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Heavy Metal Contamination and Human Health Risk Assessment of Groundwater in Osubi, and it environ, Delta State, Nigeria

[1]**W.O. Osisanya**, [2]**Y.S. Onifade**, [3]**T.A Auta**; [4]**H.S. Ukulu**

[1,2]Department of Physics, Federal University of Petroleum Resources, Effurun Delta State, Nigeria.
[3]Petroleum Analysis Laboratory Department, Petroleum Training Institute, Effurun, Delta State, Nigeria.
[4]Department of Chemistry, College of Education, Warri, Delta State.

***Corresponding author Email**: wasiu.osisanya@uniben.edu
ORCID: 0000-0001-7280-9771

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Competing Interests.

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ABSTRACT

This study evaluated the concentrations and potential health risks of selected heavy metals in groundwater resources within Osubi, Delta State, Nigeria, a rapidly urbanizing region influenced by industrial, domestic, and oil-related activities. Groundwater samples were analyzed for Fe, Mn, Zn, Cr, Cd, Ni, Pb, and B, and the results were assessed using contamination indices (Cf, PLI, DOC, MPI) and multivariate statistical tools (CM, ICM, PCA, CSC, TVE). The findings revealed that the concentrations of the studied metals were largely below critical contamination thresholds, with spatial mapping highlighting localized hotspots near Osubi Airport, Winner Chapel Osubi, Usman, BM, and CNAW. Health risk assessment showed that hazard quotient (HQ) values for both children and adults were all below 1, indicating no immediate non-carcinogenic risks. However, children exhibited higher HQs than adults due to their greater intake per unit body weight, underscoring their heightened vulnerability. While Fe, Mn, and Zn were present at non-hazardous levels, Cr, Cd, and Pb, although below threshold values, require close monitoring because of their toxicity and cumulative effects. Weak inter-metal correlations suggest multiple diffuse sources, likely from anthropogenic activities such as waste disposal and effluent discharge. Overall, the study indicates low to negligible pollution levels in Osubi groundwater but emphasizes the need for proactive measures, including regular monitoring, simple household water treatment practices, improved public awareness, and stricter regulation of industrial discharges to safeguard groundwater quality. Sustaining these relatively low contamination levels is critical for ensuring long-term water safety and public health in the Osubi community.

Keywords. Groundwater quality, Heavy metals, Hazard Quotient, Pollution index, Osubi, Nigeria

1. Introduction

Water is utilized by humans from a range of sources for numerous everyday activities, encompassing domestic, agricultural, and industrial purposes. Each of these applications, however, is governed by distinct water quality classifications that dictate their suitability. Groundwater is a significant contributor to water resources and is readily accessible in many nations (Akakauru, et al., 2025; Eyankware and Ephraim, 2021). In numerous developing countries, subsurface water is the primary source of drinking water (Esi, et al., 2025). As noted by Eyankware and Akakuru, 2022 groundwater serves as the drinking water source for over 20% of the global population. Conversely, surface water, which can act as a supplementary source when hand-dug wells and boreholes provide inadequate water, is not universally available and is considerably more susceptible to contamination than groundwater sources (Akakuru, et al., 2023; Eyankware, et al., 2023). Water is utilized by humans from a range of sources for numerous daily activities, such as those related to households, agriculture, and manufacturing. Each of these applications, however, has its specific water quality classification that assesses its suitability. Groundwater is a significant water resource and is readily accessible in many nations (Eyankware, et al., 2022a). In numerous developing countries, subsurface water constitutes the primary source of drinking water (Obasi, et al., 2021). Moreover, surface water resources are severely polluted. But deficiencies in water supply and sanitation services have caused several problems like slower urban economic growth and social unrest. To meet the increasing water demand, Dhaka Water and Sewerage Authority (DWASA) installs deep tube wells every year. Thus, due to the huge extraction of groundwater from the existing aquifers, the level of groundwater is declining at an alarming rate. As noted by Kim and Park

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(2016), more than 20% of the global population relies on groundwater for drinking purposes. Surface water, which can serve as a supplementary source for inadequate supplies from hand-dug wells and boreholes, is not universally available and is notably more susceptible to contamination compared to groundwater sources (Sorensen et al. 2015; Mbaka et al. 2017; Mazhar et al., 2019).Nevertheless, unsanitary habits such as laundering clothes, disposing of animal waste, and engaging in open defecation near groundwater sources represent significant threats to these water supplies and are major contributors to the reduction of drinkable water (Eyankware, et al. 2022b). Consequently, it is imperative for environmental scientists and policymakers to prioritize the protection of existing groundwater resources, as the quality of water is equally as crucial as its quantity (Singh and Singh 2018). Various contaminants can infiltrate water bodies from both natural and human-induced sources, diminishing the availability of potable water for communities and increasing the health risks associated with consuming contaminated water.

Metals constitute an essential component of the Earth's crust; however, their concentrations in water and porous environments, such as soil and sediment, raise significant concerns among conservationists. This is primarily due to their hazardous nature, non-biodegradable characteristics, and persistent presence in the environment (Eyankware and Ephraim, 2021; Giri and Singh 2019; Shah et al. 2019; Kumar et al. 2020). Heavy metals (HMs) refer to a category of metals and metalloids distinguished by specific gravities exceeding 5 and atomic densities greater than 4 g/cm3 (Barzegar et al. 2015; Ganiyu et al. 2017; Enuneku et al. 2018; Kumar et al. 2020c). These heavy metals can originate from both natural geological processes and anthropogenic activities, leading to their presence in water sources (Eyankware and Obasi, 2021). Heavy metals (HMs) can enter the human body through several pathways, including inhalation, skin contact, and ingestion (Olujimi et al. 2014; Igwe, et al.., 2021; Kumar et al. 2020b). It is important to recognize that only a limited number of these metals, present in trace amounts, are essential for various biochemical processes within the human body (Singh et al. 2011; Selvam et al. 2017; Shankar 2019; Kumar et al. 2020a, b, c). Due to their extended biological half-lives, the majority of heavy metals, including Cd, As, Pb, Mn, Fe, Cr, and Hg, represent a substantial risk to the proper functioning of human tissues, potentially leading to a range of diseases (Suvarapu and Baek 2017; Barzegar et al. 2019). For example, lead (Pb) is identified as the second most hazardous metal following arsenic (As), constituting 0.002% of the Earth's crust (Arias et al. 2010; Kumar et al. 2020a). In various regions, groundwater can become contaminated with arsenic due to either natural geological processes or human activities (Pal et al. 2020; Kumar et al. 2021). A significant number of individuals living in multiple countries are reported to be at risk of consuming arsenic-laden groundwater (Ravindra and Mor 2019; Kumar et al. 2021). The advancement of industrial development significantly simplifies human life, thanks to substantial strides in scientific and technological innovation. Nevertheless, as global development progresses, it introduces new obstacles related to environmental protection and conservation (Eyankware, et al., 2022). Furthermore, activities associated with development frequently contribute to environmental pollution (Eyankware, et al., 2018). Similarly, the detrimental effects of industrial pollution on the environment can result in irreversible harm to nature. Consequently, there is a rising concentration of heavy metals in water bodies (Odesa, et al., 2025; Igwe, et al.,2022), where industrial wastewater releases numerous hazardous chemical substances that have the potential to accumulate in the soil and sediment of these water systems (Eyankware, et al., 2024; Onwe, et al., 2022). More than 50 elements can be classified as heavy metals, with 17 of these being identified as highly toxic and relatively prevalent (Singh et al. 2011). Nriagu (1992) notes that approximately 90% of heavy metal emissions attributable to human activity have taken place since the year 1900 AD.

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The release of these toxic substances into the environment results in a range of harmful effects on living organisms (Eyankware, et al., 2018; Dembitsky 2003). Although several heavy metals are essential for the body in trace amounts, they can become harmful at elevated levels (Singh et al. 2011). The detrimental effects linked to heavy metal toxicity include impairments to mental and central nervous system functions, as well as disruptions in blood composition, which can severely impact crucial organs like the kidneys and liver (Prasanna, et al. 2016). Several heavy metals, including lead (Pb), chromium (Cr), cadmium (Cd), and nickel (Ni), play significant roles in various industrial processes. For instance, in 2012, global production of Pb reached approximately 10.54 million tons, with 85.1% allocated for batteries, 5.5% for pigments, 3.6% for rolled and extruded products, 1.4% for ammunition, 1.3% for alloys, 0.9% for cable sheathing, and the remaining 2.1% classified as miscellaneous (ILA 2017). Tetraethyl and tetramethyl lead are particularly noteworthy due to their widespread application as antiknock agents in gasoline (Quinn and Sherlock 1990). In industrial settings, chromium is employed in the production of steel, electroplating, pigments and dyes, wood preservation, tanning, foundry operations, and as a catalyst in hydrocarbon processing, among other uses Cadmium and nickel are predominantly utilized within the battery manufacturing and metal electroplating sectors (Singovszka, et al., 2017; Onwe, et al., 2024). The process of industrialization in Bangladesh has resulted in the contamination of both surface water and groundwater across various regions of the nation. In Osubi, the zones affected by water pollution are primarily situated within the heavily industrialized areas.

