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ORIGINAL ARTICLE

Integrating Multivariate Modelling and Health Risk Assessment to Decipher Groundwater Quality Dynamics in A Rapidly Urbanizing Basement Terrain of Akure, Southwestern Nigeria

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ABSTRACT - Groundwater constitutes a critical source of domestic water in Akure, southwestern Nigeria, yet rapid urbanization and anthropogenic activities increasingly threaten its quality. This study evaluated the hydrogeochemical characteristics and health risks associated with groundwater in the crystalline Basement Complex terrain of Akure. Twenty-one groundwater samples from motorized boreholes and hand-dug wells were analyzed for physicochemical parameters, major ions, and heavy metals to assess water quality and potential health implications. Hydrogeochemical facies classification shows that 77.3% of the samples fall within Geochemical Zone IV (strong acids exceeding weak acids), while 22.7% belong to Zone III (weak acids exceeding strong acids). The dominant ionic order ($Mg^{2+} > Na^{+} + K^{+} > HCO_3^{-} > Cl^{-} > SO_4^{2-} > Ca^{2+}$) suggests that groundwater chemistry is primarily controlled by silicate weathering and carbonate dissolution processes. Water Quality Index (WQI) results indicate that several groundwater sources require treatment prior to consumption. Contamination Factor (CF) and Geoaccumulation Index (Igeo) reveal generally low contamination levels, although the Metal Pollution Index (MPI) highlights localized heavy-metal enrichment. Multivariate statistical analysis using Principal Component Analysis (PCA) extracted three principal components (PC1–PC3) that explain the dominant hydrogeochemical processes and differentiate between geogenic contributions and minor anthropogenic inputs. Health risk assessment indicates that exposure to Pb, Cd, and Ni through groundwater ingestion may pose potential non-carcinogenic risks, particularly for children, as reflected by elevated Hazard Index (HI) values. Overall, the findings highlight emerging groundwater quality concerns in the rapidly urbanizing Akure region and underscore the need for regular monitoring, improved groundwater management, and sustainable water-safety strategies in crystalline basement aquifers. The study contributes to improved understanding of groundwater quality dynamics in rapidly urbanizing crystalline basement aquifers.

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INTRODUCTION

Groundwater geochemistry exhibits significant spatial and temporal variability due to complex interactions among natural and anthropogenic processes. Variations in lithology, geologic structure, climate, and land use collectively determine groundwater composition and quality [36; 11]. Among these factors, urbanization and increased human activity exert the greatest influence in developing regions, where industrial and agricultural expansion occurs with limited environmental oversight. These pressures often lead to aquifer contamination through infiltration of domestic effluents, leachates from septic systems, and industrial discharges [42; 10].

Ondo State, located in southwestern Nigeria, is one of the nation's most economically active regions, with a population exceeding 3.4 million and diverse agricultural and industrial activities sustaining its economy [66]. Akure, the state capital, serves as the administrative and commercial hub, characterized by rapid urbanization, limited waste management infrastructure, and rising groundwater dependence. Densely populated areas such as Shoprite, Green Park Motel, and Ilesa Garage are particularly vulnerable to subsurface contamination from domestic and commercial activities involving detergents, soaps, and organic waste [80; 82; 14]. Unregulated underground waste disposal and leakage from septic tanks further exacerbate groundwater pollution [39; 6].

Heavy metals represent some of the most persistent and hazardous groundwater pollutants. Although their occurrence is partly geogenic arising from mineral weathering and dissolution anthropogenic inputs from agricultural runoff, industrial effluents, and fuel combustion significantly elevate their concentrations in aquifers [52; 33]. Metals such as Pb, Cd, and As are particularly concerned due to their toxicity, bioaccumulative nature, and persistence in the environment [87; 13]. Chronic exposure to these elements, even at trace levels, has been associated with neurological, renal, and carcinogenic health effects [61; 23; 99]. Similar patterns have been reported in several Nigerian cities, where rapid urbanization and poor waste management have intensified groundwater contamination [31; 9; 11].

In Akure and surrounding communities, groundwater is the primary source of water for domestic, agricultural, and industrial purposes [18; 14]. However, the city's expanding population and industrial growth have led to increased water demand and deteriorating groundwater quality [16; 81]. This situation necessitates a comprehensive understanding of groundwater contamination processes and their implications for human health. Health risk assessment (HRA) frameworks have proven effective for quantifying potential exposure to toxic substances and evaluating associated risks [60; 35]. Recent advances in hydrogeochemical studies have combined multivariate statistical tools, water quality indices, and pollution load indicators to trace contaminant sources and evaluate their ecological and health implications [10; 40].

Previous investigations in Akure have examined groundwater quality using hydrochemical and index-based approaches [79]. However, limited attention has been paid to integrating hydrogeochemical characterization, heavy metal quantification, and human health risk assessment within a unified framework. Moreover, age-related and occupational vulnerabilities to heavy-metal exposure remain poorly understood in the region. This study bridges these gaps by employing an integrated hydrogeochemical and health risk assessment framework to:

(i) characterize groundwater chemistry and controlling geochemical processes;
(ii) determine the spatial distribution and concentration of major ions and heavy metals; and
(iii) evaluate the carcinogenic and non-carcinogenic risks associated with groundwater use in Akure.

By combining hydrogeochemical modeling, multivariate statistics, and health risk analysis, this study provides a more holistic understanding of groundwater quality dynamics in a rapidly urbanizing crystalline basement terrain. The findings offer critical insights for groundwater protection, public health management, and sustainable water policy development in Akure and other urban centers across sub-Saharan Africa [8; 40].

Although the analytical techniques used in this study are widely applied in hydrogeochemical investigations, their integrated application in rapidly urbanizing crystalline basement terrains such as Akure remains limited. Basement aquifers are typically characterized by heterogeneous fracture systems, shallow weathered zones, and strong lithological control on groundwater chemistry, which make groundwater quality highly variable. Consequently, applying an integrated framework combining hydrogeochemical indices, multivariate statistical modeling, and health risk assessment provides important insights into aquifer vulnerability, contaminant pathways, and public health implications in the region.

MATERIALS AND METHODOLOGY

Location and Climate

The study area is about 42.74 square kilometers and lies between latitude 07° 10`N - 07° 18`Nand longitudes 5° 09`E and 05° 16`E. The research area is in Nigeria's rainforest zone, with a wet season covering April to October and a dry season lasting November to March. From February through March, the town receives the hottest weather, as well as the dry wind (harmattan) from December to early February. The area receives moderate annual rainfall of around 1,300 to 1,700 mm, with humidity being high during the wet season and low during the dry season, with temperatures ranging from 22°C to 31°C all year [55].

Geology

The research area lies within the Basement Complex rocks of southwestern Nigeria Some of the petrological units discovered include the Migmatite-Gneiss-Quartzite Complex, Charnockitic and Dioritic rocks, Older Granites, and Unmetamorphosed Dolerite Dykes [76] see Fig. 1. According to Kazeem [74] and Olarewaju [75], the older granite suite's granite rocks make up about 65% of Akure's total land area. The three primary petrographic variations are fine-grained biotite granite, medium to coarse-grained non-porphyritic biotite-hornblende granite, and coarse-porphyritic biotite-hornblade granite. Categorization heavily relies on textural characteristics. Three fundamental charnockitic rock textural types are also distinct in Akure. There are three types: massive fine-grained, gneissic fine-grained, and coarse-grained [76]. Charnokite rocks are not typically found as smooth, rounded boulders, but rather as elongated, oval to subcircular masses. Three separate occurrences of the charnockitic rocks in the region seem to exist. As exemplified by the Akure body and a few other smaller bodies, the first is located inside what seems to be the "core" of the granite rock. The second may be seen in the charnockitic bodies of Ijare and UroEdemo-Idemo, which are on the periphery of the granite bodies. The first two types of occurrences are primarily seen in coarse-grained charnockitic types.

Hydrology

The study area is believed to be faced with decline in groundwater quality due to tremendous increase in rural urban migration. topography, access to excellent quality water is becoming more and more challenging as a result of a lack of pipe-borne water delivery, as shown in Fig. 1. Thus, groundwater extracted from certain boreholes and hand-dug wells in the city is augmenting the meager pipe-faced and moving over space and time [74]. The flow, storage, and yielding capacity of groundwater are all reliant on the geological environment due to limited pipe-borne water supply. Hand-dug wells and some boreholes throughout the city provide additional groundwater abstraction to supplement the city's meager piped water supply. Unlike other natural resources, groundwater is dynamic in nature, with variations in its occurrence and movement with time and place [45]. The geological environment affects the yielding capacity, accumulation, and circulation of groundwater. The assertions of Kazeem [74]. The most significant river in Ondo State is the Ero River, which starts from the Igbara Oke road and is located 16–18 kilometers from Akure town. Smaller rivers like the Owuruwu River and the Osun River both contribute to water runoff in Akure. Minor rivers like the Otenre River and Omi Atamo serve as local runoff and converge with the Osun River near OsunAmon. Before joining the Ogbese River in Ondo State, the Osun River flows from the eastern to the western portions of the town.

The aquifer system in Akure occurs predominantly within the weathered and fractured zones of the Precambrian crystalline Basement Complex rocks. Groundwater storage is largely confined to the regolith (weathered layer) and secondary porosity created by fractures, joints, and faults within the underlying bedrock. Consequently, groundwater occurrence in the area is highly heterogeneous and controlled by the thickness of the weathered zone and the density of structural discontinuities. Recharge to the aquifer system occurs primarily through direct infiltration of precipitation during the rainy season, supplemented by localized recharge from surface water bodies and runoff infiltration. The depth to the water table in the area typically varies between 5 and 20 m depending on topography, seasonal rainfall variability, and local geological conditions. These hydrogeological characteristics are typical of crystalline basement terrains in southwestern Nigeria and play a significant role in influencing groundwater circulation, storage capacity, and vulnerability to contamination.

