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Toxic Metal Contamination and Drinking-Water Safety in Domestic Borehole Water of Opukuma , Bayelsa State, Nigeria

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Abstract

This study evaluated the physicochemical characteristics and heavy metal contamination of groundwater from five boreholes in Opokuma, Kolokuma/Opokuma LGA, Bayelsa State, Nigeria, to assess drinking-water suitability and potential health risks. In-situ parameters showed low mineralization (EC: 30–44 µS/cm; TDS: 16–22 mg/L) and slightly acidic conditions (pH: 5.74–6.30). Heavy metals revealed severe contamination: cadmium ranged from 0.073 ± 0.001 to 0.957 ± 0.006 mg/L and lead from 0.599 ± 0.001 to 1.777 ± 0.001 mg/L, far exceeding WHO limits (0.003 and 0.01 mg/L, respectively). Arsenic exceeded guidelines at two sites (0.016 ± 0.001 and 0.160 ± 0.002 mg/L), while nickel marginally exceeded the limit at one site (0.084 ± 0.001 mg/L). Iron was extremely elevated across all boreholes (13.09–22.17 mg/L). Chromium, copper, zinc and mercury were within guideline limits. Index-based assessments classified all boreholes as unsuitable for drinking (WQI: 4557–20123; HPI: 4558–20128). Non-carcinogenic health risk was substantial (HI: 12.26–34.91), driven mainly by Cd and Pb. Multivariate analyses indicated combined geogenic and localized anthropogenic controls on metal distribution. Untreated groundwater in Opokuma poses serious public health risks due to toxic metal contamination. It is recommended that routine monitoring, provision of alternative safe water sources, and point-of-use metal removal technologies be implemented to mitigate exposure.

Keywords: Groundwater quality; Heavy metals; Drinking-water safety; Health risk assessment; Water Quality Index (WQI); Heavy Metal Pollution Index (HPI).

Introduction

Groundwater remains the primary source of potable water for millions of people in developing regions, particularly in rural communities where centralized water treatment infrastructure is limited. However, the

quality of groundwater is increasingly threatened by heavy metal contamination arising from both natural geochemical processes and anthropogenic activities. Heavy metals such as arsenic (As), cadmium (Cd), lead (Pb), chromium (Cr), and iron (Fe) are of particular concern due to their toxicity, persistence, and bioaccumulative tendencies in human tissues and ecosystems. Recent global assessments indicate that exposure to toxic metals through drinking water contributes significantly to the burden of non-communicable diseases, including renal dysfunction, neurological impairment, cardiovascular disorders, and carcinogenesis (Briffa et al., 2020; Tchounwou et al., 2022).

The Niger Delta region of Nigeria is widely recognized as one of the most environmentally stressed ecosystems in sub-Saharan Africa, largely due to decades of oil exploration, gas flaring, pipeline vandalism, artisanal refining, and poor waste management practices (Aigberua & Tarawou, 2023). These activities introduce substantial loads of potentially toxic elements into soils, sediments, surface water, and aquifers. Studies conducted across Bayelsa, Rivers, and Delta States have consistently reported elevated concentrations of Pb, Cd, Fe, and Ni in groundwater sources used for domestic purposes, often exceeding World Health Organization (WHO) guideline limits (Ede & Edokpayi, 2021; Nwankwoala et al., 2022). In low-lying deltaic environments, the combination of high rainfall, seasonal flooding, and shallow aquifers further enhances contaminant mobilization and metal leaching into groundwater systems.