2. Location, climate and Accessibility

Osubi is a town found within the Okpe Local Government Area of Delta State, Nigeria. This town is positioned in the broader Warri metropolitan region and hosts the Osubi Airstrip, commonly referred to as Warri Airport. The airport caters to the transportation needs of both Effurun and Warri. Osubi maintains elevated temperatures throughout the year, typically reaching average maximums of approximately 29°C and minimums of about 25°C. Notably, the peak temperature recorded during the timeframe spanning from April 19 to May 18, 2025, occurred on April 19, when it climbed to 31.23°C. The study area represents a growing urban center that has experienced swift urbanization, industrial growth, and significant infrastructural advancements. These developments can be attributed to the existence of the Warri Airport (commonly referred to as Osubi Airstrip), a notable educational facility in the area, as well as its closeness to the key oil-producing regions of Nigeria's Niger Delta (Ofomola, 2015). As a consequence, a variety of anthropogenic activities have emerged, including the indiscriminate disposal of industrial and domestic waste materials, as well as the release of untreated effluent onto land from multiple sources.

2.1. Geology of the Study Area

2.1.1. Location and Geology of the Study Area

According to the 2006 national census, its population is estimated to exceed 8,000 residents. The region being examined is encompassed within the Niger Delta Province, with its geological characteristics having been investigated by various scholars (Asseez, 1989; Reyment, 1965; Short and Stauble, 1967; Murat, 1970; Merki, 1970). The topography of the Osubi area is predominantly flat, with a slight inclination towards the sea (Akpokodje and Etu Efeotor, 1987), and it is underlain by the Quaternary sands of the low-lying physiographic province known as the Sombriero deltaic plain (see Fig. 1). As noted by Wigwe (1975) and Olobaniyi and Owoyemi (2006), this geological formation comprises unconsolidated sands ranging from fine to medium and coarse-grained varieties, frequently containing feldspar in quantities of 30 to 40 wt %, with occasional gravel presence.

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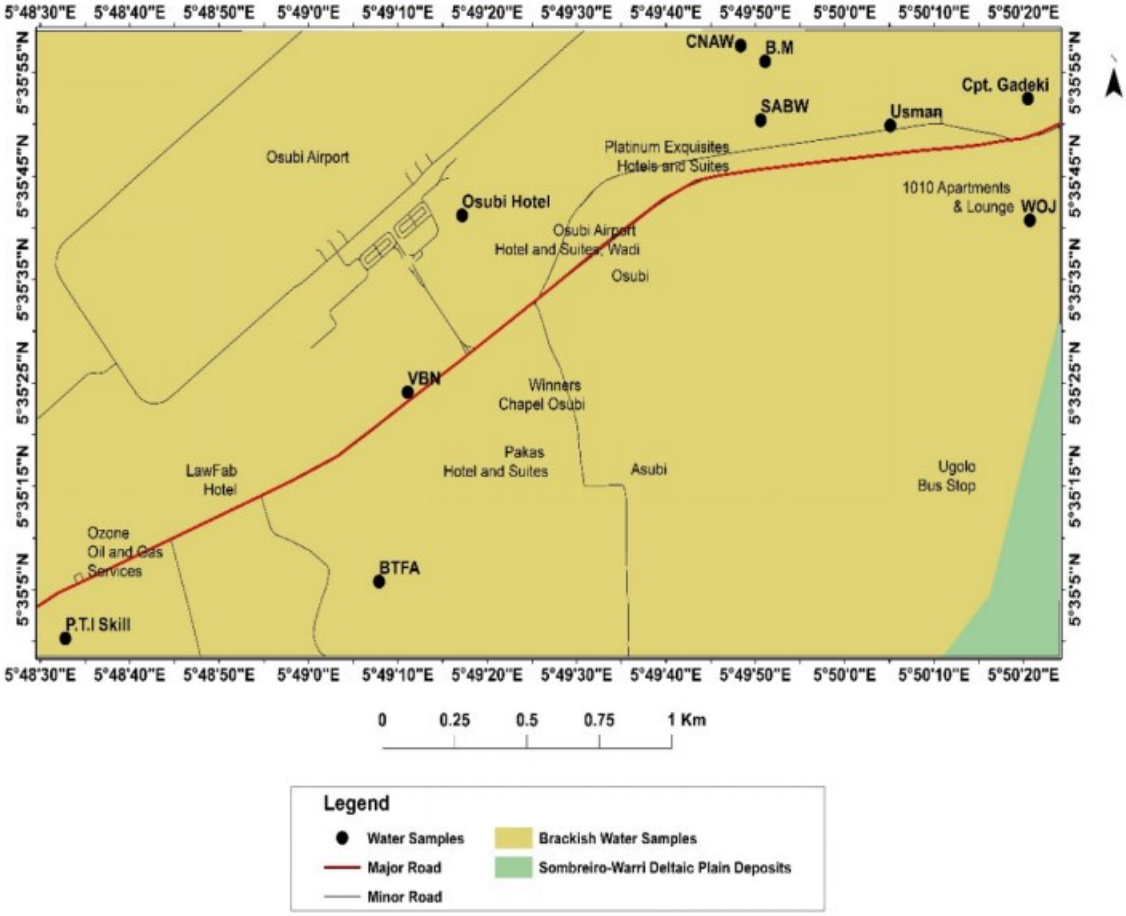

Fig. 1: Geology of the study area showing groundwater sampling points

The landscape is predominantly flat, exhibiting a gentle incline towards the north and northeast with a gradient of approximately 1:960 (Odemerho and Ejemeyovwi, 2007), where the elevation remains below 20 meters above sea level. Key characteristics of the region include the shallow depth of aquifers, with the water table fluctuating between 0 to 4 meters, a generally flat terrain, substantial annual rainfall, and soils that are highly permeable. These factors result in minimal runoff at the site and suggest that the majority of rainfall is retained within the soil. This improves the decomposition processes carried out by bacteria and fungi, as well as facilitates the leaching of pollutants into the aquifer (Olobaniyi and Owoyemi, 2006).

2.1.2. Hydrogeology of the study area

These practices directly endanger the shallow aquifers within the study area and pose significant risks to human health overall. It is widely acknowledged that pollutants resulting from human activities—whether from non-point sources or dispersed point sources—can ultimately infiltrate groundwater, leading to its contamination.

3. Methods and materials

3.1. Laboratory analysis

Upon collection, the samples were stored in polypropylene beakers for subsequent analysis. Prior to the field sampling procedure, the beakers and containers designated for sample collection underwent thorough cleaning and were soaked in distilled water, which had been acidified with 1.0 ml of HNO_3, for a duration of three (3) days. A systematic approach led to the collection of 10 water samples from diverse water sources throughout the nation.

In order to ensure that the samples accurately reflected the quality of the water resources, borehole samples were obtained following a pumping period of 5–10 minutes. Following the rinsing of the bottle with the aliquot, each sample was filtered into a designated sample bottle using disposable filters with a diameter of 0.45 m, ensuring the complete removal of all suspended contaminants. To reduce the precipitation of heavy metals (HM), the samples were acidified in the field with 1.0 ml of concentrated HNO3; to prevent sorption, new syringes were utilized for the addition of three drops of HNO3. The collected samples were then stored in ice-packed beakers, which were securely sealed, at a temperature of 4 °C. During transportation to the analytical laboratory, efforts were made to maintain a constant temperature to avoid evaporation (Singh et al. 2005; Sehgal et al. 2012). The chemical analysis of the samples was conducted utilizing a fast sequential (FS) atomic absorption spectrophotometer (Varian 240 AA) to detect heavy metals, including Fe, Mn, Zn, Cr, Cd, Ni, Pb, and B.

3.2. Heavy metal Index

3.2.1. Contamination factor (CF)

The CF was calculated using the Hakanson

(1980) formula

$$\mathrm{CF} = \frac{C_n}{B_n} \qquad (1)$$

Where: Cn is the metal concentration, Bn is the background/target value (Eyankware and Akakuru, 2022).

3.2.2. Pollution Load Index (PLI)

Hakanson's (1980) formula was used to calculate the PLI.

$$\mathrm{PLI} = \sqrt[n]{CF1 \times CF2 \times} CF3 \times \ldots \times CFn \qquad (2)$$

3.2.3. The Metal Pollution Index (MPI), which estimated the aggregate impact of individual heavy metals on water quality (Horton, 1965; Mohan et al., 1996), was evaluated using Caeiro et al., (2005) Equation 3:

$$MPI = \sqrt[n]{M_1 \times M_2 \times M_3\_\_\_\_\_\_\_\_} \ \mathrm{Mn} \qquad (3)$$

where *Mn* = concentration of the metal.

3.2.4. Degree of contamination DoC

The degree of contamination (DoC) is calculated using the formula shown in Equation (4).

$$\sum Cf_{Ni} + Cf_{cr} + Cf_{cd} + Cf_{pb} + Cf_{zn} + Cf_{cu} + Cf_{mn} + Cf_b \quad + \qquad (4)$$

The DoC is classed as DoC < 8 (low risk), 8 ≤ DoC < 16 (moderate risk), 16 ≤ DoC < 32 (considerable risk) and DoC ≥ 32 (very high risk). (Hakanson 1980, Custodio et al, 2021).