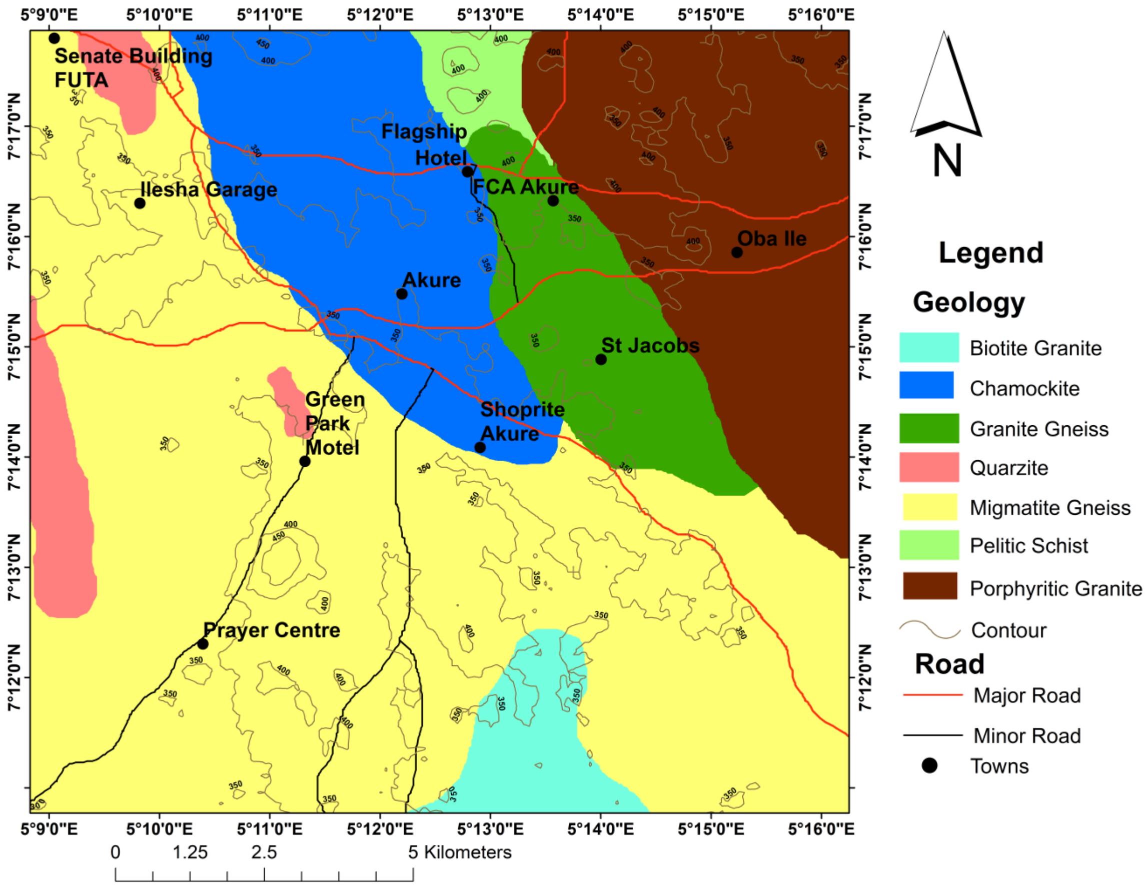

Figure 1. Geological map of the study area showing groundwater sampling points.

METHOD

Twenty-one (21) water samples were randomly selected from hand-dug wells and motorized boreholes, as shown in Fig. 1. During the dry season, when the water table dropped and the concentration of cations, anions, and trace elements was more stable, sampling was done. Before collecting water samples from the location, precautionary procedures were performed by washing the bottles with clean water, cleaning the bottles with reagents, and completely rinsing with distilled, de-ionized water. The APHA [30] standard was used to test pH, electrical conductivity, total dissolved solids, total hardness, magnesium, calcium, chloride, nitrate, sulphate, potassium, sodium, bicarbonate, iron, cobalt, lead, zinc, manganese, mercury, cadmium, and silver as in Table 1.

Table 1. Methods used to analyze physicochemical parameters

S/No	Parameters	Analytical Method
1	pH	pH meter HachsensION + PH1 portable pH meter and HachsensION + 5050 T Portable Combination pH Electrode
2	Total dissolved solids (TDS)	TDS meters (model HQ14D53000000, USA).
3	Magnesium (Mg^{2+})	EDTA titrimetric method
4	Calcium (Ca^{2+})	Titrimetric method
5	Chloride (Cl^-)	Titrimetric method
6	Sulphate (SO_4^{2-})	Turbidimetric method using a UV-Vis spectrometer
7	Potassium (K^+)	Jenway clinical flame photometer (PFP7 model)
8	Sodium (Na^+)	Jenway clinical flame photometer (PFP7 model)
9	Bicarbonate (HCO_3^-)	Titrimetric method
10	Iron (Fe)	(Flame Atomic Absorption Spectrophotometer) FAAS
11	Manganese (Mn)	FAAS
12	Arsenic (As)	FAAS
13	Zinc (Zn)	FAAS
14	Copper (Cu)	FAAS

Water Quality Index (WQI)

The WQI was used to evaluate the surface and groundwater quality for human consumption in the research region. This index was developed by Brown et al. [50], after Horton [50], to give a thorough picture of the state of surface and groundwater quality for residential use. WQI does, however, have some drawbacks, such as the possibility that it might not adequately reflect the true state of water quality. Furthermore, the index might not be sufficient for many users of water quality data. Finally, because parameter weights are assigned at the user's discretion [25], there may be bias in the calculation. Nonetheless, it seems that WQI has more advantages than disadvantages. It's a straightforward and useful method for informing the public and decision-makers about water quality [50]. In equation 1, the estimation of WQI was carried out in two steps:

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

where Wi denotes the relative importance of the parameter and Qi denotes the parameter quality index.

Phase I: Based on their respective values in the overall water quality, each parameter assessed in the water samples was given a relative weight (Wi). Each of the 10 parameters under consideration's unit weights (pH, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, Fe^{2+}, Zn^{2+}, Ni^{2+}, Cr^{3+}, and Pb^{2+}) were calculated using the following formula (Eq. 2):

$$Wi = \frac{k}{S_i} \quad (2)$$

With *Si* being the water quality parameter's acceptable standard value and *k* being the proportionality constant determined using the formula (Eq. 3) below:

$$k = 1 / \Sigma_{i=1}{}^{n} (1 / S_i) \quad (3)$$

Phase 2: Using Eq. (4), we determined the quality index for each parameter:

$$Q_i = \frac{(Va-Vi)}{(Vs-Vi)} \times 100 \quad (4)$$

where Va represents the parameter I's measured value, Vi represents the parameter I's ideal value (0 for all other parameters except pH, which is 7.0), and Vs represents the parameter I's WHO-recommended standard.

When the quality rating is 0, there aren't any contaminants present. Pollutants with a quality rating of 0 Qi 100 are above permitted limits [50]. Based on the absolute value of the index determined by calculations, the estimated WQI values are divided into four categories: "excellent," "good," "poor," "very poor," and "unfit for drinking."

In the PCA, component loading entailed breaking down a huge dataset with many variables into a smaller number of linear combinations in the component that accounted for a sufficient fraction of the total data variance and easily related the variables to the sources or processes via Equation (5).

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(X_{N} - N)^2 \tag{5}$$

When Xi is the statistical mean, I denote the variable intervals, and N denotes the number of outcomes.

Metal Pollution Index (MPI)

MPI was evaluated using Caeiro et al. [106] Equation 6, which determined the collective influence of individual heavy metals on water quality [50].

$$MPI = \sqrt[n]{M_1 \times M_2 \times M_3\_\_\_\_\_\_\_\_} \text{ Mn} \tag{6}$$

where *Mn*= concentration of the metal.

Pollution Load Index (PLI)

Hakanson's (1980); Eyankware and Akakuru, (2022) formula was used to calculate the PLI.

$$\text{PLI} = \sqrt[n]{CF1 \times CF2 \times} CF3 \times \ldots \times CFn \tag{7}$$

The contamination factor is represented by CF, and the element number is represented by n.

Geo accumulation index (Igeo)

The geo accumulation index could be used to determine the degree to which toxic materials are present (Igeo).

It is calculated as follows by Eyankware and Akakuru (2022)

$$\text{Igeo} = \log_2 \frac{C_n}{1.5\, B_n} \tag{8}$$

Where Cn expresses the content of the toxic metal n, Bn expresses background of the toxic n, and 1.5 is the factor of possible.

Health risk assessment

The US Environmental Protection Agency's criteria were used to determine the non-carcinogenic risk associated with ingesting contaminated river water [29] see Table 2. For both children and adults, the risk was computed using the following function in equation 9.

$$\text{CDI} = \frac{\text{Cw X IRW X EF X ED}}{\text{BW X AT}} \tag{9}$$

where CDI stands for Chronic Daily Intake (mg/kg/day), Cw for contaminant concentration in water (mg/L), IRW for ingestion rate (for adults, IRW is 2 L/day, while for children, IRW is 1 L/day), EF for

Exposure Frequency (equivalent to 365 days/year), and ED for exposure duration for adults and children, ED is 70 and 6 years, respectively [22; 19]. Li et al. [60] and Zhang et al. [101] developed the hazard quotient (HQ) to measure the non-carcinogenic danger provided by various elements in equation 10:

$$HQ = \frac{CDI}{RFD} \tag{10}$$

RfD stands for reference dose (mg/kg/day) for a certain element. RfDs for various elements are 0.7 (Fe), 0.3 (Zn), 0.0001 (Hg), 0.03 (Co), and 0.0035 (Co) according to Duggal et al. [19] and Barzegar et al. [19]. Finally, equation 6 is used to calculate the total HQ values for the elements to determine the hazard index of the water samples (HI).

$$HI = \sum HQ \tag{11}$$

Values more than one indicate that a certain element's noncarcinogenic risk exceeds the limit of acceptance (HI = 1), whilst values less than one show that the risk is within acceptable parameters [29; 19]. According to Bortey-Sam et al. [22] and Barzegar et al. [19], the USEPA [29] classified non-carcinogenic risk as follows: (2015). Table 2 presents the non-carcinogenic risk as designated by the United States Environmental Protection Agency (USEPA) in 1989.

