Assessing Anthropogenic Influence and Heavy Metal Contamination in The Ona River Using Pollution and Risk Indices

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Abstract: Surface water contamination by heavy metals poses significant ecological and public health challenges, particularly in rapidly urbanizing regions of developing nations. This study assessed the concentration, distribution, and associated ecological and health risks of potentially toxic elements in the Ona River, located within the Adeoyo region of Ibadan, Oyo State, Nigeria. Water samples were collected from three georeferenced sites and analyzed for Fe, Zn, Cu, Cr, As, Cd, Ni, Mn, and Mg using Atomic Absorption Spectrophotometry (AAS) following APHA (2022) standard protocols. Contamination indices including the Geo-accumulation Index (Igeo), Enrichment Factor (EF), Contamination Factor (CF), Pollution Load Index (PLI), and Ecological Risk Index (ERI) were employed to evaluate pollution intensity, while non-carcinogenic and carcinogenic health risks were computed using the United States Environmental Protection Agency (USEPA) model. Results revealed that Cr, Cd, As, Pb, and Fe concentrations were within permissible limits of WHO (2022) and Nigerian Standards for Drinking Water Quality (NSDWQ, 2015). In contrast, Ni and Mn exceeded recommended thresholds, indicating localized anthropogenic inputs, primarily from industrial and urban effluents. Nickel exhibited the highest CF (2.86–3.86) and EF (1735.29–3748.24), denoting considerable contamination and extreme enrichment, while PLI values below 1 suggested overall unpolluted status. The ERI values (15.87–21.78) indicated low ecological risk; however, Ni emerged as the most significant contributor to potential toxicity. Although the Hazard Index (HI < 1) implied minimal immediate health effects, long-term exposure may pose latent risks. The study concludes that while the Ona River water remains largely unpolluted, elevated Ni and Mn levels necessitate continuous monitoring, stricter effluent regulation, and sustainable watershed management to protect aquatic ecosystems and public health.

Keywords: Heavy metals; Ona River; Water quality; Contamination indices; Ecological risk; Public health

I. Introduction

Access to safe drinking water is essential for human health and well-being; however, natural surface water bodies are increasingly contaminated by diverse pollutants, posing serious health risks to communities (WHO 2000; Bessa 2024). The vital importance of water to life is beyond expression, as no human activity can occur without its involvement (Obunwo and Opurum, 2013). As noted by Obunwo and Opurum (2013), water is the source of life and fulfills various functions that nothing else can replace. For decades, the deterioration of surface water quality has remained a critical global issue, most notably in developing nations and in countries with struggling economies (Amoo et al., 2017). The surge in water-borne diseases across developing nations is largely due to insufficient infrastructure for proper water treatment and distribution, leading to heightened morbidity and mortality in recent times (Shallom et al., 2011). A significant amount of attention has been devoted to the issue of water pollution and its resulting effects on human and animal health (Odeyemi et al., 2013; Iroha et al., 2020).

Heavy metals constitute a major environmental challenge and are of serious global concern (Zhu et al., 2020). Rapid industrialization and urbanization have caused heavy metals to contaminate the atmosphere and it is a problem for human health (Nour et al., 2019; Liu et al., 2019; Kahal et al., 2020).Heavy metals are naturally occurring trace elements in aquatic environments, but their concentrations can rise due to both natural processes and human activities such as domestic, industrial, agricultural, and mining operations. These metals are non-biodegradable and persist in the environment for extended periods. Heavy metals are a major environmental concern because of their high toxicity and tendency to accumulate in living organisms and ecosystems (Islam et al., 2015).

Heavy metals constitute a serious environmental hazard to both living organisms and their habitats, owing to their persistence, stability, non-biodegradability, bioaccumulation, and inherent toxicity. (Khan et al., 2019; Ustaoğlu and Islam 2020; Zhang et al., 2019) Heavy metals are commonly found throughout various environmental systems and possess properties such as persistence, carcinogenicity, and the ability to biomagnify and bioconcentrate, all of which contribute to serious environmental pollution and health risks. Although certain heavy metals are necessary for biological structure and metabolic activity, excessive levels can have toxic effects on the human body (Anthony et al., 2022; Asare-Donkor et al., 2016; Hussain et al., 2019; Çiner et al., 2021).

Yahaya et al. (2024) investigated the contamination levels and associated risks of heavy metals in water and fish species from the Bunza River in Kebbi State, Nigeria. The study focused on assessing heavy metal concentrations in water as well as in tilapia (*Oreochromis niloticus*) and catfish (*Clarias gariepinus*). Results indicated that both water and fish samples contained heavy metal levels sufficient to pose toxicity risks. Based on these findings, the study recommends the formulation and enforcement of policies aimed at the effective decontamination of the river to safeguard environmental and public health. Bardi et al., 2025 also study "Analysis of Heavy Metal Concentration of Surface Water Around Gas-flaring Stations in Selected Areas of Delta State, Nigeria". This research investigated the heavy metal concentration in surface water around gas flaring stations

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in selected areas of Delta state. Results demonstrate a progressive accumulation of heavy metals in the environment adjacent to the water body influenced by gas flaring. Despite this, there is insufficient comprehensive research on the effects of domestic and industrial activities on the Ona River, limiting the implementation of effective local surface water monitoring and management strategies. Therefore, this study aimed to assess the heavy metal safety of water samples obtained from the Ona River in Adeoyo region of Ibadan in Oyo State, Nigeria.

