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Interpretation of hydrochemical data in selected parts of Warri, Southern Nigeria using health risk assessment and heavy metal index

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ABSTRACT

Groundwater quality assessment is crucial for ensuring public health and sustainable water resource management. Health risk assessment evaluates health hazards from contaminated groundwater, guiding protective measures; also, heavy metal indices quantify contamination, aiding pollution assessment and regulatory compliance. These tools ensure comprehensive groundwater quality understanding, supporting sustainable resource management and health and environmental protection. Seventeen (17) groundwater samples were taken in Warri, Delta State, Nigeria, and analyzed using the American Public Health Association (APHA) technique to assess their hydrochemical properties and potential health concerns when utilized as drinking water. Sixteen (16) physicochemical parameters were analyzed. The analysis of heavy metals' statistical indices, such as the Contamination Index (CI), Contamination Factor (Cf), Pollution Load Index (PLI), Metal Pollution Index (MPI), Quantification of Contamination (QoC), Potential Ecological Risk Index (ERI), and Pollution Index of Groundwater (PIG), was successfully used to assess the effects of heavy metal contamination on the area's groundwater resources. Deductions from the suggested that there is interaction between geochemical ions found in groundwater within the study area and there are weak to moderate connections between parameters, according to additional findings using Pearson correlation and Principal Component Analysis (PCA). Additionally, PCA reveals that loadings within the groundwater system could be the result of nearby anthropogenic activities that are changing the water's chemistry. Results from hydrogeochemical facies showed that in the cation area, $Na+K> Mg>Ca>Cl>SO_4>HCO_3$, with a tendency of 35.3 percent SO_4> 5.9 percent HCO_3> 41.2 percent Cl> 17.6 percent, there is no dominant ionic species. According to results from heavy metal indices such as Cf and PLI, there is no relationship between them and readily accessible groundwater. Additional MPI data indicate that the groundwater in the research area is deemed to be clean, but QoC and ERI results showed that geological processes promote the transfer of heavy metals, which is a possible ecological danger associated with groundwater. The analysis revealed elevated concentrations of heavy metals in certain areas, which may be associated with local human activities. Both correlation and Principal

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Component Analysis (PCA) highlighted the significant roles that natural processes and anthropogenic influences play in determining groundwater quality. Health risk evaluations indicated heightened risks for children, suggesting that human activities contribute to these health threats. This research underscores the necessity of regular groundwater monitoring to identify any decline in water quality. The results illustrate the intricate relationship between geological conditions and human activities affecting groundwater quality, highlighting the need for thorough management strategies to ensure sustainable use of water resources and safeguard public health in the region studied.

Keywords: Pollution, Contamination, Rating, Groundwater, Ecological

1. INTRODUCTION

Our survival depends on having access to enough clean water. But groundwater's quantity and quality are relatively consistent (Eyankware et al., 2020a & 2020b; Eyankware et al., 2023a & 2023b). When it is present at sustainable levels, it is quickly contaminated by usual anthropogenic activities, according to Appelo and Postma (2004) and Eyankware et al. (2021a). To meet the ever-growing requirements of the swiftly expanding populations in developing nations, various practices such as industrial operations, mining activities, waste management, and agricultural methods may lead to the gradual introduction of leachates into surface water reservoirs. This contamination ultimately makes the water unsuitable and incurs substantial costs for treatment (Awotwi et al., 2017; Eyankware and Ephraim, 2021). For a variety of uses in the study region, groundwater is the main supply of water. There may be some additional small and large enterprises there, as well as the renowned Federal University of Petroleum Resources in Effurun. People are currently flocking into the study region in greater numbers as a result of growing companies. In contrast, groundwater demonstrates a marked reliability regarding both its quantity and quality (Asare-Donkor et al., 2016). Warri, found in the lively Southern region of Nigeria, exemplifies urban development shaped by a blend of natural and anthropogenic influences. Given its evolving socioeconomic environment and increasing populace, effective management of water resources is essential for preserving both human health and the integrity of ecosystems. Specific anthropogenic activities in Warri, Nigeria, which could potentially impact groundwater quality, include industrial activities, agricultural practices, urbanization and infrastructure development, mining and resource Extraction, domestic and municipal waste disposal, and transportation and shipping.

Eyankware and Ephraim (2021), discovered that groundwater in riverine communities is much more susceptible to pollution than groundwater in upland areas. As a result, a thorough investigation of groundwater quality in the Warri metropolis and its surroundings is required to ensure the safe exploitation of potable water with little or no health risk. In this context, interpreting hydrochemical data emerges as a critical task, providing insights into water quality, potential health risks, and environmental sustainability. The petroleum hydrocarbon contamination of surface water and groundwater in Nigeria's Niger Delta Region had a variety of negative effects on human health (including exposed populations), the natural environment, and other ecological receptors. Meanwhile, the groundwater quality in a specific area of the Niger Delta revealed significant variations in most water characteristics due to petroleum production, artisanal refining, illegal tapping, and industrial activities. Similarly, the groundwater contamination at petroleum-impacted sites in Nigeria's Niger Delta site determined that the oil spill was a possible environmental contaminant. Based on a comparison of assessment chemical data and regulated standards, they determined that the spill had an impact on the groundwater body in the spill area, necessitating soil and groundwater cleanup and remediation at the site. Adamu & Umar (2013) carefully reviewed previous research in the study area to determine where the nitrate and hydrocarbon pollutants found in soils, surface water, and groundwater in Nigeria's Niger-Delta region originated, how they are chemically, and what health and environmental effects they may have. These pollutants are primarily caused by oil and gas exploration and exploitation. The authors proposed that integrated laws and policies be implemented to address the issue of gas flaring and prevent the continued release of nitrate and organic pollutants into the region's overall ecosystem. Particular surface water bodies are created over time in regions where there is some ground subsidence. The low terrain facilitates the easier passage of leaching water from farming drainage and domestic sewage into water bodies. The notion of constructing a plain reservoir has been floated, given the vast expanses of subsidence waters. Consequently, for the purpose of growth and usage (e.g., aquaculture business), an examination of the water quality in the subsidence zones is crucial. Poisonous and hard-to-biodegrade substances are generally considered to be potentially dangerous elements. They can enter the human body through ingestion, cutaneous contact, or inhalation exposure. They are easily discharged into a variety of environmental media. It has been suggested that even at measured levels, potentially hazardous components could still be damaging. Evidence of the detrimental consequences of repeated, low-level exposures to some metals on health is mounting. Therefore, according to several studies (Chanpiwat et al., 2010; Haque et al., 2020; Khan & Zubair 2011; Li et al., 2022), there are elements in surface water, groundwater, and top water that may be detrimental. It is more prevalent, significantly more mineralized, and more protected from surface pollutants in nature. Its natural occurrence is more prevalent, considerably more mineralized, and better shielded from surface pollution sources. vadose zone capacity and surface water infiltration with time. Water contact with geologic media is made possible by the movement of water through soil pores and rock fissures, which can also reduce pollutant loads (often completely) zoning before reaching the saturated zone. Conversely, the challenges related to water security are increasingly prevalent, driven by swift population growth, economic development, and the desire of communities to achieve a better quality of life. A significant portion of Nigeria's populace continues to live in rural regions, positioning it as the largest developing country on the African continent. Consequently, assessing the quality of groundwater in rural Nigerian communities is of paramount importance (Eyankware and Akakuru, 2023). Achieving sustainable development hinges on the effective management of water resources and the maintenance of water quality. Various factors, including climate, soil properties, the movement of groundwater through different rock types, local geography, saline water intrusion in coastal regions, and anthropogenic impacts on land, play a crucial role in influencing water quality (Onwe et al., 2024). Recently, there has been a growing focus on the critical role of water quality in relation to human health. Research conducted by Olajire and Imeokparia indicates that more than 80% of diseases in low-income countries can be attributed, either directly or indirectly, to inadequate drinking water quality and unsanitary conditions (Eyankware et al., 2023a).

Numerous researchers have concentrated on studying groundwater quality since dangerous elements, including heavy metals (HMs), can infiltrate groundwater, enter the food chain, and eventually affect aquatic and human beings. Groundwater makes up between 13% and 30% of the hydrosphere's total freshwater volume, and it is home to more than 50% of the world's population (Dragoni and Sukhija, 2008). The presence of heavy metals (HMs) in groundwater supplies poses a significant threat to public health. Contamination of aquatic environments by these heavy metals has emerged as a critical global issue, largely attributed to their biological persistence and propensity for accumulation. Metals can exist for thousands of years and are inherently poisonous, biodegradable, impermeable, and intolerant. These hazardous substances can be classified as either carcinogenic or non-carcinogenic based on their level of risk, which can be determined using a health risk assessment method (USEPA, 1994). The health risk assessment, which can quantify the risk of heavy metals (HMs), is a useful and efficient method of assessing the relationship between the environment and human health. In their study, Burgess et al. (2010), examined the health risks associated with the consumption of contaminated water within the local community. Their findings indicated that both geogenic processes and anthropogenic activities were the main contributors to pollution in the Kohistan area (Burgess et al., 2010).

Research conducted by Chanpiwat et al. (2010) alongside Burgess et al. (2010) revealed that while certain heavy metals (HMs) are essential for plant development, they can pose significant health risks to humans when their levels exceed the permissible limits in drinking water. In order to safeguard human health, it is essential to evaluate and regulate the presence of heavy metals (HMs) in groundwater intended for drinking purposes. This situation arises from a variety of pollution sources, limited water availability and distribution—particularly in mountainous regions—and insufficient infrastructure along with ineffective wastewater management practices. The accessibility of drinkable water in rural areas was investigated by Eyankware et al. (2020a). The presence of low concentrations of various chemical constituents in drinking water can be attributed to several activities, including rock weathering, the discharge of industrial wastewater, and agricultural runoff. While these compounds exist in minimal amounts and do not pose an immediate threat to health, their gradual accumulation may lead to detrimental effects over time. For instance, fluorosis has occurred worldwide due to long-term exposure of populations to high levels of fluoride in drinking water (Villaescusa and Bollinger 2008; Wen et al. 2013), and chronic arsenism has been reported from drinking water sources. Therefore, it is crucial to identify concerning chemical constituents in the water surrounding the Federal University of Petroleum Resources and in specific areas of Delta State, Nigeria, to conduct comprehensive health risk assessments. The objective of this research is to evaluate the groundwater quality in Warri, located in Delta State, Nigeria. It emphasizes the examination of hydrochemical characteristics, the presence of heavy metals, and the related health risks. The study seeks to enhance sustainable management of water resources and safeguard public health within the area. The objectives are outlined as follows:

i. To evaluate the hydrochemical properties of groundwater samples collected from Warri, Delta State, Nigeria, using the American Public Health Association (APHA) technique.

ii. To assess the extent and sources of heavy metal contamination in the groundwater through the application of statistical indices such as Contamination Index (CI), Contamination Factor (Cf), Pollution Load Index (PLI), Metal Pollution Index (MPI), Quantification of Contamination (QoC), and Potential Ecological Risk Index (ERI).

iii. To examine the relationships between geochemical ions and parameters in groundwater samples using Pearson correlation and Principal Component Analysis (PCA) to understand natural and anthropogenic influences on groundwater quality.

iv. To determine the geographical distribution of heavy metal concentrations and identify potential hotspots of contamination linked to nearby anthropogenic activities.

v. To conduct health risk assessments, particularly focusing on vulnerable groups such as children, to evaluate potential health hazards associated with consuming contaminated groundwater.

vi. To provide recommendations for comprehensive management strategies aimed at sustainable water resource utilization and public health protection in Warri, Delta State, Nigeria.

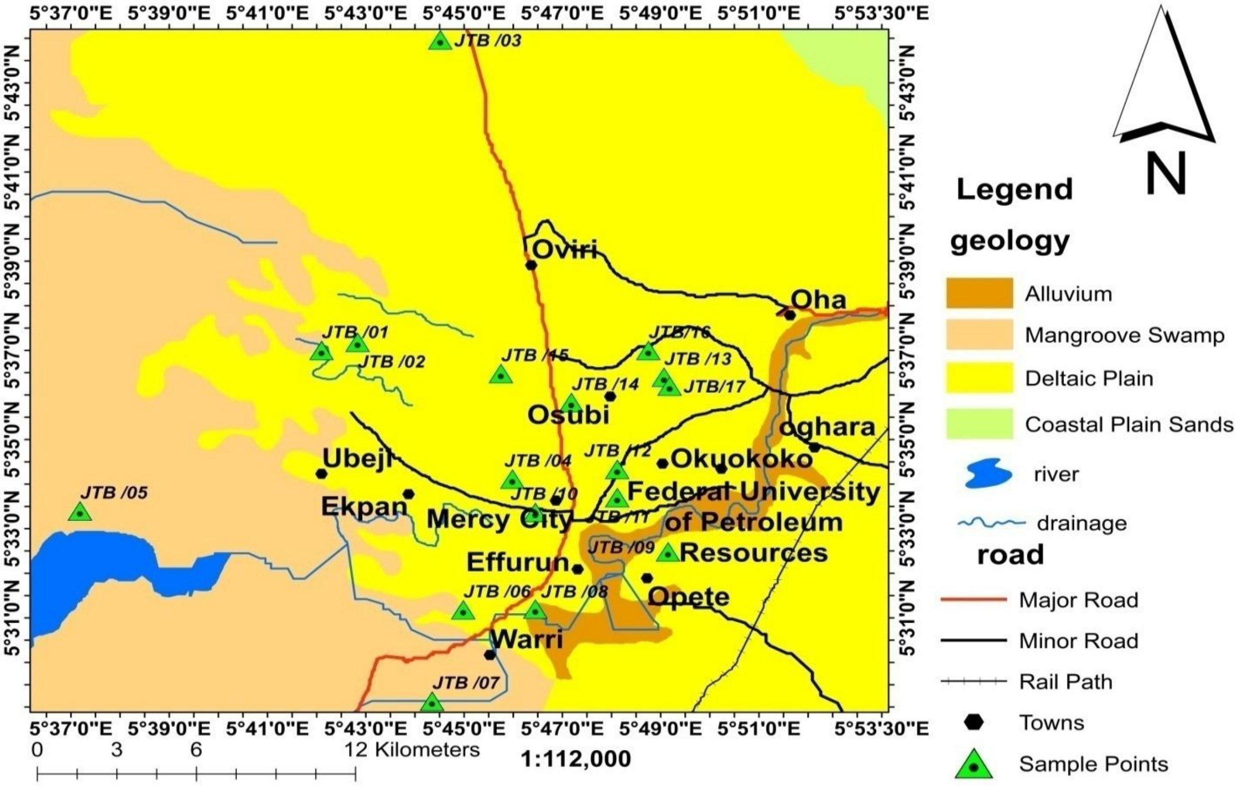

Fig.1. Groundwater sampling spots are shown on the research area's geology map.

Location and accessibility

The research area is situated within the latitudinal and longitudinal coordinates of 5º30ˈN to 5º38ˈN and 5º40ˈE to 5º52ˈE, corresponding to the southern region of Nigeria (see Fig. 1). A study conducted in 2006 indicated that the population within this region totals 182,500 individuals. Recently, the local populace has experienced a substantial influx of newcomers, primarily attributed to the processes of industrialization and urbanization. A prominent physiographic characteristic of this area is the undulating marsh plain, which is closely associated with its topographical features.