Table 2. Non-carcinogenic risk was designated by the United States Environmental Protection Agency (USEPA) in 1989.

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

Contamination factor (CF)

The CF was calculated using the Hakanson [25] formula

$$CF = \frac{C_n}{B_n} \tag{12}$$

Where: Cn is the metal concentration, Bn is the background/target value [25; 5; 103].

RESULTS AND DISCUSSION

The physicochemical and heavy metal concentrations of groundwater within the study area is presented in Table 3.

Table 3. Illustrates the study's findings, which include physicochemical and heavy metal concentrations in groundwater in the studied area.

Sample code	TDS (mg/L)	pH	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	HCO_3^- (mg/L)	Na^+ (mg/L)	Cl^- (mg/L)	$SO4_2^-$ (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	As (mg/L)	Zn (mg/L)	Cu (mg/L)
IG/01	12.3	5.6	11.9	13.5	30.5	12.1	63.2	19.7	2.4	0.01	0.04	0.002	0.02	0.21
IG /02	36.5	4.8	29.3	24.2	28.7	47.2	19.5	3.8	5.1	0.02	0.01	0.004	0.01	0.03
IG /03	11.8	7.5	62.4	98.5	9.1	16.3	34.2	24.7	6	0.01	0.02	0.002	0.03	0.06
IG /04	7.3	6.2	27.3	57.4	27.9	2.9	9.6	16.2	4.1	0.001	0.01	0.004	0.1	0.18
IG /05	29.5	7.1	30.9	10.5	42.2	4.3	26.3	49.3	10.3	0.01	0.03	0.004	0.03	0.06
IG /06	34.1	7.4	58.8	49.4	10.8	11.4	35.4	6.8	7.8	0.01	0.01	0.001	0.01	0.71
IG /07	20.3	5.8	10.2	138.2	62.2	27.1	10.9	19.2	2.9	0.02	0.01	0.003	0.02	0.04
IG /08	60.3	7	21.1	56.8	120.1	18	40.7	10.1	9	0.03	0.04	0.001	0.02	0.06
1G/09	27.4	7.5	39.5	79.4	69.3	22.5	12.4	17.7	1.6	0.01	0.02	0.01	0.03	0.921
IG/10	13.5	7.7	14.9	51.2	59.1	18.8	63.8	68.2	0.4	0.001	0.01	0.03	0.01	0.05
IG/11	20.8	6.9	20.4	69.4	20.5	28	12.2	17.4	11.3	0.01	0.01	0.06	0.03	0.02
IG/12	79.2	7.5	33.4	88.3	30.2	18.1	37.4	15.1	1.4	0.001	0.01	0.01	0.01	0.02
IG/13	11.3	8.1	70.7	27.5	17.8	22.3	30.6	10.3	9.2	0.01	0.02	0.01	0.04	0.03
IG/14	18.3	5.6	55	55.8	39.8	18.9	8.3	27.5	6.1	0.03	0.01	0.002	0.009	0.04
IG /15	49.9	7.3	28.3	49.5	50.5	27.3	17.8	16.8	3.6	0.02	0.01	0.001	0.11	0.04
IG/16	59.2	6.1	19.9	29.4	79.2	58.9	40.8	2.3	4.2	0.02	0.02	0.004	0.02	0.22
IG /17	30.3	7.5	27.3	19.5	100.2	37.4	32.7	36.6	1.5	0.01	0.01	0.007	0.01	0.47
IG /18	45.1	7.3	18.4	20.7	94.8	18.7	61.5	16.2	6.6	0.03	0.03	0.001	0.01	0.19
IG /19	29.4	8.2	36.6	60.8	69.2	24.8	44.6	20.9	8.4	0.01	0.01	0.001	0.001	0.74
IG /20	30.3	7.3	27.1	38.9	40.4	30.2	18.3	14.3	14.3	0.03	0.02	0.001	0.005	0.09
IG /21	59.3	7.5	38.6	41.7	99.7	11.2	10.7	16.2	5.7	0.02	0.01	0.004	0.001	0.5
Min	7.3	4.8	10.2	10.5	9.1	2.9	8.3	2.3	0.4	0.001	0.01	0.001	0.001	0.02
Max.	79.2	8.2	70.7	138.2	120.1	58.9	63.8	68.2	14.3	0.03	0.04	0.06	0.11	0.921
Aver.	32.67	6.95	32.48	51.46	52.49	22.69	30.04	20.44	5.80	0.01	0.02	0.01	0.03	0.22
Stand Dev.	19.61	0.91	16.78	31.24	32.17	13.21	17.96	15.16	3.68	0.01	0.01	0.01	0.03	0.28

Hydrogeochemical Processes of Groundwater

Piper Diagram Interpretation

The Piper diagram is a tool used in determining the sources of dissolved salts and the origin of groundwater. It also gives an insight into the hydrogeochemical processes of the study area, showing the scenario of groundwater interaction solutions in a lithologic structure [4; 5]. Dissolved ion sources are studied concerning groundwater as it modifies the water character, since water passes through a region with similar geochemical processes [84]. From the Piper plot as presented in Fig. 2, it shows that in the cation region, 90% of the samples are of Mg ionic species while 9.1% is of Na +K ionic species. In the anion area, 22.7%, 31.8%, and 45.5% of the entire samples are of Cl, HCO_3, and no dominant ionic species. Furthermore, 77.3 % of the samples fall into geochemical zone 4 (strong acids outnumber weak acids), and 22.7 percent fall into geochemical zone 3 (weak acids outnumber strong acids) [96; 7; 35]. Magnesium (Mg^{2+}) is a mineral that is found in abundance in the human body. Magnesium in groundwater was got from the decay of dolomite, ferromagnesian minerals like olivine, pyroxene, amphiboles, and dull shaded micas. In the transformative rocks, magnesium happens in the construction of chlorite, montmorillonite, and serpentine [67; 25; 3]. The response including an arrangement of magnesium is impacted by how much CO_2 is in the groundwater in broken-up conditions.

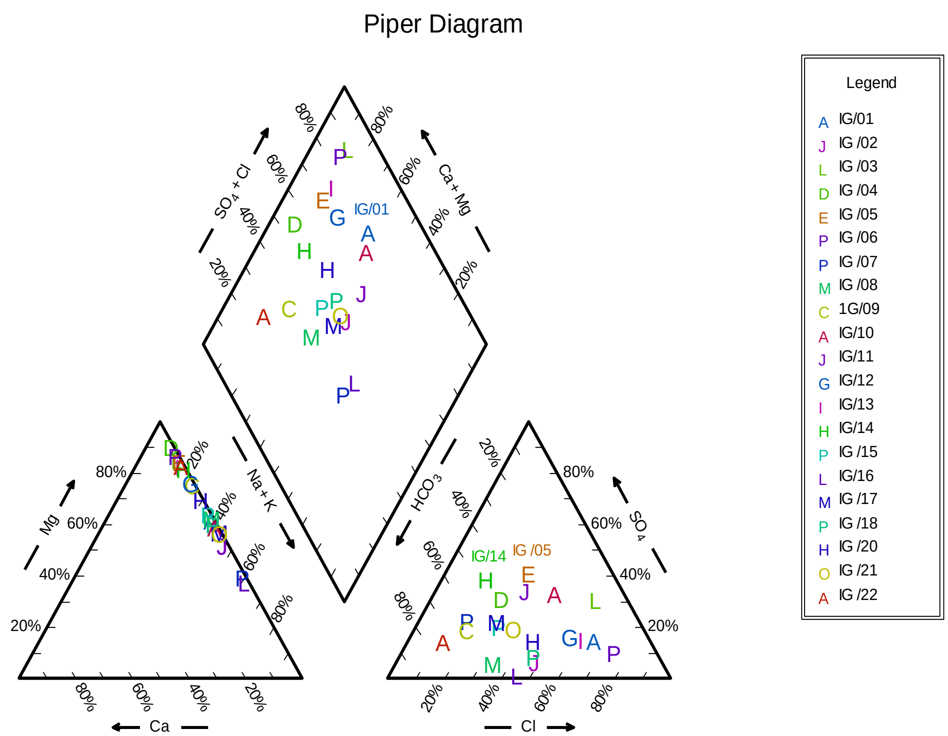

Figure 2. Piper diagram of groundwater sample for the study area

Durov Diagram Interpretation

As demonstrated in Fig. 3, the Durov diagram can be used to examine evolutionary tendencies and hydrochemical processes in the groundwater system, as well as the mixing of different water types and ion exchange and reverse ion exchange activities. The Durov plot aligns with the results of the Piper plot. However, it shows that there was a simple dissolution or mixing [4; 5; 2].