Hydrogeochemical processes play a critical role in controlling the distribution, mobility, and bioavailability of heavy metals in groundwater. Factors such as pH, redox potential, mineral weathering, aquifer lithology, and groundwater residence time influence metal solubility and transport. In deltaic terrains dominated by alluvial sands, silts, and clay-rich sediments, iron-rich formations and reducing conditions often promote the dissolution of Fe-bearing minerals, which can co-mobilize toxic trace metals such as arsenic and lead into groundwater (Smedley & Kinniburgh, 2021; Bhattacharya et al., 2022). Consequently, understanding the hydrogeochemical behavior of metals is essential for accurate assessment of groundwater vulnerability and associated human health risks. Communities within Kolokuma/Opokuma Local Government Area of Bayelsa State, including Opokuma, depend largely on shallow boreholes and hand-dug wells for drinking, cooking, and other domestic uses. The absence of routine water quality monitoring and limited access to treatment facilities increase the likelihood of chronic exposure to contaminated groundwater. Prolonged ingestion of water containing elevated levels of Cd and Pb has been linked to kidney damage, skeletal disorders, developmental toxicity in children, and increased risk of hypertension, while excessive Fe, although an essential micronutrient, causes aesthetic problems and may contribute to gastrointestinal disturbances and microbial regrowth in distribution systems (WHO, 2022; Aigberua & Tarawou, 2023; Mohan et al., 2021). These public health implications underscore the urgency of localized groundwater quality assessments in oil-impacted rural communities of the Niger Delta.

Against this background, the present study provides a hydrogeochemical evaluation of selected heavy metals in groundwater sources within Opokuma, Kolokuma/Opokuma LGA, Bayelsa State, Nigeria. By quantifying the concentrations of As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, and Fe and comparing them with international drinking water standards, this study aims to generate baseline data on groundwater quality, identify potential contamination hotspots, and infer possible geogenic and anthropogenic controls on metal distribution. However, site-specific evidence integrating hydrogeochemistry, pollution indices, multivariate diagnostics, and human health risk for domestic boreholes in Opokuma remains scarce (Ede & Edokpayi, 2021; Bodrud-Doza et al., 2020). The findings are expected to contribute to evidence-based water resource management, risk communication, and policy interventions targeted at safeguarding public health and ensuring the sustainable use of groundwater resources in the Niger Delta.

Materials and Methods

Study Area

The study was conducted in Opokuma, Kolokuma/Opokuma Local Government Area (LGA), Bayelsa State, Nigeria, located within the lower Niger Delta sedimentary basin (approximately 4.95° N, 6.23° E) (figure 1). The area is characterized by low-lying deltaic plains, extensive creeks and floodplains, mangrove–freshwater swamp vegetation, and shallow unconfined aquifers. The climate is humid tropical, with mean annual rainfall ranging from 2,500 to 4,000 mm and average temperatures of 26–30 °C. The hydrogeological setting comprises predominantly alluvial sands, silts, and clayey sediments of Quaternary age, which influence groundwater chemistry through mineral weathering, redox reactions, and ion exchange processes. The communities rely largely on boreholes for domestic water supply, rendering groundwater quality assessment critical for public health protection (Nwankwoala et al., 2022; Ede & Edokpayi, 2021).