The geology of the research area

The Somebreiro Warri Deltaic Plain Sands, Agbada Formation, Akata Formation, and Benin Formation (from oldest to newest) are all parts of the Cretaceous to recent clastic sediment piles of the Niger Delta basin that make up the research area and its surrounds. The

Niger Delta geologic sequence's basic unit, the basement complex, rests unevenly on the Akata Formation. The deposit from the Paleocene epoch is around 7,000 meters thick. In the Niger Delta, an oil reservoir is formed by the 3700 m-thick Eocene Agbada Formation, which is composed of alternating layers of deltaic sands and shales. With a few intercalations of clay, the Oligocene Benin Formation is primarily composed of porous sands and gravels. As you approach the coast, the silt and clay sequences in the quaternary top level, which range in thickness from 40 to 150 m, become increasingly apparent. The Benin Formation, which has a thickness range of more than 2000m and is particularly shallow in the northern section of Warri, is the most prolific aquifer in the Niger Delta region. The study area is immediately underlain by the Somebreiro-Warri Deltaic Plain Sand.

2. MATERIALS AND METHODS

Sampling and analysis

During the dry season, a total of 17 water samples were collected from different boreholes. The groundwater was collected, stored, and analyzed using polypropylene beakers. Prior to the field sampling, the sample beakers and containers were meticulously cleaned. Subsequently, they were immersed in distilled water that was acidified with 1.0 ml of HNO_3 for a duration of three days. Borehole samples were collected five to ten minutes after pumping commenced. To ensure the complete removal of suspended particles from each sample, single-use filters with a diameter of 0.45 micrometers were employed. In the field, the samples were acidified with 1.0 ml of concentrated HNO3 to prevent the precipitation of heavy metals. Additionally, three drops of HNO3 were added using fresh syringes to inhibit sorption. The samples were stored in ice-filled, hermetically sealed beakers, maintaining a constant temperature of 4 degrees Celsius. This temperature was consistently upheld during transportation to the analytical laboratory to avoid any evaporation (Eyankware et al., 2022a). The analysis of HCO3 and SO42 was conducted using a fast sequential (FS) atomic absorption spectrophotometer (AAS) model Varian 240 AA, while heavy metals, including Fe, Ag, Cu, Co, Cd, Mn, Zn, and Pb, were detected using a Hach DR/2010 spectrophotometer (refer to Table 1). The temperatures of all samples were recorded with portable thermometers, and pH levels were measured utilizing a portable pH meter (WGS 84) that included temperature electrode attachments. Data collection and analysis were performed in compliance with the APHA guidelines (1995).

Statistical analysis

The parameters being evaluated were analyzed through principal component analysis (PCA), Pearson correlation analysis, contamination assessments, and metal pollution indices. As noted by Eyankware et al. (2022b), the process of component loading in PCA entails condensing a substantial dataset comprising multiple variables into a limited set of linear combinations. This reduction captures a considerable portion of the total variance in the data, facilitating an easier identification of the connections between the variables and their respective sources or processes as illustrated in Equation (1).

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

The intervals of the variables are represented by I, while the total count of outcomes is indicated by N, and the statistical average is symbolized by Xi.

Metal Pollution Index (MPI)

The MPI, which indicated the cumulative effect of all heavy metals on water quality, was computed by Horton in 1965 and Mohan et al. in 1996, employing equation 2.

$$MPI = \sqrt[n]{M_1 \times M_2 \times M_{3\_\_\_\_\_\_\_\_\_}}\ \mathrm{Mn} \qquad (2)$$

when the metal concentration is Mn.

Table 1. Physicochemical characteristics of water's output

Sample code	EC (µS/cm)	TDS mg L^{-1}	pH	Mg^{++} (meq/L)	Na^{+} (meq/L)	Ca^{++} (meq/L)	Cl^{-} (meq/L)	SO_4^{2-} (meq/L)	CO_3^{2-} (mg/L)	Cd (mg/l)	Fe (mg/l)	As (mg/l)	Mn (mg/l)	Cu (mg/l)	Co (mg/l)	Ni (m/gl)
JTB /01	536.3	648.1	6.3	0.30	1.02	1.38	0.37	1.83	0.11	0.001	0.001	0.001	0.011	N/A	0.001	0.011
JTB /02	383.7	292.7	6.5	0.47	1.32	2.41	1.45	1.69	0.93	0.002	0.0120	0.001	0.001	0.001	N/A	0.001
JTB /03	470.9	94.1	6.7	0.39	1.36	0.93	0.46	0.63	0.46	0.001	0.002	0.001	0.002	0.001	N/A	0.002
JTB /04	537.1	52.2	6.7	1.01	0.99	1.91	0.94	0.24	0.63	0.001	0.001	0.001	0.001	0.0001	N/A	0.001
JTB /05	1190.1	386.2	6.2	0.82	0.37	1.63	0.35	1.11	0.71	0.002	0.002	0.0001	0.001	0.002	0.0001	0.001
JTB /06	117.2	122.8	6.4	0.68	0.26	0.28	0.94	0.37	0.88	0.001	0.001	0.001	0.002	0.001	0.011	0.002
JTB /07	537.1	53.3	6.2	1.38	0.83	0.26	0.88	0.52	0.91	0.001	0.011	0.001	0.010	0.001	0.001	0.010
JTB /08	983.3	46.4	7.0	1.00	0.27	0.37	1.07	0.23	0.20	0.001	0.001	0.001	0.001	0.002	0.002	0.001
JTB /09	1001.1	47.1	7.1	0.92	0.93	0.61	2.08	0.25	0.39	0.0001	0.002	0.001	0.0001	0.010	0.001	0.0001
JTB /10	746.3	79.2	6.7	0.75	0.99	1.37	0.47	0.93	0.10	0.0002	0.001	0.0001	0.002	0.001	0.001	0.001
JTB /11	438.9	199.1	6.8	1.02	1.83	1.03	0.88	0.27	0.37	0.001	0.001	N/A	0.001	0.0001	0.002	0.001
JTB /12	378.9	204.7	6.9	0.73	1.38	0.38	0.19	1.93	0.62	0.001	0.002	0.0001	0.001	N/A	0.010	0.002
JTB /13	530.0	110.1	6.2	1.38	1.93	0.99	0.37	0.33	1.07	N/A	0.010	0.002	0.002	N/A	0.001	0.010
JTB /14	739.1	92.4	6.3	1.87	1.34	1.81	0.74	0.81	0.93	N/A	0.001	0.001	0.010	0.001	0.0001	0.001
JTB /15	883.1	55.0	6.5	0.83	0.73	1.90	0.46	1.37	0.63	N/A	0.0001	0.0001	0.001	0.002	N/A	N/A
JTB/16	1005.4	18.2	6.3	0.99	0.81	0.45	0.11	0.77	0.46	N/A	0.002	N/A	0.0001	0.001	0.001	N/A
JTB/17	839.2	47.8	6.8	1.02	0.36	0.74	0.47	0.38	0.37	0.0001	0.001	N/A	0.001	0.001	0.0001	N/A
WHO, 2011	1000	5000	6.5 -8.5	250	-	75	250	250	-	-	0.3	-	-	2	-	-
Min	117.2	18.2	6.2	0.3	0.26	0.26	0.11	0.23	0.1	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Max	1190.1	648.1	7.1	1.87	1.93	2.41	2.08	1.93	1.07	0.002	0.012	0.002	0.011	0.01	0.011	0.011
Aver	664.4737	169.2474	6.573684	0.933158	0.995263	1.111579	0.758947	0.832632	0.575789	0.000967	0.003326	0.000844	0.003068	0.002144	0.002827	0.00345

Contamination factor (CF)

The CF was calculated through the utilization of the Hakanson (1980) formula.

$$CF = \frac{C_n}{B_n} \tag{3}$$

Where: Cn is the metal concentration,Bn is the background/target value (Akakuru et al., 2021).

Pollution Load Index (PLI)

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

$$PLI = \sqrt[n]{CF1 \times CF2 \times} CF3 \times \ldots \times CFn \tag{4}$$

Where CF stands for contamination factor and n stands for element number.

Pollution Index of Groundwater (PIG)

The PIG serves as a tool for assessing the suitability of groundwater for human consumption (SubbaRao et al., 2018). When employing the PIG, five key factors must be considered. In Step I, the relative weight (Rw) of each factor is calculated to evaluate the impact of water quality on human health, using a scale from 1 to 5. Step II requires the computation of the weight parameter (Wp) for each groundwater quality parameter, which helps in understanding the contribution of each parameter to the overall condition of groundwater quality (refer to equation 5). In Step III, the concentration status (Sc) is determined by multiplying the concentration (C) of each sample by the relevant quality standard limit (Ds) (see equation 6). This study assessed the PIG based on the standards set by WHO (2011). To ascertain the overall groundwater quality (Ow), both the weight parameter (Wp) and concentration status (Sc) are integrated as illustrated in

$$\mathrm{Wp} = \frac{R_w}{\sum R_w} \quad (5)$$

$$\mathrm{Sc} = \frac{C}{D_c} \quad (6)$$

$$\mathrm{Ow} = \mathrm{Wp} * \mathrm{Si} \quad (7)$$

$$\mathrm{PIG} = \sum O_w \quad (8)$$

Health risk assessment

The non-carcinogenic risk of drinking tainted river water was calculated in accordance with the standards of the US Environmental Protection Agency (USEPA, 1994). In equation 9, the risk was calculated for both adults and children. Children are between 0-18 years while adults are 18 years and above. The HRA was calculated using the following function.

$$\mathrm{CDI} = \frac{\mathrm{Cw\ X\ IRW\ X\ EF\ X\ ED}}{\mathrm{BW\ X\ AT}} \quad (9)$$

where CDI is an acronym for Chronic Daily Intake (mg/kg/day), Cw is an acronym for contaminant concentration in water (mg/L), IRW is an acronym for ingestion rate (for adults, IRW is 2 L/day, while for children, IRW is 1 L/day), EF is an acronym for exposure frequency (equivalent to 365 days/year), and ED is an acronym for exposure duration (Bortey-Sam et al., 2015; Barzegar et al., 2018). The non-carcinogenic risk supplied by various components in equation 10 was calculated using the hazard quotient (HQ), according to Zhang et al. (2018):

$$\mathrm{HQ} = \frac{\mathrm{CDI}}{\mathrm{RFD}} \quad (10)$$

The abbreviation (mg/kg/day) stands for the reference dosage of an element. According to Barzegar et al. (2018), RfD for various elements is comparable to 0.7 (Fe), 0.3 (Zn), 0.0001 (Hg), 0.03 (Co), and 0.0035 (Pb). Equation 11 sis then used to calculate the hazard index (HI) of the water samples by adding the sum of the HQ values for each component.

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$$\mathrm{HI} = \sum \mathrm{HQ} \quad (11)$$

When the value surpasses one (HI = 1), the noncarcinogenic risk associated with a specific element is deemed to exceed the acceptable threshold; conversely, if the value is below one, it is considered acceptable (USEPA 1994) (refer to Table 11). The classification of non-carcinogenic risk as outlined by USEPA (1994) is referenced by Bortey-Sam et al. (2015) and Barzegar et al. (2018), as illustrated in Table 2.

Table 2: The risk of non-carcinogens by the United States Environmental Protection Agency (USEPA,1994)

Risk Level	Hazard Index (HI)	Chronic risk
1	<0.1	Negligible
2	0.1-1	Low
3	1-4	Medium
4	>4	High

Quantification of contamination (QoC)

QoC serves as a method for assessing pollutants, aimed at pinpointing the origin of a contaminant, whether it is of geogenic or anthropogenic nature. This determination was achieved through the application of Equation 5.

$$\frac{C_n - B_n}{C_n} x \frac{100}{1} \quad (12)$$

In this context, QoC refers to the contamination index, Cn denotes the concentration of metals within the sample, and Bn indicates the concentration of metals present in the background.

Potential Ecological Risk Index (ERI)

The ecological risk index, initially introduced by Hakanson, (1980), was computed in the present study using the methodology outlined below:

$$\mathrm{ERI} = \sum T_i * PI \quad (13)$$

$$\mathrm{PI} = \frac{C_S}{C_b} \quad (14)$$

In this context, Cs represents the concentration while Cb denotes the background value. The research conducted by Akakuru et al. (2021) identifies the Ti response factors as follows: Cd = 30, Fe = 1, Pb = 5, As = 10, Cr = 1, and Ni = 5.

Heavy Metal Evaluation Index (HEI)

The HEI evaluates the comprehensive quality of water concerning heavy metal content, and it is computed as follows:

$$\mathrm{HEI} = \sum^{n} \frac{H_c}{H_{MAC}} \quad (15)$$

In this context, Hc denotes the observed significance, while Hmac signifies the permissible maximum concentration (MAC) for the ith parameter.

Quality Assurance (QA):

Sampling Protocol: We meticulously followed the established protocols set forth by the American Public Health Association (APHA) to guarantee both consistency and reliability in our sampling process. Samples were gathered in clean, sterile containers at specific monitoring sites throughout Warri, Delta State, Nigeria. Personnel in the field adhered to stringent procedures regarding the collection, handling, and transportation of samples to the laboratory, thereby minimizing the risk of contamination and ensuring the preservation of sample integrity.

Analytical Techniques: Groundwater samples underwent analysis employing cutting-edge instruments and rigorously validated analytical methods in accordance with APHA standards. We utilized reputable laboratories with accredited facilities and employed rigorous quality control measures, including instrument calibration, method blanks, and duplicate analyses, to ensure the accuracy and precision of our results.

Quality Control Procedures: During the course of the study, we instituted rigorous quality control procedures to oversee the quality and reliability of the data. Our laboratory protocols encompassed routine evaluations of instrument functionality, strict compliance with standard operating procedures (SOPs), and engagement in proficiency testing programs designed to confirm our analytical competencies and maintain uniformity in our findings.

Data Validation: We conducted thorough data validation procedures to verify the accuracy and completeness of our dataset. Any outliers or discrepancies identified during data analysis were carefully reviewed and addressed, with documented justifications provided for their inclusion or exclusion from the final analysis.

Uncertainty Assessment: An extensive uncertainty assessment was performed to evaluate and quantify the sources of uncertainty associated with our study findings. We meticulously considered factors such as sampling variability, measurement error, and methodological limitations to provide a transparent assessment of the reliability and robustness of our results.

Statistical Analysis: Statistical analyses were conducted using appropriate methods, including Pearson correlation and Principal Component Analysis (PCA), to identify patterns and relationships within the dataset. All statistical outcomes were transparently reported, with comprehensive documentation of confidence intervals, p-values, and effect sizes to facilitate interpretation and reproducibility. Documentation and Archiving: A thorough compilation of all activities associated with the study, encompassing field notes, laboratory records, and raw data, has been diligently archived to guarantee both traceability and transparency. This data will be made available for peer review and validation, thereby enhancing accountability and cultivating trust in the dependability of our research outcomes.

3. RESULTS AND DISCUSSION

Principal Component Analysis (PCA)

A pattern-recognition method called PCA can be used to explain the variation of many related variables (Akakuru et al., 2021). It simplifies the dataset by illuminating the connections between the variables. The covariance matrix of the initial data is used by PCA to extract the eigenvalues and eigenvectors. Principal components (PCs), or orthogonal (uncorrelated) variables, are created by multiplying the initial correlated variables by the eigenvectors (loadings). The PCs' eigenvalues indicate the variance associated with those variables, while the scores refer to the converted observations, the loadings identify the original variables that were used in the PCs, and the loadings identify the original variables (Marghade et al., 2020).