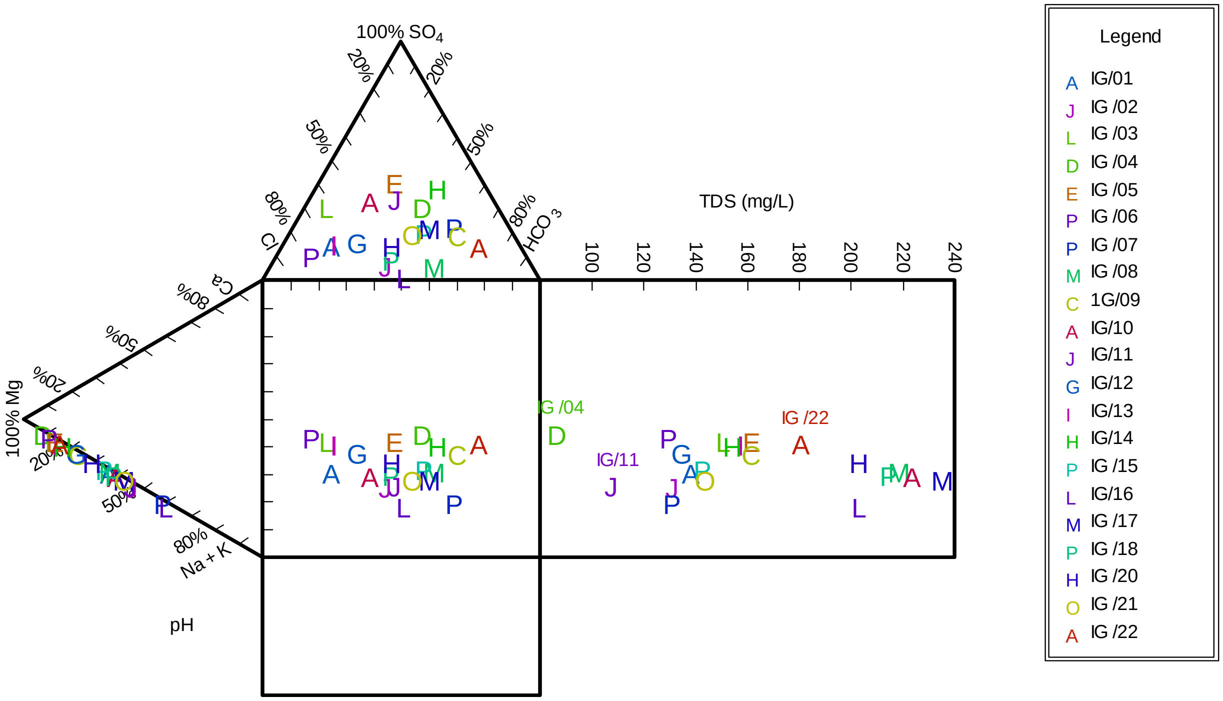

Figure 3. Durov plot of groundwater in the Akure area

Schoeller Diagram Interpretation

Schoeller [91] proposed a diagram that represents a series of investigations on equidistant verticals, the number of which is dictated by the number of elements transported [90; 78]. According to the Schoeller diagram (Fig. 4), the hydrogeochemical trend showed Mg>Na+K>HCO3>Cl>SO4>Ca. Water hardness is mostly caused by magnesium. Most of the groundwater naturally becomes hard due to the weathering of sedimentary rock, limestone, and calcium-containing minerals. On a local level, hardness in groundwater can be attributed to chemical and mining industrial effluent as well as excessive lime application to the soil in agricultural areas [4; 69; 95].

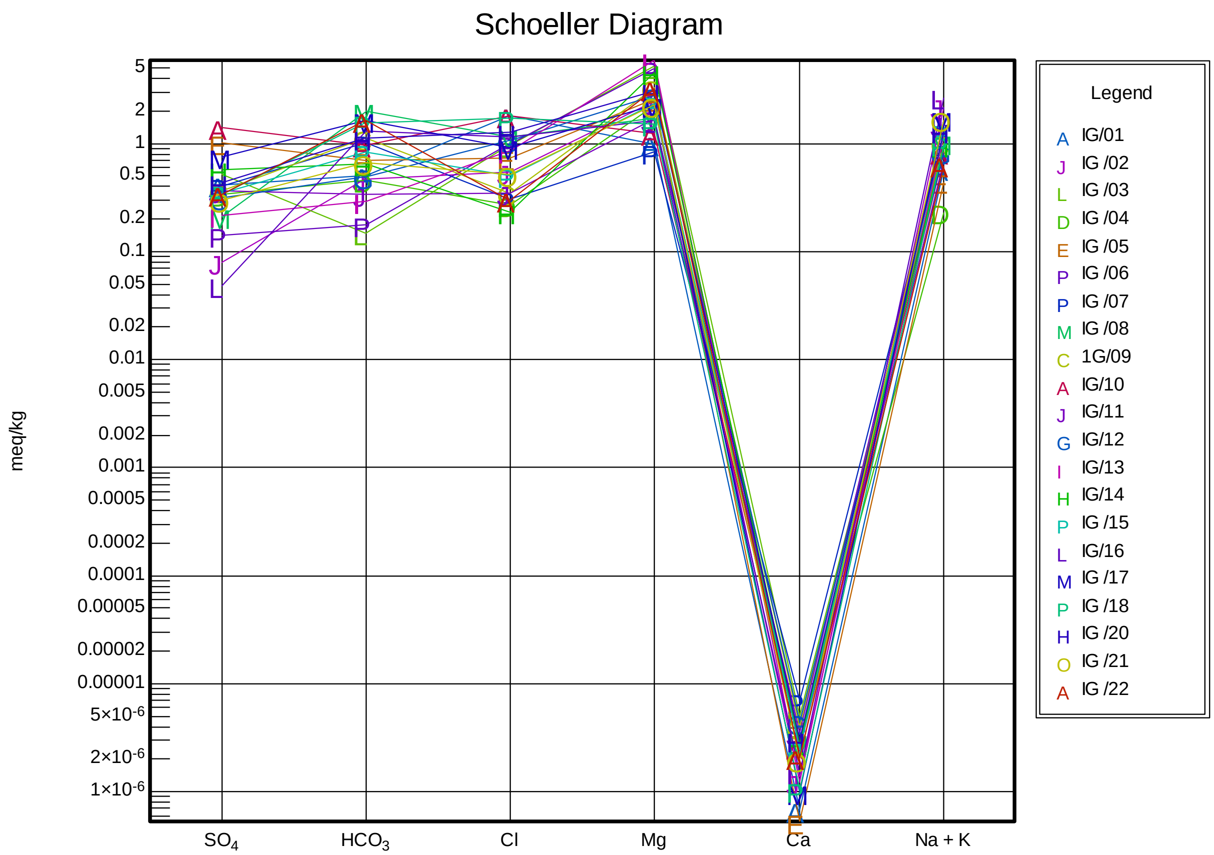

Figure 4. Scholler diagram of the study area

Multivariate Statistics

Principal Component Analysis (PCA)

The PCA is a crucial technique for locating designs, examining the variation of groups of connected components, and further isolating the Eigenvalues and Eigenvectors (loadings) for head parts from their associated change [92; 103; 9]. It illustrates the relationship between the factors to pinpoint the most likely sources of groundwater contamination in the review area. There were found to be three important Principal Components. In the analysis interpretation, every loading that is more than 0.4 (+ or -) is regarded as having been a substantial contributor [92]. From Table 4, it showed that in PC1, 50% of the parameters had loadings, in PC2 and PC3, 28.6% of the parameters had loadings. This finding implies that interactions with the atmosphere, the surface environment, soil, and bedrock cause a wide variety of different components to dissolve in groundwater [31; 2; 3]. Most constituents in groundwater are typically found in much higher concentrations than in surface waters, and deep groundwater that has had prolonged contact with rock is likely to have higher concentrations than shallow or young waters [92].

Correlation Matrix

For analyzing the relationships between two variables, the correlation matrix is a helpful tool. The correlation coefficient is typically between -1 and +1. If the r-value is near to -1, the connection is said to have a negative slope or to be anti-correlated. When the value of r is close to +1, the relationship is considered to be correlated or to have a positive slope. If the value is zero, the points are deemed to be uncorrelated [92]. There was a link between TDS and HCO3 (0.474), Mg and HCO3 (-0.435), Cl and Mn (0.453), and K and Fe (0.453), according to the correlation matrix (Table 4). In Table 5, the bulk of the elements are not connected and there is only a weak correlation between them, indicating that there is no connection between variables. In other words, when one variable changed, another changed in a completely unrelated manner. The result of this correlation matrix indicates that human activities within the locality is the primary source of heavy metals in groundwater. Furthermore, this suggests groundwater occurrences were influenced by some factors. Weak correlations observed in these parameters confirm that the groundwater samples did not mix with saline water, and this goes to affirm that freshwater was the major source of recharge for groundwater in the study area [31; 2; 3].

Table 4. PCA and communalities

	Communalities	**Components**		
		PC1	**PC2**	**PC3**
TDS	0.64	**0.59**	-0.03	0.02
pH	0.80	-0.24	**0.53**	**0.46**
Mg	0.82	**-0.46**	-0.19	**0.70**
Ca	0.56	-0.35	-0.27	-0.23
HCO	0.85	**0.68**	0.35	-0.13
Na	0.81	**0.45**	-0.29	-0.37
Cl	0.78	0.29	**0.74**	-0.01
SO	0.74	-0.35	**0.63**	-0.31
K	0.91	0.14	-0.29	**0.60**
Fe	0.84	**0.70**	**-0.45**	0.13
Mn	0.76	**0.47**	0.25	0.32
As	0.81	-0.25	0.10	**-0.47**
Zn	0.60	**-0.41**	-0.35	-0.13
Cu	0.62	-0.05	0.36	0.33
	Eigenvalues	1.21	1.08	0.93
	Variance (%)	0.19	0.16	0.14
	Cumulative var. (%)	0.19	0.35	0.48