3.2.5. Geo-accumulation index (Igeo)

$$I_{geo} = log_2\left({}^{C_n}/_{kB_n}\right) \qquad 5$$

As proposed by Muller, (1979)

In this context, Cn represents the quantified concentration (μg g^{-1}) of element n, while Bn indicates the geochemical

3.2.6. Statistical analyses

The evaluation of the studied parameters was conducted using principal component analysis (PCA), Pearson correlation analysis, contamination metrics, and metal pollution indices. Within the framework of PCA, the process of component loading involved condensing a vast dataset encompassing numerous variables into a limited set of linear combinations that represented a significant portion of the overall data variance. This method facilitated a straightforward association of the variables with their respective sources or processes, as illustrated in Equation (6).

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (X_{N-} N)^2 \qquad (6)$$

When Xi represents the statistical mean, I represents the intervals between variables, and N represents the number of outcomes 2.

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The modeling of concentration distribution and dispersion patterns in the area was conducted utilizing Microsoft Excel and Surfer 12 software. The results obtained were compared against the guidelines set forth by the World Health Organization (WHO). Additionally, Pearson's correlation coefficient was computed with the aid of version 23 of the Statistical Package for Social Sciences (SPSS).

4. Results and Discussion

Assessment of heavy metal pollution has emerged as a critical environmental concern. This is attributed to the detrimental effects of drinking water tainted with heavy metals. To facilitate a clear comprehension of both the pollution index and the extent of contamination, the heavy metal evaluation index is employed (Odesa, et al., 2025; Prasanna et al. 2012).

4.1. Contamination Factor (Cf)

In the field of groundwater research, the contamination factor (CF) has been employed to determine the concentration ratio of heavy metals relative to background values. The criteria used to characterize the values of the contamination factor are outlined as follows: if CF < 1, it's low contamination; 1 ≤ CF < 3, it's moderate contamination; 3 ≤ CF < 6, significant contamination; CF > 6, and very high contamination. (Akakuru et al., 2017; Bhutian et al., 2017). The contamination factor (Cf) presented in Table 2, of this study indicates C.F for Fe indicates moderated contaminated except streets CG, WOJ and PTI skill which reflect low contamination. The C.F for Cr are all moderatedly contaminated except at streets SA, which is low contamination. C.F for Pb are all moderately contaminated except streets SA and CN which indicate low contamination. Meanwhile, all C.F for Mn, Zn, Cd, Ni and B sh3eeow low contamination.

4.2. Degree of concentration (DoC)

Degree of concentration denotes the quantity of that specific metal found within a certain sample—be it water, soil, or biological tissue. This quantity is generally quantified in units such as milligrams per liter (mg/L) or milligrams per kilogram (mg/kg). These measured concentrations are then evaluated against defined safety or toxicity thresholds, as outlined by organizations like the World Health Organization (WHO) or the U.S. Environmental Protection Agency (EPA), in order to determine possible hazards to human health and ecological systems. Deductions from DoC in Table 2, suggested that all the water samples collected from all the streets are at low risk based on the fact that the values are DoC < 8. Although the result from the finding is contract to result obtained elsewhere in Biseni community, Bayelsa state, Niger Delta, Nigeria (Aigberua, 2021).

4.3. Pollution load index (PLI)

PLI has demonstrated its effectiveness as a valuable tool for assessing the overall level of toxicity in contaminated groundwater samples (Eyankware, et al., 2024; Agidi et al. 2022; Eyankware and Akakuru 2022). PLI is typically classified as having no pollution (PLI < 1), moderate pollution (1 < PLI < 2), heavy pollution (2 < PLI < 3), or extremely heavy pollution (3 > PLI). According to the results in Tables 2. Deductions from Table 2, suggested that the value of PLI ranges from 0.07 to 0.29, with average value of 0.179. According to the findings presented in Table , the concentration value of groundwater in the study area was recorded as being less than one. This indicates the absence of pollution. These results are at odds with those of research conducted in India (Bhutian et al., 2017; Gopinath et al., 2019), yet they align with the findings from Nigeria as reported by Yahaya et al. (2021).

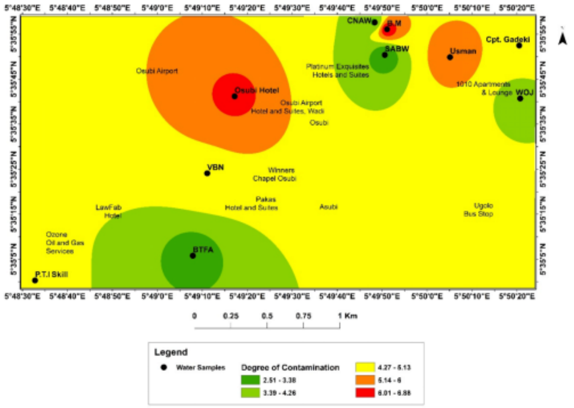

Fig. 2: Spatial distribution of DOC within the study area

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Table 1: Concentration (mg/kg) of heavy metals in water samples within the study area

Sample site	Latitude	Longitude	Fe	Mn	Zn	Cr	Cd	Ni	Pb	B
Usman	05^0 35’ 49.9”	05^0 50’ 5.1”	0.301	0.148	0.244	0.093	0.014	0.006	0.02	0.012
CG	05^0 35’ 52.5”	05^0 50’ 20.5”	0.294	0.123	0.222	0.087	0.012	0.005	0.016	0.014
WOJ	05^0 35” 40.72’	05^0 50” 20.72’	0.27	0.092	0.193	0.061	0.009	0.003	0.011	0.013
P.T.I Skill	05^0 35’ 0.3”	05^0 48 ’ 32.8”	0.281	0.11	0.201	0.074	0.01	0.003	0.013	0.011
OAH	05^0 35’ 41.2”	05^0 49’ 17.2”	0.311	0.167	0.254	0.11	0.015	0.007	0.02	0.012
B.M	05^0 35’ 56.1”	05^0 49’ 51.1”	0.351	0.188	0.26	0.123	0.017	0.008	0.021	0.01
BTF	05^0 35’ 5.8”	05^0 49’ 07.9”	0.342	0.001	0.224	0.059	0.001	0.032	0.001	0.015
SA	05^0 35’ 50.4	05^0 49’ 50.6”	0.313	0.001	0.193	0.043	0.001	0.028	0.001	0.01
CN	05^0 35’ 57.61”	05^0 49’ 48.36”	0.365	0.001	0.215	0.062	0.001	0.036	0.001	0.013
VBN	05^0 35’ 24.1”	05^0 49.’ 11.1”	0.487	0.001	0.297	0.074	0.001	0.048	0.011	0.017
WHO			0.3	0.5	3	0.05	0.003	0.07	0.01	2.4
Max.			0.487	0.188	0.297	0.123	0.017	0.048	0.021	0.017
Min.			0.27	0.001	0.193	0.043	0.001	0.003	0.001	0.01
Aveg.			0.339333	0.085083	0.23275	0.079333	0.00825	0.018917	0.011417	0.012833
CONTROL POINT										
Fupre			0.223	0.084	0.18	0.056	0.007	0.002	0.01	0.011

Table 2: Results of Contamination Factor (Cf), Degree of Concentration (DoC), Pollution Load Index (PLI), and Metal Pollution Index (MPI)

STREET	Fe (CF1)	Mn (CF2)	Zn (CF3)	Cr (CF4)	Cd (CF5)	Ni(CF6)	Pb(CF7)	B(CF8)	DOC	PLI	MPI
Usman Us	1.003333	0.296	0.081333	1.86	0.4666	0.0857	2	0.005	5.798	0.2551	0.046094
CG	0.98	0.246	0.074	1.74	0.4	0.0714	1.6	0.0058	5.1173	0.2316	0.041837
WOJ	0.9	0.184	0.064333	1.22	0.3	0.0429	1.1	0.0054	3.8166	0.17773	0.032106
P.T.I Skill	0.936667	0.22	0.067	1.48	0.3333	0.0429	1.3	0.0046	4.3844	0.1905	0.034425
OAH	1.036667	0.334	0.084667	2.2	0.5	0.1	2	0.005	6.2603	0.2745	0.049589
B.M	1.17	0.376	0.086667	2.46	0.5666	0.11429	2.1	0.0041	6.8778	0.2922	0.052785
BTF	1.14	0.002	0.074667	1.18	0.0333	0.4571	0.1	0.006	2.9934	0.08132	0.014691
SA	1.043333	0.002	0.064333	0.86	0.0333	0.4	0.1	0.0041	2.5071	0.074	0.012815
CN	1.216667	0.002	0.071667	1.24	0.033	0.5143	0.1	0.0054	3.1834	0.0818	0.01478
VBN	1.623333	0.002	0.099	1.48	0.0333	0.6857	1.1	0.0070	5.0305	0.1306	0.023595