Pearson's Correlation Matrix

Pearson's correlation matrix analysis is a trustworthy method for determining the connection and origin of hydrogeochemical indicators used in groundwater quality research. Correlation coefficients between 0.5 and 0.7, which are more than 0.7, demonstrate a significant relationship between the two borders (Akakuru et al. 2021).

Pollution Indices

The Ecological Risk Index, the Pollution Load Index, the Metal Pollution Index, and the Pollution Index of Groundwater were the four categories into which Yang et al. (2011) divided pollution indicators (PIG). These indices were utilized in the present investigation (ERI).

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Pollution Index of Groundwater (PIG)

Many studies have found PIG to be a useful method for assessing the quality of water (both surface and groundwater) (SubbaRao and Chaudhary, 2019). Table 10 includes a summary of the components needed to calculate the PIG, the PIG values for 17 groundwater samples collected across the study region, a distribution map of the PIG, and the PIG values for each sample.

Contamination Factor

The CF has been used in groundwater studies to calculate the ratio of heavy metal concentrations to background levels. The following criteria are used to describe the values of the contamination factor: $CF<1$ Low contamination $1 \leq CF \geq 3$ ($CF<1$), moderate contamination $3 \leq CF \geq 6$, significant contamination $CF > 6$, and very high contamination. (Akakuru & Akudinobi, 2017).

Pollution Load Index (PLI)

The PLI is an effective method for assessing the toxicity of heavy metals in normal samples (Akakuru et al., 2021; Yang et al., 2011). The most common PLI categories are zero pollution ($PLI>1$), light pollution ($PLI>2$), moderate pollution ($PLI>3$), high pollution ($2<PLI>3$), and extremely heavy pollution ($3>PLI$).

Metal Pollution Index (MPI)

MPI has demonstrated that classifying groundwater is a viable use. The MPI range for pure water is from 0.3 to 1.0, while the MPI range for very pure water is 0.3 or less. Individuals in Class III with an MPI of 1.0 to 2.0 are regarded as having a minimal impact, whereas those in Class IV are regarded as having a big impact.

Health Risk Assessment

Drinking water with heavy metals can have a number of negative health effects. Individuals living in the area face increased health risks associated with metal ingestion, largely due to the significant contamination levels of most metals. The presence of heavy metals in drinking water can lead to discoloration of clothing and various materials, accumulation in the plumbing infrastructure, and an unpleasant flavor in beverages. Although there are no specific health guidelines regarding water temperature, the use of hot water can result in corrosion, undesirable tastes and odors, as well as promote bacterial growth, all of which could pose threats to human health (WHO, 2011).

Hydrogeochemical Facies

The principal cations and anions, which constitute the primary dissolved elements in groundwater, are depicted graphically with respect to their hydrochemical history, classification, and spatial distribution (Akakuru & Akudinobi, 2017; Eyankware et al., 2021a). This research assessed the variations in hydrochemical facies by employing Piper trilinear diagrams, Durov plots, and Scholler plots.

Durov plots and Piper trilinear plots

The Piper trilinear plot, which displays chemical interactions more precisely than other plotting methods and aids in understanding shallow groundwater geochemistry, is one of the most useful graphical representations in groundwater quality investigations.

Spatial distrubtion of physicochemical parameters and heavy metals

pH

The pH of water reflects the equilibrium between acids and bases. The pH ranges from 6.2 to 7.1, with a mean of 6.5, as shown in Table 1. Fig. 2a shows that the research area's NE, NW, and a few spots in the SW and NE all had high pH values. The high concentrations in the study area along the Mercy City (NE) axis may be brought on by human activities there, including corrosion of storage bowls, fetching buckets, tanks, borehole casings, and plumbing fittings in the water distribution system (Efe and Mogoborrukor, 2012). Similar research by Efe and Mogoborukor (2012) showed that the Niger Delta region frequently has low pH values, especially during rains.

Electrical conductivity (EC)

Electrical conductivity (EC) plays a crucial role in the indirect assessment of water salinity. EC can serve as a means to gauge salinity across diverse contexts, which frequently influences taste and significantly affects public perception regarding the potability of water. Furthermore, Eyankware et al. (2020b) highlight that EC is an essential metric in evaluating groundwater quality for numerous applications. Ec values vary from 117.2 to 1190.1 μS/cm, with an average value of 664.6 μS/cm. As shown in Fig. 2b, the research area's NE, SE, and a few chosen SW areas have the highest EC concentrations. These high levels could be the result of the area's shifting geology. Other probable reasons include groundwater seepage, industrial and agricultural wastewater, precipitation runoff, and sewage effluent that flows into streams.

Total Dissolved Solids (TDS)

According to Kareem et al. (2016), TDS values are indicative of both the total mass of dissolved solids in a solution and the extent of groundwater salinization. To assess the appropriateness of groundwater for various applications, it is crucial to classify it based on its hydrochemical characteristics and TDS levels (Todd, 2009). As illustrated in Table 1, the concentration of TDS ranges from 18.2 to 648.1 mg/L, with a mean value of 169.24 mg/L. Furthermore, Figure 2c highlights that the southwestern regions of the study area, such as Benji, Ekpan, and Ogunu, along with the central area that includes Tori, exhibit elevated TDS concentrations.

Chloride (Cl^-)

There are several sources of chloride in groundwater, including anthropogenic sources, marine water trapped in sediments, and the breakdown of halite and related minerals. As indicated in Table 2, the chloride-dominating concentration in the groundwater exhibits an average of 0.75 meq/L, with values spanning from 0.11 to 2.08 meq/L. The elevated levels of chloride found in streams and creeks can be attributed to the infiltration of seawater into these aquatic systems. As illustrated in Fig. 2d, significant concentrations of Cl are notably present in the regions of Mercy City, Okuokoko, Benji, Ogunu, and Odi, situated in the northeastern and southwestern parts of the study area. This phenomenon may stem from the runoff of seawater into the adjacent water bodies in that vicinity.

Sodium (Na^+)

Among the alkali metals present in the examined groundwater, sodium is the most readily available. It is also the alkali metal with the highest concentration in the analyzed groundwater, averaging 0.99 meq/L, as illustrated in Table 1. Notably, elevated levels of sodium can be observed in the southwestern, southeastern, and northeastern regions of the study area (see Fig. 2e).

Carbonate (CO_3^-)

As reported by the WHO (2011), cations that contribute to water hardness can be classified into two categories: carbonate (temporary) and non-carbonate (permanent) forms. In this study, the concentration of CO3 varies from 0.1 to 1.07 meq/L, with an average recorded at 0.57 meq/L, as detailed in Table 1. The analysis presented in Fig. 2f indicates that notable CO_3 concentrations were identified in the northeastern (NE), northwestern (NW), southeastern (SE), and specific regions of the southwestern (SW) areas. These levels are likely influenced by both natural geological processes and anthropogenic activities occurring within the study area.

Magnesium (Mg^{2+})

Magnesium serves as an essential ion for cellular functions and the activity of enzymes; however, when present in excessive amounts, it is regarded as a laxative. Conversely, a deficiency in magnesium can lead to both structural and functional changes within the human body. The permissible concentration is set at 30 mg/l, in accordance with established guidelines. As illustrated in Table 1, the mean concentration of Mg^{2+} is recorded at 0.93 meq/L, falling within a spectrum of 0.3 to 1.87 meq/L. Elevated levels of Mg2+ were detected in the northeastern and southwestern regions, as well as in select areas along the northwest axis of the study area, as depicted in Fig. 2g. This phenomenon may be attributed to geogenic activity, where groundwater interacts with specific rock formations.

Calcium (Ca^{2+})

Earth metal is made of alkali. Calcium is a frequent component of many rock minerals. Calcium is typically found in groundwater as a result of its simple solubility and availability in most forms of rock (Ezeh et al., 2016). Calcium is the most common alkaline earth element found in the groundwater of the aquifer (Saha et al., 2019; Omo-Irabor et al., 2018). The calcium concentrations measured in this study range from 0.26 to 2.41 meq/L, yielding an average of 1.11 meq/L (refer to Table 1). Notably, higher levels of Ca2+ were identified in the southwestern part of the study area, particularly near Ubeji, Odi, Ekpan, and Ogidigbo, as illustrated in Fig. 2h. Ezeh et al. (2016) state that the presence of calcium in groundwater is attributed to its high solubility and prevalence in various rock types; thus, elevated calcium levels may be associated with both natural geological and human-induced activities in the region under investigation.

Sulphate (SO_4^{2-})

Sulfate can be present naturally or as a result of sewage from cities or businesses. The primary natural sources are rock weathering, biological or biochemical processes, and volcanic activity. Sulfate concentrations range from 0.23 to 1.93 meq/L, with an average of 0.83 meq/L. (View Table 1). According to the findings of Fig. 2i, the research area's NW and SW regions, including the areas in and around Odi and Ogunu, exhibited high concentrations of SO_4 and other pollutants. The high level of combustion in the area's sulfur-containing hydrocarbon fuel may be to blame for the high concentration of sulfate (Efe and Mogoborrukor, 2012).

Spatial Distribution of Heavy Metals in Groundwater

Copper (Cu)

From this investigation. Cu concentration ranges from 0.0001 to 0.001 mg/l, with an average value of 0.0021. (See Table 1). The majority of the time, it either forms complexes with inorganic ligands like copper or is adsorbed to insoluble particles (Florence et al., 1992). Copper traces are present in water sources (Abedi Sarvestani and Aghasi 2019; Araya et al. 2001). Copper can be discharged into the environment as a result of several human activities, most notably land and mining operations (Abedi Sarvestani and Aghasi 2019; Taylor et al. 2020). The presence of copper in water is also promoted by various sources such as sewage treatment facilities, antifouling coatings, soil degradation, the discharge of industrial waste into aquatic systems, and river systems. A significant contributor to the rising levels of copper in water is the manner in which water is distributed. In numerous countries, the predominant materials used for pipelines and plumbing fixtures are copper, which can leach into the water supply. Factors such as acidic water conditions, rugged geological formations, elevated temperatures, and the prevalent use of copper piping in residential settings exacerbate the leaching of copper into water sources (USEPA, 1994). This study observed elevated concentrations of copper in the northeastern region, particularly in Okuokoko, as illustrated in Fig. 2j.

Arsenic (As)

The Earth's crust contains arsenic (As), an element that exists naturally. Both natural and anthropogenic processes have the potential to release As into sources of drinking water. According to Table 1, the average As concentration for this investigation is 0.0008, with a range of 0.0001 to 0.002 mg/l. According to deductions from Fig. 2k, there were substantial concentrations of As in the NE, SE, SW, and certain areas of the NW.

Cadimum (Cd)

Table 1 indicates that the average cadmium (Cd) content observed in this study is 0.00096 mg/l, with a range spanning from 0.0001 to 0.002 mg/l. It is uncommon to detect high levels of cadmium in groundwater, except in cases where there has been contamination due to leaching from hazardous waste sites, as well as from mining or industrial activities. In environments characterized by soft or acidic water, cadmium and lead present in plumbing systems are more likely to dissolve, leading to increased cadmium concentrations in stagnant water within residential pipes. As illustrated in Fig. 2i, notable concentrations of Cd were found in the areas such as Ekpan, Ubeji, Odi, Ogidigbo, and Ogunu.

Cobalt (Co)

Natural elements like iron and nickel also exist, but cobalt has unique qualities all its own. In most rocks, soils, waters, plants, and animals, trace levels of cobalt are present naturally. Oxygen, sulfur, and arsenic are all elements that are regularly found in the environment alongside cobalt. The soil, plants, animals, and rocks all contain trace amounts of these substances. Cobalt can be found in water as an ion or dissolved molecule, even in extremely small concentrations. Ions are defined as positive or negative electric-charged atoms, clusters of atoms, or molecules. According to Table 1, the average CO concentration for this experiment ranges from 0.0011 to 0.0028 mg/l. The NW portions of the research zone showed high CO concentrations during this examination, as shown by Fig. 2m.

Manganese (Mn)

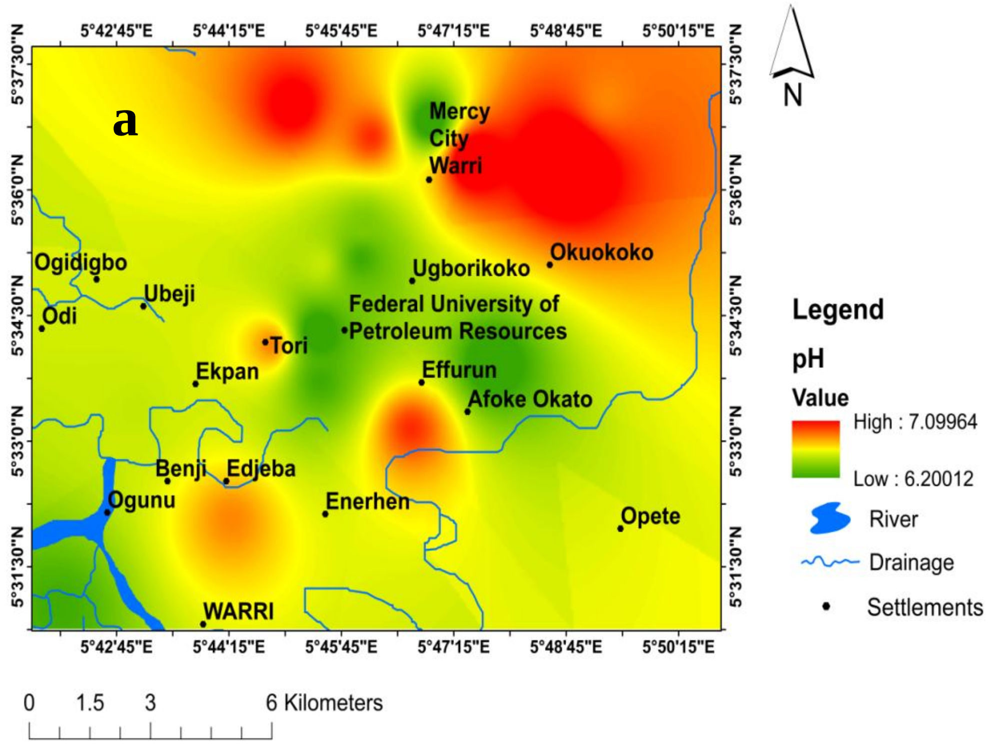
The weathering of rocks and minerals containing iron and manganese is one of the most common natural sources of these metals in groundwater. Industrial effluent, sewage, acid mine drainage, landfill leachate, and other waste products are additional sources of iron and manganese for the local groundwater (Eyankware et al., 2022a). The Mn concentration for this experiment varied from 0.0001 to 0.011 mg/l, with an average value of 0.0030, according to Table 1. According to Fig. 2n, the NE and SW axes of the research region had high Mn concentrations.

Nickel (Ni)

Nickel is a substance that occurs naturally (Ni). Nickel in water is mostly produced by leaching from metal alloys that come into contact with drinking water (Eyankware et al., 2022b). Water-soluble Ni salts have the most relevant toxicology data for assessing potential health risks from Ni exposure in drinking water. Ni exposure through the skin or inhalation can result in Ni sensitization, which is most commonly associated with gastrointestinal and neurological symptoms in people after acute exposure (Obasi & Akudinobi, 2020). Table 1 displays the average Cd concentration for this experiment, which ranged from 0.0001 to 0.0011 mg/l. Data from Fig. 2o showed that the NE, SE, and SW parts of the study area were notable for having large Ni concentrations.