II. Materials and Methods

Description of Study Area

This study concentrated on strategically selected segments of the Ona River, situated within Ibadan, Oyo State, Nigeria. This river constitutes a vital natural resource, underpinning local livelihoods through its provision of water for domestic, agricultural, and industrial purposes, while concurrently supporting a diverse array of aquatic and riparian biodiversity. A detailed georeferenced map in Figure 1 and Figure 2 of the sampling locations was meticulously developed to facilitate a comprehensive analysis. This map delineates the precise geographic distribution of sampling points along the river continuum and integrates critical contextual information regarding surrounding land use patterns, including agricultural zones, industrial facilities, and urban settlements.

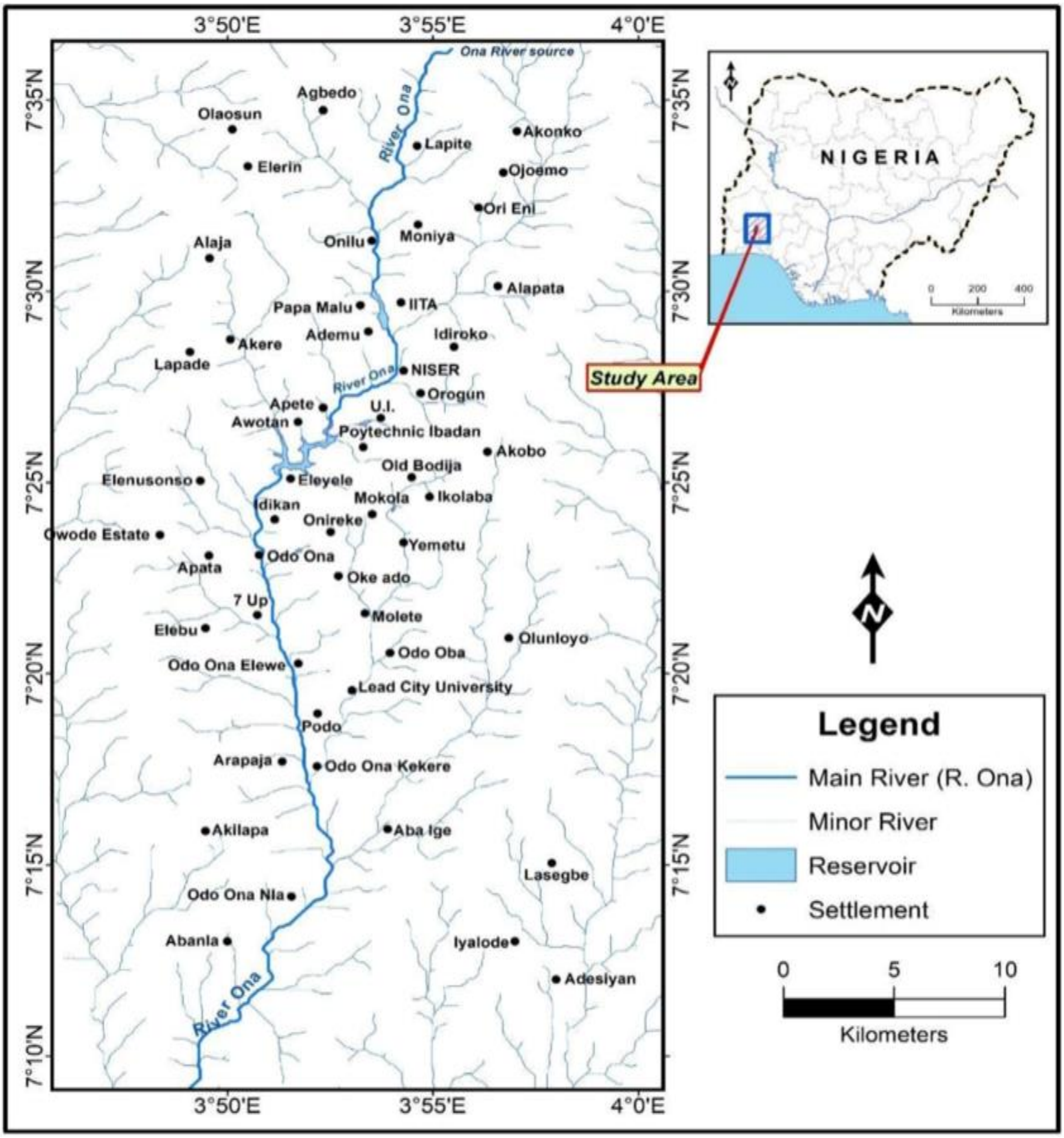

Figure 1. Map showing the Ona River (Olabamiji et al., 2023)

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Figure 1. Sample locations

Sample Collection Procedure

Water samples were collected following standard procedures using pre-labeled, acid-washed bottles and disposable gloves to prevent contamination. The sampler faced upstream to avoid sediment disturbance, and samples were taken at mid-depth (≈30 cm) while avoiding surface films and bottom debris. Bottles for heavy metal analysis were pre-treated and filled carefully to minimize aeration. Immediately after collection, samples were stored in ice-packed coolers (< 4 °C) and protected from sunlight to prevent algal or photochemical changes. Analyses for heavy metal parameters were conducted within 24 hours. Field data sheets were completed for each sampling event, recording sample ID, GPS coordinates, location, and time of collection.