Table 5. Pearson's coefficients of correlation (r) between different parameters

	TDS	pH	Mg	Ca	HCO_3	Na	Cl	SO_4	K	Fe	Mn	As	Zn	Cu
TDS	1.00													
Ph	0.12	1.00												
Mg	-0.17	0.35	1.00											
Ca	-0.05	0.03	0.04	1.00										
HCO_3	**.474***	0.15	**-.435***	-0.13	1.00									
Na	0.25	-0.27	-0.22	-0.09	0.20	1.00								
Cl	0.07	0.22	-0.24	-0.34	0.18	-0.03	1.00							
SO_4	-0.36	0.25	-0.17	-0.06	0.07	-0.32	0.26	1.00						
K	-0.07	0.17	0.24	-0.20	-0.17	-0.08	-0.20	-0.24	1.00					
Fe	0.26	-0.31	-0.15	-0.07	.378	0.25	-0.17	-0.35	**.401***	1.00				
Mn	-0.06	-0.06	-0.21	-0.31	0.18	-0.20	**.453***	-0.09	0.30	0.30	1.00			
As	-0.22	0.05	-0.28	0.12	-0.12	0.13	-0.06	0.27	0.07	-0.22	-0.16	1.00		
Zn	-0.19	-0.05	0.01	0.07	-0.26	-0.18	-0.35	-0.08	-0.13	-0.16	-0.15	-0.04	1.00	
Cu	0.04	0.35	0.20	-0.02	0.26	-0.06	0.00	-0.12	-0.15	-0.28	-0.06	-0.12	-0.22	1.00

Contamination Factor (CF)

The CF has been used in groundwater research to measure the ratio of heavy metal concentrations to background levels. The values of the contamination factor are described using the criteria listed: A CF of 1 indicates little contamination, a CF of 1 is moderate contamination, a CF of 3 is substantial contamination, and a CF of 6 indicates extremely high contamination [21; 4] Fe, As, Mn, Zn, and Cu had relatively low concentrations of 1 in the entire study area, according to the CF of this study, which is shown in Table 6. Mg, Ca, HCO3, and most of the SO4 had mean concentrations between 1-3 (moderate contamination), while Cl and Na had mean concentrations between 3 -6 (considarable contamination) and above 6 (high concentration), respectively. This finding indicates that geogenic processes are the main cause of pollution. This conclusion conflicts with the MPI findings of the current investigation, which indicated that most of the samples were really of alarming quality. This result matches that of a study conducted in India and Nigeria by Bhutian et al. [21]. Additionally, the outcomes disagree with those of Iranian research by Mohammadi et al. [65].

Metal Pollution Index (MPI)

MPI has proven to be a useful tool. MPI of less than 0.3 is considered practically unpolluted, MPI of 0.3-1.0 is said to be slightly polluted, MPI of 1.0-2.0 are considered moderately polluted, whereas those with an MPI of 2.0- 4.0 are strongly polluted, MPI of 4.0 and above, is considered very strong pollution. According to Table 6's findings, 4.8% of the samples had MPI values between 1-2, indicating moderately polluted, 9.5% had MPI values between 2-4, indicating a strong pollution, and 85.4% had MPI values above 4 and above, indicating very strong pollution. The spatial distribution of MPI is presented in Figure 5. The main causes of these increased MPI values are anthropogenic sources and residents' waste disposal practices. This study's findings concur with research done in Nigeria by Eyankware and Akakuru [35] and with research done in Iran by Mohammadi et al. [65], but they disagree with research done in Bangla by Haque et al. [49].

Pollution Load Index (PLI)

PLI is an essential technique for determining how much heavy metal contamination is present in materials [35; 104]. PLI is frequently divided into four groups: PLI1 (zero pollution), PLI>2 (moderate pollution), PLI>3 (heavy pollution), and PLI>4 (severe pollution). According to the results, the groundwater in the research region had a concentration of PLI of less than 1 (Table 6). As a result, there isn't any pollution. The spatial distribution of PLI is presented in Figure 5. The result of this PLI in this present study is in line with the CF result which observed minimal contamination of the samples. However, it contradicts the results of the MPI which found out that majority of the water samples were greatly polluted with heavy metals. This research contradicts the Indian review [47; 21], however, it is consistent with Yahaya et al. [103] work in Nigeria, in China by Wu et al. [101] and Bangladish by Haque et al. [49].

Geoaccumulation Index (Igeo)

Muller [62] founded the geoaccumulation index (Igeo) to examine the amount of pollution of vital concentrations in waste, water, biomass, and soil, and it has been widely utilized in researching their contamination status all over the world [35]. The properties of Igeo and their individual translations are Igeo ≤ 0 (essentially uncontaminated), 0 (uncontaminated), 1 (quite contaminated), 2 (moderately heavily contaminated), 3 (heavily contaminated), 4 (obviously heavily contaminated) and Igeo ≥ 5 (clearly heavily contaminated) [95; 2; 96]. From the results in Table 6, it shows that 4.8% of the samples are unpolluted, 47.6% of the samples are moderately heavily contaminated), and 47.6% of the samples are 3 heavily contaminated. The spatial distribution of Igeo is presented in Figure 5. Anthropogenic sources are majorly the cause of pollution in the area. The result of this Igeo in this present study is in line with the MPI results which reported high contamination of the samples by the pollutants. However, it contradicts the results of the CF and PLI which observed minimal pollution of groundwater samples in the locality by heavy metals. This result is similar to the work done in Iran by Mohammadi et al. [65], west coast of Peninsular Malaysia by Looi et al. [62] and also similar to a work done in Nigeria by Eyankware and Akakuru [35].

Table 6. Results of MPI, PLI and Igeo results

	Contamination Factor											**MPI**	**PLI**	**Igeo**
	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	HCO_3^- (mg/L)	Na+ (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	Fe (mg/L)	Mn (mg/L)	As (mg/L)	Zn (mg/L)	Cu (mg/L)			
IG/01	0.540909	0.377095	0.532286	11.2037	3.648961	2.60582	0.25	0.000471	0.0004	0.000143	0.005833	**6.403191**	**6.73E-07**	**2.068651**
IG /02	1.331818	0.675978	0.500873	43.7037	1.125866	0.502646	0.5	0.000118	0.0008	7.14E-05	0.000833	**3.906792**	**1.77E-07**	**2.090434**
IG /03	2.836364	2.751397	0.158813	15.09259	1.974596	3.267196	0.25	0.000235	0.0004	0.000214	0.001667	**17.15932**	**1.01E-06**	**3.356785**
IG /04	1.240909	1.603352	0.486911	2.685185	0.554273	2.142857	0.025	0.000118	0.0008	0.000714	0.005	**1.623106**	**1.61E-07**	**1.93747**
IG /05	1.404545	0.293296	0.736475	3.981481	1.518476	6.521164	0.25	0.000353	0.0008	0.000214	0.001667	**18.86042**	**5.49E-07**	**2.239034**
IG /06	2.672727	1.379888	0.188482	10.55556	2.04388	0.899471	0.25	0.000118	0.0002	7.14E-05	0.019722	**10.96837**	**3.34E-07**	**2.371856**
IG /07	0.463636	3.860335	1.085515	25.09259	0.62933	2.539683	0.5	0.000118	0.0006	0.000143	0.001111	**9.027748**	**6.61E-07**	**3.665629**
IG /08	0.959091	1.586592	2.095986	16.66667	2.349885	1.335979	0.75	0.000471	0.0002	0.000143	0.001667	**76.32929**	**1.67E-06**	**3.652739**
1G/09	1.795455	2.217877	1.209424	20.83333	0.715935	2.34127	0.25	0.000235	0.002	0.000214	0.025583	**139.6482**	**1.04E-05**	**3.30847**
IG/10	0.677273	1.430168	1.031414	17.40741	3.683603	9.021164	0.025	0.000118	0.006	7.14E-05	0.001389	**4.796133**	**1.01E-06**	**3.77794**
IG/11	0.927273	1.938547	0.357766	25.92593	0.704388	2.301587	0.25	0.000118	0.012	0.000214	0.000556	**31.73599**	**1.07E-06**	**2.299185**
IG/12	1.518182	2.46648	0.527051	16.75926	2.159353	1.997354	0.025	0.000118	0.002	7.14E-05	0.000556	**3.891283**	**1.82E-07**	**3.045206**
IG/13	3.213636	0.768156	0.310646	20.64815	1.766744	1.362434	0.25	0.000235	0.002	0.000286	0.000833	**22.1717**	**1.03E-06**	**2.453531**
IG/14	2.5	1.558659	0.69459	17.5	0.479215	3.637566	0.75	0.000118	0.0004	6.43E-05	0.001111	**8.435049**	**4.56E-07**	**2.810402**
IG /15	1.286364	1.382682	0.881326	25.27778	1.027714	2.222222	0.5	0.000118	0.0002	0.000786	0.001111	**25.81617**	**9.64E-07**	**2.605018**
IG/16	0.904545	0.821229	1.382199	54.53704	2.355658	0.304233	0.5	0.000235	0.0008	0.000143	0.006111	**52.29392**	**1.82E-06**	**3.157859**
IG /17	1.240909	0.544693	1.748691	34.62963	1.887991	4.84127	0.25	0.000118	0.0014	7.14E-05	0.013056	**51.74617**	**3.79E-06**	**3.478361**
IG /18	0.836364	0.578212	1.65445	17.31481	3.550808	2.142857	0.75	0.000353	0.0002	7.14E-05	0.005278	**49.99584**	**1.45E-06**	**3.154808**
IG /19	1.663636	1.698324	1.207679	22.96296	2.575058	2.76455	0.25	0.000118	0.0002	7.14E-06	0.020556	**23.09659**	**6.94E-07**	**3.525636**
IG /20	1.231818	1.086592	0.705061	27.96296	1.056582	1.891534	0.75	0.000235	0.0002	3.57E-05	0.0025	**16.9543**	**4.08E-07**	**2.317192**
IG /21	1.754545	1.164804	1.739965	10.37037	0.617783	2.142857	0.5	0.000118	0.0008	7.14E-06	0.013889	**17.77432**	**4.77E-07**	**2.991622**

Water Quality Index (WQI)

WQI offers a thorough picture of the quality of surface and groundwater for most home applications. The Water Quality Index (WQI) is a metric that assesses the impact of multiple water quality parameters [32]. The WQI is calculated from the standpoint of surface and/or groundwater suitability for human consumption. As a result, in the current investigation, the WQI was calculated using the values indicated in Table 2. From Table 7, the computed value of WQI for this study ranges from 282.1572 at sample location IG/04 to 3526.282 at sample location IG/11. Findings from Tables 7,8 and 9, revealed that groundwater needs proper treatment before it can be used, except for sample location IG/04, which is considered suitable for irrigation use. The spatial distribution of WQI is presented in Figure 5. A previous study conducted by Olubukola et al. [79]; Asiwaju-Bello et al. [17] suggested that groundwater within Akure town is highly faced with salinity challenge, the process involve in recharge of aquifer often lead to groundwater pollution (rock weathering), and anthropogenic activities. This could be one of the reasons why groundwater is considered unsuitable for various users using the WQI set limit. They further pointed out that rock-water interaction is the major hydrogeochemical process that influences groundwater [17]. This result is in line with the work of Kadam et al. [57] done in Shivganga River basin, India. Also, it conforms to the result of a work done in China by Wu et al. [101] and in Nigeria, Akakuru et al. [4] but it is not in line with the study of Narsimha [89] done in semiarid region of South India.