Iron (Fe)

The most prevalent sources of iron and manganese in groundwater are naturally occurring, such as from the weathering of minerals and rocks that contain iron and manganese (Obasi & Akudinobi, 2020; Eyankware et al., 2022a). Local groundwater may also contain iron and manganese from industrial effluent, sewage, acid mine drainage, and landfill leachate. According to Table 1, the average Cd content for this investigation is 0.0033, ranging from 0.0001 to 0.012 mg/l. According to Fig. 2p, the research area's NE, SW, and SE regions all have high amounts of Fe. High quantities of Fe were discovered in groundwater, which may be attributed to the erosive activity's washing or leaching of lateritic Fe inside soil particles as well as the dissolution of Fe from specific scraps, metallic wastes, and soil particles.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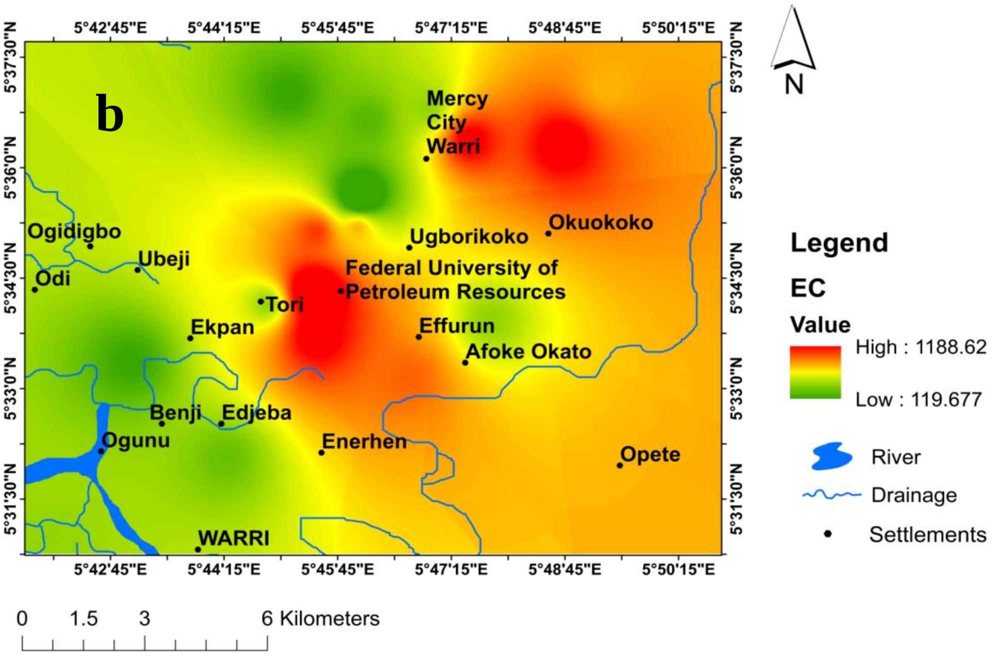
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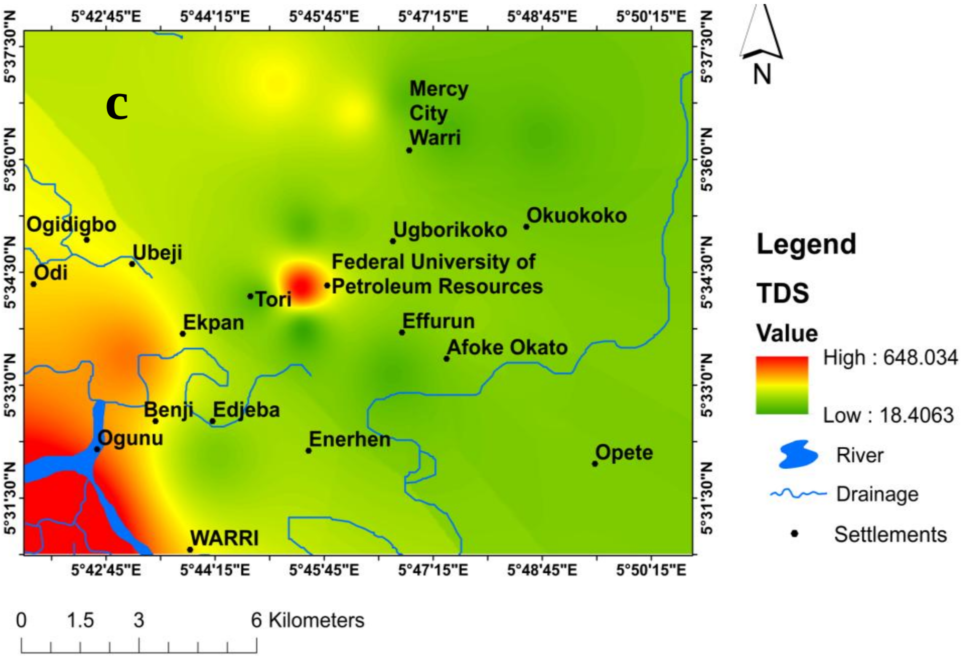
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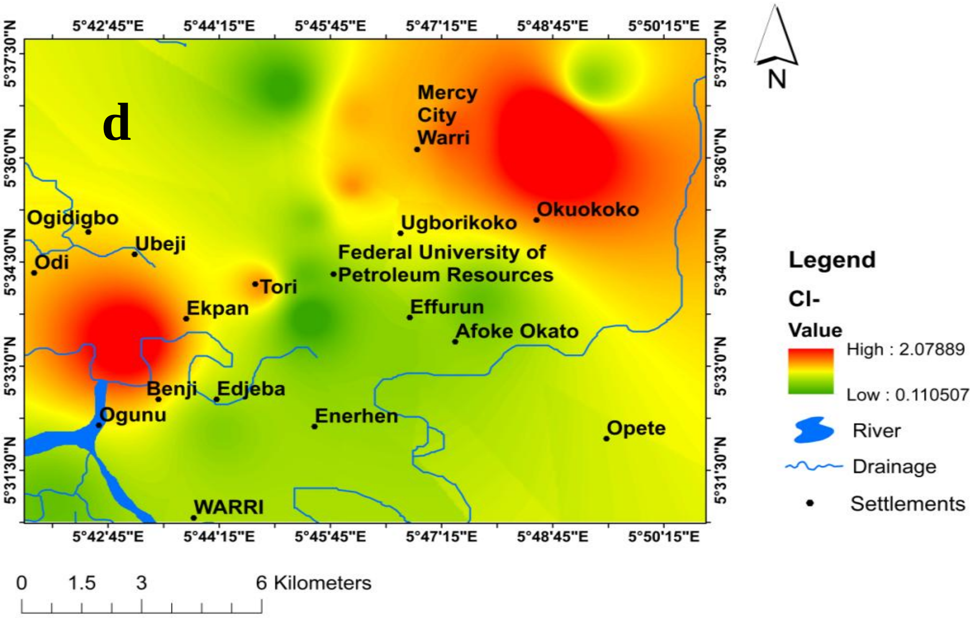
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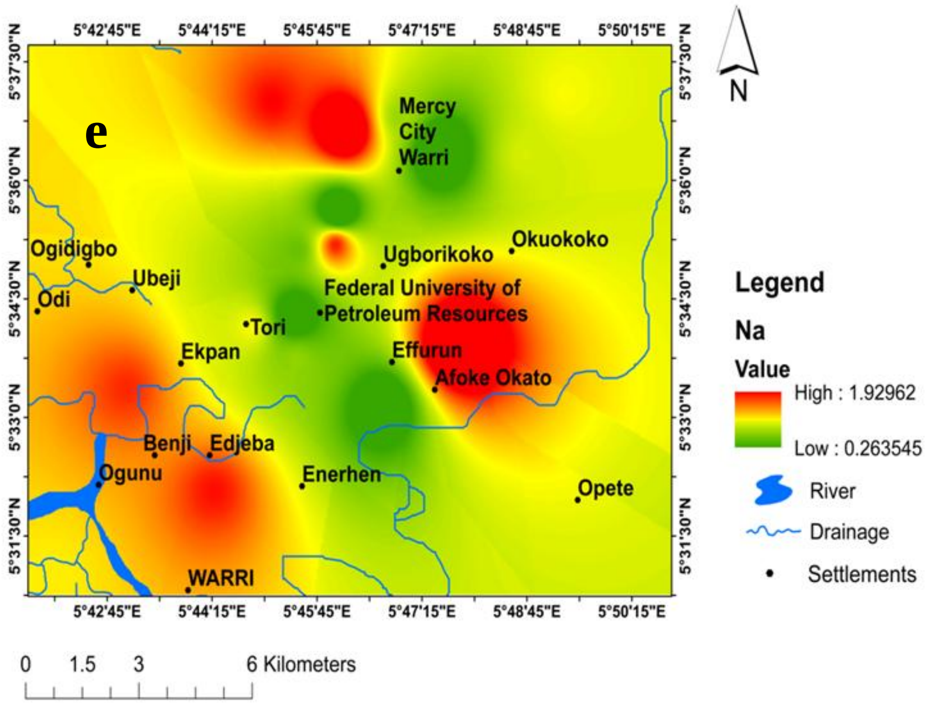