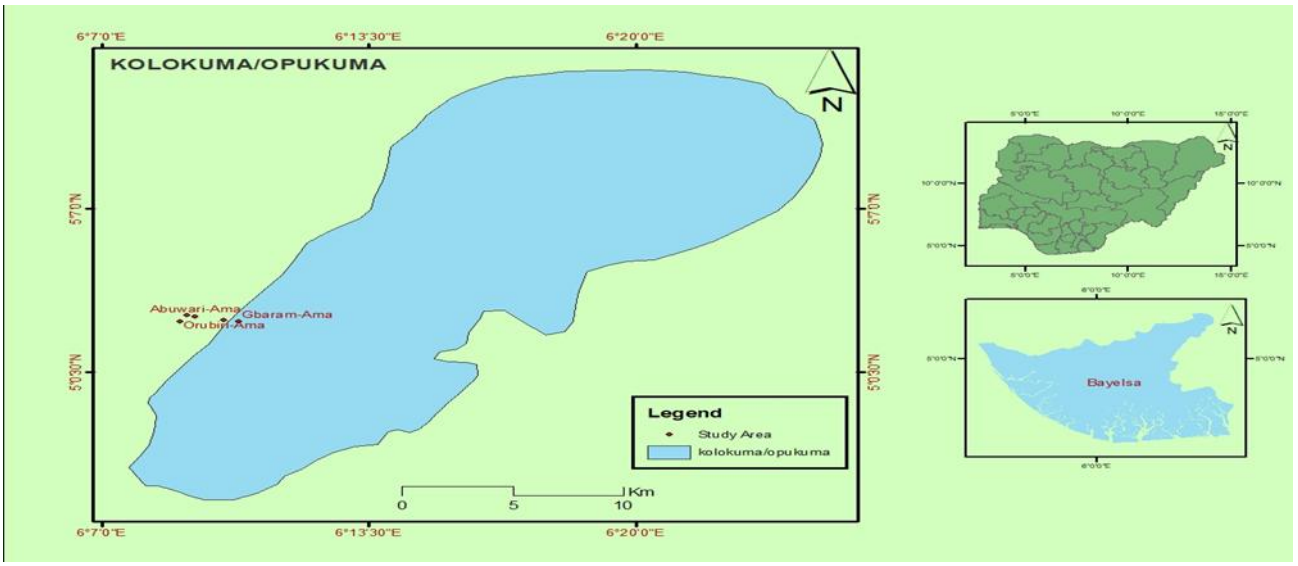


Figure 1. The study located Coordinates (Approximate) Latitude: 4.95° N Longitude: 6.23°

Sampling Design and Borehole Selection

A cross-sectional sampling design was adopted. Five functional boreholes (BH1–BH5) distributed across different communities within Opukuma were purposively selected based on accessibility, frequency of domestic use, and spatial coverage of the study area. Global Positioning System (GPS) coordinates were recorded for each sampling point to enable spatial referencing and future monitoring. Prior to sampling, boreholes were pumped continuously for approximately 15–20 minutes to purge stagnant water and ensure that samples represented aquifer conditions. This approach minimizes bias associated with standing water in borehole casings and improves the representativeness of hydrochemical measurements (APHA, 2017; WHO, 2022).

Sample Collection, Preservation, and Transportation

Groundwater samples were collected in pre-cleaned 1-L high-density polyethylene (HDPE) bottles. All sample containers were washed with non-ionic detergent, rinsed with deionized water, and finally rinsed with the sampled groundwater prior to collection to prevent cross-contamination. For heavy metal analysis, samples were immediately acidified in situ with ultrapure nitric acid (HNO_3) to pH < 2 to inhibit microbial

activity and prevent metal precipitation or adsorption onto container walls. Samples were stored in ice-chilled coolers (≈4 °C) and transported to the laboratory within 24 h for analysis. Field blanks and duplicate samples were included to ensure quality assurance and quality control (QA/QC) of the sampling procedure (APHA, 2017; Bhattacharya et al., 2022).

In-situ Physicochemical Measurements

Physicochemical parameters including temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured in situ using calibrated portable meters following standard protocols. In-situ measurements were preferred to minimize changes in water chemistry due to degassing, oxidation, or temperature variation during transport. The instruments were calibrated daily using certified buffer solutions and standard reference solutions. These parameters provide essential context for interpreting metal mobility, speciation, and hydrogeochemical behavior in groundwater systems (Smedley & Kinniburgh, 2021).

Laboratory Analysis of Heavy Metals

The concentrations of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), zinc (Zn), and iron (Fe) were determined using Atomic Absorption Spectrophotometry (AAS) following digestion with nitric acid in accordance with Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Analytical calibration was performed using multi-element standard solutions, and reagent blanks were run to correct for background contamination. Method detection limits (MDLs) were established for each metal, and values below detection limits were reported as BDL. Analytical accuracy and precision were verified through analysis of certified reference materials and replicate measurements. Instrument performance was routinely checked to ensure analytical reliability (WHO, 2022).

Calibration and Quantification

Calibration curves were prepared for each metal using a series of freshly prepared standard solutions (0.00, 0.05, 0.10, 0.50, 1.00 mg/L) obtained by serial dilution of certified 1000 mg/L stock solutions. The linearity of calibration curves was verified with correlation coefficients (R^2) ≥ 0.995. Blank solutions were analyzed between sample runs to check for carryover and instrument drift. Sample concentrations were computed directly from the calibration curves, and results were expressed in mg/L. For values below the method detection limit (MDL), concentrations were reported as below detection limit (BDL). The MDLs were established as three times the standard deviation of replicate measurements of reagent blanks (APHA, 2017; WHO, 2022).