Laboratory Analysis and Procedures

All laboratory procedures adhered to the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF, 24th Edition, 2022). Quantitative analysis of heavy metals was conducted to evaluate the concentration and distribution of toxic trace elements in the river water.

Heavy Metals Analysis

River water samples were digested using a mixed acid solution of concentrated nitric (HNO_3) and perchloric ($HClO_4$) acids to decompose organic matter and release metals into solution. Heavy metal concentrations (Pb, Cd, Cr, Cu, Zn, Ni, Mn, Fe, and As) were quantified by Atomic Absorption Spectrophotometry (AAS). The target metals were selected based on their environmental persistence and toxicological relevance. Results were evaluated against permissible limits recommended by the World Health Organization (WHO, 2022) and the Nigerian Standards for Drinking Water Quality (NSDWQ, 2015).

Data Analysis and Indices Computation

Geo-Accumulation Index (Igeo)

The Geo-accumulation Index (I_{geo}) was applied to quantify the degree of heavy metal contamination in surface water relative to pre-industrial background concentrations, as expressed in Equation (2.1).

$$I_{geo} = log_2 \left(\frac{C_n}{1.5 \ x \ B_n} \right) \quad 2.1$$

Where,

C_n = measured concentration of the metal in the sample

B_n = geochemical background concentration of the metal

The constant **1.5** accounts for possible variations in background values due to lithogenic effects.

Interpretation of Igeo Values **(Müller, 1969):**

Igeo	≤	0	→	Uncontaminated		
0	<	Igeo	<	1	→	Uncontaminated to moderately contaminated
1	≤	Igeo	<	2	→	Moderately contaminated
2	≤	Igeo	<	3	→	Moderately to heavily contaminated

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3 ≤ Igeo < 4 → Heavily contaminated

4 ≤ Igeo < 5 → Heavily to extremely contaminated

Igeo ≥ 5 → Extremely contaminated

The Igeo provides a clear indication of anthropogenic influence. Higher values in the Ona River would suggest that industrial, agricultural, or domestic discharges are contributing significantly to metal enrichment.

Contamination Factor (CF)

The Contamination Factor (CF) was used to evaluate the level of contamination of individual heavy metals in the water samples. It was computed using Equation (2.2):

$$CF = \frac{C_i}{C_n} \qquad 2.2$$

Where:

Ci = Measured concentration of the element in the sample

Cn = Background concentration or reference value (e.g., WHO standard or local baseline)

Interpretation of CF Values

CF < 1 → Low contamination (no significant pollution)

1 ≤ CF < 3 → Moderate contamination

3 ≤ CF < 6 → Considerable contamination

CF ≥ 6 → Very high contamination

Elevated Contamination Factor (CF) values for metals such as lead (Pb), chromium (Cr), and cadmium (Cd) indicate anthropogenic enrichment and potential ecological or health risks. In this study, CF was employed to identify metals occurring at levels significantly above permissible limits, reflecting possible inputs from industrial or urban sources.

Enrichment Factor (EF)

The Enrichment Factor (EF) is employed to assess the extent of anthropogenic influence on heavy metal concentrations in surface water relative to natural crustal inputs. It involves normalizing the concentration of each metal to that of a reference element—commonly Fe, Al, or Ti—as expressed in Equation (2.3):

$$EF = \frac{\left(\frac{C_x}{C_{ref}}\right) sample}{\left(\frac{B_x}{B_{ref}}\right) background} \qquad 2.3$$

Where:

Cx = concentration of the target heavy metal in the sample

Cref = concentration of the reference element in the sample

Bx = background concentration of the target heavy metal

Bref = background concentration of the reference element

Interpretation of EF Values

EF ≈ 1 → Metal originates mainly from crustal materials (no enrichment)

1 < EF < 3 → Minor enrichment

3 ≤ EF < 5 → Moderate enrichment

5 ≤ EF < 10 → Significant enrichment

10 ≤ EF < 25 → Very high enrichment

EF > 25 → Extremely high enrichment

An Enrichment Factor (EF) above 5 in the Ona River samples signifies substantial anthropogenic contribution, likely arising from industrial effluents, vehicular emissions, or agricultural runoff.

Pollution Load Index (PLI):

The Pollution Load Index provides a cumulative indication of the overall level of heavy metal pollution at a site. It is calculated as the nth root of the product of n contamination factors (Equation. 2.4):

$$PLI = \sqrt[n]{CF_1 \; x \; CF_2 \; x \; CF_3 \; x \; .... x \; CF_n} \qquad 2.4$$

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Where;

CF_1, CF_2, CF_n = contamination factors for n different metals

Interpretation of PLI Values

PLI = 1 → Baseline level of pollutants (no pollution)

PLI < 1 → No or low pollution

PLI > 1 → Pollution exists and its severity increases with the value

The PLI allows comparison between locations or samples. A PLI greater than 1 in the surface water samples would suggest cumulative pollution, warranting immediate attention for source identification and remediation.

Human Health Risk Assessment (HHRA)

Human Health Risk Assessment (HHRA) evaluates the potential health risks associated with human exposure to heavy metals through ingestion, dermal contact, and inhalation. It is divided into non-carcinogenic risk and carcinogenic risk.