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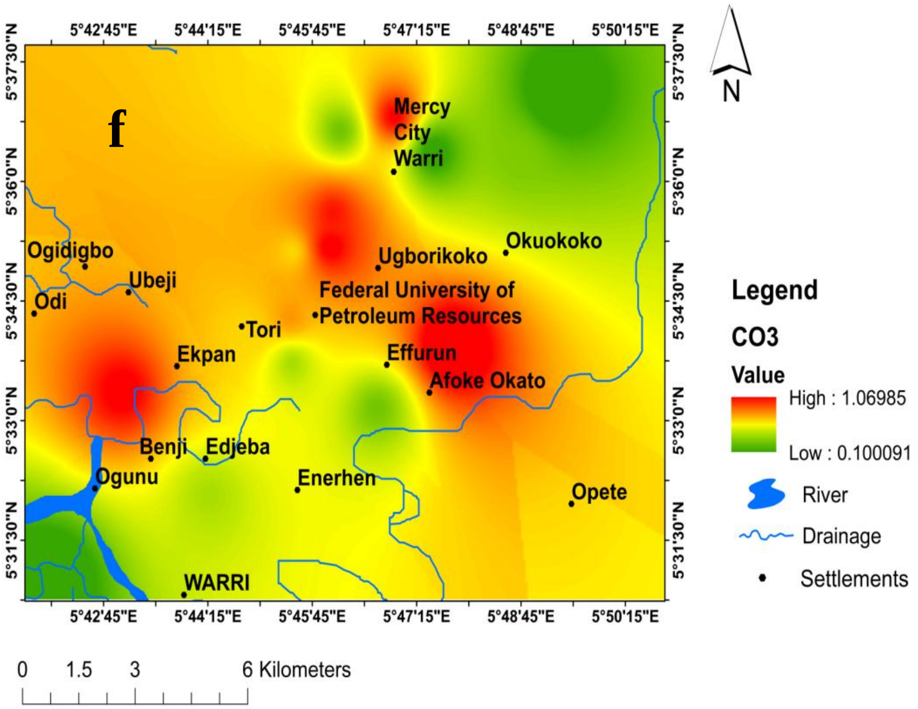
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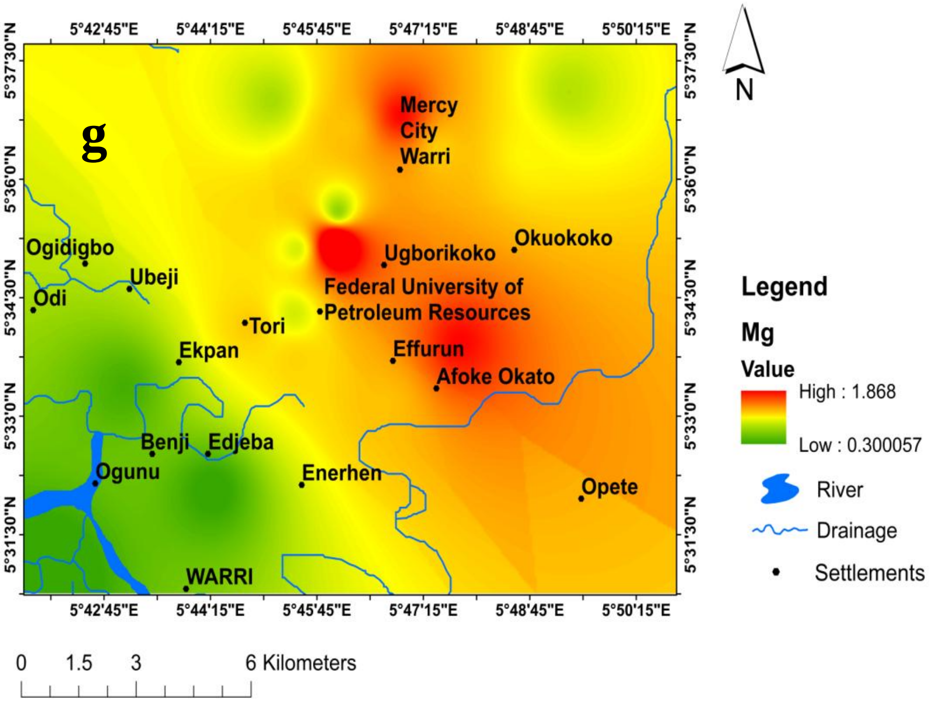
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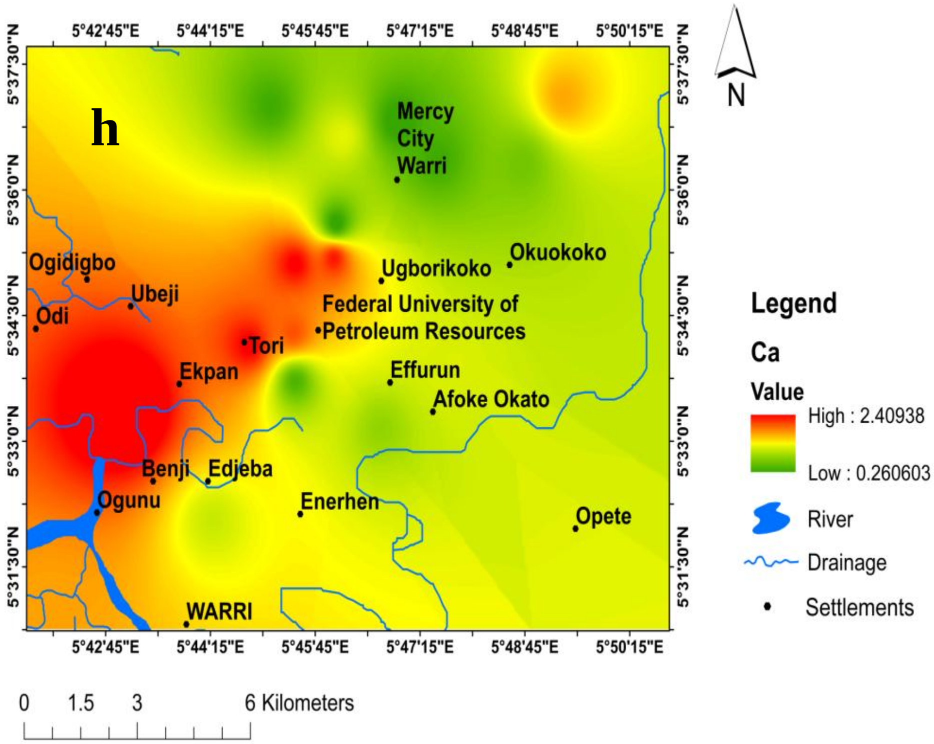
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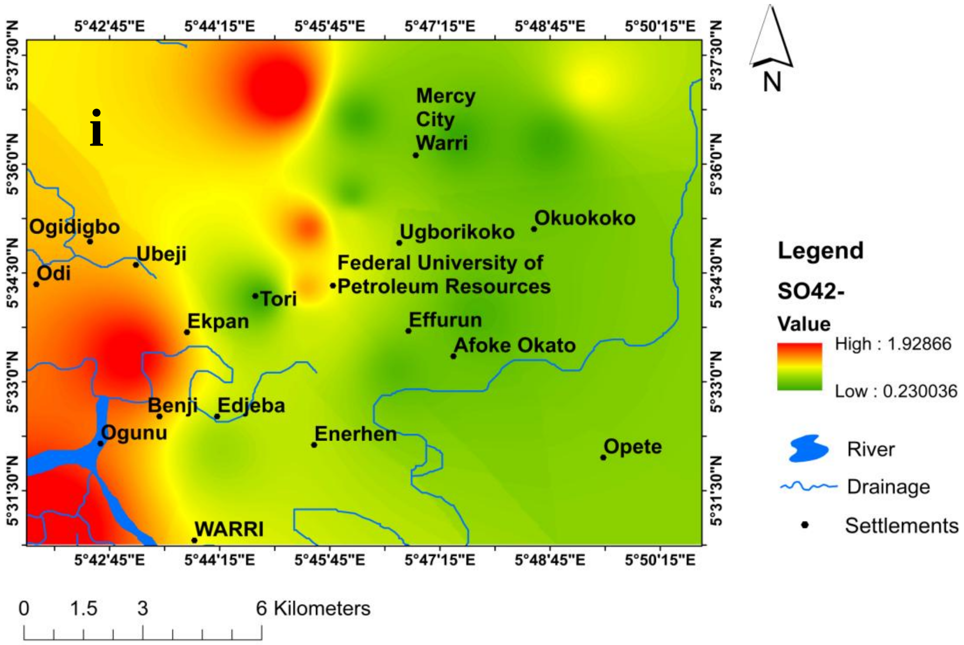
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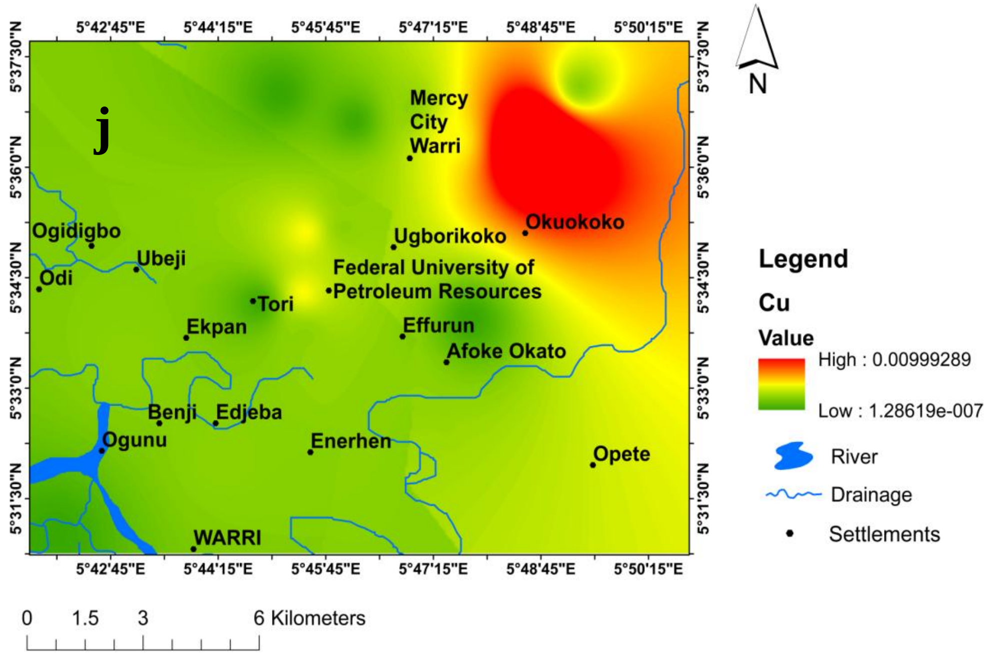
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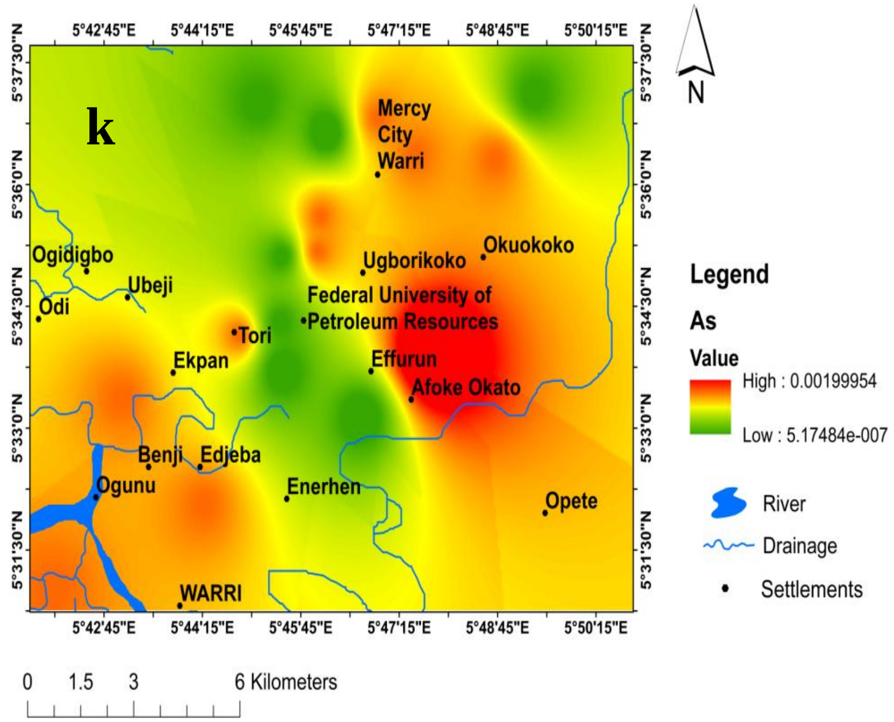
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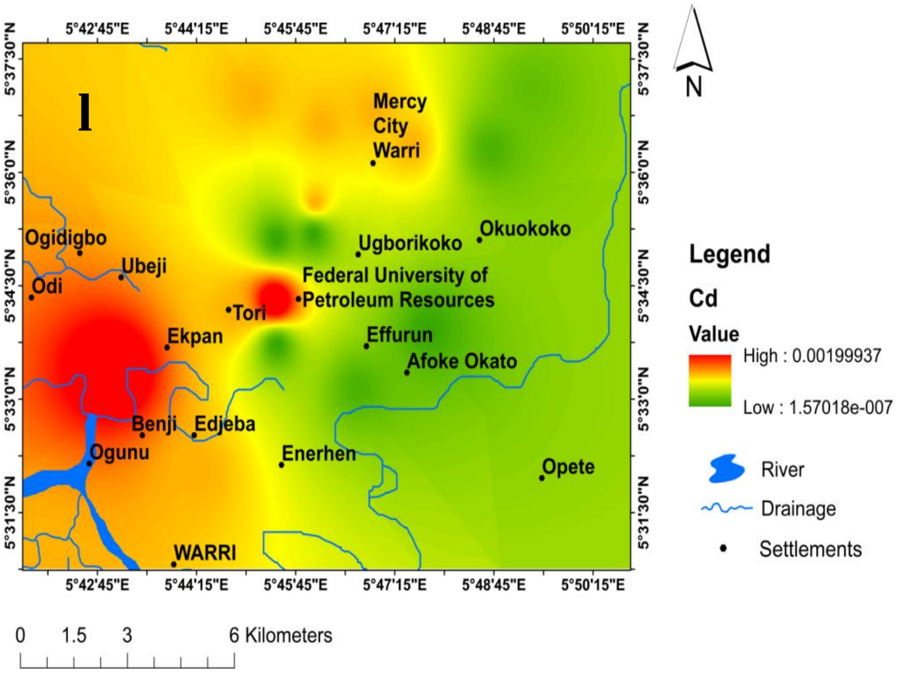
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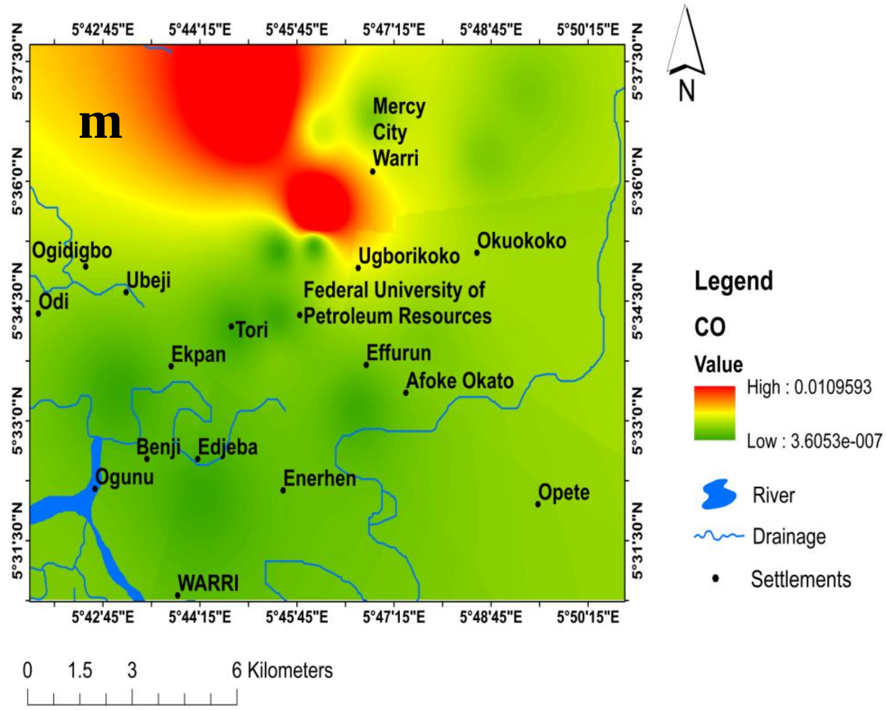
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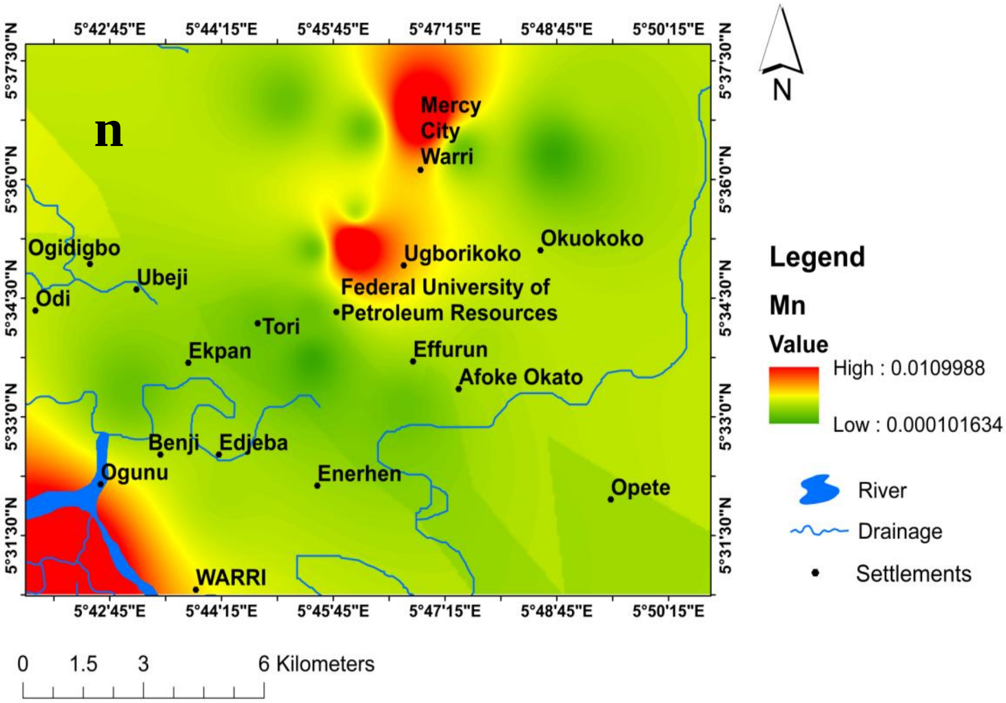
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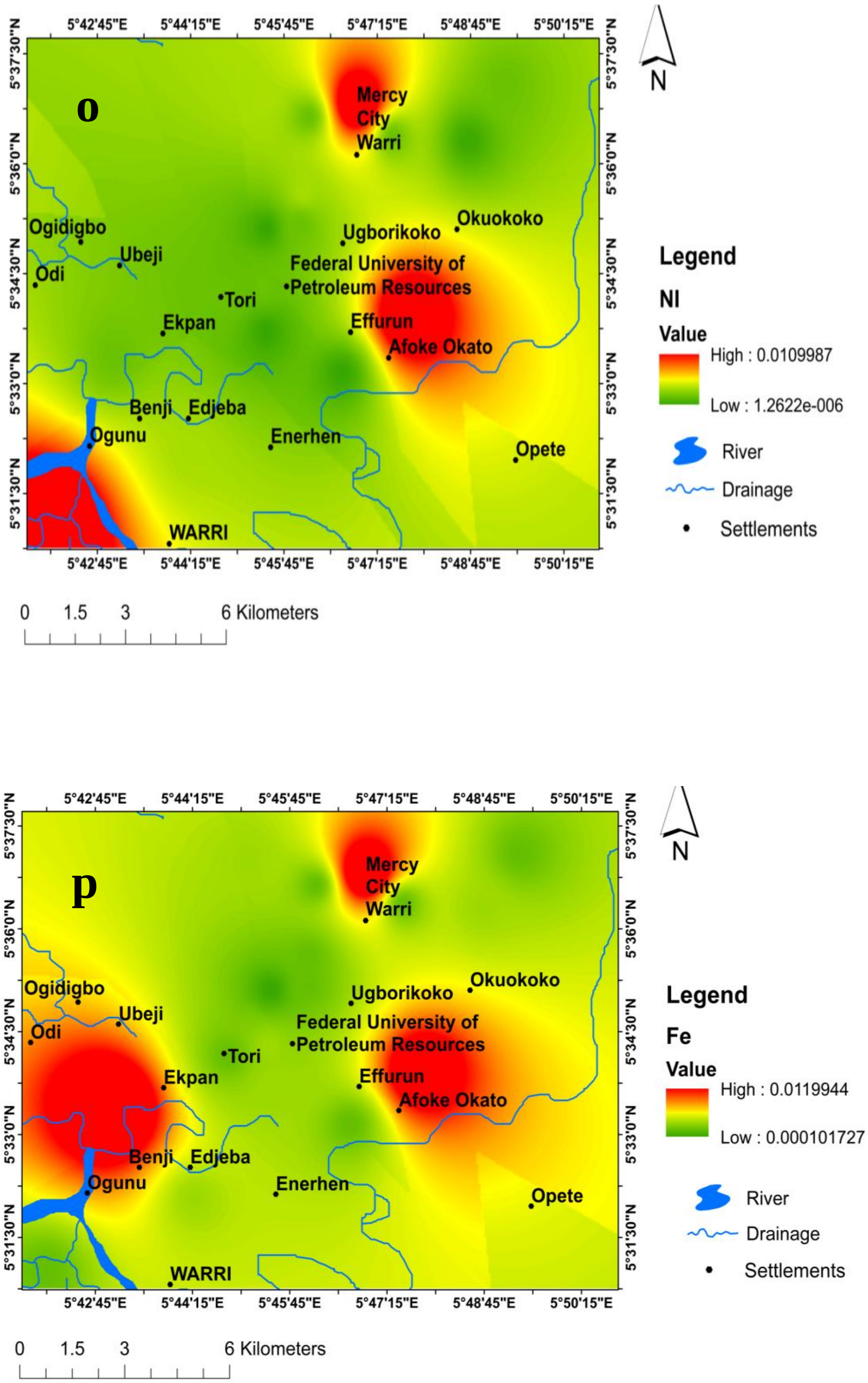

Fig. 2: a, b, c, d, e, f, g, h, I, j, k, l, m, n, o, and p spatial distribution of pH, EC, TDS, Cl$^-$, Na$^+$, CO$_3^-$, Mg^{2+}, Ca^{2+}, SO$_4^{2-}$, Cu, As, Cd, CO, Mn, Ni and Fe respectively.

