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ORIGINAL STUDY

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Abstract

Borehole water is a primary drinking water source in Effurun, Delta State, Nigeria, making its quality a critical public health concern. Contaminants such as major ions and trace metals can affect water safety, necessitating comprehensive assessment. This study evaluates the hydrochemical characteristics of borehole water, identifies contamination sources, and assesses compliance with World Health Organization (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) guidelines. The study aims to determine the spatial distribution of major ions and trace metals in borehole water, assess water quality variations, and identify contamination patterns due to natural and anthropogenic influences. Water samples were collected from ten boreholes (BH1−BH10) and analyzed for significant cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), anions (Cl^{-}, SO_4^{2-}, NO_3^{-}, HCO_3^{-}), and trace metals (Pb, Cu, Zn, Mn). Statistical analysis, spatial mapping using ArcGIS, and hydrogeochemical modeling (Piper and Durov diagrams) were conducted to determine concentration trends and geochemical interactions. Calcium ranged from 29.95 to 64.50 mg/L, showing moderate correlations with sodium and potassium. Magnesium remained stable (9.50−14.20 mg/L), while chloride levels (39.50−52.70 mg/L) suggested seawater intrusion. Sulfate (18.76−31.20 mg/L) and nitrate (16.78−30.70 mg/L) exceeded permissible limits, indicating contamination from agricultural and industrial sources. Lead levels (0.092−0.127 mg/L) exceeded WHO limits (0.01 mg/L) by over tenfold, posing significant health risks. Higher contaminant concentrations in BH7, BH8, and BH9 indicate surface-groundwater interactions, with increased lead (0.127 mg/L in BH8), chloride (49.90 mg/L in BH7), and nitrate (22.40 mg/L in BH9). The spatial analysis identified southeastern Effurun as a contamination hotspot requiring urgent mitigation. Continuous monitoring, pollution control, and water treatment interventions are essential to ensure safe drinking water. This study uniquely integrates hydrogeochemical, statistical, and geospatial approaches to assess borehole water contamination, providing actionable insights for sustainable groundwater management.

Keywords: Borehole water quality, Hydrochemical analysis, Major ions and trace metals, Spatial distribution, Water contamination and public health

1. Introduction

Human society's existence depends profoundly on accessible clean water because it safeguards both personal wellness and community political and economic security [1,2]. The importance of water extends across all population sectors that depend on it for their domestic and agricultural needs, plus industrial and recreational activities [3]. People must turn to substitute water sources because surface water resources are either polluted or depleted from environmental pollution, such as excessive extraction or changing climate patterns in affected regions. Borehole water functions as the primary water source, delivering life support to communities that cannot access surface water

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sources effectively [4,5]. The underground water source accessed through boreholes represents an essential water supply reservoir that delivers water that demonstrates purity and resists surface pollution [6,7]. Borehole water represents the primary water source that enables agricultural development while fulfilling the needs of drinking water, sustaining both sanitation practices and earning potential across a large number of regions throughout the world. Major ion concentration assessments in borehole water samples stand as a critical factor for both human health protection and various application suitability [8]. Ions such as calcium, magnesium, sodium, and potassium, together with bicarbonate sulfate chloride and nitrate, influence water chemistry [9,10]. The measurement of significant ions determines both water taste and smell, yet it controls how water reacts to corrosion and how it affects scaling and nutrition. The threshold levels of particular ions in water exceed permitted limits, which results in significant health hazards for water consumers. High nitrate levels in water may develop into methemoglobinemia, regarded as "blue baby syndrome," which predominantly affects newborn infants. The consumption of high sodium water supply exacerbates hypertension rates in medically at-risk groups while raising their cardiovascular disease risks.