Table 7. Water quality index results

Sample code	q1*wi														WQI (∑ q1*wi)
	TDS	pH	Mg^{2+}	Ca^{2+}	HCO_3^-	Na^+	Cl^-	SO_4^{2-}	K	Fe	Mn	As	Zn	Cu	
IG/01	0.00492	11.4288	0.476	0.03375	0.07625	0.03025	0.10112	0.021867	0.006	1111	0.0016	80	0.008889	9.33334E-07	1203.189
IG /02	0.0146	9.796114	1.172	0.0605	0.07175	0.118	0.0312	0.004218	0.01275	2222	0.0004	160	0.004445	1.33333E-07	2393.286
IG /03	0.00472	15.30643	2.496	0.24625	0.02275	0.04075	0.05472	0.027417	0.015	1111	0.0008	80	0.013334	2.66667E-07	1209.228
IG /04	0.00292	12.65331	1.092	0.1435	0.06975	0.00725	0.01536	0.017982	0.01025	111.1	0.0004	160	0.044447	8E-07	285.1572
IG /05	0.0118	14.49009	1.236	0.02625	0.1055	0.01075	0.04208	0.054723	0.02575	1111	0.0012	160	0.013334	2.66667E-07	1287.017
IG /06	0.01364	15.10234	2.352	0.1235	0.027	0.0285	0.05664	0.007548	0.0195	1111	0.0004	40	0.004445	3.15556E-06	1168.736
IG /07	0.00812	11.83697	0.408	0.3455	0.1555	0.06775	0.01744	0.021312	0.00725	2222	0.0004	120	0.008889	1.77778E-07	2354.877
IG /08	0.02412	14.286	0.844	0.142	0.30025	0.045	0.06512	0.011211	0.0225	3333	0.0016	40	0.008889	2.66667E-07	3388.751
1G/09	0.01096	15.30643	1.58	0.1985	0.17325	0.05625	0.01984	0.019647	0.004	1111	0.0008	400	0.013334	4.09334E-06	1528.383
IG/10	0.0054	15.7146	0.596	0.128	0.14775	0.047	0.10208	0.075702	0.001	111.1	0.0004	1200	0.004445	2.22222E-07	1327.922
IG/11	0.00832	14.08191	0.816	0.1735	0.05125	0.07	0.01952	0.019314	0.02825	1111	0.0004	2400	0.013334	8.88889E-08	3526.282
IG/12	0.03168	15.30643	1.336	0.22075	0.0755	0.04525	0.05984	0.016761	0.0035	111.1	0.0004	400	0.004445	8.88889E-08	528.2006
IG/13	0.00452	16.53094	2.828	0.06875	0.0445	0.05575	0.04896	0.011433	0.023	1111	0.0008	400	0.017779	1.33333E-07	1530.634
IG/14	0.00732	11.4288	2.2	0.1395	0.0995	0.04725	0.01328	0.030525	0.01525	3333	0.0004	80	0.004	1.77778E-07	3426.986
IG /15	0.01996	14.89826	1.132	0.12375	0.12625	0.06825	0.02848	0.018648	0.009	2222	0.0004	40	0.048891	1.77778E-07	2278.474
IG/16	0.02368	12.44923	0.796	0.0735	0.198	0.14725	0.06528	0.002553	0.0105	2222	0.0008	160	0.008889	9.77778E-07	2395.776
IG /17	0.01212	15.30643	1.092	0.04875	0.2505	0.0935	0.05232	0.040626	0.00375	1111	0.0004	280	0.004445	2.08889E-06	1407.905
IG /18	0.01804	14.89826	0.736	0.05175	0.237	0.04675	0.0984	0.017982	0.0165	3333	0.0012	40	0.004445	8.44445E-07	3389.126
IG /20	0.01176	16.73503	1.464	0.152	0.173	0.062	0.07136	0.023199	0.021	1111	0.0004	40	0.000444	3.28889E-06	1169.714
IG /20	0.01212	14.89826	1.084	0.09725	0.101	0.0755	0.02928	0.015873	0.03575	3333	0.0008	40	0.002222	4E-07	3389.352
IG /21	0.02372	15.30643	1.544	0.10425	0.24925	0.028	0.01712	0.017982	0.01425	2222	0.0004	160	0.000444	2.22222E-06	2399.306

Table 8. WQI characterization of groundwater (Agidi, *et al.,* 2022)

*WQI value	*Water quality status	Sample no	Possible Usage
<50	Excellent water	-	Drinking, irrigation
50 – 100	Good water	-	Drinking, irrigation
100 – 200	Poor water	-	Industrial and industrial
200 – 300	Very poor water	IG/04	Irrigation
>300	Unsuitable for drinking	1G/01, 02, 03, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22	Proper treatment is needed before use

Table 9. Computed WQI for each groundwater sample compared to WQI rating.

Sample Code	WQI	Water quality status
IG/01	1203.189	Unsuitable for drinking
IG/02	2393.286	Unsuitable for drinking
IG/03	1209.228	Unsuitable for drinking
IG/04	285.1572	Irrigation
IG/05	1287.017	Unsuitable for drinking
IG/06	1168.736	Unsuitable for drinking
IG/07	2354.877	Unsuitable for drinking
IG/08	3388.751	Unsuitable for drinking
IG/09	1528.383	Unsuitable for drinking
IG/10	1327.922	Unsuitable for drinking
IG/11	3526.282	Unsuitable for drinking
IG/12	528.2006	Unsuitable for drinking
IG/13	1530.634	Unsuitable for drinking
IG/14	3426.986	Unsuitable for drinking
IG/15	2278.474	Unsuitable for drinking
IG/16	2395.776	Unsuitable for drinking
IG/17	1407.905	Unsuitable for drinking
IG/18	3389.126	Unsuitable for drinking
IG/19	1169.714	Unsuitable for drinking
IG/20	3389.352	Unsuitable for drinking
IG/21	2399.306	Unsuitable for drinking
Min	285.1572	
Max	3526.282	
Aver	1941.789	

Human Health Risk Assessment

The technique of identifying the level of negative health effects linked with human exposure to environmental dangers is referred to as human health risk assessment in this study. Hazard identification, exposure evaluation, dose-response evaluation, and risk characterization are the four essential phases in risk assessment [97; 83]. The hazard identification procedure, according to Obiri et al. [72]; Asante-Duah [15], entails a study of key literature to identify any potential health concerns that metals and metalloids can cause. The degree, period, and sequences of heavy metal exposure are all determined throughout the exposure assessment process. Dose-response analysis determines how much metals and metalloids are required to create varying degrees of health impacts that could result in illnesses. Finally, risk characterization entails determining the likelihood that heavy metals may cause cancer or other disorders in the target population [37]. The inhabitants of Akure, Ondo State, SW Nigeria, are the population of interest in this study. From the result of the CDI of samples within the study area (Table 10) and Hazard quotient (HQ), and Hazard index (HI) in Table 11, it shows that for Fe, it is higher in adults than in children, Mn is higher in adults than in children. As is low in both adults and children, Zn is higher in adults than in children. same applies to Cu, which is higher in adults than in children. This implies that most of these heavy metals accumulate in human body with increase in age. The main cause of high HI in the study area may be anthropogenic causes. A hazard quotient less than or equal to 1 indicates that adverse effects are not likely to occur and thus can be considered to have negligible hazard. HQs greater than 1 are not statistical probabilities of harm occurring. Instead, they are a simple statement of whether (and by how much) an exposure concentration exceeds the reference concentration (RfC).

It is important to note that drinking contaminated water is the main cause of detectable human exposure to heavy metals. The health problems that may follow from this exposure include cardiovascular problems, neurological damage, renal injuries, and an increased risk of cancer and diabetes. The generation of reactive oxygen species, which causes oxidative damage and detrimental consequences on health, is acknowledged as the main mechanism underlying heavy metal-induced toxicity [3]. Thus, the use of heavy metal-contaminated water contributes to high rates of sickness and mortality around the world [2]. The findings of this HRA are comparable to those of Narsimha's (2019) semiarid South Indian research, which discovered that youngsters are more susceptible to HI than adults. The research agrees with that of Tokatli and Ustaolu [94], who found that children in Turkey have significant levels of HI and HQ.

