollutants in certain areas along the Osin River.

Heavy Metal Toxicity Index

The Heavy Metal Toxicity Index (HMTI) is a composite measure used to determine the cumulative toxicity risk of different heavy metals in an aquatic environment. It provides a

more detailed picture of contamination in relation to the analysis of the concentrations of single metals. Figure 10 showed that the HMTI values of the five sampling sites (L1-L5) in the present study were within the range of 147-471, much higher than the critical level of 100, which is usually regarded as the critical level of drinking water or even ecological safety (Cui *et al.*, 2021; Singh *et al.*, 2025).

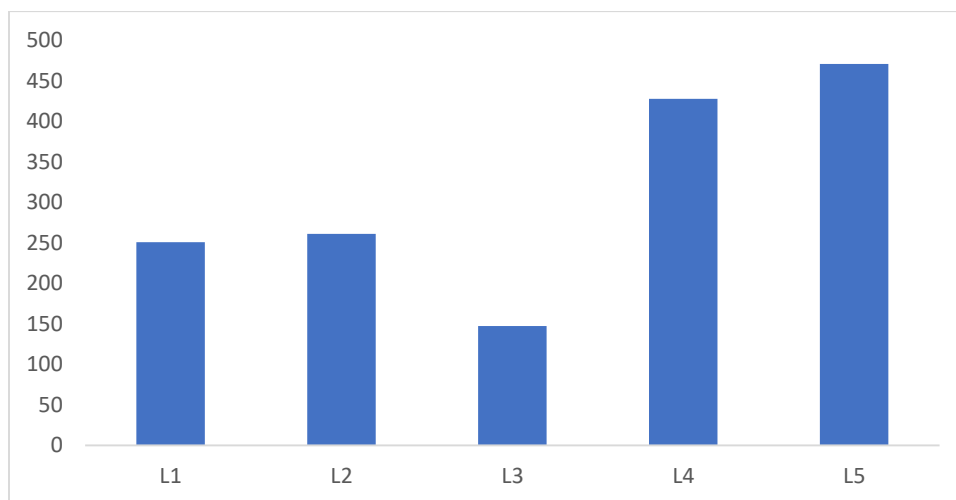


Figure 10: Heavy Metal Toxicity Index (HMTI)

The HMTI value of L5 was the highest (471), followed by L4 (428), and the lowest value obtained was at L3 (147). This implies that contamination levels vary spatially, with L5 showing the greatest burden of heavy metals, suggesting possible point-source inputs such as effluent discharges, agricultural runoff, or urban wastes that augment the toxicity load and subsequent ecological/health risks. HMTI values in all locations are high, which supports the idea that heavy metals have a significant impact on the study area. This indicates potential environmental risk to aquatic organisms and a significant risk to human health through direct or indirect exposure pathways. Similar observations have been

made by recent studies by Eze *et al.* (2021) and Chukwu and Obiora (2023), who have attributed higher values of HMTI to anthropogenic activities, including industrialization, urbanization, and agricultural activities.

Lifetime Cancer Risk (LCR)

Table 7 presents the differing degrees of potential carcinogenic risk estimated as Lifetime Cancer Risk (LCR). The LCR values for ingestion and dermal pathways at the five sampling locations varied from 1.29×10^{-5} (L1, children) to 4.91×10^{-4} (L4, adults).

Sample	Lifetime Cancer Risk				Hazard Index			
	Ingestion		Dermal		Ingestion		Dermal	
	Children	Adult	Children	Adult	Children	Adult	Children	Adult
L1	1.29E-05	0.000612	7.61E-06	0.000207	0.096005	0.89573	0.10397	2.82207
L2	0.000123	0.0011455	1.08E-05	0.000295	0.167702	1.56547	0.06904	1.8723
L3	3.35E-05	0.0003124	7.31E-06	0.000934	0.083181	0.77618	0.05208	1.41224