Pearson's Correlation Matrix

You can use a correlation matrix to look at how two variables are related to one another. The correlation coefficient usually lies between -1 and +1. The relationship is deemed to be anti-correlated or to have a downhill slope if the r-value is close to -1. A positive slope, or correlation, is visible in the relationship when r is close to 1. If the value is 0, the correlation between the values is thought to be zero (Abbasnia et al., 2018). When assessing the quality of groundwater, correlation matrix analysis can be utilized to establish the connection and source of hydrogeochemical indicators (Egbueri, 2020; Akakuru et al., 2021). Strong correlations exist between two limits when their correlation is larger than 0.7; weak correlations and moderate correlations exist when their correlation is between 0.5 and 0.7. (Akakuru et al., 2021). The relationship between the variables EC and Na, Co, TDS and Mg, SO_4, Cd, Ni, pH and Cl, CO_3, Mn, Ni, Mg and SO_4, CO_3, Ca and Co, Cl and Cr, CO_3 and Fe, Cd and As, Fe and Ni, and Mn and Ni is depicted in Table 3. The groundwater aquifer system is iterative, as evidenced by the weak to moderate relationships between parameters. This outcome is comparable to that of the study Akakuru et al. (2021) carried out in Nigeria.

Table 3: Pearson correlation matrix

	EC	**TDS**	**pH**	**Mg**	**Na**	**Ca**	**Cl**	**SO_4**	**CO_3**	**Cd**	**Fe**	**As**	**Mn**	**Cr**	**Co**	**Ni**
EC	1.00															
TDS	-0.15	1.00														
pH	0.07	-0.31	1.00													
Mg	0.22	**-0.50**	-0.22	1.00												
Na	**-0.41**	0.10	-0.05	0.15	1.00											
Ca	0.05	0.32	-0.23	-0.08	0.24	1.00										
Cl	-0.03	-0.17	0.44	0.03	-0.05	0.05	1.00									
SO_4	-0.11	**0.64**	-0.22	**-0.47**	0.12	0.38	-0.34	1.00								
CO_3	-0.33	-0.15	**-0.55**	**0.44**	0.23	0.17	0.06	-0.02	1.00							
Cd	-0.13	**0.49**	-0.30	-0.23	-0.06	0.27	0.02	0.34	0.26	1.00						
Fe	-0.29	0.03	-0.39	0.14	0.35	0.08	0.21	0.08	**0.61**	0.24	1.00					
As	-0.04	-0.38	0.38	0.09	0.07	-0.20	-0.21	0.01	-0.21	**-0.68**	-0.06	1.00				
Mn	-0.19	0.38	**-0.51**	0.27	0.10	0.06	-0.11	0.21	0.12	0.10	0.17	-0.21	1.00			
Cr	0.39	-0.22	**0.46**	0.07	-0.02	-0.20	**0.67**	-0.29	-0.11	-0.34	-0.05	-0.08	-0.29	1.00		
Co	**-0.59**	-0.02	0.19	-0.26	-0.15	**-0.41**	-0.05	0.17	0.18	0.05	-0.15	0.20	-0.21	-0.14	1.00	
Ni	-0.31	**0.41**	**-0.54**	0.05	0.28	-0.18	-0.22	0.12	0.19	-0.05	**0.51**	-0.01	**0.66**	-0.22	-0.12	1.00

Bold = Relationship

Principal Component Analysis

The PCA is an essential tool for identifying designs, analyzing the variation of networks of connected components, and obtaining the Eigenvalues and Eigenvectors (loadings) for head sections from the change that they are subject to (Yahaya et al., 2022). It demonstrates how the variables are connected in order to identify the most likely sources of groundwater contamination in the study area. Each loading that exceeds 0.4 (+/-) is regarded as a significant input in the analytical interpretation. Table 4 shows that there were loadings for 62% of the parameters in PC1, 31.25% of the parameters in PC2, which was the same as in PC3, and 25% of the samples overall in PC4. The findings of this PCA suggest that loadings within the groundwater system may be caused by neighboring anthropogenic activities that are changing the chemistry of the water.

Table 4: Results of PCA

Parameters	**Communalities**	**Components**			
		1	**2**	**3**	**4**
EC	0.83	**-0.41**	-0.03	**0.60**	**-0.54**
TDS	0.75	**0.65**	**-0.54**	0.17	-0.02

pH	0.77	**-0.79**	-0.26	-0.10	0.26
Mg	0.73	-0.07	**0.81**	0.09	-0.26
Na	0.24	0.31	0.30	-0.16	0.15
Ca	0.39	0.36	-0.17	**0.48**	0.01
Cl	0.73	-0.35	0.24	**0.42**	**0.61**
SO_4	0.62	**0.54**	**-0.57**	-0.08	-0.02
CO_3	0.72	**0.45**	**0.59**	-0.01	**0.41**
Cd	0.72	**0.55**	-0.32	0.39	0.39
Fe	0.65	**0.50**	**0.53**	0.02	0.35
As	0.67	-0.39	0.08	**-0.67**	-0.27
Mn	0.55	**0.62**	0.22	0.01	-0.35
Cr	0.59	**-0.58**	0.21	0.39	0.25
Co	0.79	-0.05	-0.26	**-0.67**	**0.52**
Ni	0.63	**0.64**	0.32	-0.27	-0.23
	Eigen Value	1.98	1.13	0.62	1.26
	Variance (%)	24.33	16.28	14.00	11.65
	Cumm. Variance (%)	24.33	40.61	54.61	66.26

Bold = loadings

Hydrogeochemical evaluation

Piper Diagram

The Piper trilinear plot (Fig. 3) is among the most useful graphics used to monitor groundwater quality (Piper, 1944). Comparatively to other existing charting techniques, it enhances understanding of the geochemistry of shallow groundwater and clarifies chemical interactions (Eyankware et al., 2020b). There is a 35.3 percent SO_4 dominance, a 5.9 percent HCO_3 dominance, a 41.2 percent Cl dominance, and a 17.6 percent absence of an obvious ionic species in the cation area. The majority of the sample's constituent ions are Na+ and K, which are found in the anion region. According to the Piper diagram, the region is in geochemical zone 2. (Alkalines exceed Akaline earths.) Common compounds in rocks and soils include sodium and potassium. They are a member of the class of substances known as "alkali metals." Chloride and bromide are frequently linked with sodium and potassium. Rocks dissolve, gently releasing sodium and potassium. As a result, concentrations rise as groundwater residence times rise (Ezeh et al., 2016).

Durov Diagram

Many academics have utilized the Durov diagram to characterize the hydrogeochemical composition of groundwater. Its effectiveness has long been recognized. The Durov plot in Fig. 4 demonstrates how similar the Durov is to the Piper diagram. It also demonstrates that there is ionic exchange occurring within the groundwater zone. This research agrees with that of Nigerian researchers Agidi et al. (2022) and Akakuru et al. (2021).

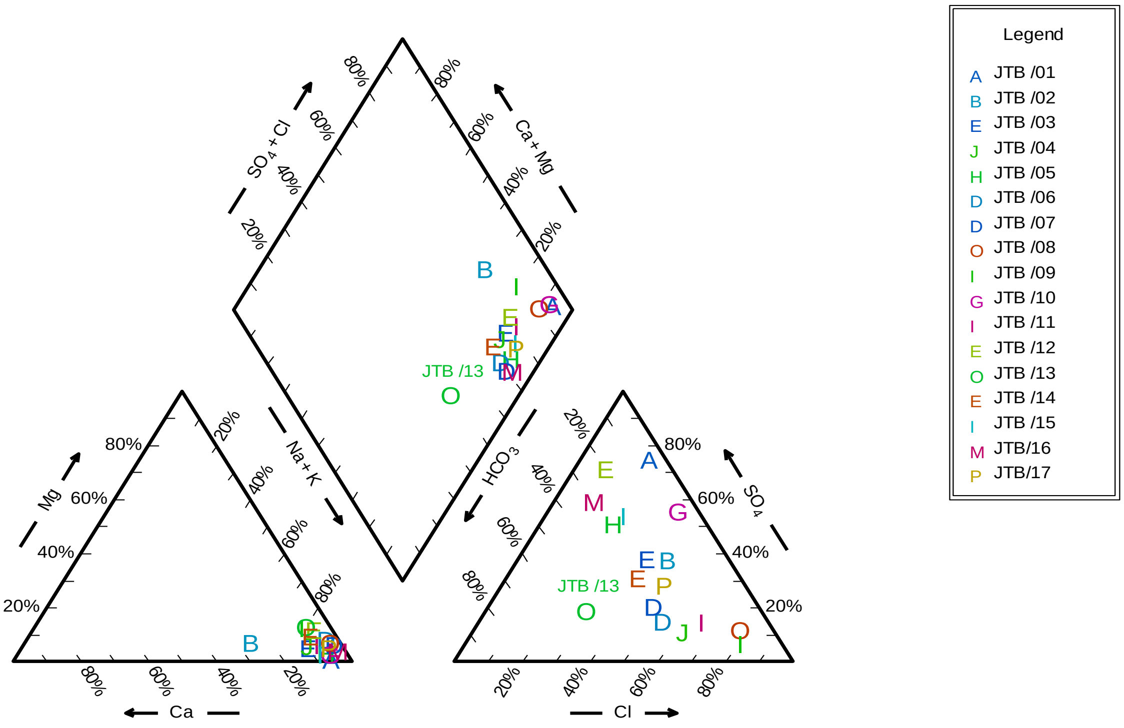

Fig. 3: Piper Diagram

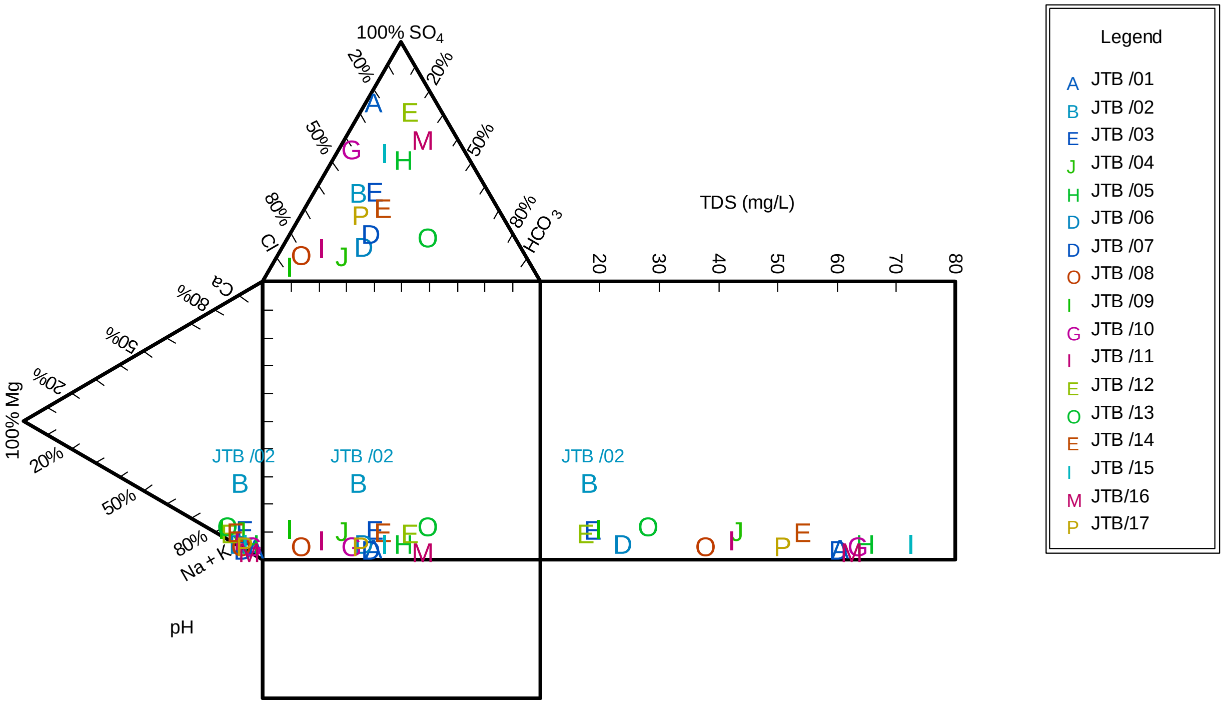

Fig. 4: Durov plot

Schoeller Diagram

The Schoeller semi-logarithmic chart is a different relationship method that makes use of direct graphics (Fig. 5). Scales that are either algebraic or logarithmic are used on the majority of water quality charts (Sakram et al., 2013). According to Schoeller's proposed diagram from 1977, the number of components being transported dictates how many investigations will take place on equidistant verticals (Olofinlade et al., 2018; Sakram et al., 2013, respectively). The samples are migrating in a similar manner to the hydrogeochemical trend, as shown by the Schoeller diagram. $Na+K>Mg>Ca>Cl>SO_4>HCO_3$. Clay particles in the soil have a great affinity for potassium, an essential nutrient. Therefore, only coarse-textured soils are significant for potassium leaching through the soil profile and into groundwater. Numerous rocks contain potassium, and since many of these rocks are very soluble, groundwater potassium concentrations increase over time. Road salt and animal feces are significant sources of sodium produced by humans. Since sodium is more mobile in soil than potassium, it is frequently used as a sign of how human activity has affected shallow groundwater. Another typical chemical found in minerals is sodium. Similar to potassium, sodium slowly leaks out of rocks. As a result, concentration gets better over time. (Eyankware et al., 2020b; Akakuru et al., 2021).