Water Quality Index (WQI)

The overall suitability of groundwater for drinking was evaluated using the Water Quality Index (WQI) based on the weighted arithmetic method. The WQI integrates multiple physicochemical and chemical parameters into a single numerical value representing water quality status. Parameters considered included pH, total dissolved solids (TDS), electrical conductivity (EC), and selected heavy metals (As, Cd, Cr, Cu, Ni, Pb, Zn, and Fe). The WQI was computed using the following steps:
Assignment of weights (w_i): Each parameter was assigned a weight inversely proportional to its WHO drinking-water guideline value (S_i), such that parameters with stricter standards exert greater influence

$$w_i = \frac{1}{S_i}$$

Calculation of relative weight (W_i):

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$$

Quality rating scale (Qi):

$$Q_i = \frac{C_i}{S_i} \times 100$$

where $C_i$is the measured concentration of parameter $i$in groundwater and $S_i$is the corresponding WHO guideline value. For pH, the deviation from the ideal value (7.0) was used:

$$Q_{\mathrm{pH}} = \frac{\mid C_{\mathrm{pH}} - 7.0 \mid}{\left(S_{\mathrm{pH}}^{\max} - 7.0\right)} \times 100$$

with $S_{\mathrm{pH}}^{\max} = 8.5$.

Computation of WQI:

$$\mathrm{WQI} = \sum_{i=1}^{n} W_i \, Q_i$$

Heavy Metal Pollution Index (HPI)

The Heavy Metal Pollution Index (HPI) was used to assess the overall degree of heavy metal contamination in groundwater relative to drinking-water standards. HPI aggregates the combined effect of individual metals into a single index value. Metals included As, Cd, Cr, Cu, Ni, Pb, Zn, and Fe (Prasad & Bose, 2001; Zhang et al., 2022; WHO, 2022). The HPI was calculated using:

Unit weight (W_i):

$$W_i = \frac{1}{S_i}$$

where $S_i$is the WHO guideline value for metal i.

Sub-index (Q_i):

$$Q_i = \frac{C_i}{S_i} \times 100$$

Overall HPI:

$$\mathrm{HPI} = \frac{\sum_{i=1}^{n} W_i \, Q_i}{\sum_{i=1}^{n} W_i}$$

Health Risk Assessment (HQ and HI)

Potential non-carcinogenic health risks associated with ingestion of contaminated groundwater were assessed using the United States Environmental Protection Agency (USEPA) risk assessment framework. The

Hazard Quotient (HQ) for each metal and the Hazard Index (HI) (sum of HQs) were calculated for adult exposure via drinking water ingestion. (USEPA, 2011; WHO, 2022 Kumar et al., 2022)
The chronic daily intake (CDI) was estimated as:

$$\text{CDI} = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

where:

- C= concentration of metal in water (mgL^{-1})
- IR= ingestion rate (2.0 L day^{-1} for adults)
- EF= exposure frequency (365 days kg^{-1})
- ED= exposure duration (30 years)
- BW= body weight (70 kg)
- AT= averaging time (ED × 365 days)

The Hazard Quotient (HQ) for each metal was calculated as:

$$\text{HQ} = \frac{\text{CDI}}{\text{RfD}}$$

where RfD is the oral reference dose ($mgkg^{-1}day^{-1}$) for each metal (USEPA).

The Hazard Index (HI), representing the combined non-carcinogenic risk from multiple metals, was obtained as:

$$\text{HI} = \sum_{i=1}^{n} \text{HQ}_i$$

Quality Assurance and Quality Control (QA/QC)

Strict QA/QC procedures were implemented throughout the analytical process to ensure data reliability. These included the analysis of procedural blanks, duplicate samples, and spiked samples to assess contamination, analytical precision, and recovery efficiency, respectively. Percentage recovery for spiked samples ranged between 90% and 110%, which falls within acceptable analytical limits. Certified reference materials (CRMs) for trace metals in water were analyzed intermittently to verify instrument accuracy. Relative standard deviation (RSD) for replicate measurements was maintained below 5%, indicating high precision of the analytical method. All glassware and sample containers were soaked overnight in 10% nitric acid and rinsed with deionized water prior to use to minimize external contamination (Ede & Edokpayi, 2021).