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L4	0.000491	0.0045877	1.58E-05	0.830206	0.72275	6.74743	0.22911	6.21645
L5	0.000259	0.0024193	8.12E-06	0.00022	0.188321	1.75783	0.03697	2.70094

The dermal exposure in children was lower, with values ranging from 7.31×10^{-6} (L3) to 1.58×10^{-5} (L4). It is worth remarking that the risk of ingestion for adults was consistently greater than for children, indicating the higher exposure dose per body weight following continuous consumption of contaminated water. The highest ingestion-related LCR (0.00459) was obtained in L4, exceeding the U.S. EPA's acceptable cancer risk range of 10^{-6} to 10^{-4} , suggesting a potential public health issue for adults in the study area.

Dermal exposure pathways exhibited lower risks comparatively, this is consistent with the previous report that ingestion is the primary

route for carcinogenic risk from heavy metals and organic pollutants in drinking water and sediments (Adimalla and Qian, 2021; Kamunda *et al.*, 2020). However, the dermal LCR values for children at L4 and L5, remained within the acceptable risk range, suggesting relatively lower carcinogenic concern through skin contact. However, Figure 11 revealed that locations L2, L4, and L5 presented higher cancer risks through ingestion, especially for adults, whereas children showed comparatively greater susceptibility through dermal exposure due to higher skin permeability and prolonged recreational contact.

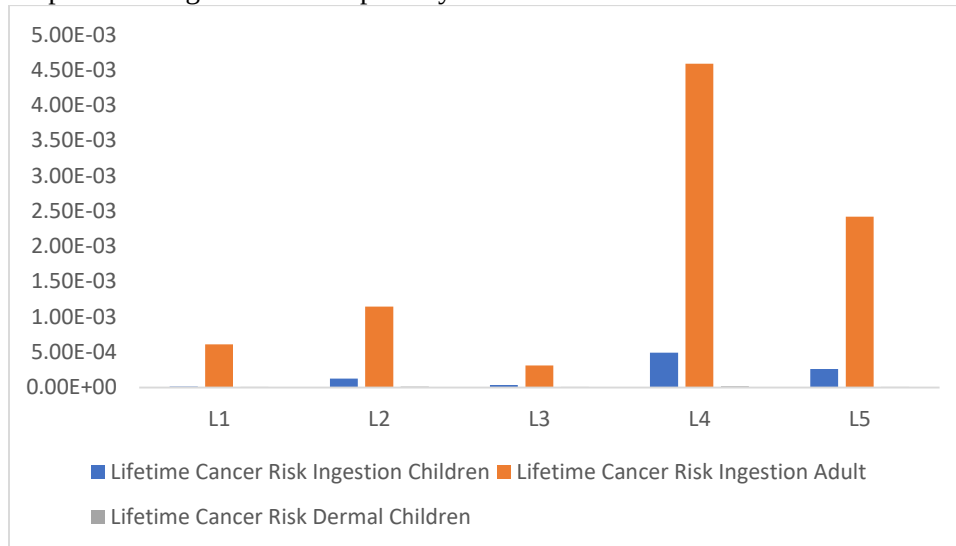


Figure 11: Lifetime Cancer Risk

The observed elevated risks may be attributed to greater pollutant loading at these locations, possibly associated with anthropogenic activities such as waste discharges, agricultural and mining activities in the study area. The LCR of some locations surpassing the acceptable risk threshold highlights the urgent necessity for risk mitigation strategies, such as regular monitoring, controlling

pollution sources, and ensuring safe alternative water supplies.

Hazard Index

The evaluation of non-carcinogenic risk through the Hazard Index (HI) shows that adult exposures at all sampling locations surpass the safe limit ($HI > 1$); in contrast, children's HIs are < 1 for all measured pathways (Table 7 and Figure 12).