Groundwater quality assessment is a critical aspect of environmental sustainability, particularly in regions where groundwater serves as a primary source of water for domestic, agricultural, and industrial purposes. Various studies have employed hydrochemical and geophysical approaches to evaluate groundwater quality and its suitability for different uses. Hydrochemical analyses of groundwater in the Delta Central region of Nigeria revealed a predominance of chloride and bicarbonate ions, with heavy metals such as lead present in some locations due to anthropogenic pollution. The acidic nature of groundwater in this region, with pH values ranging from 3.75 to 6.23, indicates possible contamination and the need for pre-use treatment measures [11]. Similarly, a study in Abi, southeastern Nigeria, found that groundwater quality was generally suitable for drinking and irrigation, though influenced by local geology and anthropogenic activities. The presence of calcium, magnesium, and bicarbonate ions suggested significant geochemical interactions within the aquifers [12]. In Ayede Ekiti, southwestern Nigeria, groundwater quality was assessed using borehole inventory and geophysical surveys. The study found that while water samples generally met World Health Organization (WHO) standards, poor borehole maintenance and encrustation affected water availability. The hydrochemical facies analysis showed the dominance of calcium-bicarbonate and sodium-bicarbonate water types, highlighting the influence of rock-water interactions on groundwater chemistry [13]. A regional study in the Pra Basin, Ghana, examined the impact of illegal mining activities on groundwater and surface water quality. The analysis revealed that 74 % of surface water and 20 % of groundwater samples were of poor drinking quality due to elevated levels of iron and manganese. However, irrigation water quality remained within acceptable limits, indicating differential contamination impacts on various water uses [14]. In contrast, a study in the Komadugu-Yobe Basin of Nigeria's Sahel region found that groundwater was primarily influenced by rock-water interactions, with bicarbonate-rich water types dominating the hydrochemical landscape. The groundwater quality index (GWQI) showed that 63 % of samples were excellent for drinking, while 27 % were classified as good [15]. These studies underscore the importance of continuous groundwater quality monitoring, particularly in regions experiencing rapid population growth and industrialization. The findings suggest that while some groundwater sources remain suitable for consumption and irrigation, contamination from anthropogenic activities necessitates targeted interventions, such as improved borehole management, pollution control, and treatment processes.

The quality of borehole water is crucial for public health and sustainable water resource management, particularly in communities like Effurun, Delta State, Nigeria, where groundwater is a primary water source. However, increasing groundwater reliance raises concerns about contamination from both natural geological formations and anthropogenic activities. The presence of significant ions in borehole water can pose health risks, yet systematic evaluation and monitoring remain limited. Existing studies often lack comprehensive statistical and analytical approaches to identify contamination sources and spatial variations in water quality.

This research addresses these gaps by systematically assessing primary ion concentrations in borehole water samples across Effurun. Using analytical and statistical techniques, the study identifies spatial variations, potential contamination sources, and deviations from WHO and NSDWQ standards. The findings provide critical insights for improving water treatment, distribution, and management strategies, ensuring safer drinking water for residents. By bridging knowledge gaps on borehole water contamination, this study supports policymakers in implementing targeted interventions, thus advancing equitable access to clean and safe water in the region.

2. Research area

The research analyzes the main ion concentration variations in Effurun, which lies within the Uvwie Local Government Area of Delta State, Nigeria. The geographical coordinates of Effurun span 5°42′0″E to 5°50′0″E and 5°40′0″N to 5°30′0″N, as depicted in Fig. 1. Such a strategic geographical location necessitates exploring the modifications that occur in the groundwater main ion concentrations. Effurun encompasses major settlements including Ekpan, Igbudu, and Okuokoko, which are primarily residential and mixed-use zones that influence groundwater through domestic activities and infrastructure patterns. Geological and hydrological characteristics at Effurun determine how primary water ions spread, as well as their overall groundwater behavior patterns. The study of the geologic framework, especially aquifer composition, sedimentary structures, and hydrological flow patterns, leads to a better understanding of processes that alter primary ion levels [16].

Effurun's position in the Niger Delta region, known for its intricate geological history and hydrological patterns, contributes further complexity to the research area. The interplay of sedimentary deposits, tectonic activity, and hydrological processes causes the fluctuations in significant ion concentrations found in Effurun's groundwater.