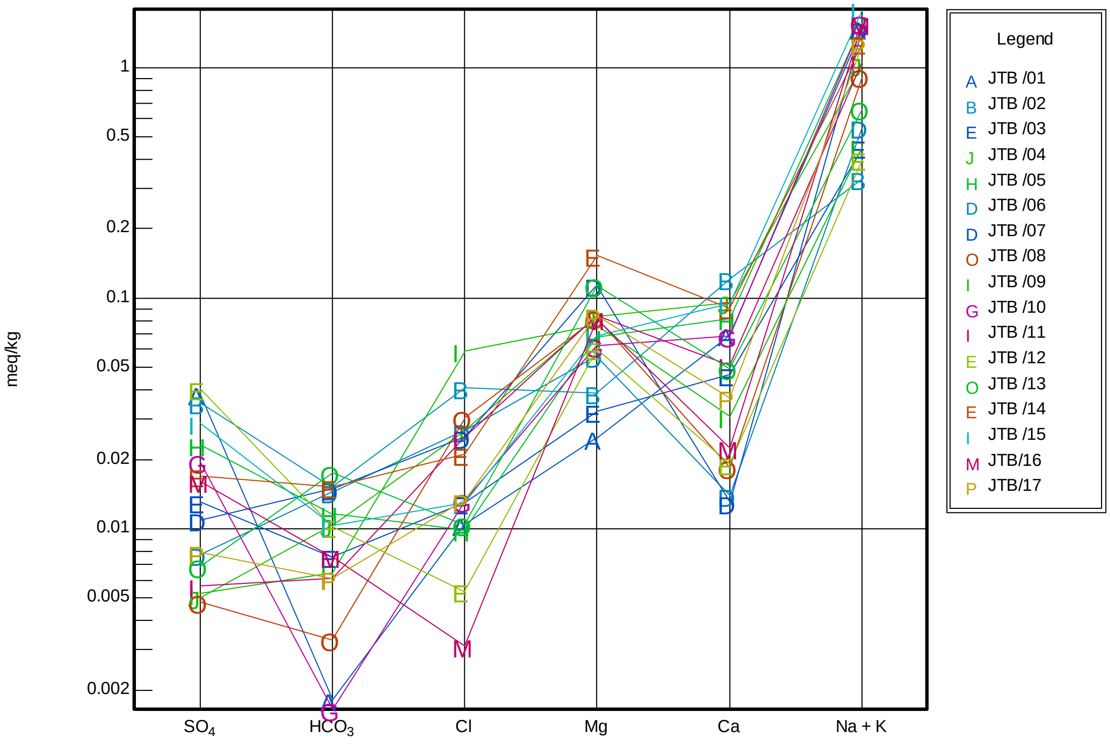

Fig. 5: Schoeller Diagram

Heavy Metal Index

An important environmental issue today is heavy metal contamination. This is because drinking water that has been contaminated with heavy metals has negative effects. The HM assessment index is utilized to gain a fundamental understanding of the pollution index and level of pollution (Prasanna et al., 2012).

Contamination Index

One method for the evaluation and visualization of areas characterized by anomalous or dangerous concentrations of defined elements as well as ionic species is the calculation and mapping of the degree of contamination using a guide value of the potentially harmful elements as well as the concentrations exceeding these limit values. CI value of <0.1 = slight contamination, 0.1-0.25 = slight contamination, 0.26–0.5 = moderate contamination, 0.51-0.75 = severe contamination, 0.76–1 = very severe contamination, 1.1–2.0 = slight pollution, 2.1-4.0 = moderate pollution, 4.1-8.0 = severe pollution, 8.1-16.0 =very severe pollution, and above 16.0= excessive pollution. According to Table 6's CI data, Mn and Cu have CI values that are less than 0.1, whereas Cd, As, Fe, Co, and Ni have values that fall between mild and severe contamination (Slight contamination). The primary source of contamination is anthropogenic.

Heavy Metal Rating Index (HEI)

Bhuiyan et al. (2010) created a groundwater HEI pollution-level rating for the studied area. Following the method used by Bortey-Sam et al. (2015), the estimated HEI values were divided into three classes using a multiple of the mean value. The three classes demarcated are HEI < 10 low, HEI 10–20 medium, and HEI > 20 high. As shown in Table 5, the HEI values in groundwater were considered low. This result is not in line with other pollution indices in the present study. Anthropogenic activity might be the main reason for the high HEI observed in this study. Table 5 displays the CI and HEI for the study area. This result is comparable to studies carried out in Nigeria by Eyankware & Akakuru (2023), and Egbueri (2020), along Peninsular Malaysia's west coast by Bortey-Sam et al. (2015), and in Iran by Abedi Sarvestani & Aghasi (2019).

Table 5: Contamination index and HEI in the study area

Sample code	Contamination Index							HEI
	Cd	Fe	As	Mn	Cu	Co	Ni	
JTB /01	0.333333	0.033333	0.1	0.0275	0.00005	0.2	0.55	1.244217
JTB /02	0.666667	0.4	0.1	0.0025	0.0005	0.4	0.05	1.619667
JTB /03	0.333333	0.066667	0.1	0.005	0.0005	0.2	0.1	0.8055
JTB /04	0.333333	0.033333	0.1	0.0025	0.00005	0.4	0.05	0.919217
JTB /05	0.666667	0.066667	0.01	0.0025	0.001	0.02	0.05	0.816833
JTB /06	0.333333	0.033333	0.1	0.005	0.0005	2.2	0.1	2.772167
JTB /07	0.333333	0.366667	0.1	0.025	0.0005	0.2	0.5	1.5255
JTB /08	0.333333	0.033333	0.2	0.0025	0.001	0.4	0.05	1.020167
JTB /09	0.033333	0.066667	0.1	0.00025	0.005	0.2	0.005	0.41025
JTB /10	0.066667	0.033333	0.2	0.005	0.0005	0.2	0.05	0.5555
JTB /11	0.333333	0.033333	0.1	0.0025	0.001	0.4	0.05	0.920167
JTB /12	0.333333	0.066667	0.2	0.0025	0.0005	2	0.1	2.703
JTB /13	0.033333	0.333333	0.2	0.005	0.001	0.2	0.5	1.272667
JTB /14	0.333333	0.033333	0.1	0.025	0.0005	0.02	0.05	0.562167
JTB /15	0.033333	0.003333	0.2	0.0025	0.001	0.4	0.005	0.645167
JTB/16	0.333333	0.066667	0.1	0.00025	0.0005	0.2	0.05	0.75075
JTB/17	0.033333	0.033333	0.2	0.0025	0.0005	0.4	0.005	0.674667

Contamination factor (Cf)

The contamination factor serves as an example of how the research area's pollution looks and behaves. It displays the degree of environmental pollution brought on by a specific metal in a particular medium. The contamination factor was calculated using the relationship between the heavy metal concentration and the background concentration of the relevant metal. The following criteria are used to describe the values of the contamination factor: CF<1, low contamination; 1≤CF≥3, moderate contamination; 3≤CF≥6, considerable contamination; and CF C >6, very high contamination (Akakuru et al., 2021). Since all of the groundwater samples in Table 6 were below 1, there is no contamination. According to the CF's findings, there is no evidence that the area's anthropogenic activities are directly related to the groundwater supply. This outcome is consistent with research carried out in other parts of Nigeria by Agidi et al. (2022), and Eyankware et al. (2020a).

Pollution Load Index (PLI)

The Pollution Load Index (PLI) is an important instrument for assessing the toxicity levels in contaminated groundwater samples, supported by findings from prior research (Akakuru et al., 2021; Agidi et al., 2022; Eyankware and Akakuru, 2023). The interpretation of PLI values is generally as follows: pollution-free (PLI<1), moderate pollution (1<PLI<2), heavy pollution (2<PLI<3), or extremely heavy pollution (PLI>3).

The findings presented in Table 6, indicating that 100% of the groundwater samples have a PLI concentration value of less than one, suggest a lack of contamination in the study area. This outcome is reassuring and implies a minimal impact of anthropogenic activities on the groundwater supply. High PLI values are often associated with human influence on the environment; however, our results suggest that there is no direct correlation between anthropogenic activities and groundwater quality in this area.

It is worth noting that our findings are consistent with a study conducted in Nigeria (Akakuru et al., 2021; Agidi et al., 2022), further supporting the reliability of our results. However, they differ from another study conducted in Nigeria (Yahaya et al., 2022), highlighting the variability in groundwater quality assessments across different regions and environmental contexts.

In conclusion, the PLI analysis reinforces the favorable groundwater quality observed in our study area, underscoring the importance of continued monitoring to preserve this vital resource.

Metal Pollution Index (MPI)

A useful technique for classifying groundwater quality is the Multidimensional Pollution Index (MPI). This index categorizes water quality based on the degree of pollution. Very clean water typically has an MPI of 0.3 or below, while pure water falls within the range of 0.3 to 1.0. Water samples with an MPI of 1.0–2.0 are categorized as slightly affected (Class IV), and those with MPI values between 2.0 and 4.0 are considered moderately affected (Class V). Furthermore, MPI values exceeding 4.0 may indicate considerable (Class VI) or severe (Class VII) pollution levels, as suggested by previous studies (Ogunkunle et al., 2015; Singovszka et al., 2016). According to the results presented in our study, the MPI values are less than 0.3, indicating that the water is exceptionally clean. This finding is encouraging and suggests a low level of pollution in the groundwater samples analyzed. It's worth noting that our findings contrast with studies conducted in Iran by Abedi Sarvestani & Aghasi (2019) and Nigeria by Eyankware and Akakuru (2023). However, they are consistent with research conducted in Bangladesh by Saha et al. (2019). These variations in findings highlight the importance of considering regional differences and local factors that may influence groundwater quality.

Table 6: CF, PLI, and MPI in the study area

Sample code	CF							PLI	MPI
	Cd	Fe	As	Mn	Cu	Co	Ni		
JTB /01	0.00125	0.025	0.0002	0.000129	2.77778E-06	2.94118E-05	7.85714E-05	7.20557E-14	1.1E-10
JTB /02	0.0025	0.3	0.0002	1.18E-05	2.77778E-05	5.88235E-05	7.14286E-06	1.43515E-13	2.1909E-10
JTB /03	0.00125	0.05	0.0002	2.35E-05	2.77778E-05	2.94118E-05	1.42857E-05	5.85896E-14	8.9443E-11
JTB /04	0.00125	0.025	0.0002	1.18E-05	2.77778E-06	5.88235E-05	7.14286E-06	9.26384E-15	1.4142E-11
JTB /05	0.0025	0.05	0.00002	1.18E-05	5.55556E-05	2.94118E-06	7.14286E-06	5.85896E-15	8.9443E-12
JTB /06	0.00125	0.025	0.0002	2.35E-05	2.77778E-05	0.000323529	1.42857E-05	1.37405E-13	2.0976E-10
JTB /07	0.00125	0.275	0.0002	0.000118	2.77778E-05	2.94118E-05	7.14286E-05	6.87024E-13	1.0488E-09
JTB /08	0.00125	0.025	0.0004	1.18E-05	5.55556E-05	5.88235E-05	7.14286E-06	5.85896E-14	8.9443E-11
JTB /09	0.000125	0.05	0.0002	1.18E-06	0.000277778	2.94118E-05	7.14286E-07	2.92948E-15	4.4721E-12
JTB /10	0.00025	0.025	0.0004	2.35E-05	2.77778E-05	2.94118E-05	7.14286E-06	1.85277E-14	2.8284E-11
JTB /11	0.00125	0.025	0.0002	1.18E-05	5.55556E-05	5.88235E-05	7.14286E-06	4.14291E-14	6.3246E-11
JTB /12	0.00125	0.05	0.0004	1.18E-05	2.77778E-05	0.000294118	1.42857E-05	1.85277E-13	2.8284E-10
JTB /13	0.000125	0.25	0.0004	2.35E-05	5.55556E-05	2.94118E-05	7.14286E-05	1.85277E-13	2.8284E-10

JTB /14	0.00125	0.025	0.0002	0.000118	2.77778E-05	2.94118E-06	7.14286E-06	2.07146E-14	3.1623E-11
JTB /15	0.000125	0.0025	0.0004	1.18E-05	5.55556E-05	5.88235E-05	7.14286E-07	1.85277E-15	2.8284E-12
JTB/16	0.00125	0.05	0.0002	1.18E-06	2.77778E-05	2.94118E-05	7.14286E-06	9.26384E-15	1.4142E-11
JTB/17	0.000125	0.025	0.0004	1.18E-05	2.77778E-05	5.88235E-05	7.14286E-07	4.14291E-15	6.3246E-12

In summary, the MPI analysis reaffirms the favorable quality of the groundwater samples in our study area, emphasizing the importance of continued monitoring and conservation efforts to preserve this valuable resource.

Quantification of Contamination (QoC)

The investigation into HM sources necessitated the application of the QoC model, given that heavy metals are acknowledged as significant contaminants within the research domain. Consequently, the source department finalized the PLI model, and this review incorporated the QoC model. In Table 7, the QoC values identified for each examined heavy metal are presented. Generally, positive QoC levels indicate anthropogenic influences, whereas negative QoC values often reflect geological factors. According to the findings in Table 8, the study area reveals that Cd, Fe, As, Mn, Cu, Co, and Ni exhibit completely negative values. The role of geological processes in the transport of these metals within water supplies remains poorly understood. Heavy metal toxicity is a well-recognized and evolving environmental concern. Various human activities, such as extensive metal mining, refining, the use of petroleum products, and the application of pesticides and sewage, along with geological factors like rock drainage, have influenced the prevalence of certain heavy metals (Egbueri, 2020; Agidi et al., 2022). These metals not only negatively affect plant physiology upon entering the ecosystem but also pose a continuous risk to human health. The findings of this study contradict those reported by Egbueri (2020) in the context of Nigerian Ojoto.

Table 7: Quantification of Contamination (QoC)

Sample code	Cd	Fe	As	Mn	Cu	Co	Ni
JTB /01	-79900	-3900	-499900	-772627	-35999900	-3399900	-1272627
JTB /02	-39900	-233.333	-499900	-8499900	-3599900	-1699900	-1.4E+07
JTB /03	-79900	-1900	-499900	-4249900	-3599900	-3399900	-6999900
JTB /04	-79900	-3900	-499900	-8499900	-35999900	-1699900	-1.4E+07
JTB /05	-39900	-1900	-4999900	-8499900	-1799900	-3.4E+07	-1.4E+07
JTB /06	-79900	-3900	-499900	-4249900	-3599900	-308991	-6999900
JTB /07	-79900	-263.636	-499900	-849900	-3599900	-3399900	-1399900
JTB /08	-79900	-3900	-249900	-8499900	-1799900	-1699900	-1.4E+07
JTB /09	-799900	-1900	-499900	-8.5E+07	-359900	-3399900	-1.4E+08
JTB /10	-399900	-3900	-249900	-4249900	-3599900	-3399900	-1.4E+07
JTB /11	-79900	-3900	-499900	-8499900	-1799900	-1699900	-1.4E+07
JTB /12	-79900	-1900	-249900	-8499900	-3599900	-339900	-6999900
JTB /13	-799900	-300	-249900	-4249900	-1799900	-3399900	-1399900
JTB /14	-79900	-3900	-499900	-849900	-3599900	-3.4E+07	-1.4E+07
JTB /15	-799900	-39900	-249900	-8499900	-1799900	-1699900	-1.4E+08
JTB/16	-79900	-1900	-499900	-8.5E+07	-3599900	-3399900	-1.4E+07
JTB/17	-799900	-3900	-249900	-8499900	-3599900	-1699900	-1.4E+08

Potential Ecological Risk Index (ERI)

The section effectively incorporates pollution indices, providing a comprehensive overview of water quality. However, the discussion lacks insights into specific pollution levels, trends, or comparisons with established standards. The sum of all the prospective ecological risk index (ERI) values represents the potential ecological risk for a particular aquatic system. ERI values are classified as follows: ERI < 150 indicates a low potential ecological risk for the water system; 150 ≤ ERI < 300 suggests a moderate potential ecological risk; 300 ≤

ERI < 600 indicates a considerable potential ecological risk, and ERI ≥ 600 signifies a very high ecological risk for the water system (Eyankware et al., 2021b). A review of the ERI values of the study area presented in Table 8 reveals that all groundwater samples, amounting to 100 percent, exhibit ERI values below 150. This observation implies that the water system poses a minimal ecological risk. Although our study indicates a low potential for ecological harm, it is crucial to maintain a watchful eye on the water system over time. Regular monitoring is imperative to identify any fluctuations in pollutant concentrations and to safeguard the long-term vitality and sustainability of the aquatic ecosystem. The ERI values highlight the necessity for continuous monitoring and effective management strategies to maintain water quality and reduce possible ecological threats in the area under investigation.