Non-Carcinogenic Risk (HQ)

The Average Daily Dose (ADD) for each exposure pathway is calculated using standard USEPA (1989, 2011) models as shown in Eqn 2.5.

$$ADD = \frac{C \ x \ IR \ x \ EF \ x \ ED}{BW \ x \ AT} \qquad 2.5$$

Where;

C = concentration of metal in water/soil (mg/L or mg/kg)

IR = ingestion rate (L/day or mg/day)

EF = exposure frequency (days/year)

ED = exposure duration (years)

BW = body weight (kg)

AT = averaging time (days)

The Hazard Quotient (HQ) is then derived ass shown in Eqn. 2.6

$$HQ = \frac{ADD}{RfD} \qquad 2.6$$

Where;

RfD = Reference dose (mg/kg/day)

The Hazard Index (HI) is the sum of HQs across all metals and pathways;

$$HI = \sum HQ_i \qquad 2.7$$

Interpretation of HL Values

HI < 1 → No significant non-carcinogenic health risk

HI ≥ 1 → Potential adverse health effects

2.10.2 Carcinogenic Risk

Carcinogenic risk is assessed using the Cancer Risk (CR) mode

$$CR = ADD \ x \ SF \qquad 2.8$$

Where;

SF = Slope factor $(mg/kg/day)^{-1}$

The cumulative cancer risk (TCRTCRTCR) is calculated by summing CR across metals and pathways:

$$TCR = \sum CR_i \qquad 2.9$$

Interpretation (USEPA guidelines)

1×10^{-6} to 1×10^{-4} → Acceptable risk range

TCR > 1×10^{-4} → Potentially unacceptable cancer risk

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In the context of Ona River, elevated HQ or HI values would suggest potential non-carcinogenic risks (e.g., kidney or neurological damage), while high CR or TCR values would indicate long-term cancer risks due to chronic exposure to toxic metals such as arsenic, cadmium, or chromium.

Ecological Risk Index (Er)

The Ecological Risk Index assesses the potential ecological risk posed by individual heavy metals. It combines the contamination factor with the toxic response factor (Tr) of each metal (Eqn. 2.10):

$$ERI = CF \times Tr \quad (2.10)$$

Where:

Tr = Toxic response factor, which varies by metal

(e.g., Cd = 30, As = 10, Pb = 5, Cu = 5, Cr = 2, Zn = 1, Ni = 5)

Interpretation of ERI Values

$ERI < 40 \rightarrow$ Low potential ecological risk

$40 \leq ERI < 80 \rightarrow$ Moderate risk

$80 \leq ERI < 160 \rightarrow$ Considerable risk

$160 \leq ERI < 320 \rightarrow$ High risk

$ERI \geq 320 \rightarrow$ Very high risk

Calculating the Ecological Risk Index (ERI) for each metal identifies pollutants that not only occur at elevated concentrations but also exert significant ecological impact based on their toxicity coefficients. For instance, cadmium (Cd) and arsenic (As) may exhibit high ERI values even at low concentrations due to their pronounced toxicity.

III. Results and Discussion

Tests and Results

This chapter delineates the findings of heavy metal assessments of water samples obtained from the Ona River during wet seasons, across three sampling stations situated between Adeoyo Hospital and Zeatech. Nine samples (three from each of three locations) were analysed for selected potentially toxic elements (PTEs), including Fe, Zn, Cu, Cr, As, Cd, Ni, and Pb. The results are analysed concerning national and international drinking water quality standards, specifically those established by the World Health Organisation (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ), to evaluate contamination levels, ecological risks, and public health consequences. The analyses were additionally evaluated using pollution indices including the Geo-accumulation Index (Igeo), Enrichment Factor (EF), Contamination Factor (CF), and Pollution Load Index (PLI). Health risk assessments for both non-carcinogenic and carcinogenic risks were performed to determine the possible public health implications of heavy metal exposure. Results are displayed in tables accompanied by a comprehensive discussion of national and international standards.

Heavy Metals and Potentially Toxic Elements (PTEs)

Chromium (Cr)

Chromium concentrations were below detection limits at Locations 1 and 2 but measured 0.01 ± 0.00 mg/L at Location 3 as shown in Table 1, remaining within the WHO and NSDWQ guideline of 0.05 mg/L and the EPA limit of 0.1 mg/L. Although this level poses no immediate health risk, its isolated detection suggests localized contamination, likely from industrial effluents, waste disposal, or material corrosion. Chromium's occurrence is of concern because hexavalent chromium (Cr^{6+}) is highly toxic and carcinogenic, associated with oxidative stress, renal, hepatic, and cardiovascular dysfunction (Sazakli et al., 2024; Pan et al., 2024). Ongoing surveillance and effluent regulation are therefore essential to prevent possible accumulation and future exceedance of safety thresholds

Table 1: Average Concentration of Heavy Metals in Water Samples Collected at Asese/Mowe Industrial Area

S/N	Loc 1	Loc 2	Loc 3	WHO Guideline	Nigerian Standard	EPA Maximum Contaminant Level
Chromium	BDL	BDL	0.01 ± 0.00	0.05	0.05	0.1
Cadmium	BDL	BDL	BDL	0.005	0.003	0.005
Arsenic	BDL	BDL	BDL	0.05	0.01	0.01
Magnesium	5.56 ± 0.99	8.47 ± 0.55	9.93 ± 0.24			
Mn	0.05 ± 0.04	0.10 ± 0.01	0.24 ± 0.05	0.4	0.4	0.4