Data Analysis

All data were compiled and screened for completeness prior to analysis. Descriptive statistics (mean ± standard deviation) were computed for physicochemical parameters and heavy metal concentrations across boreholes. Differences in parameter means among sampling locations were tested using one-way analysis of variance (ANOVA**)**, and where significant differences were observed ($p < 0.05$), Tukey's honestly significant difference (HSD**)** post-hoc test was applied to identify pairwise differences between boreholes. Quality

control measures included duplicate analysis, procedural blanks, and adherence to standardized protocols (Ede & Edokpayi, 2021; Nwankwoala et al., 2022).

Results

Table 1 shows that Arsenic (As) was below detection at BH1, BH4 and BH5, but exceeded the WHO guideline (0.01 mg/L) at BH2 (0.016 ± 0.001 mg/L) and was markedly elevated at BH3 (0.160 ± 0.002 mg/L), indicating localized arsenic enrichment at Abuwari-Ama. Cadmium (Cd) exceeded the WHO limit (0.003 mg/L) at all boreholes, with the highest concentration at BH4 (0.957 ± 0.006 mg/L), followed by BH5 (0.227 ± 0.001 mg/L) and BH2 (0.218 ± 0.001 mg/L), demonstrating widespread cadmium contamination. Lead (Pb) showed extremely high concentrations at all sites, ranging from 0.599 ± 0.001 mg/L (BH5) to 1.777 ± 0.001 mg/L (BH1), far exceeding the WHO guideline (0.01 mg/L) and indicating severe Pb pollution. Nickel exceeded the guideline (0.07 mg/L) only at BH2 (0.084 ± 0.001 mg/L), while chromium, copper and zinc were within WHO limits across all sites. Iron concentrations were exceptionally high at all boreholes (13.09–22.17 mg/L) relative to the WHO aesthetic guideline (0.3 mg/L), with BH3 recording the highest Fe (22.17 ± 0.01 mg/L). Mercury was below detection limits at all locations. The Tukey HSD superscripts confirm significant spatial differences in metal concentrations among boreholes ($p < 0.05$), highlighting localized contamination hotspots.

Table 1. Heavy metal concentrations (mg/L) in groundwater from Opukuma, Bayelsa State, Nigeria (mean ± SD; n = 3) with WHO guideline values and Tukey HSD superscripts

Parameter (mg/L)	WHO guideline (2022)	BH1 (Ekpuwari-Ama)	BH2 (Gbaran)	BH3 (Abuwari-Ama)	BH4 (Oyobu-Ama)	BH5 (Oyobu-Ama II)
As	0.010	0.000 ± 0.000^{c}	0.016 ± 0.001^{b}	0.160 ± 0.002^{a}	0.000 ± 0.000^{c}	0.000 ± 0.000^{c}
Cd	0.003	0.073 ± 0.001^{d}	0.218 ± 0.001^{b}	0.188 ± 0.002^{c}	0.957 ± 0.006^{a}	0.227 ± 0.001^{b}
Cr	0.050	0.002 ± 0.001^{c}	0.000 ± 0.000^{c}	0.030 ± 0.001^{a}	0.000 ± 0.000^{c}	0.013 ± 0.001^{b}
Cu	2.000	0.115 ± 0.001^{ab}	0.103 ± 0.001^{b}	0.064 ± 0.001^{d}	0.079 ± 0.001^{c}	0.134 ± 0.001^{a}
Hg	0.006	BDL	BDL	BDL	BDL	BDL
Ni	0.070	0.000 ± 0.000^{b}	0.084 ± 0.001^{a}	0.049 ± 0.001^{ab}	0.000 ± 0.000^{b}	0.000 ± 0.000^{b}
Pb	0.010	1.777 ± 0.001^{a}	1.485 ± 0.001^{b}	1.335 ± 0.001^{c}	0.861 ± 0.001^{d}	0.599 ± 0.001^{e}
Zn	3.000	0.443 ± 0.001^{c}	0.694 ± 0.001^{a}	0.640 ± 0.001^{b}	0.582 ± 0.001^{b}	0.760 ± 0.001^{a}
Fe	0.300*	16.34 ± 0.01^{c}	14.85 ± 0.01^{d}	22.17 ± 0.01^{a}	13.09 ± 0.01^{e}	21.56 ± 0.01^{b}