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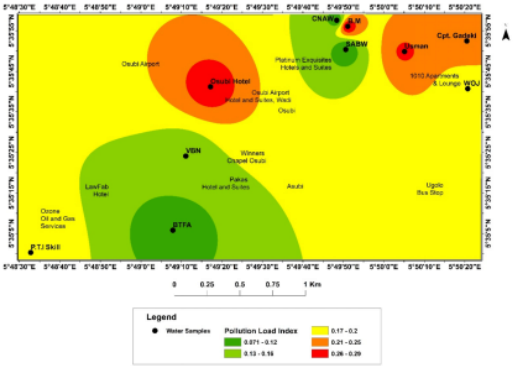

Fig. 2: Spatial distribution of PLI within the study area

4.4. Metal pollution index (MPI)

The MPI has been established as an essential instrument for classifying groundwater quality. Water samples that exhibit an MPI of 0.3 or below are designated as Very Pure, while those with an MPI ranging from 0.3 to 1.0 are considered Pure. Samples falling within the 1.0 to 2.0 MPI range are categorized as minimally impacted, corresponding to Class III, whereas those in Class IV and moderately affected with an MPI of 2.0–4.0. Water with an MPI between 4.0 and 6.0 is classified as significantly affected, placing it in Class V, and samples exceeding an MPI of 6.0 are regarded as seriously affected in Class VI (refer to Table 12). As indicated by the MPI data in Table 2, the groundwater sample from the study area registers a value of less than 0.3, confirming its classification in Class I and its status implies pure.

4.5. Index of Geo-accumulation (Igeo)

In order to check the level of contamination of elements concentrations in sediment, water, dust, and soil, Muller (1979) created the index of geoaccumulation (Igeo), which has been widely used in evaluating their pollution status globally (Hazzeman et al., 2017). The classifcations of (Igeo) and their respective interpretations are Igeo ≤ 0 (practically unpolluted), 0 <Igeo ≤ 1 (unpolluted to moderately polluted), 1 <Igeo ≤ 2 (moderately polluted), 2 <Igeo ≤ 3 (moderately to strongly polluted), 3 <Igeo ≤ 4 (strongly polluted),4 <Igeo ≤ 5 (strongly to extremely polluted), and Igeo ≥ 5 (extremely polluted) (see Table 3), (Osisanya et al,. 2024). Igeo for Mn, Zn, Ni and B fall between 0 and 1 which implies they vary from Unpolluted to Moderately polluted, Meanwhile, Igeo for Fe at VBN; Cr at Usman, CG, OAH and BM;and Pb at Usman, CG, OAH and BM vary between 1 and 2 which connote that they are moderately polluted the rest of their values fall between 0 and 1 which connotes that they are Unpolluted to Moderately polluted. Igeo for Cd at Usman, OAH and BM fall between 3 and 4 which implies strongly polluted. The values at CG, WOJ and PTI skill fall between 2 and 3 which implies modertely to strongly polluted while the rest value within the street fall betweeb 0 and 1 which implies Unpolluted to Moderately polluted.

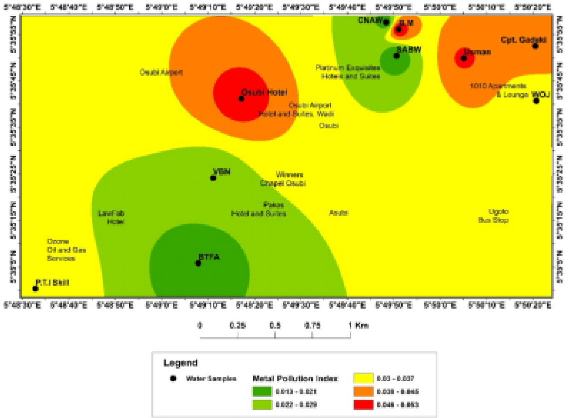

Fig. 3: Spatial distribution of MPI within the study area

4.6. Statistical Approach

4.6.1. Pearson correlation matrix

In groundwater research, a Pearson correlation matrix serves as an essential instrument for examining the interrelations among various hydrogeochemical parameters. It facilitates the determination of the strength and direction of linear correlations between factors and diverse ion concentrations, thereby uncovering potential sources and mechanisms that influence groundwater quality (Osisanya et al., 2025). The findings indicate correlations within the following pairs: Zn and Fe (0.7564), Ni and Fe (0.8302), B and Fe (0.6054), Cr and Mn (0.8627), Cd and Mn (0.9992), Pb and Mn (0.9261), Cr and Zn (0.58797), Pb and Zn

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Table 3: Results of Geoaccumulation Index (Igeo)

Str.	Fe	Mn	Zn	Cr	Cd	Ni	Pb	Boron
Usman	0.6689	0.1973	0.0542	1.24	3.1111	0.0571	1.3333	0.0033
Capt.	0.6533	0.164	0.0493	1.16	2.6667	0.047619	1.066667	0.003889
WOJ	0.6	0.1227	0.0429	0.813333	2	0.028571	0.733333	0.003611
P.T.I	0.6244	0.1467	0.0447	0.986667	2.222222	0.028571	0.866667	0.003056
Osubi	0.6911	0.2227	0.0564	1.466667	3.333333	0.066667	1.333333	0.003333
B.M	0.78	0.2507	0.0578	1.64	3.777778	0.07619	1.4	0.002778
BTFA	0.76	0.0013	0.04978	0.786667	0.222222	0.304762	0.066667	0.004167
SABW	0.6956	0.001333	0.0429	0.573333	0.222222	0.266667	0.066667	0.002778
CNAW	0.8111	0.0013	0.047778	0.826667	0.222222	0.342857	0.066667	0.003611
VBN	1.0822	0.00133	0.066	0.986667	0.222222	0.457143	0.733333	0.004722

(0.4612), B and Zn (0.4352), Cd and Cr (0.8584), Pb and Cr (0.8921), Pb and Cd (0.92796), B and Ni (0.5623).More so, strong negative correlations were observed within the following pairs: Mn and Fe (-0.4671), Cd and Fe (-0.4712), Ni and Mn (-0.8551), B and Mn (-0.4795), Ni and Cr (-0.4861), Ni and Cd (-0.8577), B and Cd (-0.4671 and Pb and Ni (-0.6757). According to Odesa, et al., (2025); such insights are vital for comprehending the dynamics of groundwater and formulating effective management approaches (Table 4).

4.6.2. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a statistical method aimed at elucidating the complexity arising from numerous interrelated variables (Eyankware and Akakuru 2022; Akakuru et al. 2021a). It illustrates the relationships among these variables, thereby simplifying the dataset's complexity. PCA derives eigenvalues and eigenvectors from the covariance matrix of the initial data. The principal components (PCs) represent uncorrelated (orthogonal) variables obtained by transforming the original correlated variables using the eigenvectors (loadings). The eigenvalues associated with the PCs quantify their respective variances, while the loadings indicate the contribution of the original variables to the PCs, with the transformed representations referred to as scores. High positive or negative loadings greater than or equal to 0.7 ($\geq |0.7|$) indicate a strong association while each component represents an underlying source or process influencing metal concentrations.

4.6.3. Anthropogenic Influences Analysis: It could be observed in PCA1, that there is Strong positive loadings in Ni (0.931), Zn (0.760), B (0.766) while Strong negative loadings in Cr (-0.784), Cd (-0.808), Pb (-0.647). This connotes two contrasting groups, that is Ni, Zn, B may reflect agro-chemical inputs, waste leachates, or industrial effluents while Cr, Cd, Pb (negative correlation) indicate they come from a different anthropogenic pathway, such as metal plating, batteries, fuel combustion, or traffic-related sources.

4.6.4. Geogenic Control (Water-Rock Interaction): It was observed that PCA 2, high positive loadings in Mn (0.938), Pb (0.676), Cd (0.587), Zn (0.648), B (0.642) indicates that Mn mobilization from bedrock/weathering processes is dominant here, with Pb, Cd, and Zn partly linked. Geogenic release of Mn is often tied to redox-sensitive conditions in aquifers. Lastly, PCA 3 shows Strong positive loading in Fe (0.867) and moderate positive loadings in Cr (0.438), Ni (0.356), Pb (0.285). This shows Fe is controlled by a separate geochemical process, likely redox reactions or dissolution of Fe-bearing minerals, which can also mobilize trace metals like Cr and Ni. Conclusively, the

PCA indicates both natural (geogenic) and anthropogenic contributions, that is the study area is being controlled by multiple contamination sources. In summary, according to table 8 (the PCA result), PCA 1 has a loading of 75%, PCA 2 has a loading of 75% and PCA 3 has a loading of 25%.

Table 7: **Communalities**

	Initial	Extraction
Fe	1.000	.995
Mn	1.000	.999
Zn	1.000	1.000
Cr	1.000	.958
Cd	1.000	.998
Ni	1.000	.993
Pb	1.000	.958
B	1.000	1.000
Extraction Method: Principal Component Analysis.		