Zinc	0.13 ± 0.03	0.14 ± 0.03	0.12 ± 0.02	5	3	5
Iron	0.04 ± 0.01	0.04 ±0.01	0.05 ± 0.00	0.3	0.3	0.3
Copper	0.01 ± 0.00	0.02 ± 0.00	0.03 ± 0.00	1.0	1	1.3
Nickel	0.27 ± 0.15	0.20 ± 0.00	0.27 ± 0.06	0.07	0.02	0.07
Lead	BDL	BDL	BDL	0.01	0.01	0.01

Cadmium (Cd) and Arsenic (As)

Cadmium was below detection limits (BDL) in all sampling locations (Table 1). This is encouraging, as cadmium is highly toxic, and even trace exposure has been associated with renal impairment, bone demineralization, and carcinogenic effects (WHO, 2023; Pan et al., 2024). The recorded values are well below the WHO and EPA guideline of 0.005 mg/L and the more stringent NSDWQ limit of 0.003 mg/L. The absence of detectable cadmium indicates that industrial effluents from sources such as battery manufacturing, electroplating, and pigment production are unlikely influencing the study area, suggesting minimal anthropogenic input.

Arsenic concentrations were below detection limits across all sampling locations (Table 1). This finding is noteworthy, as arsenic is a highly toxic metalloid associated with skin lesions, carcinogenesis, cardiovascular disorders, and neurotoxicity following long-term exposure (WHO, 2022; Demissie et al., 2024). The WHO guideline value for arsenic in drinking water is 0.05 mg/L, while the NSDWQ and EPA specify more stringent limits of 0.01 mg/L, reflecting updated health risk assessments. The absence of detectable arsenic suggests that surface and groundwater within the Ona River catchment are presently unaffected by geogenic inputs or anthropogenic sources such as pesticide residues or industrial effluents.

Magnesium (Mg)

Magnesium concentrations ranged from 5.56 ± 0.99 mg/L at Location 1 to 9.93 ± 0.24 mg/L at Location 3, all within acceptable limits for drinking water (Table 1). As the WHO, NSDWQ, and EPA recognize magnesium as an essential mineral rather than a contaminant, the observed levels indicate good water quality. The moderate concentrations suggest minimal anthropogenic influence, with magnesium likely derived from natural geogenic sources such as the dissolution of magnesium-rich rocks and soil minerals.

Manganese (Mn)

Manganese (Mn) concentrations varied notably across the sampling sites, ranging from 0.05 ± 0.04 mg/L at Location 1 to 0.24 ± 0.05 mg/L at Location 3 (Table 1). While the WHO and NSDWQ recommend a limit of 0.2 mg/L and the EPA sets a secondary standard of 0.05 mg/L, levels at Locations 2 and 3 exceeded the EPA guideline, with Location 3 also surpassing WHO/NSDWQ limits. The elevated concentration at Location 3 likely reflects stronger geogenic inputs or localized anthropogenic influence from industrial activities in the Ona River along Adeoyo area. Manganese above recommended limits may cause water discoloration, metallic taste, and plumbing stains, and prolonged exposure has been linked to neurological effects, particularly in children. The increasing trend from Locations 1 to 3 highlights the need for regular monitoring and potential treatment interventions to ensure safe water quality.

Zinc (Zn)

Zinc (Zn) concentrations were relatively uniform across the three sites, ranging from 0.12 ± 0.02 to 0.14 ± 0.03 mg/L (Table 1), all well below permissible limits of 5 mg/L (WHO, EPA) and 3 mg/L (NSDWQ). These low levels indicate minimal zinc contamination and no associated health or aesthetic risks. As an essential trace element, zinc supports immune and enzymatic functions but can cause metallic taste and gastrointestinal irritation at high concentrations. Relatively uniform distribution of zinc across all sites indicates a predominantly geogenic origin, likely resulting from the natural dissolution of zinc-bearing minerals rather than anthropogenic activities. Overall, zinc exerts minimal influence on the Water Quality Index (WQI), affirming that the water remains safe concerning this parameter (WHO, 2023; Rahman et al., 2024).

Nickel (Ni)

Nickel (Ni) concentrations ranged from 0.20 ± 0.00 to 0.27 ± 0.15 mg/L across the three sites, surpassing all permissible limits—0.07 mg/L (WHO, EPA) and 0.02 mg/L (NSDWQ). This identifies nickel as a major contaminant in the Ona River within Adeoyo. The consistently high levels indicate dominant anthropogenic inputs, likely from industrial effluents, metal processing, or corrosion of steel infrastructure, rather than natural sources. Elevated nickel poses serious health risks, including dermatitis, organ toxicity, and carcinogenic effects. Unlike zinc and magnesium, which remained within safe limits, nickel contamination represents a critical water quality issue requiring urgent remediation and stronger regulatory monitoring (WHO, 2023; Rahman et al., 2024). Nickel levels present a major water quality concern in the study area, unlike zinc and magnesium, which remained within safe limits. The elevated concentrations indicate that industrial effluents are the primary source of contamination, emphasizing the need for continuous monitoring and effective regulatory intervention (WHO, 2023; Rahman et al., 2024).

Lead (Pb)

Lead (Pb) was below detectable limits (BDL) across all sampling locations, indicating an absence of contamination by this highly toxic metal. Given the permissible limit of 0.01 mg/L set by WHO, NSDWQ, and EPA (Table 1), this result reflects

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good water quality with respect to lead. The non-detection suggests limited industrial activity involving lead, effective waste management, or geochemical conditions that restrict its mobility. This is notable since chronic lead exposure is linked to neurological and developmental disorders in children and cardiovascular and renal effects in adults. Nonetheless, as other metals such as nickel and manganese exceeded safe limits, continued monitoring remains essential to prevent future lead contamination and ensure long-term water safety (WHO, 2023; Rahman et al., 2024).