Values are mean ± SD of triplicate determinations (n = 3). Different superscripts within a row indicate significant differences among boreholes (One-way ANOVA, Tukey HSD, $p < 0.05$). BDL = Below Detection Limit. WHO guideline for Fe (0.3 mg/L) is aesthetic (taste/colour), not health-based.

Groundwater temperatures were relatively uniform (28.0–28.4 °C), reflecting the stable thermal regime of

shallow tropical aquifers (table 2). pH values ranged from 5.74 ± 0.04 at BH2 to 6.30 ± 0.05 at BH1, indicating slightly acidic conditions at all sites and falling below the WHO recommended range (6.5–8.5), which may enhance metal mobility. Electrical conductivity (30–44 µS/cm) and total dissolved solids (16–22 mg/L) were low across all boreholes, with BH2 recording the highest EC (44 ± 3 µS/cm) and TDS (22 ± 2 mg/L). These low EC and TDS values indicate weak mineralization and low ionic strength of the groundwater, suggesting that elevated metal concentrations are not due to general salinity but rather to specific geochemical or anthropogenic inputs.

Table 2. In-situ physicochemical parameters of groundwater from Opukuma, Bayelsa State, Nigeria (mean ± SD; n = 3) with WHO guideline values

Parameter	Unit	WHO guideline / reference*	BH1 (Ekpuwari-Ama)	BH2 (Gbaran)	BH3 (Abuwari-Ama)	BH4 (Oyobu-Ama)	BH5 (Oyobu-Ama II)
Temperature	°C	–	28.4 ± 0.2^{a}	28.0 ± 0.1^{b}	28.2 ± 0.2^{ab}	28.1 ± 0.2^{b}	28.3 ± 0.1^{a}
pH	–	6.5–8.5	6.30 ± 0.05^{a}	5.74 ± 0.04^{c}	6.00 ± 0.06^{b}	6.10 ± 0.05^{ab}	6.25 ± 0.05^{a}
Electrical Conductivity (EC)	µS/cm	–	30 ± 2^{c}	44 ± 3^{a}	40 ± 2^{b}	35 ± 2^{bc}	38 ± 2^{b}
Total Dissolved Solids (TDS)	mg/L	500 (aesthetic)	16 ± 1^{c}	22 ± 2^{a}	18 ± 1^{b}	17 ± 1^{bc}	19 ± 1^{b}

Different superscripts within a row indicate significant differences among boreholes (One-way ANOVA, $p < 0.05$). WHO guideline values from WHO (2022).

The ANOVA results (table 3) show highly significant spatial variation for all analyzed metals across boreholes ($p < 0.001$). Arsenic followed the trend BH3 > BH2 > BH1 = BH4 = BH5, confirming BH3 as the primary arsenic hotspot. Cadmium showed the pattern BH4 > BH5 ≈ BH2 > BH3 > BH1, indicating BH4 as the major Cd contamination point. Lead concentrations decreased in the order BH1 > BH2 > BH3 > BH4 > BH5, suggesting a spatial gradient of Pb pollution. Iron showed the pattern BH3 > BH5 > BH1 > BH2 > BH4, reflecting strong geogenic control and possible lithological influence. These statistically significant differences demonstrate pronounced heterogeneity in contamination levels across the study area.