Table 10. CDI of samples within the study area

Sample code	Fe (A)	Fe (C)	Mn (A)	Mn (C)	As (A)	As (C)	Zn (A)	Zn (C)	Cu (A)	Cu (C)
IG/01	186515	3197.4	746060	12789.6	37303	639.48	373030	6394.8	3916815	67145.4
IG /02	373030	6394.8	186515	3197.4	74606	1278.96	186515	3197.4	559545	9592.2
IG /03	186515	3197.4	373030	6394.8	37303	639.48	559545	9592.2	1119090	19184.4
IG /04	18651.5	319.74	186515	3197.4	74606	1278.96	1865150	31974	3357270	57553.2
IG /05	186515	3197.4	559545	9592.2	74606	1278.96	559545	9592.2	1119090	19184.4
IG /06	186515	3197.4	186515	3197.4	18651.5	319.74	186515	3197.4	13242565	227015.4
IG /07	373030	6394.8	186515	3197.4	55954.5	959.22	373030	6394.8	746060	12789.6
IG /08	559545	9592.2	746060	12789.6	18651.5	319.74	373030	6394.8	1119090	19184.4
1G/09	186515	3197.4	373030	6394.8	186515	3197.4	559545	9592.2	17178032	294480.5
IG/10	18651.5	319.74	186515	3197.4	559545	9592.2	186515	3197.4	932575	15987
IG/11	186515	3197.4	186515	3197.4	1119090	19184.4	559545	9592.2	373030	6394.8
IG/12	18651.5	319.74	186515	3197.4	186515	3197.4	186515	3197.4	373030	6394.8
IG/13	186515	3197.4	373030	6394.8	186515	3197.4	746060	12789.6	559545	9592.2
IG/14	559545	9592.2	186515	3197.4	37303	639.48	167863.5	2877.66	746060	12789.6
IG /15	373030	6394.8	186515	3197.4	18651.5	319.74	2051665	35171.4	746060	12789.6
IG/16	373030	6394.8	373030	6394.8	74606	1278.96	373030	6394.8	4103330	70342.8
IG /17	186515	3197.4	186515	3197.4	130560.5	2238.18	186515	3197.4	8766205	150277.8
IG /18	559545	9592.2	559545	9592.2	18651.5	319.74	186515	3197.4	3543785	60750.6
IG /19	186515	3197.4	186515	3197.4	18651.5	319.74	18651.5	319.74	13802110	236607.6
IG /20	559545	9592.2	373030	6394.8	18651.5	319.74	93257.5	1598.7	1678635	28776.6
IG /21	373030	6394.8	186515	3197.4	74606	1278.96	18651.5	319.74	9325750	159870
MIN	**18651.5**	**319.74**	**186515**	**3197.4**	**18651.5**	**319.74**	**18651.5**	**319.74**	**373030**	**6394.8**
MAX	**559545**	**9592.2**	**746060**	**12789.6**	**1119090**	**19184.4**	**2051665**	**35171.4**	**17178032**	**294480.5**
STDV.	**178792.4**	**3065.012**	**187842.5**	**3220.158**	**253903.2**	**4352.627**	**534634**	**9165.154**	**5137166**	**88065.7**

Table 11. Hazard quotient (HQ), and Hazard index (HI)

	Fe (A)	Fe (C)	Mn (A)	Mn (C)	As (A)	As (C)	Zn (A)	Zn (C)	Cu (A)	Cu (C)
IG/01	266450	4567.714	16218696	278034.8	124343333	2131600	1243433	21316	97920375	1678635
IG /02	532900	9135.429	4054674	69508.7	248686667	4263200	621716.7	10658	13988625	239805
IG /03	266450	4567.714	8109348	139017.4	124343333	2131600	1865150	31974	27977250	479610
IG /04	26645	456.7714	4054674	69508.7	248686667	4263200	6217167	106580	83931750	1438830
IG /05	266450	4567.714	12164022	208526.1	248686667	4263200	1865150	31974	27977250	479610
IG /06	266450	4567.714	4054674	69508.7	62171667	1065800	621716.7	10658	3.31E+08	5675385
IG /07	532900	9135.429	4054674	69508.7	186515000	3197400	1243433	21316	18651500	319740
IG /08	799350	13703.14	16218696	278034.8	62171667	1065800	1243433	21316	27977250	479610
1G/09	266450	4567.714	8109348	139017.4	621716667	10658000	1865150	31974	4.29E+08	7362014
IG/10	26645	456.7714	4054674	69508.7	1.865E+09	31974000	621716.7	10658	23314375	399675
IG/11	266450	4567.714	4054674	69508.7	3.73E+09	63948000	1865150	31974	9325750	159870
IG/12	26645	456.7714	4054674	69508.7	621716667	10658000	621716.7	10658	9325750	159870
IG/13	266450	4567.714	8109348	139017.4	621716667	10658000	2486867	42632	13988625	239805
IG/14	799350	13703.14	4054674	69508.7	124343333	2131600	559545	9592.2	18651500	319740
IG /15	532900	9135.429	4054674	69508.7	62171667	1065800	6838883	117238	18651500	319740
IG/16	532900	9135.429	8109348	139017.4	248686667	4263200	1243433	21316	1.03E+08	1758570
IG /17	266450	4567.714	4054674	69508.7	435201667	7460600	621716.7	10658	2.19E+08	3756945
IG /18	799350	13703.14	12164022	208526.1	62171667	1065800	621716.7	10658	88594625	1518765
IG /19	266450	4567.714	4054674	69508.7	62171667	1065800	62171.67	1065.8	3.45E+08	5915190
IG /20	799350	13703.14	8109348	139017.4	62171667	1065800	310858.3	5329	41965875	719415
IG /21	532900	9135.429	4054674	69508.7	248686667	4263200	62171.67	1065.8	2.33E+08	3996750
MIN	**26645**	**456.7714**	**4054674**	**69508.7**	**62171667**	**1065800**	**62171.67**	**1065.8**	**9325750**	**159870**
MAX	**799350**	**13703.14**	**16218696**	**278034.8**	**3.73E+09**	**63948000**	**6838883**	**117238**	**4.29E+08**	**7362014**
STDV.	**255417.7**	**4378.589**	**4083533**	**70003.43**	**846344078**	**14508756**	**1782113**	**30550.51**	**1.28E+08**	**2201643**
HI	**8339885**	**142969.5**	**1.46E+08**	**2502313**	**1.007E+10**	**1.73E+08**	**32702297**	**560610.8**	**2.18E+09**	**37417574**

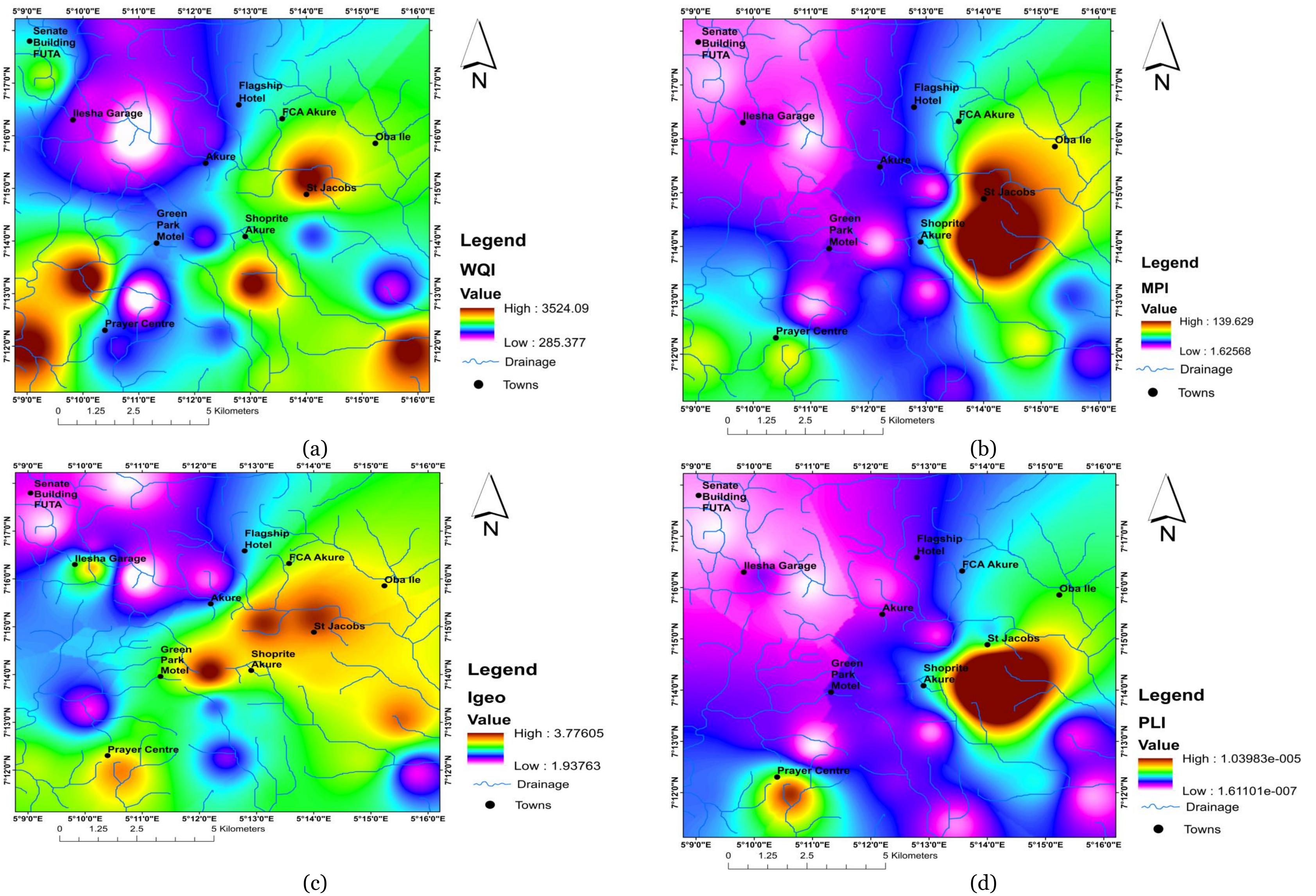

Figure 5. Spatial distribution of WQI, MPI, Igeo and PLI.