Iron

Iron (Fe) concentrations ranged from 0.04 ± 0.01 to 0.05 ± 0.00 mg/L (Table 1) across the three locations, remaining well below the 0.3 mg/L permissible limit set by WHO, NSDWQ, and EPA standards. These consistently low values indicate that iron is not a pollutant of concern in the study area and is primarily of geogenic origin, derived from the natural dissolution of iron-bearing minerals rather than anthropogenic inputs. The uniform distribution of Fe suggests stable hydrogeochemical conditions with minimal external influence. Moreover, enrichment factor (EF) analysis classified iron as minimally enriched (EF = 1–2.6), reinforcing its role as a natural reference element. From a health perspective, the concentrations pose no risk and do not affect the aesthetic quality of the water, confirming iron as environmentally benign within the River Ona system (WHO, 2022; Adedeji et al., 2023).

Copper

Copper (Cu) concentrations ranged from 0.01 ± 0.00 to 0.03 ± 0.00 mg/L across the three locations, remaining well below permissible limits of 1.0 mg/L (WHO, NSDWQ) and 1.3 mg/L (EPA) (Table 1). These values indicate minimal copper contamination and no immediate health risk, as copper is essential in trace amounts but toxic at higher levels. The slight downstream increase suggests minor anthropogenic influence, possibly from plumbing corrosion or domestic effluents. Although dissolved copper levels are low, enrichment factor (EF) analysis revealed extreme enrichment (EF > 400) in sediments, implying potential long-term accumulation and remobilization risks under changing redox conditions. Overall, copper levels confirm good water quality but warrant continued monitoring to mitigate future sediment-related impacts (WHO, 2022; Adeyemi et al., 2024).

Heavy Metal Pollution Indices

Geo-Accumulation Index (Igeo)

he Geo-Accumulation Index (Igeo) serves as an effective measure for evaluating heavy metal contamination in sediments, soils, or water by comparing observed concentrations with natural background values. As shown in Table 2, most metals in the Ona River (Adeoyo region) exhibited negative Igeo values, indicating an unpolluted condition.

Chromium (Cr), cadmium (Cd), arsenic (As), and lead (Pb) were either below detection limits or highly negative (e.g., Cr at –13.72 in Location 3), signifying no anthropogenic enrichment or contamination—consistent with earlier reports showing these metals at trace or non-detectable levels (Rahman et al., 2024). Manganese (Mn) exhibited Igeo values from –14.64 at Location 1 to –12.38 at Location 3, indicating a slight increase but still within the unpolluted range. Although Mn concentrations marginally exceeded permissible limits at Location 3, the Igeo results suggest this enrichment is geogenic rather than anthropogenic. Magnesium (Mg) also showed consistently negative Igeo values (–11.98 to –11.15), confirming its natural geochemical origin and indicating no pollution influence (Rahman et al., 2024).

Table 2: Geo-Accumulation Index (Igeo)

Metal	Loc 1	Loc 2	Loc 3
Cr	BDL	BDL	-13.7207
Cd	BDL	BDL	BDL
As	BDL	BDL	BDL
Mn	-14.6382	-13.6382	-12.37518
Mg	-11.9826	-11.3753	-11.14584
Zn	-10.0982	-9.99132	-10.21371
Ni	-8.56139	-8.99435	-8.561394
Fe	-20.7553	-20.7553	-20.43339
Cu	-13.7207	-11.7207	-11.13571
Pb	BDL	BDL	BDL

Zinc (Zn) and nickel (Ni) showed negative Igeo values (–10.10 to –9.99 and –8.56 to –8.99, respectively), indicating minimal accumulation relative to natural background levels. Although Ni concentrations slightly exceeded drinking water standards, the Igeo values imply limited enrichment compared to global crustal norms, suggesting localized rather than severe contamination (Loska and Wiechuła, 2003; Singh et al., 2022).

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Iron (Fe) showed extremely low Igeo values (–20.76 to –20.43), confirming it's purely geogenic origin with no anthropogenic input. Copper (Cu) also exhibited strongly negative Igeo values (–13.72 to –11.14) (Table 2), with a slight downstream increase at Location 3 but still within the "uncontaminated" range. Overall, the negative Igeo values for all analyzed metals indicate that the Ona River is dominated by natural geochemical processes rather than human-induced pollution. This supports the view that, although certain elements like Ni and Mn exceed drinking water limits, the low Igeo values highlight limited sediment enrichment and emphasize the importance of integrating both health-based standards and geochemical baselines in water quality assessment (Islam et al., 2023).

Enrichment Factor (EF)

The Enrichment Factor (EF) serves as an effective geochemical index for distinguishing natural from anthropogenic metal sources. EF values close to 1 indicate geogenic origin, while those exceeding 10 reflect significant human influence. As presented in Table 3, EF values varied across metals and sites in the Ona River in along Adeoyo region, revealing distinct contamination trends. Chromium (Cr) exhibited EF values below detection at Locations 1 and 2 but reached 65.56 at Location 3, indicating strong anthropogenic enrichment likely linked to industrial effluents from metal plating, leather tanning, or chemical processing activities.