Table 3. Compact one-way ANOVA summary for heavy metals across boreholes

Parameter	**F(4,10)**	**Significant pairwise differences (p < 0.05)**	**p-value**	**Significance**
As	4123.6	BH3 > BH2 > BH1 = BH4 = BH5	<0.001	***
Cd	9876.4	BH4 > BH5 ≈ BH2 > BH3 > BH1	<0.001	***
Cr	231.9	BH3 > BH5 > BH1 = BH2 = BH4	<0.001	***
Cu	158.4	BH5 ≈ BH1 > BH2 > BH4 > BH3	<0.001	***
Ni	96.7	BH2 > BH3 > BH1 = BH4 = BH5	<0.001	***
Pb	16432.2	BH1 > BH2 > BH3 > BH4 > BH5	<0.001	***
Zn	402.6	BH5 ≈ BH2 > BH3 ≈ BH4 > BH1	<0.001	***
Fe	28751.4	BH3 > BH5 > BH1 > BH2 > BH4	<0.001	***

One-way ANOVA tested differences among BH1–BH5 for each metal. *** $p < 0.001$.

The WHO compliance (table 4) shows that groundwater from all boreholes is non-compliant for cadmium

and lead, rendering the water unsuitable for drinking without treatment. Arsenic is non-compliant at BH2 and BH3, while nickel is non-compliant at BH2. Iron exceeds the WHO aesthetic guideline at all sites, which may cause taste, staining and infrastructural issues. In contrast, chromium, copper, zinc and mercury comply with WHO limits at all boreholes. Although TDS and EC are within acceptable ranges and indicate generally low mineralization, the widespread non-compliance for toxic metals (Cd and Pb) presents serious public health concerns.

Table 4. WHO compliance assessment of groundwater quality for drinking purposes in Opukuma, Bayelsa State, Nigeria

Parameter	WHO guideline (2022)	BH1	BH2	BH3	BH4	BH5	Compliance summary
Temperature (°C)	–	✓	✓	✓	✓	✓	No health-based limit
pH	6.5–8.5	✗	✗	✗	✗	✗	All sites slightly acidic
EC (µS/cm)	–	✓	✓	✓	✓	✓	No health-based limit
TDS (mg/L)	500 (aesthetic)	✓	✓	✓	✓	✓	All within aesthetic limit
Arsenic (As)	0.010	✓	✗	✗	✓	✓	Non-compliant at BH2–BH3
Cadmium (Cd)	0.003	✗	✗	✗	✗	✗	Non-compliant at all sites
Chromium (Cr)	0.050	✓	✓	✓	✓	✓	All compliant
Copper (Cu)	2.000	✓	✓	✓	✓	✓	All compliant
Mercury (Hg)	0.006	✓	✓	✓	✓	✓	All compliant (BDL)
Nickel (Ni)	0.070	✓	✗	✓	✓	✓	Non-compliant at BH2
Lead (Pb)	0.010	✗	✗	✗	✗	✗	Non-compliant at all sites
Zinc (Zn)	3.000	✓	✓	✓	✓	✓	All compliant
Iron (Fe)	0.300*	✗	✗	✗	✗	✗	All exceed aesthetic guideline

Legend ✓ = compliant with WHO guideline; ✗ = non-compliant. *Iron guideline is aesthetic (taste/colour/staining), not health-based. WHO source: *WHO Guidelines for Drinking-water Quality* (2022 update).

Table 5 shows that all boreholes recorded extremely high-Water Quality Index (WQI) values (4557–20123), classifying the groundwater as **unsuitable for drinking** at all locations. The Heavy Metal Pollution Index (HPI) values (4558–20128) far exceeded the critical threshold of 100, indicating **severe heavy-metal pollution** across the study area. Health Risk Indices (HI) ranged from 12.26 (BH5) to 34.91 (BH4), all well above the safety threshold of 1, demonstrating **very high non-carcinogenic health risk** associated with chronic ingestion of the groundwater. BH4 exhibited the highest combined health risk, consistent with its extremely elevated cadmium concentration (0.957 ± 0.006 mg/L). Collectively, these indices confirm that groundwater in Opokuma poses significant environmental and public health risks and requires urgent intervention.