We conducted a factor analysis. To begin with, a scree plot was generated (refer to Fig. 4), indicating that three factors were sufficient to account for the total variability. Consequently, we performed the factor analysis utilizing the varimax rotation method (see Table 7). Factor accounted for approximately 46.3% of the overall variation, while the remaining two factors explained 19.4% and 6.1% of the variation, respectively.

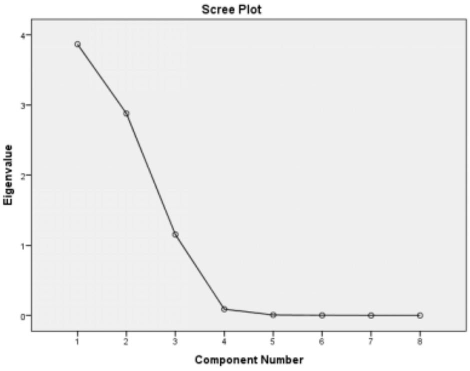

Fig. 4: Scree plot to assess the number of Principal components for the multivariate analysis.

Table 8: **Component Matrix**[a]

	Component		
	1	2	3
Fe	.171	**-.462**	**.867**
Mn	.346	**.938**	.009
Zn	**.760**	**.648**	.045
Cr	**-.784**	.391	**.438**
Cd	**-.808**	**.587**	-.004
Ni	**.931**	-.012	.356
Pb	**-.647**	**.676**	.285
B	**.766**	**.642**	.010
Extraction Method: Principal Component Analysis.			
a. 3 components extracted.			

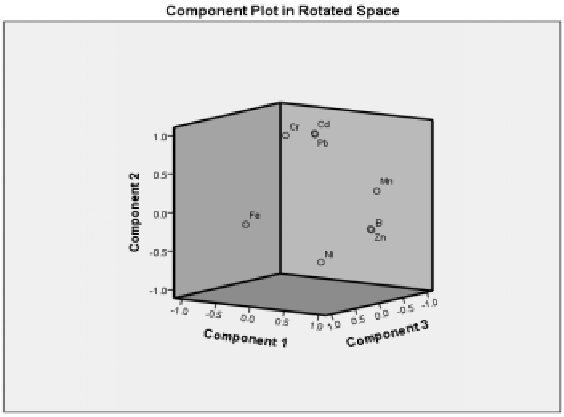

Fig. 5: Spatial Distribution of Heavy Metals within the Study Area

4.6.5. Zinc (Zn) concentration within the study area

In natural environments, the concentration of zinc in groundwater generally falls between 10 and 40 µg/litre. Conversely, levels in tap water may be significantly elevated owing to the leaching of zinc from plumbing and fixtures (Eyankware, et al., 2023). Although zinc is recognized as a vital trace element, its excessive presence can pose health risks. Zn concentration of the study area ranges from 0.29 to 0.30 as shown in Table 1, and Fig.6, high concentrations of Zn was observed around Pakas hotel and suites, and Winner Chapel Osubi. Zinc occurs naturally in the earth's crust and may leach into groundwater from various geological sources such as rocks and soil.

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Additionally, activities such as industrial discharges, mining operations, and the application of fertilizers containing zinc can lead to increased concentrations of zinc in groundwater resources. Consequently, the World Health Organization (WHO) has established a guideline recommending a maximum permissible concentration of 3 mg/L (3000 µg/L) for drinking water. Further indicate groundwater is considered fit for drinking based Zn concentration in groundwater within the study area

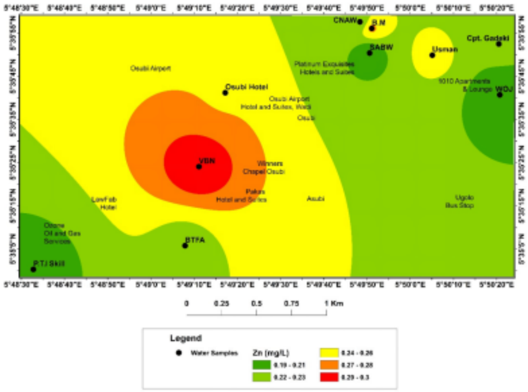

Fig. 6: Spatial distribution of Zn within the study area

4.6.6. Nickel (Ni) concentration within the study area

Deduction from Table 1, and Fig. 7, showed that the concentration of Ni in groundwater ranges from 0.003 to 0.048 mg/L, further findings suggested that areas within Winner Chapel Osubi, and CNAW has the highest concentration. Ni concentrations found in groundwater exhibit significant variability, shaped by various factors such as the composition of the soil, pH levels, depth, and the nearness to industrial or mining operations. Although low levels of nickel in groundwater are typically deemed non-hazardous, increased concentrations can present health dangers, particularly in regions affected by mining or industrial contamination.

4.6.7. Manganese (Mn) concentration within the study area

Manganese, similar to iron, is a naturally occurring metallic element that can be found in soils, rocks, and various minerals (Omo-Irabor, et al., 2019; Eyankware, et al., 2025). Groundwater has the ability to dissolve these substances, leading to the introduction of manganese into the water supply.

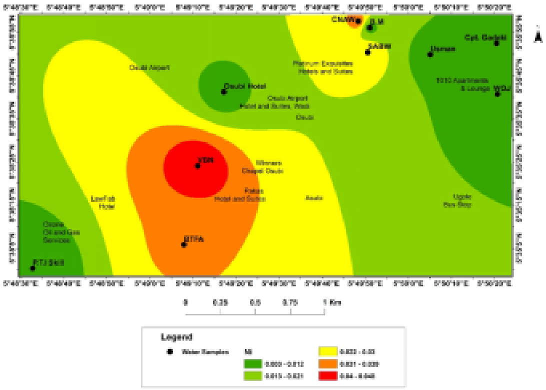

Fig. 7: Spatial distribution of Ni within the study area

Findings from Table 1, and Fig. 8, revealed that the concentration of Mn in groundwater ranges from 0.001 to 0.19 mg/L, further findings suggested that areas within Winner Chapel Osubi, and CNAW has the highest concentration. The concentration of manganese in groundwater can differ widely as a result of natural leaching processes, with levels possibly ranging from less than 0.001 mg/L to exceeding 1 mg/L. Several factors, including the specific types of rocks and minerals present, pH levels, and redox conditions, play a role in determining these concentrations. Although manganese is a vital nutrient in small quantities, elevated concentrations can lead to unpleasant tastes, odors, and staining in water, as well as present potential health hazards (Obasi, et al., 2021).

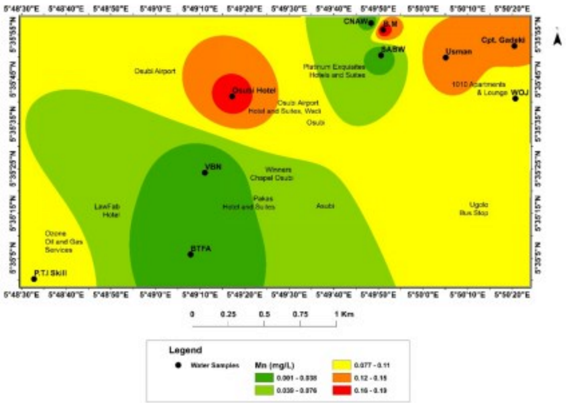

Fig. 8, : Spatial distribution of Mn within the study area

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Lead (Pb) concentration within the study area

From Table 1, and Fig.9, it was 0.001 to 0.021 mg/L, areas with Osubi airport, Usman, and BM. According to Akakuru, et al., (2023), certain geological structures possess elevated natural concentrations of lead, which can subsequently dissolve into groundwater. Similarly, groundwater can be contaminated by lead originating from several sources, such as: materials that contain lead: Older water distribution systems, including pipes, solder, and plumbing fixtures, may leach lead into the water supply. Industrial processes: Activities like mining, smelting, and battery production can emit lead into the environment, posing a risk to groundwater quality.

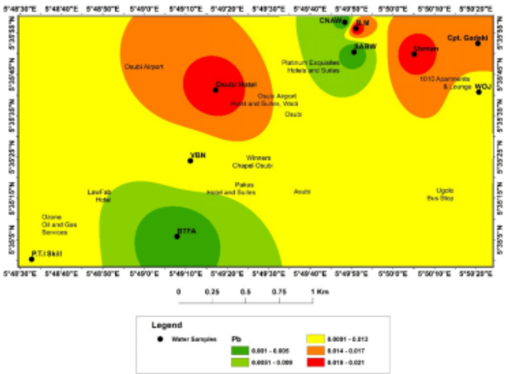

Fig. 9: Spatial distribution of Pb within the study area

4.6.8. Iron (Fe) concentration within the study area

The primary source of iron found in groundwater stems from the natural process of iron-bearing minerals and rocks dissolving as water seeps through the subterranean layers of the earth (Esi, et al., 2025; Eyankware, et al., 2021). From Table 1, and Fig. 10, it was observed that the value of Fe ranges from 0.27 to 0.49 mg/L, high concentration of Fe was observed around Pakas hotel and suites. Various factors, including the rock type, the availability of oxygen, and the acidity level (pH) of the water, play a significant role in this occurrence of Fe in groundwater . Additionally, there are less prevalent sources of iron, such as the corrosion of iron pipes and human-induced activities, including industrial wastewater and leachate from landfills (Odesa, et al., 2025).