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Table 3: Enrichment Factor (EF)

Metal	Loc 1	Loc 2	Loc 3
Cr	BDL	BDL	65.55556
Cd	BDL	BDL	BDL
As	BDL	BDL	BDL
Mn	55.52941	69.41176	166.5882
Mg	349.9093	333.1533	390.58
Zn	1291.789	869.4737	745.2632
Ni	3748.235	1735.294	2342.647
Fe	0.8	0.5	0.625
Cu	209.7778	262.2222	393.3333
Pb	BDL	BDL	BDL

Zinc (Zn) displayed very high EF values (745.26–1291.79), indicating substantial anthropogenic enrichment likely from galvanization, battery disposal, metal smelting, and industrial effluents typical of industrial zones. Nickel (Ni) showed extreme EF values (1735.29–3748.24), far exceeding contamination thresholds and reflecting severe anthropogenic input from metal processing, alloy production, or industrial wastewater consistent with its previously elevated concentrations above drinking water limits, confirming Ni as the principal pollutant of concern. Cadmium (Cd), arsenic (As), and lead (Pb) were below detection limits, suggesting no measurable enrichment, while iron (Fe) exhibited low EF values (0.5–0.8), indicating a geogenic origin suitable for normalization. In contrast, copper (Cu) recorded EF values between 209.78 and 393.33, signifying extreme enrichment likely linked to corrosion, industrial emissions, and agrochemical runoff.

The Enrichment Factor (EF) results reveal that while elements like magnesium (Mg) are predominantly geogenic, metals such as nickel (Ni), zinc (Zn), manganese (Mn), and chromium (Cr) exhibit strong anthropogenic enrichment, with Ni emerging as the principal contaminant. These findings underscore the substantial impact of industrial activities on the water quality of Ona River along Adeoyo region and highlight the urgent need for regulatory monitoring and remediation to mitigate associated human and ecological health risks.

Contamination Factor

The Contamination Factor (CF) values for the six analyzed metals reveal varying pollution contributions. Nickel (Ni) recorded the highest CF values (2.86–3.86) as in Table 4, indicating considerable contamination, as CF > 3 denotes significant enrichment. This identifies Ni as the major pollutant of concern, likely derived from industrial activities, metal plating, or alloy corrosion. In contrast, magnesium (Mg) (0.56–0.99), manganese (Mn) (0.25–1.20), zinc (Zn) (0.024–0.028), iron (Fe) (0.13–0.17), and copper (Cu) (0.008–0.023) all showed CF < 1, reflecting minimal contamination from natural geogenic sources. Overall, while most metals remain within safe levels, Ni exhibits clear anthropogenic enrichment that warrants monitoring (Zhang et al., 2024).

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Pollution Index

The Pollution Load Index (PLI) values for the three sampling sites 0.1558, 0.2028, and 0.2741 are all below 1(Table 4), indicating an overall unpolluted status. Although nickel shows a relatively high CF, the low PLI values suggest minimal cumulative metal contamination. The gradual rise in PLI from Location 1 to Location 3 points to a localized increase in pollution, likely linked to industrial or urban runoff influences downstream (Zhang et al., 2024; Ali et al., 2023).

Table 4: Contamination Factor (CF), Pollution Load Index (PLI), and Ecological Risk Index (ERI) of Heavy Metals in the Water Samples

Sample	Contamination Factor (CF)								PLI	ERI
	Magnesium	Manganese	Zinc	Iron	Copper	Nickel				
Loc 1	0.556	0.25	0.026	0.133333	0.007692	3.857143			0.155791	20.28951
Loc 2	0.847	0.5	0.028	0.133333	0.015385	2.857143			0.202766	15.87097
Loc 3	0.993	1.2	0.024	0.166667	0.023077	3.857143			0.274119	21.78477

Ecological Risk Index

The Ecological Risk Index (ERI), which integrates contamination levels with metal-specific toxic-response factors, provides a measure of potential ecological harm. ERI values of 20.29, 15.87, and 21.78 for Locations 1, 2, and 3, respectively, all fall below 40, indicating low ecological risk. This suggests that overall heavy metal levels pose minimal threat to aquatic and soil ecosystems. However, slightly higher ERI values at Locations 1 and 3 align with elevated nickel concentrations, identifying localized risk zones. Although the area remains largely safe, continued monitoring particularly for Ni is advisable (Chen et al., 2023; Zhang et al., 2024).

Human Health Risk Assessment (HHRA)

Table 5: Carcinogenic Risk Assessment

Sample	Carcinogenic Risk Assessment				
		Chromium	Arsenic	Nickel	
	ADD	0	0	0.0077143	
Loc 1	SF	0.27	32.0	0.91	
	CR	0	0	0.00702000	$\sum = 0.00702000$
Loc 2	ADD	0	0	0.0057143	
	SF	0.27	32.0	0.91	
	CR	0	0	0.00520000	$\sum = 0.00520000$
Loc 3	ADD	0.0002857	0	0.0077143	
	SF	0.27	32.0	0.91	
	CR	0.0000771	0	0.00702000	$\sum = 0.0070971$

Carcinogenic Risk

The carcinogenic risk assessment estimates the lifetime probability of cancer from continuous exposure to metals in water, using the USEPA (1989, 2011) model. CR is calculated as the product of the Average Daily Dose (ADD) and the metal-specific Slope Factor (SF), which reflects the incremental cancer probability per unit dose. According to USEPA guidelines, acceptable CR values range from 1×10^{-6} to 1×10^{-4}; values above this threshold indicate potential public health concerns requiring intervention.