Table 8: Potential Enrichment Risk Factor

Sample	Ti*PI							
code	Cd	Fe	As	Mn	Cu	Co	Ni	ERI
JTB /01	0.0375	0.025	0.002	0.000129	1.38889E-05	0.000147	0.000393	0.065183
JTB /02	0.075	0.3	0.002	1.18E-05	0.000138889	0.000294	3.57E-05	0.37748
JTB /03	0.0375	0.05	0.002	2.35E-05	0.000138889	0.000147	7.14E-05	0.089881
JTB /04	0.0375	0.025	0.002	1.18E-05	1.38889E-05	0.000294	3.57E-05	0.064855
JTB /05	0.075	0.05	0.0002	1.18E-05	0.000277778	1.47E-05	3.57E-05	0.12554
JTB /06	0.0375	0.025	0.002	2.35E-05	0.000138889	0.001618	7.14E-05	0.066351
JTB /07	0.0375	0.275	0.002	0.000118	0.000138889	0.000147	0.000357	0.315261
JTB /08	0.0375	0.025	0.004	1.18E-05	0.000277778	0.000294	3.57E-05	0.067119
JTB /09	0.00375	0.05	0.002	1.18E-06	0.001388889	0.000147	3.57E-06	0.057291
JTB /10	0.0075	0.025	0.004	2.35E-05	0.000138889	0.000147	3.57E-05	0.036845
JTB /11	0.0375	0.025	0.002	1.18E-05	0.000277778	0.000294	3.57E-05	0.065119
JTB /12	0.0375	0.05	0.004	1.18E-05	0.000138889	0.001471	7.14E-05	0.093193
JTB /13	0.00375	0.25	0.004	2.35E-05	0.000277778	0.000147	0.000357	0.258556
JTB /14	0.0375	0.025	0.002	0.000118	0.000138889	1.47E-05	3.57E-05	0.064807
JTB /15	0.00375	0.0025	0.004	1.18E-05	0.000277778	0.000294	3.57E-06	0.010837
JTB/16	0.0375	0.05	0.002	1.18E-06	0.000138889	0.000147	3.57E-05	0.089823
JTB/17	0.00375	0.025	0.004	1.18E-05	0.000138889	0.000294	3.57E-06	0.033198

Pollution Index of Groundwater (PIG)

The Pollution Index of Groundwater (PIG) was calculated for the total sample, with values ranging from 0.090 to 0.269 (Tables 9 and 10). According to SubbaRao et al. (2018), a PIG value larger than 0.1 indicates that the sample contributes 10% of the PIG's 1.0 value, making the influence of the parameters affecting the groundwater body very evident.In interpreting PIG values, it's essential to consider established standards for categorizing contamination levels in drinking water. PIG values less than 1 (<1) suggest light pollution, while values between 1 and 1.5 indicate low pollution, 1.5-2.0 signify moderate pollution, 2.0-2.5 represent high pollution, and values greater than 2 indicate very high pollution (SubbaRao et al., 2018). Our study's PIG results (Table 10) fall below the threshold of 1, indicating light pollution. This finding aligns with research conducted in Nigeria by Akakuru et al. (2021) and in Turkey by Taylor et al. (2020), further validating our observations. Despite the absence of pollution levels exceeding regulatory thresholds, it is crucial to remain vigilant, as even light pollution can have adverse effects on groundwater quality and ecosystem health over time. Therefore, ongoing monitoring and implementation of preventive measures are imperative to ensure the sustainability of water resources and safeguard public health.

Table 9: PIG assessment components

	Rw	Wp	WHO (2017)
Cd	5	0.090909	0.003
Fe	4	0.072727	0.03
As	5	0.090909	0.01
Mn	4	0.072727	0.4
Cu	4	0.072727	2
Co	4	0.072727	0.005
Ni	5	0.090909	0.02
pH	3	0.054545	7
Mg	2	0.036364	50
Na	4	0.072727	200
Ca	2	0.036364	200
Cl	4	0.072727	250
SO_4^{2-}	5	0.090909	30
CO_3^{2-}	4	0.072727	200
	55		

Table 10: Results of PIG

	Ow= Wp*Sc													PIG
	Cd	Fe	As	Mn	Cu	Co	Ni	Mg	Na	Ca	Cl	SO_4^{2-}	CO_3^{2-}	
JTB /01	0.030303	0.002424	0.009091	0.002	3.63635E-06	0.014545	0.05	0.000218	0.000371	0.000438	0.000108	0.005545	3.88889E-05	**0.164177**
JTB /02	0.060606	0.029091	0.009091	0.000182	3.63635E-05	0.029091	0.004545	0.000342	0.00048	0.000169	0.000422	0.005121	0.000328788	**0.190154**
JTB /03	0.030303	0.004848	0.009091	0.000364	3.63635E-05	0.014545	0.009091	0.000284	0.000495	0.000347	0.000134	0.001909	0.000162626	**0.123817**
JTB /04	0.030303	0.002424	0.009091	0.000182	3.63635E-06	0.029091	0.004545	0.000735	0.00036	0.000296	0.000273	0.000727	0.000222727	**0.130462**
JTB /05	0.060606	0.004848	0.000909	0.000182	0.000072727	0.001455	0.004545	0.000596	0.000135	5.09E-05	0.000102	0.003364	0.00025101	**0.125428**
JTB /06	0.030303	0.002424	0.009091	0.000364	3.63635E-05	0.159999	0.009091	0.000495	9.45E-05	4.73E-05	0.000273	0.001121	0.000311111	**0.26352**
JTB /07	0.030303	0.026667	0.009091	0.001818	3.63635E-05	0.014545	0.045455	0.001004	0.000302	6.73E-05	0.000256	0.001576	0.000321717	**0.179752**
JTB /08	0.030303	0.002424	0.018182	0.000182	0.000072727	0.029091	0.004545	0.000727	9.82E-05	0.000111	0.000311	0.000697	0.000070707	**0.14136**
JTB /09	0.00303	0.004848	0.009091	1.82E-05	0.000363635	0.014545	0.000455	0.000669	0.000338	0.000249	0.000605	0.000758	0.000137879	**0.090433**
JTB /10	0.006061	0.002424	0.018182	0.000364	3.63635E-05	0.014545	0.004545	0.000545	0.00036	0.000187	0.000137	0.002818	3.53535E-05	**0.102448**
JTB /11	0.030303	0.002424	0.009091	0.000182	0.000072727	0.029091	0.004545	0.000742	0.000665	6.91E-05	0.000256	0.000818	0.000130808	**0.131377**
JTB /12	0.030303	0.004848	0.018182	0.000182	3.63635E-05	0.145454	0.009091	0.000531	0.000502	0.00018	5.53E-05	0.005848	0.000219192	**0.269198**
JTB /13	0.00303	0.024242	0.018182	0.000364	0.000072727	0.014545	0.045455	0.001004	0.000702	0.000329	0.000108	0.001	0.000378282	**0.157722**
JTB /14	0.030303	0.002424	0.009091	0.001818	3.63635E-05	0.001455	0.004545	0.00136	0.000487	0.000345	0.000215	0.002455	0.000328788	**0.103955**
JTB /15	0.00303	0.000242	0.018182	0.000182	0.000072727	0.029091	0.000455	0.000604	0.000265	8.18E-05	0.000134	0.004152	0.000222727	**0.107362**
JTB/16	0.030303	0.004848	0.009091	1.82E-05	3.63635E-05	0.014545	0.004545	0.00072	0.000295	0.000135	3.2E-05	0.002333	0.000162626	**0.116155**
JTB/17	0.00303	0.002424	0.018182	0.000182	3.63635E-05	0.029091	0.000455	0.000742	0.000131	0	0.000137	0.001152	0.000130808	**0.108678**

Human Health risk assessment

There are several health problems associated with drinking water that contains heavy metals. Locals are particularly susceptible to the health concerns of metal consumption because the majority of metals have significant properties that contribute to environmental contamination. Water containing heavy metals can flavor beverages, create stains on clothing and linen, leave behind sticky residue, and build up in water pipes (WHO, 2011; Egbueri, 2020). Despite the lack of temperature guidelines based on health, it has been shown that hot water promotes the growth of germs that are harmful to human systems, causing issues with taste, odor, color, and corrosion

(WHO, 2011; Egbueri, 2020). The technique employed in this study to quantify the gravity of the adverse health effects associated with human exposure to environmental hazards is known as human health risk assessment. Hazard identification, exposure assessment, dose-response assessment, and risk characterization are the four primary stages of risk assessment. Based on an analysis of the pertinent literature, Asante-Duah (2002) sought to determine potential health hazards related to metals and metalloids. The degree, duration, and order of heavy metal exposure are all established as part of the exposure evaluation. The amount of metal and metalloid needed to cause different levels of unfavorable health effects that could lead to disease is determined through the use of dose-response analysis. Evaluating the possibility that heavy metals may cause cancer or other diseases in the target population is the last stage in risk characterization (Eyankware et al., 2022b).

Table 11: Results of HQ and HI

Sample code	Cd (A)	Cd (c)	Fe (A)	Fe (C)	As (A)	As ©	Mn (A)	Mn (C)	Cu (A)	Cu (C)	Co (A)	Co (C)	Ni (A)	Ni (C)
JTB /01	0.0571	0.1333	0.0000	0.0001	0.0952	0.2222	0.0068	0.0159	0.0001	0.0002	0.0010	0.0022	0.0157	0.0367
JTB /02	0.1143	0.2667	0.0005	0.0011	0.0952	0.2222	0.0006	0.0014	0.0007	0.0017	0.0019	0.0044	0.0014	0.0033
JTB /03	0.0571	0.1333	0.0001	0.0002	0.0952	0.2222	0.0012	0.0029	0.0007	0.0017	0.0010	0.0022	0.0029	0.0067
JTB /04	0.0571	0.1333	0.0000	0.0001	0.0952	0.2222	0.0006	0.0014	0.0001	0.0002	0.0019	0.0044	0.0014	0.0033
JTB /05	0.1143	0.2667	0.0001	0.0002	0.0095	0.0222	0.0006	0.0014	0.0014	0.0033	0.0001	0.0002	0.0014	0.0033
JTB /06	0.0571	0.1333	0.0000	0.0001	0.0952	0.2222	0.0012	0.0029	0.0007	0.0017	0.0105	0.0244	0.0029	0.0067
JTB /07	0.0571	0.1333	0.0004	0.0010	0.0952	0.2222	0.0062	0.0145	0.0007	0.0017	0.0010	0.0022	0.0143	0.0333
JTB /08	0.0571	0.1333	0.0000	0.0001	0.1905	0.4444	0.0006	0.0014	0.0014	0.0033	0.0019	0.0044	0.0014	0.0033
JTB /09	0.0057	0.0133	0.0001	0.0002	0.0952	0.2222	0.0001	0.0001	0.0071	0.0167	0.0010	0.0022	0.0001	0.0003
JTB /10	0.0114	0.0267	0.0000	0.0001	0.1905	0.4444	0.0012	0.0029	0.0007	0.0017	0.0010	0.0022	0.0014	0.0033
JTB /11	0.0571	0.1333	0.0000	0.0001	0.0952	0.2222	0.0006	0.0014	0.0014	0.0033	0.0019	0.0044	0.0014	0.0033
JTB /12	0.0571	0.1333	0.0001	0.0002	0.1905	0.4444	0.0006	0.0014	0.0007	0.0017	0.0095	0.0222	0.0029	0.0067
JTB /13	0.0057	0.0133	0.0004	0.0010	0.1905	0.4444	0.0012	0.0029	0.0014	0.0033	0.0010	0.0022	0.0143	0.0333
JTB /14	0.0571	0.1333	0.0000	0.0001	0.0952	0.2222	0.0062	0.0145	0.0007	0.0017	0.0001	0.0002	0.0014	0.0033
JTB /15	0.0057	0.0133	0.0000	0.0000	0.1905	0.4444	0.0006	0.0014	0.0014	0.0033	0.0019	0.0044	0.0001	0.0003
JTB/16	0.0571	0.1333	0.0001	0.0002	0.0952	0.2222	0.0001	0.0001	0.0007	0.0017	0.0010	0.0022	0.0014	0.0033
JTB/17	0.0057	0.0133	0.0000	0.0001	0.1905	0.4444	0.0006	0.0014	0.0007	0.0017	0.0019	0.0044	0.0001	0.0003
HI	0.8343	1.9467	0.0021	0.0049	2.1048	4.9111	0.0293	0.0684	0.0209	0.0487	0.0383	0.0893	0.0647	0.1510

4. CONCLUSION

This study comprehensively evaluated the hydrogeochemical composition of groundwater using various techniques such as the Piper, Durov, and Schoeller diagrams, as well as indices like the Heavy Metal Index, Contamination Index, Heavy Metal Rating Index, and Pollution Load Index. The analyses revealed intriguing patterns: the Piper diagram illustrated a geochemical zone dominated by sodium and potassium, indicating the influence of rock dissolution over time. Moreover, the Durov plot underscored ongoing ionic exchange within the groundwater, corroborating previous research in Nigeria. Additionally, the Schoeller diagram delineated the migration trend of key ions, highlighting the significance of anthropogenic sodium sources and geological potassium leaching. These findings align with earlier studies, further emphasizing the impact of human activities on groundwater quality. However, it's essential to acknowledge the limitations of our study. Firstly, the sample size might not fully represent the variability in hydrogeochemical characteristics across the study area. Although efforts were made to collect samples from diverse locations, the spatial distribution might not capture localized variations adequately. Secondly, while the methodologies employed are well-established, there could be inherent uncertainties, particularly in the estimation of pollution indices and quantification of contamination levels. Variations in sampling techniques, laboratory analyses, and data interpretation could introduce biases, affecting the accuracy of our findings. Moreover, the absence of real-time monitoring data limits our ability to capture temporal fluctuations in groundwater quality accurately.

Furthermore, the interpretation of results relies heavily on existing literature and theoretical frameworks, which might not fully encapsulate the complex hydrogeochemical processes at play. Assumptions made in the modeling and assessment of contamination sources could introduce errors and uncertainties, impacting the robustness of our conclusions. Despite these limitations, our study offers valuable insights into the hydrogeochemical dynamics and contamination sources in the studied area, providing a basis for informed groundwater management and environmental protection initiatives. Major stakeholders, including government agencies, policymakers, and local communities, can leverage our findings to develop effective strategies for groundwater resource management, pollution prevention, and public health protection. Additionally, the scientific community can benefit from our research by building upon our methodologies, refining theoretical frameworks, and addressing the identified limitations in future studies. Collaborative efforts between researchers, policymakers, and stakeholders are essential to address the complex challenges posed by groundwater contamination and ensure sustainable water resource management for current and future generations.

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Informed consent

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Ethical approval

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

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Data and materials availability

All data associated with this study are present in the paper.

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