3. Material and methods

3.1. Groundwater sampling and analysis

Groundwater sampling was carried out between September and October 2024, a period representing the transition from the wet to the dry season in Effurun, Delta State. This timeframe was strategically selected to minimize the effects of heavy precipitation while still capturing residual hydrological influence from the wet season. Samples were collected from ten functional boreholes (BH1–BH10) situated across residential and mixed-use settlements, which are characterized by varying population densities and infrastructure types that may influence contamination levels, with depths ranging from 35 to 60 m. The boreholes, constructed with steel or PVC casings, were allowed to run for several minutes before sampling to ensure representative aquifer water was obtained. Samples were collected in pre-cleaned plastic containers, following strict protocols to avoid contamination. Standard geochemical methods, including titration, ion chromatography, and spectrophotometry, were applied to analyze significant ions such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, and NO_3^{-}. Each sampling point was georeferenced, and proximity to potential pollution sources—such as waste dumps,

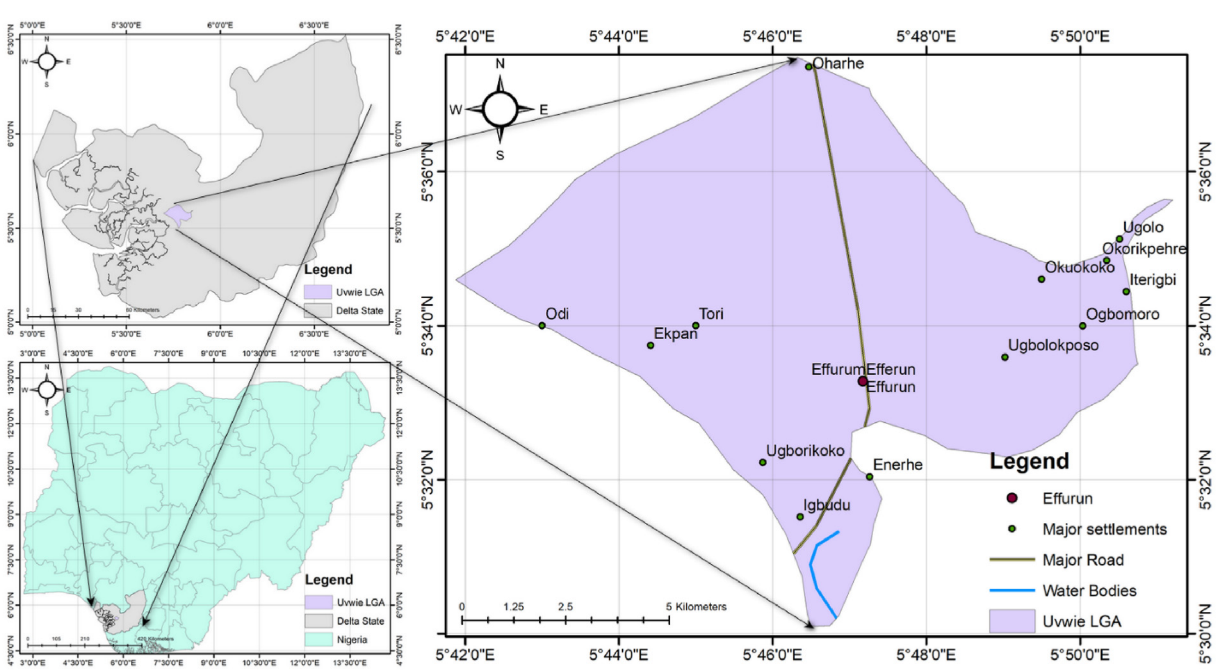

Fig. 1. Map of the study area, Delta State and Nigeria.

roads, and water bodies—was noted during fieldwork. Additional details regarding borehole coordinates and usage characteristics are available upon request and were also used in the spatial analysis.