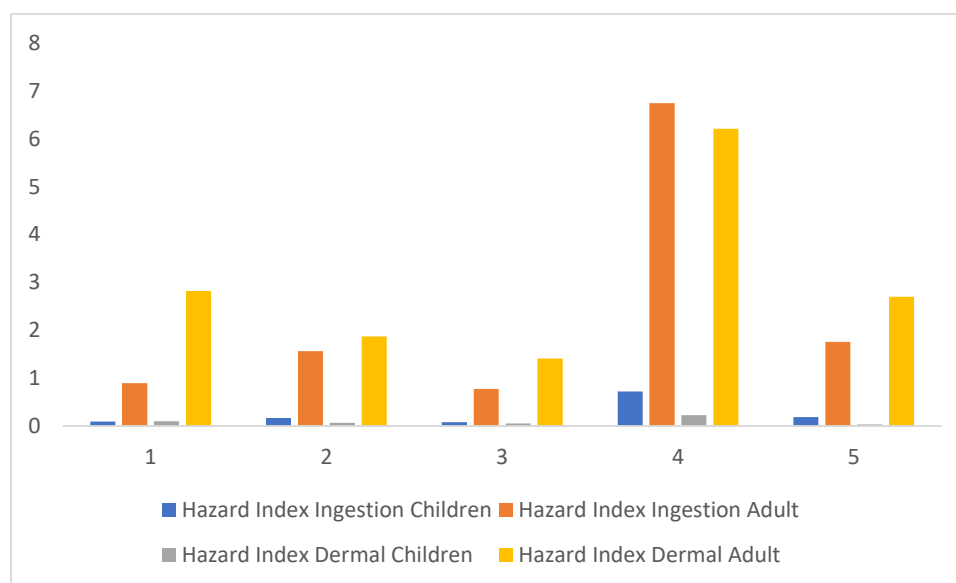


Figure 12: Hazard Index

In particular, locations L2, L4, and L5 show HI values for adults that exceed 1 for ingestion and all locations for dermal routes, with L4 showing the most severe risk in both ingestion and dermal (HI_{ingestion} 6.75; HI_{dermal} 6.22). In contrast, the children's HIs for both ingestion and dermal contact are < 1 , indicating that there is no immediate non-carcinogenic concern for children based on the exposure assumptions. The present study corresponds with the various regional evaluations in which adults engage in activities involving frequent physical contact. For instance, surface-water and groundwater HI assessments reported by Eid *et al.* (2024) indicated values ranging from 1.12 to 11.58, showing that adult HI values can surpass 1 in regions affected by industrial or agricultural inputs. Additionally, dermal contributions are substantial in these cases, reflecting the pattern observed at L2-L5. The trend observed in this study is in contrast to research that utilizes exposure parameters focusing on children (such as higher intake relative to body weight or play/soil-hand-mouth behaviors), which classically indicates that children face greater risk; this underscores that the risk differences across age groups observed vary according to the exposure model and local behavior patterns.

Conclusion

This study evaluated the distribution of heavy metals and their associated ecological and human health risks in the Osin River, Ila-

Orangun, Osun State. The findings revealed that heavy metal concentrations in water were generally within permissible limit, while sediments served as the major reservoir for metal accumulation particularly Fe and Mn. Essential trace metals such as Fe, Zn, Mn, and Se accumulated in fish tissues indicating their nutritional importance at safe levels. The absence of highly toxic metals such as Pb and Cd across the studied matrices suggests limited anthropogenic contamination. Ecological assessment indicated good overall water quality, although localized sediments contamination was observed at some sampling points. Non-carcinogenic risk assessment showed no significant health risk ($HI < 1$) for both adults and children, however, carcinogenic risk assessment revealed potential cancer risk at certain locations, particularly for children due to ingestion and dermal exposure pathways. Overall, the study suggest that that Osin River is presently suitable for domestic use and fish consumption, but continuous environmental monitoring and stricter pollution control measures are necessary to prevent future ecological and public health concerns.

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Declarations

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Consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and materials: All data used to support the conclusions of this study are provided in the manuscript.

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