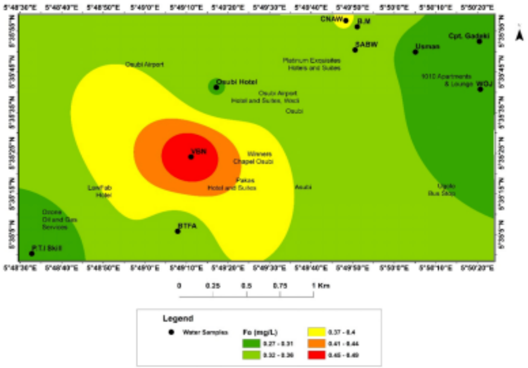

Fig. 10: Spatial distribution of Fe within the study area

4.6.9. Chromium (Cr) concentration within the study area

Chromium, especially in its hexavalent state Cr (VI), is frequently linked to industrial contamination and has the potential to be both toxic and carcinogenic. Although both forms of chromium may coexist, the origins and effects of each vary considerably. It was observed that from Table 1, and Fig. 11, high concentrations of Cr was noticeable around Osubi airport, BM, CNAW, Usman, with value range of 0.043 to 0.123 mg/L. According to Eyankware, et al., (2023), anthropogenic activities contributing to Cr contamination in groundwater consist of industrial effluents, inappropriate waste management practices, and mining operations.

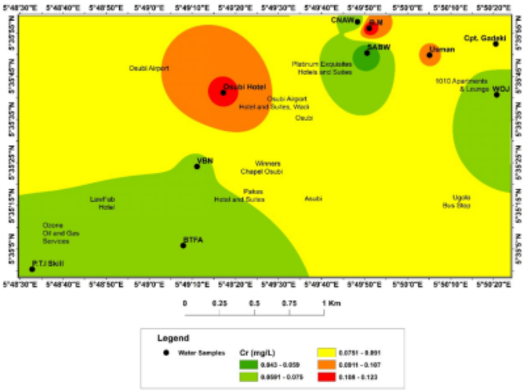

Fig. 11: Spatial distribution of Cr within the study area

4.7.0. Cadmium (Cd) concentration within the study area

Cadmium is a naturally occurring element found in the Earth's crust, and it can leach into groundwater as a result of the weathering

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process affecting rocks and soil (Ulkapa, and Eyankware, 2021). Findings from Table 1, and Fig.12, revealed high concentration of Cd as noticed around Osubi airport, SABW, and BM, high concentrations of Cd. Research indicates that sedimentary rocks typically contain higher levels of cadmium compared to igneous or metamorphic rocks, highlighting a concerning aspect of groundwater contamination. The presence of cadmium in groundwater presents a considerable environmental and health issue due to its toxic properties and the risk of extensive contamination. Both natural phenomena and anthropogenic activities can lead to increased cadmium concentrations in groundwater, which may result in serious health hazards if ingested.

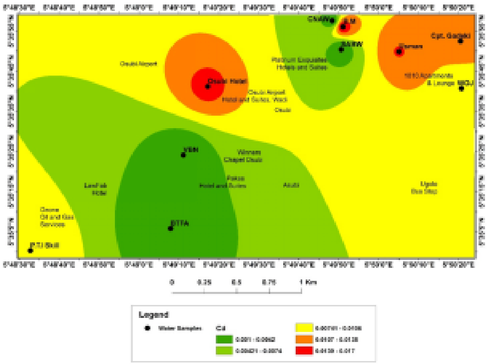

Fig. 12: Spatial distribution of Cd within the study area

4.7.1. Boron (B) concentration within the study area

B is found naturally in rocks and soils, and it can be released into groundwater through processes such as weathering and leaching. Additionally, sources like volcanic eruptions, geothermal processes, and marine water contribute to the presence of boron in groundwater. Deduction from Table 1, and Fig. 13, showed that Br concentrations in groundwater tends to increase towards southwest parts of the study area with value 0.017. According to Eyankware, et al., (2016), anthropogenic activities, such as discharge of wastewater, agricultural runoff—which encompasses fertilizers and pesticides—and industrial effluents, can also lead to the introduction of boron into groundwater systems.

From the result of the calculation of health risk assessment in table 5, it could be seen that the *total HQ values* (sum across metals for children vs adults) have all their values below I meaning no immediate non-carcinogenic risk is indicated from these groundwater samples for either adults or children.

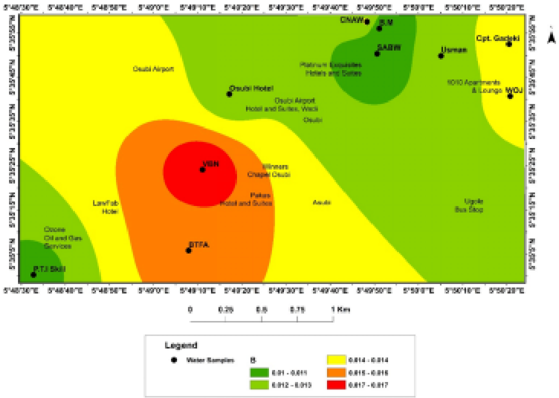

Fig. 13: Spatial distribution of B within the study area.

HQ in iron, Fe ranges from 0.0002–0.0004 in child while in adult, it ranges from 5.3 x 10^{-7}–8.610^{-7}. Fe is very necessary the body use and typically not harmful at the level. HQ for Mn in child is up to 5.57E-05 while in adult up to 0.0013. All are still well below 1, but Mn can affect neurological development in children if found above 1. HQ of Zn is extremely low which ranges from 10^{-5} to 10^{-6} implying is an essential micronutrient. The HQ of Chromium (Cr) **in** child is up to 0.017 while adult is up to 0.0001. comparing the HQ of chromium, higher relative to others but still less than 1 which Suggests low risk, but chromium species are toxic, so close monitoring is advised. Conclusively, lead can cause neurodevelopmental effects, even if found in a smaller doze. Nickel can cause allergic and systemic effects at higher exposures. All tested heavy metals are found to be less than 1. Children generally have higher HQs than adults due to lower body weight and higher intake per unit weight. This confirms that children are more vulnerable, and any rise in contamination would first pose risks to them. Currently, no non-carcinogenic health risks are indicated. However, Chromium, Cadmium, and Lead need close monitoring because of their toxic and cumulative nature.

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Table 5: the result of Non-carcinogenic health risk assessment HQ and HI.

Sample site	Fe (child)	Fe (Adult)	Mn (child)	Mn (Adult)	Zn (child)	Zn (Adult)	Cr (child)	Cr (Adult)	Cd (child)	Cd (Adult)	Ni (child)	Ni (Adult)	Pb (child)	Pb (Adult)
Usman	0.000262	0.00000053	4.38586E-05	0.001044785	1.49912E-05	3.12926E-06	0.012953	8.13481E-05	0.001117	6.88144E-05	5.55262E-05	2.74571E-06	7.39341E-05	1.0402E-05
CG	0.000256	0.00000052	3.645E-05	0.000868301	1.36396E-05	2.84711E-06	0.012117	7.60998E-05	0.000965	5.89838E-05	4.62718E-05	2.28809E-06	5.91473E-05	8.32162E-06
WOJ	0.000235	0.00000048	2.72634E-05	0.000649461	1.18578E-05	2.47519E-06	0.008496	5.33574E-05	0.000724	4.42378E-05	2.77631E-05	1.37286E-06	4.06638E-05	5.72111E-06
P.T.I Skill	0.000245	0.00000050	3.25976E-05	0.00077653	1.23493E-05	2.57779E-06	0.010307	6.47286E-05	0.000805	4.91531E-05	2.77631E-05	1.37286E-06	4.80572E-05	6.76132E-06
OAH	0.000271	0.00000055	4.94891E-05	0.001178913	1.56056E-05	3.25751E-06	0.015321	9.62182E-05	0.001207	7.37297E-05	6.47806E-05	3.20333E-06	7.39341E-05	1.0402E-05
B.M	0.000306	0.00000062	5.57122E-05	0.00132716	1.59743E-05	3.33446E-06	0.017131	0.000107589	0.001368	8.35603E-05	7.40349E-05	3.66095E-06	7.76308E-05	1.09221E-05
BTF	0.000298	0.00000061	2.96342E-07	7.05936E-06	1.37624E-05	2.87276E-06	0.008218	5.16079E-05	8.05E-05	4.91531E-06	0.00029614	1.46438E-05	3.6967E-06	5.20101E-07
SA	0.000273	0.00000055	2.96342E-07	7.05936E-06	1.18578E-05	2.47519E-06	0.005989	3.76126E-05	8.05E-05	4.91531E-06	0.000259122	1.28133E-05	3.6967E-06	5.20101E-07
CN	0.000318	0.00000065	2.96342E-07	7.05936E-06	1.32095E-05	2.75734E-06	0.008635	5.42321E-05	8.05E-05	4.91531E-06	0.000333157	1.64743E-05	3.6967E-06	5.20101E-07
VBN	0.000424	0.00000086	2.96342E-07	7.05936E-06	1.82475E-05	3.80898E-06	0.010307	6.47286E-05	8.05E-05	4.91531E-06	0.00044421	2.19657E-05	4.06638E-05	5.72111E-06
Total	**0.002888**	**5.87E-06**	**0.000247**	**0.005873**	**0.000141**	**2.95E-05**	**0.109474**	**0.000688**	**0.006508**	**0.000398**	**0.001629**	**8.05E-05**	**0.000425**	**5.98E-05**