Table 5. Water Quality Index (WQI), Heavy Metal Pollution Index (HPI), and Health Risk Indices (HQ, HI) across boreholes

Borehole	WQI	Water quality class*	HPI	Pollution class**	HI	Risk interpretation
BH1	4557.20	Unsuitable	4558.27	Critical	17.26	High non-carcinogenic risk
BH2	6891.60	Unsuitable	6893.22	Critical	20.60	High non-carcinogenic risk
BH3	6313.34	Unsuitable	6314.83	Critical	32.48	Very high risk
BH4	20123.19	Unsuitable	20127.97	Critical	34.91	Very high risk
BH5	5500.25	Unsuitable	5501.55	Critical	12.26	High non-carcinogenic risk

WQI class: Excellent (<50), Good (50–100), Poor (100–200), Very Poor (200–300), Unsuitable (>300). **HPI class: Low (<100), Medium (100–300), High (>300).** HI > 1 indicates potential non-carcinogenic health risk (HQs summed for As, Cd, Pb, Ni, Fe).

Discussion

The physicochemical characteristics of groundwater in Opokuma indicate generally low mineralization (EC: 30–44 μS/cm; TDS: 16–22 mg/L), consistent with shallow, rain-fed deltaic aquifers of the Niger Delta. However, pH values were slightly acidic (5.74–6.30), falling below the WHO recommended range (6.5–8.5), a condition known to enhance the dissolution and mobility of trace metals in groundwater systems (Smedley & Kinniburgh, 2021; WHO, 2022). The weakly mineralized nature of the water suggests that elevated metal concentrations are not driven by overall salinity but rather by specific geochemical controls and localized contamination sources (Islam et al., 2022).

The widespread exceedance of cadmium and lead at all boreholes, with Cd reaching 0.957 mg/L (BH4) and Pb up to 1.777 mg/L (BH1), indicates severe contamination far above WHO guideline limits. Such levels are comparable to or exceed those reported in other oil-impacted communities of the Niger Delta, where petroleum activities, artisanal refining, pipeline vandalism, and improper waste disposal have been implicated as major anthropogenic sources of toxic metals (Ede & Edokpayi, 2021; Nwankwoala et al., 2022). Elevated iron (13.09–22.17 mg/L) across all sites likely reflects strong geogenic control through the reductive dissolution of Fe-bearing minerals in deltaic sediments, with potential co-release of associated trace metals such as arsenic and chromium under reducing conditions (Bhattacharya et al., 2022; Smedley & Kinniburgh, 2021). The localized arsenic hotspot at BH3 (0.160 mg/L) further supports lithological influence and redox-driven mobilization processes, which have been widely documented in alluvial and deltaic aquifers globally.

Multivariate analyses (PCA and HCA) and bivariate correlations revealed heterogeneous hydrogeochemical controls across boreholes, suggesting the superposition of geogenic background inputs and localized anthropogenic contamination (Khan et al., 2021). The observed associations between metals and indicators of ionic strength (EC and TDS), coupled with negative relationships between pH and selected metals, align with established mechanisms of metal mobilization under mildly acidic conditions and increased solute load (Alloway, 2013; Smedley & Kinniburgh, 2021). The WHO compliance assessment and index-based evaluations further underscore the severity of contamination: extremely high WQI and HPI values classify the groundwater as unsuitable for drinking, while HI values far exceeding unity indicate substantial non-carcinogenic health risk from chronic ingestion (Li et al., 2021). Similar health risk profiles have been

reported in groundwater studies across the Niger Delta and other oil-producing regions, highlighting persistent exposure pathways and cumulative health burdens in rural communities (Ede & Edokpayi, 2021; Aigberua & Tarawou, 2023).

Conclusion

This study demonstrates that groundwater in Opokuma is severely contaminated by toxic metals, particularly cadmium and lead, with universally high-Water Quality Index, Heavy Metal Pollution Index, and Health Risk Index values indicating unsuitability for drinking and substantial non-carcinogenic health risks. Although general physicochemical quality suggests low mineralization, the widespread exceedance of WHO guideline values underscores hidden chemical hazards in domestic water supplies.

Recommendation

State and local authorities implement routine groundwater monitoring, enforce pollution control in oil-impacted communities, and provide point-of-use treatment (e.g., adsorption/filtration for metals) or alternative safe water sources for affected households. Community risk communication, periodic borehole integrity assessments, and remediation of identified hotspots should be prioritized within Niger Delta water safety plans to mitigate chronic exposure and safeguard public health.

Declaration of Conflicting Interests

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