At Location 1, nickel was the only detected carcinogenic metal, with a CR of 0.00702 (ΣCR = 0.00702; Table 5), exceeding the USEPA threshold and indicating a high potential cancer risk from long-term exposure. The absence of chromium and arsenic suggests that nickel, likely originating from industrial effluents or corroded pipelines, is the primary driver of carcinogenicity at this site.

At Location 2, nickel was the sole contributor to carcinogenic risk, with a total CR of 0.0052 (Table 5), exceeding the acceptable threshold. Although slightly lower than Location 1, this value indicates potential lifetime cancer risks from prolonged water consumption, including respiratory and gastrointestinal effects. The reduced risk corresponds to lower nickel concentrations (0.0057 mg/L) compared to Location 1.

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At Location 3, chromium and nickel contributed to the total carcinogenic risk (ΣCR = 0.0070971; Table 5). Chromium showed a CR of 7.71×10^{-5}, within the upper acceptable threshold (10^{-4}), indicating a low-to-moderate risk, whereas nickel exhibited a substantially higher CR of 0.00702, surpassing safety limits and identifying it as the primary carcinogenic agent. Nickel contamination consistently elevated total CR values across all sampling sites (0.0052–0.0071), exceeding the USEPA's permissible level and suggesting potential lifetime cancer risk from long-term water consumption. Chromium contributed minimally, while arsenic remained below detection limits. Nonetheless, the high slope factor of arsenic (32.0) indicates that even trace concentrations could pose significant carcinogenic hazards in future assessments. Overall, the dominance of nickel underscores industrial and anthropogenic influences as key drivers of carcinogenic risk within the study area.

Table 6: Non-Carcinogenic Risk Assessment

Sample										HI
		Chromium	Arsenic	Manganese	Magnesium	Zinc	Nickle	Iron	Copper	
RFD		0.003	0.0003	0.14	0.08	0.3	0.02	0.30	0.04	
IR (L/day)		2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	
EF (days/year)		365	365	365	365	365	365	365	365	
ED (adult)		30 years	30 years	30 years	30 years	30 years	30 years	30 years	30 years	
BW		70 kg	70 kg	70 kg	70 kg	70 kg	70 kg	70 kg	70 kg	
AT (ED x 365) (days)		10,950	10,950	10,950	10,950	10,950	10,950	10,950	10,950	
Loc 1	C	0	0	0.05	5.56	0.13	0.27	0.04	0.01	
	ADD	0	0	0.001429	0.158857	0.003714	0.007714	0.001143	0.000286	
	HQ	0	0	0.010204	1.985714	0.012381	0.385714	0.00381	0.007143	2.404966
Loc 2	C	0	0	0.10	8.47	0.14	0.20	0.04	0.02	
	ADD	0	0	0.002857	0.242	0.004	0.005714	0.001143	0.000571	
	HQ	0	0	0.020408	3.025	0.013333	0.285714	0.00381	0.014286	3.362551
Loc 3	C	0.01	0	0.24	9.93	0.10	0.27	0.05	0.03	
	ADD	0.000286	0	0.006857	0.283714	0.002857	0.007714	0.001429	0.000857	
	HQ	0.095238	0	0.04898	3.546429	0.009524	0.385714	0.004762	0.021429	4.112075

At Location 3, the total Hazard Index (HI) was 4.11 (Table 6), indicating the highest non-carcinogenic health risk among all sampling points. Magnesium (HQ = 3.55) and nickel (HQ = 0.39) were the dominant contributors, while manganese and chromium showed minimal influence. The consistent dominance of magnesium and nickel across sites identifies them as the key pollutants controlling health risk patterns. All sites exhibited HI values above 1.0, suggesting potential adverse effects from prolonged ingestion. Elevated magnesium concentrations likely arise from geogenic processes, such as mafic rock weathering, with additional input from industrial effluents, whereas nickel enrichment reflects industrial discharge and corrosion activities. The higher HI at Location 3 implies greater contamination or exposure duration, designating it as a critical zone for intervention. Overall, these findings underscore the need for sustained groundwater monitoring and targeted treatment measures to mitigate cumulative non-carcinogenic health risks.

Non-carcinogenic risk assessment indicates that long-term consumption of water from the study sites may threaten vulnerable populations due to elevated magnesium and nickel levels, potentially causing metabolic disorders, kidney stress, and other chronic health effects in the absence of adequate treatment or pollution control.

Conclusion

The assessment of heavy metals in Ona River water along the Adeoyo–Zeatech stretch indicates generally good water quality for most elements, with magnesium, iron, copper, zinc, cadmium, arsenic, and lead remaining within permissible limits. However, nickel and manganese exceed national and international drinking water standards at several locations, highlighting localized contamination likely from industrial effluents. Pollution indices (Igeo, EF, CF, PLI) confirm that while most metals are geogenic, nickel exhibits strong anthropogenic enrichment, making it the principal contaminant. Ecological risk remains low overall, but human health risk assessment reveals that nickel poses significant carcinogenic potential, exceeding USEPA thresholds. Continuous monitoring, regulatory enforcement, and targeted remediation are recommended to mitigate nickel-related public health risks and maintain the river's water quality.

Recommendations

Implement regular monitoring of heavy metals, especially nickel and manganese, along the Ona River. Enforce stricter regulation of industrial discharges, and promote remediation measures in hotspots. Educate local communities on potential health risks and restrict direct use of contaminated water for drinking until quality improves.

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