5. Conclusion

This study has provided a detailed assessment of heavy metal concentrations in groundwater within Osubi, a rapidly developing urban area in Delta State, Nigeria, influenced by industrial, domestic, and oil-related activities. The measured concentrations of Fe, Mn, Zn, Cr, Cd, Ni, Pb, and B largely fell below critical contamination thresholds, and multivariate statistical analyses (CM, ICM, PCA, CSC, TVE) indicated a minimal influence of heavy metals on the overall groundwater chemistry. Spatial distribution mapping, however, revealed localized hotspots—particularly at Osubi Airport, Winner Chapel Osubi, Usman, BM, and CNAW—where heavy metal levels were comparatively elevated. Although the contamination indices (Cf, PLI, DOC, MPI) reflected low to negligible pollution levels, the presence of detectable heavy metals underscores the potential for cumulative impacts over time, especially in light of ongoing population growth, urban expansion, and industrial activity. The weak correlations observed between metal concentrations suggest multiple diffuse sources rather than a single dominant contaminant source, consistent with anthropogenic inputs from waste disposal and effluent discharge. Given these findings, proactive measures are recommended to safe-guard groundwater quality. Periodic monitoring should be institutionalized to detect early shifts in contamination trends, and simple water treatment practices should be encouraged prior to domestic consumption. Public awareness initiatives and stricter regulation of industrial waste disposal will further mitigate future risks. Sustaining the relatively low contamination levels observed in this study is essential to ensuring the long-term safety and reliability of groundwater resources for the Osubi community.

References

Akakuru, O. C., Emile T., Patrick A. R., Eyankware, M. O., Aigbadon, G. O.,. Obite, C. P., Thomas J. Algeo, Adedibu Sunny Akingboye (2025). Leveraging Novel Machine Learning Models in Predicting Groundwater Irrigation Suitability in Southeastern Nigeria: A Hydrogeochemical Approach, Scientific African doi: https://doi.org/10.1016/j.sciaf.2025.e0264

Akakuru, O.C., Adakwa, C.B., Ikoro, D.O., Eyankware., M. O., Opara, A.I., Njoku, A.O., Iheme, K.O., Usman, A. (2023). Application of artificial neural network and multi-linear regression techniques in groundwater quality and health risk assessment around Egbema, Southeastern Nigeria. Environmental Earth Sciences (2023) 82: 77. https://doi.org/10.1007/s12665-023-10753-1

Akakuru, O.CObinna C. A., Emile T., Patrick A. R. , M. O. Eyankware, G. O. Aigbadon, C. P. Obite, Thomas J. Algeo , Adedibu Sunny Akingboye (2025). Leveraging Novel Machine Learning Models in Predicting Groundwater Irrigation Suitability in Southeastern Nigeria: A Hydrogeochemical Approach, Scientific African doi: https://doi.org/10.1016/j.sciaf.2025.e0264

Aigberua, O.A. (2021) An Assessment of Trace Metal Pollution Indicators in Soils around Oil Well Clusters. Petroleum Research, 7, 275-285

Asseez,. O. L. (1989). Review of the Stratigraphy, Sedimentation and Structure of the Niger Delta. Edited by Kogbe, Rock View (Nig) Ltd. Jos. Pp 311-324.

Akpokodje, .G., Etu-Efeotor. J. O. (1987). The Occurrence and Economic Potential of clean sand deposits of the Niger Delta. Journal of African Earth Sciences, 6(1): 61-65

Ayedun H, Gbadebo AM, Idowu OA, Arowolo TA (2015) Toxic elements in groundwater of Lagos and Ogun States southwest Nigeria and their human health risk assessment. Environ Monit Assess 187(6):1–17.

Bhutian, R., Dipali-Bhaskar, K., Khanna, D. R. (2017). A Geochemical distribution and environmental risk assess ment of heavy metals in groundwater of an industrial area and its surroundings, Haridwar, India. Energy, Ecology and Environment., 2(2), 155–167. https:// doi. org/ 10. 1007/ s40974- 016- 0019-6

Chen J, Wu H, Qian H, Gao Y (2017) Assessing nitrate and fluoride contaminants in drinking water and their health risk of rural residents livings in a semiarid region of Northwest China. Expo Health 9(3):183–195

Chounlamany, V., Tanchuling, M. A., Inoue, T. (2017). Spatial and temporal variation of water quality of a segment of Marikina River using multivariate statistical methods. Water Science

https://dx.doi.org/10.4314/aujst.v6i2.12

and Technology, 76 (6), 1510–1522.

Custodio, M., Fow, A., Chanamé, F., Orellana-Mendoza, E., Peñaloza, R., Alvarado, J. C., Cano, D., & Pizarro, S. (2021). Ecological Risk Due to Heavy Metal Contamination in Sediment and Water of Natural Wetlands with Tourist Influence in the Central Region of Peru. *Water*, *13*(16), 2256. https://doi.org/10.3390/w13162256

Dembitsky, V. (2003) Natural Occurrence of Arseno Compounds in Plants, Lichens, Fungi, Algal Species, and Microorganisms. Plant Science, 165, 1177-1192. http://dx.doi.org/10.1016/j.plantsci.2003.08.007

Enuneku A, Omoruyi O, Tongo I, Ogbomida E, Ogbeide O, Ezemonye L (2018) Evaluating the potential health risks of heavy metal pollution in sediment and selected benthic fauna of Benin River, Southern Nigeria. Appl Water Sci 8:224. https://doi.org/10.1007/s13201-018-0873-9.

Esi. E.O, Orisekpabor, O.P., M. O. Eyankware (2025). Integration of geophysical and radiological assessment of solid waste diposal impact on groundwater and human health in southern Nigeria, Geosystems and Geoenvironment , doi:https://doi.org/10.1016/j.geogeo.2025.100425.

Eyankware. M. O., Nnajieze, V.S., Aleke, C.G. (2018). Geochemical assessment of water quality for irrigation purpose, in abandoned limestone quarry pit at Nkalagu area, Southern Benue Trough Nigeria. Environ Earth Science. https://doi.org/10.1007/s12665-018-7232-x.

Eyankware, M. O., & Ephraim, B. E. (2021). A comprehensive review of water quality monitoring and assessment in Delta State, Southern Part of Nigeria. Journal of Environment and Earth Science, 3(1), 16–28. https:// doi. org/ 10. 30564/ jees. v3i1. 2900

Eyankware, M. O., Eyankware, O. E., & Ulkapa, R. O. E. (2016). Assessment of impact of leachate on soil phys icochemical parameters in the vicinity of Eliozu Dump site, Port Harcourt, Nigeria. Basic Resource Journal of Soil and Environment and Science, Benin, Nigeria, 4(2), 15–25.

Eyankware, M. O., Obasi, P. N. (2021). A holistic review of heavy metals in water and soil in Ebonyi SE. Nigeria; with emphasis on its effects on human, aquatic organisms and plants. World News of Natural Science, 38; 1-19.

Eyankware, M. O., & Akakuru, C. O. (2022). Appraisal of groundwater to risk contamination near an abandoned limestone quarry pit in Nkalagu, Nigeria, using enrich ment factor and statistical approaches. Journal of Energy and Water Resources, 7(4), 603–621. https:// doi. org/ 10. 1007/ s42108- 022- 00186-0

Eyankware, M. O., Akakuru, C. O., & Eyankware, E. O. (2022a). Interpretation of hydrochemical data using vari ous geochemical models: a case study of Enyigba mining district of Abakaliki, Ebonyi state. SE. Nigeria. Sustain able Water Resources Management, 8(1), 33. https:// doi. org/ 10. 1007/ s40899- 022- 00613-4

Eyankware, M. O., Eyankware, R. O., & Akakuru, O. C. (2022b). Hydrogeophysical delineation of aquifer vulnerability in parts of Nkalagu and Ohofia Agba areas of Abakaliki, SE. Nigeria. Sustainable Water Resources Management. https:// doi. org/ 10. 1007/ s40899 - 022- 00603-6

Eyankware, M. O., Akakuru, O. C., Osisanya, W. O., et al. (2023). Assessment of heavy metal pollution on ground water quality in the Niger Delta Region of Nigeria. Sus tainable Water Resources Management, 9, 189. https:// doi. org/ 10. 1007/ s40899- 023- 00955-7.

Eyankware, M. O., Akakuru, O. C., Igwe, E. O.,. Olajuwon, W. O., Ukor. K. P. (2024). Pollution Indices, Potential Ecological Risks and Spatial distribution of Heavy Metals in soils around Delta State, Nigeria. Water, air, & soil Pollution. https://doi.org/10.1007/s11270-024-07209-yI.