Statistical Approach to Health Risk Assessment

A sample questionnaire was designed and administered to fifty-five (55) people to determine the potential health risk of water on the inhabitants of the area in the last ten (10) years. The result showed that certain percentage of the sampled people have suffered or experienced every common waterborne disease listed in the questionnaire, namely, diarrhea, typhoid fever, cholera, dysentery, hepatitis A and Giardia (Table 12). The results on diarrhea are as follows (2% most often, 2% always, 11% occasionally, 9% rarely while 76% never experience diarrhea) in the last 10 years. The result of typhoid fever is as follows (16% very often, 29% occasionally, 22% rarely while 33% never experience typhoid fever) in the last ten years. About 2% occasionally, 7% rarely and 85% never experience dysentery in the last ten years. About 2% occasionally, 6% rarely and 92% never experience hepatitis A in the last ten years. About 4% rarely and 96% never experience Giardia in the last ten years. 20% of the people sample fall between 16 to 20years age group, 47% fall between 21 to 25 years age group, 15% fall between 26 to 30 years, 2% fall between 31 to 35 years age group and 16% are 35 years and above.

The result revealed that majority of those prone to this potential health risk are children and youths in the sampled area.In the same vein, Nkpaa et al. [68] conducted research to assess the level of heavy metal in south Nigeria as well as evaluate the possible health risks to the consumer of aquatic food (shellfish) in the study area. It was discovered that the carcinogenic risk for chromium in all shellfish exceeded the maximum permissible level of 10E-4. Also, for As and Ni which also exceeded the maximum permissible level of 10E-4. Hence, it was deduced that the consumers of shellfish in the study area might be soon prone to poisonous metal infection in process of time. Some water samples were taking from sources of water such as taps, wells, streams and surface tank reservoirs for a microbiological test by Uzuegbu et al. [97]. The result revealed that there was high degree of coliform in sream and hand dug wells and the existence of esherichia cell (E. cell) in water sample taking there in four consecutive week connotes that the water bodies have been contaminated by various anthropogenic activities in the area. However, the result of the assessment of heavy metals in aquatic organism such (fish monger) in Akure metropolis revealed that the degree of heavy metals discovered in those fishes were within acceptable limit of FAO/WHO [77].

Table 12. Result of the potential health risk of water research

	Most often	Always	Very often	Occasionally	Rarely	Never
Diarrhea	1	1	0	6	5	42
Typhoid fever	0	0	9	16	12	18
Cholera	0	0	0	1	4	50
Dysentery	0	0	0	0	8	47
Hepatitis A	0	0	0	1	3	51
Giardia	0	0	0	0	2	53

DISCUSSION

The hydrogeochemical composition of groundwater in Akure reveals that the prevailing water type is Mg–Na–HCO_3–Cl, indicating that silicate weathering, carbonate dissolution, and limited ion-exchange reactions are the principal geochemical processes controlling the ionic makeup. This chemical evolution pattern corresponds closely with earlier studies conducted in Akure and adjoining basement terrains of southwestern Nigeria [79], where similar dominance of bicarbonate facies was reported. The predominance of alkaline-earth cations and weak acids underscores the natural weathering of biotite gneiss and granitic rocks typical of the region. Comparable hydrochemical facies have also been identified in southeastern Nigeria [33; 10] and globally in crystalline aquifers of South Asia and East Africa [60; 23], supporting the inference that the chemistry of the groundwater is largely governed by water–rock interactions under open-system carbonate equilibrium.

Although the overall water quality indices (WQI) indicate that most of the groundwater samples are within the permissible limits for general use, the results show that a significant proportion requires treatment before consumption. This finding corroborates the reports of Omotola et al. [79] and Akintorinwa and Olatokunbo-Ojo [14], who highlighted the susceptibility of Akure's aquifer system to quality deterioration resulting from unregulated land use and poor waste management. The

Contamination Factor (CF) and Geoaccumulation Index (I_geo) values generally revealed minimal to moderate contamination; however, the Metal Pollution Index (MPI) identified localized zones of elevated heavy-metal concentrations, particularly in densely populated and industrialized areas. Similar spatial disparities have been reported in other Nigerian cities such as Port Harcourt, Aba, and Owerri [35; 13], where anthropogenic inputs such as effluent discharge, vehicular emissions, and leachates from dumpsites have been shown to amplify trace-metal levels above the natural geogenic background. Globally, studies by Chen et al. [23] and Wang et al. [98] have also shown that localized enrichment of Pb, Cd, and Ni occurs in urban aquifers due to vehicular exhaust deposition, industrial waste, and aging plumbing infrastructure.

The principal component analysis (PCA) and correlation matrix further confirmed that the dominant sources of solute enrichment are a combination of natural mineral dissolution and anthropogenic activities. The lack of strong inter-element correlations, particularly among heavy metals, suggests multiple and independent sources rather than single geogenic control. These findings agree with those of Eyankware et al. [42] and Akakuru et al. [9], who emphasized the dual control of natural and human-induced processes on groundwater composition in the Niger Delta and southeastern Nigeria. The observed pattern of Cd–Pb association also aligns with reports from Igwe et al. [52] and Chen et al. [23], who attributed similar correlations to mixed inputs from industrial runoff, atmospheric deposition, and weathering of sulfide-bearing minerals.

The health risk assessment revealed that both carcinogenic and non-carcinogenic risks are primarily associated with Pb and Cd exposure, with children showing higher susceptibility due to their lower body mass and higher intake rate. This outcome supports previous hydrogeochemical health studies across Nigeria [35; 10] and corroborates international toxicological findings [60; 99], which indicate that prolonged ingestion of trace metals through drinking water poses serious health threats to vulnerable populations. Although the computed hazard indices for most metals were below the critical threshold, elevated values in a few samples call for urgent mitigation through point-of-use treatment and improved waste management practices.

Irrigation suitability indices such as SAR, %Na, KR, and PI generally classified the groundwater as suitable for agricultural purposes, with minor salinity and sodicity constraints indicated by MAR values in a few locations. This observation is consistent with findings from previous Nigerian studies [79; 13] and corroborated by similar global evaluations of basement terrain aquifers in India and China [60; 23], where seasonal flushing and soil amendments mitigate potential sodicity hazards.

Overall, the hydrogeochemical and health risk profiles of Akure groundwater demonstrate a system influenced by both natural and anthropogenic factors. The close agreement between this study and other regional investigations [79] strengthens the understanding that uncontrolled urban growth and inadequate sanitation remain critical drivers of groundwater contamination in southwestern Nigeria. On a global scale, the trends observed align with those reported in other urbanizing crystalline basement environments, emphasizing that groundwater quality degradation is an emerging challenge in developing regions. The outcomes of this research therefore underscore the importance of continuous groundwater monitoring, enforcement of sanitary regulations, and adoption of integrated water-resource management frameworks that couple geochemical data with public health surveillance.

These results reflect the strong lithological control typical of Precambrian crystalline basement aquifers, where groundwater chemistry is largely influenced by silicate weathering, mineral dissolution, and fracture-controlled flow systems. In rapidly urbanizing cities such as Akure, anthropogenic inputs from waste disposal, septic systems, and urban runoff further interact with these geogenic processes, producing complex groundwater quality patterns. Therefore, the observed hydrochemical signatures represent the combined influence of natural geological processes and localized anthropogenic pressures within the Akure aquifer system.

The findings of this study have important implications for achieving Sustainable Development Goal 6, particularly Target 6.1, which seeks to ensure universal and equitable access to safe and affordable drinking water. The identification of hydrogeochemical processes, localized heavy-metal enrichment, and potential non-carcinogenic health risks associated with groundwater consumption highlights the need for regular groundwater monitoring and improved water quality management in rapidly urbanizing basement terrains such as Akure. By integrating hydrogeochemical indices, multivariate statistical analysis, and health risk assessment, this study provides a scientific framework that can support evidence-based groundwater governance, pollution mitigation strategies, and sustainable water-supply planning. Such approaches are critical for safeguarding groundwater resources and protecting public health in developing urban centers where groundwater remains a primary source of domestic water.

CONCLUSION

This study provides a comprehensive hydrogeochemical and health risk assessment of groundwater within Akure, southwestern Nigeria. The findings reveal that the chemical composition of the groundwater is primarily controlled by silicate weathering, carbonate dissolution, and limited ion-exchange processes, with $Mg–Na–HCO_3–Cl$ water types predominating. Despite the generally low contamination factors and pollution load indices, the elevated Metal Pollution Index (MPI) and Geoaccumulation Index (Igeo) in several samples indicate localized zones of heavy-metal enrichment, likely resulting from anthropogenic influences such as improper waste disposal, agricultural leachates, and urban runoff. Multivariate statistical analyses (PCA and correlation matrix) confirmed that heavy-metal distributions stem from mixed geogenic and anthropogenic sources, with weak inter-element correlations suggesting independent input pathways. Water Quality Index (WQI) values exceeding acceptable limits demonstrate that most sampled wells are unsuitable for direct human consumption without adequate treatment. Health-risk modeling further underscores that both adults and children, especially the latter, face potential non-carcinogenic hazards due to elevated levels of Fe, Mn, Pb, and Cd. Higher Hazard Index values among children highlight age-related vulnerability to bioaccumulative toxicants.

Overall, the hydrogeochemical characteristics of Akure's aquifers reflect the combined effects of lithological control and anthropogenic stress. The results emphasize the urgent need for continuous groundwater monitoring, improved sanitation practices, and the implementation of water-treatment and pollution-control strategies. These findings contribute valuable baseline data for environmental policy formulation and sustainable groundwater management in crystalline basement terrains across sub-Saharan Africa.

Although the analytical techniques used in this study are widely established in groundwater research, their integrated application provides new insights into groundwater quality dynamics in the crystalline basement aquifer system of Akure. The findings contribute to the broader understanding of hydrogeochemical evolution, contaminant pathways, and public health risks in rapidly urbanizing basement terrains. Such knowledge is essential for developing evidence-based groundwater management strategies and sustainable water-resource policies in Akure and other similar urban centers across sub-Saharan Africa. These findings contribute to advancing Sustainable Development Goal 6 by providing scientific evidence necessary for improving groundwater quality monitoring, ensuring safe drinking water, and supporting sustainable groundwater management in crystalline basement aquifers.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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