Igwe, E. O., Ede, C. O., & Eyankware, M. O (2021). Heavy metals concentration and distribution in soils around Oshiri and Ishiagu lead – zinc mining areas, southeastern Nigeria. World Scientific News, 158, 22–58.

Igwe, E. O., Ede, C. O., Eyankware, M. O., Nwachukwu, C. M., & Onyekachi, B. W. (2022). Assessment of poten tially toxic metals from mine tailings and waste rocks aroundmining areas of Oshiri-Ishiagu region, southeast ern Nigeria. Earth Systems and Environment, 6(2), 597 615. https:// doi. org/ 10. 1007/ s41748-022- 00306-0

Ganiyu SA, Olurin OT, Awaye KT, Adeleke OO (2017) Heavy metals content and physico-chemical status of groundwater around lead smelting area in southwestern Nigeria Urban settlement. Afr Rev Phys 12:14–22

Kim H, Park S (2016) Hydrogeochemical characteristics of Groundwater highly polluted with nitrate in an agricultural area of Hongseong, Korea. Water 8:345. https://doi.org/10.3390/w808a0345

Kumar A, Kumar A, Cabral-Pinto MMS et al (2020) Lead toxicity: health hazards, influence on food chain, and sustainable remediation approaches. Int J Environ Res Public Health 17:2179. https://doi.org/10.3390/ijerph17072179

Kumar A, Ali M, Kumar R, Kumar M et al (2021) Arsenic exposure in Indo Gangetic plains of Bihar causing increased cancer risk. Sci Rep 11:2376. https://doi.org/10.1038/s41598-021-81579-9

Mazhar I, Hamid A, Afzal S (2019) Groundwater quality assessment and human health risks in Gujranwala District, Pakistan. Environ Earth Sci 78:634. https://doi.org/10.1007/s12665-019-8644-y

Mbaka PK, Mwangi JK, Kiptum CK (2017) Assessment of water quality in selected shallow wells of Keiyo Highlands, Kenya. Afr J Sci Technol Innov Dev. https://doi.org/10.1080/20421338.2017.1327476

Merki. J. P. (1970) Structural Geology of the Cenozoic Niger Delta: In African Geology. University of Ibadan Press, 251-267

Nawab J, Khan S, Khan MA, Sher H, Rehamn UU, Ali S, Shah SM (2017) Potentially toxic metals and biological contamination in drinking water sources in Chromite mining-impacted areas of Pakistan: a comparative study. Expo Health 9:275–287

Nriagu, J. (1992) Toxic Metal Pollution in Africa. The Science of the Total Environment, 121, 1-37. https://doi.org/10.1016/0048-9697(92)90304-B.

Obasi, P.N., Eyankware M. O.., Akudinobi, B.E.B. (2021).Characterization and evaluation of the effects of mine discharges on surface water resources for irrigation: a case study of the Enyigba Mining District, Southeast Nigeria. Applied Water Science, https://doi.org/10.1007/s13201-021-01400-w.

Odesa, G. E., Ozulu, G. U., Eyankware. M. O., Mba-Otike, M. N., Okudibie, E. J. (2024). A holistic review three-decade oil spillage across the Niger Delta Region, with emphasis on its impact on soil and water. World News of Science. 190(2); 119-139.

Odesa, G.E., Okanigbuan, P.N., Eyankware, M.O., Ngozi-Chika, C.S., Efetobo O. (2025).Health risk assessment of water resources within the lignite series of Obomkpa and environs, southern Nigeria. Journal of Contaminant Hydrology. https://doi.org/10.1016/j.jconhyd.2025.104665

Onwe, I. M., Eyankware. M. O., Obasi, P. N., Ifeanyichukwu, K. A. (2022). Hydrochemical and statistical approaches in the evaluation of groundwater quality for drinking and irrigation uses around Ezzangbo–Ngbo area, Southeastern Nigeria. Modeling2 Earth Systems and Environment, https://doi.org/10.1007/s40808-022-01503-6.

Odemerho, O., Ejemeyovwi, D.O. (2007). The Physiographic Provinces and Drainage Systems of Delta State, Nigeria, In: F.O. Odemerho et al. (eds) Delta State in Maps, Delta State University, Abraka, pp. 9-17.

Olobaniyi, S. B., Owoyemi. F. B. (2006). Characterization by Factor Analysis of the Chemical Facies of Groundwater in the Deltaic Plain Sands Aquifer of Warri, Western Niger Delta, Nigeria. African Journal of Science and Technology, 7(1): 73 - 81

Olujimi O, Steiner O, Goessler W (2014): Pollution indexing and health risk assessment of trace elements in indoor dust from classrooms, living rooms and offices in Ogun State, Nigeria. J Afr Earth Sci 101:396–404

Onwe, I. M., Obasi, I. A., Eyankware, M. O., Uchenna, O. L. (2024). An integration of hydrochemical data and stable isotopes in groundwater evaluation in Ngboejogu, Southern Benue Trough, Nigeria. Modeling Earth Systems and Environment https://doi.org/10.1007/s40808-024-02166-1

https://dx.doi.org/10.4314/aujst.v6i2.12

Osisanya W.O., Agho I.F, Ovri A.A, Eyankware M.O (2024). Studies of heavy metal in soil at Omoku, River State, Nigeria, using Pollution Indices and Potential Ecological Risk. Anchor University Journal of Science and Technology (AUJST). Vol. 5 No 2, December 2024, Pp. 240 -257

Paul R, Brindha K, Gowrisankar G, Tan ML, Singh MK (2019) Identification of hydrogeochemical processes controlling groundwater quality in Tripura, Northeast India using evaluation indices, GIS and multivariate statistical methods. Environ Earth Sci 78:470. https://doi.org/10.1007/s12665-019-8479-6

Prasanna MV, Praveena SM, Chidambaram S, Nagarajan R, Elayaraja A (2012) Evaluation of water quality pollution indices for HM contamination monitoring: a case study from Curtin Lake, Miri City, East Malaysia. Environ Earth Sci 67:1987–2001. https:// doi. org/ 10. 1007/ s12665- 012- 1639-6

Ravindra K, Mor S (2019) Distribution and health risk assessment of arsenic and selected heavy metals in groundwater of Chandigarh, India. Environ Pollut 250:820–830

Selvam S, Anthony Ravindran A, Venkatramanan S, Singaraja C (2017) Assessment of heavy metal and bacterial pollution in coastal aquifers from SIPCOT Industrial zones, Gulf of Mannar, South coast of Tamil Nadu, India. Appl Water Sci 7:897–913. https://doi.org/10.1007/s13201-015-0301-3

Singh AL, Singh VK (2019) Assessment of groundwater quality of Balha district, Uttar Pradesh, India with reference to arsenic contamination using multivariate statistical analysis. Appl Water Sci 8:95. https://doi.org/10.1007/s13201-018-0737-3

Shah MH, Ilyas A, Akhter G, Bashir A (2019) Pollution assessment and source apportionment of selected metals in rural (Bagh) and Urban (Islamabad) farmlands, Pakistan. Environ Earth Sci 78:199. https://doi.org/10.1007/s12665-019-8198-z

Shankar BS (2019) A critical assay of heavy metal pollution index for the groundwater of Peenya Industrial Area, Bangalore, India. Environ Monit Assess 191:289. https://doi.org/10.1007/s10661-019-7453-9

Sorensen JPR, Lapworth DJ, Read DS, Nkuwa DCW, Bell RA, Chibesa M, Chirwa M, Kabika J, Liemisa M, Pedly S (2015) Tracing enteric pathogen contamination in Sub-saharan Africa groundwater. Sci Total Environ 538:888–895

Shah MH, Ilyas A, Akhter G, Bashir A (2019) Pollution assessment and source apportionment of selected metals in rural (Bagh) and Urban (Islamabad) farmlands, Pakistan. Environ Earth Sci 78:199. https://doi.org/10.1007/s12665-019-8198-z

Singovszka E, Balintova M, Demcak S, Pavlikova P (2017) Metal pol lution indices of bottom sediment and surface water affected by acid mine drainage. Metals 7:284. https:// doi. org/ 10. 3390/ met70 80284

Short, C., Stauble, A. J. (1967). Outline of Geology of Niger Delta: AAPG Bull., 51, 761-779.

Reyment, R. A (1965), Aspects of the Geology of Nigeria. University of Ibadan Press, Ibadan. (1965) 132pp

Ulakpa, R.O.E, Ulakpa, C. E., M. O. Eyankware. (2021). Quantitative analysis of physical and chemical attribute of soil around power-line dumpsite at Boji-Boji Owa, Delta State, Nigeria. World News of Natural Sciences, 3; 118-134.

Abbreviations

WOJ-Wood market Junction
B.M- Barrister Mademedor
BTF- Beside Trade Fare
SA-Samuel Ariko
CN- Colnel Newton
CG-Captain Geideki
OAH-Osubi Airport Hotel