3.2. Statistical analysis

Statistical parameters, including mean (μ), standard deviation (σ), coefficient of variation (CV), and range, were computed to characterize the distribution and variability of significant ion concentrations within the dataset. These parameters were calculated using standard formulae: mean as the average concentration, standard deviation as the measure of data dispersion, coefficient of variation as the relative variation, and range as the difference between the highest and lowest values. The statistics used to describe data consist of mean, standard deviation, coefficient of variation, and range, which present both location and spread information. The calculated mean values of essential ions function as baseline indicators for water quality analysis, but the deviation standard shows how much the actual measurements differ from this mean value [17]. The coefficient of variation shows data spread as a proportion, while the range shows the complete set of value ranges.

By performing statistical calculations on each central ion, researchers can gain an essential understanding of ion concentration distribution patterns in groundwater samples [18]. Water quality assessments and source contamination detection rely on this data to develop targeted protective measures to defend environmental and public health.

3.3. Spatial analysis

Spatial analysis requires researchers to collect data across various locations surrounding the lake as well as within its catchment area to recognize distinct spatial distribution patterns of limnological properties. ArcGIS, which operates as a strong geospatial information system (GIS) software, is helpful in analyzing spatial data and showing results. Interpolation functions as a vital spatial analysis approach within ArcGIS operations. The measured values at sampled locations provide the basis for the estimation of values that would exist at unsampled locations through interpolation. Among all interpolation methods utilized in limnological spatial analyses, inverse distance weighting (IDW) stands as the most frequently used method [19]. The IDW method uses closer sampled locations with increased weighting while employing lower weighting on more distant ones to estimate unsampled location values.

The IDW interpolation equation can be expressed as [12]:

$$z(u) = \frac{\sum \frac{z(i)}{d(u,i)^p}}{\sum \frac{1}{d(u,i)^p}} \qquad 1$$

Where: $z(u)$ Is the estimated value at the unsampled location u. $z(i)$ Is the measured value at the sampled location i. $d(u,i)$ is the distance between the unsampled location u and the sampled location i. p is the power parameter that determines how the distance affects the estimation. By applying the IDW method in ArcGIS, researchers can generate spatial distribution maps of various ion concentrations. These maps help visualize the spatial patterns and variations in these properties across the study area. The maps can reveal areas of high or low values, hotspots of pollution or eutrophication, and potential impacts on water quality.

ArcGIS allows for spatial analysis through the calculation of spatial statistics. For example, researchers can perform spatial autocorrelation analysis to detect spatial clustering or dispersion of limnological properties. The Moran's I index is commonly used to measure spatial autocorrelation [12]:

$$I = \left(n \Big/ \sum \sum w_{ij} \right) * \sum \sum w_{ij} * (z_i - \bar{z}) * (z_j - \bar{z}) \qquad 2$$

Where n is the number of locations. w_{ij} is the spatial weight between location i and location j. z_i and z_j are the values of the limnological property at locations i and j, respectively. $\bar{z}$ is the mean value of the ion concentration property.

Moran's I index ranges from −1 to 1, where positive values indicate positive spatial autocorrelation (clustering of similar values), negative values indicate negative spatial autocorrelation (dispersion of dissimilar values), and values close to zero indicate spatial randomness.

3.4. Hydrogeochemical plots

Since the beginning of the 1920s, researchers have developed multiple graphical and multivariate statistical tools that help with water sample classification. The objective involves organizing sample collections into distinct hydrogeochemical groups, which demonstrate homogeneity within their clusters. An extensive dataset served as the basis for studying these techniques to evaluate their ability to classify water chemistry samples according to meaningful groups [20]. The research made use of the Piper and Durov diagrams for its assessment. The analysis through graphical methods stays limited to certain selected parts of the data, whereas statistical procedures handle all available information. The purpose of the evaluation of these methods is to discover shared chemical properties in water samples. Water samples with equivalent chemical composition share identical hydrologic backgrounds that involve areas of recharging, mineral composition, infiltration paths, flow patterns, climatic conditions, and duration of storage.

The Piper diagram displays water chemistry through two separate ternary plots, with each plot showing distinctly positive and negative ions. A cation plot presents calcium together with magnesium, sodium, and potassium as key chemical elements, yet the anion plot depicts sulfate followed by chloride and carbonate followed by bicarbonate. Two ternary plots create a condensed, diamond-shaped matrix structure to represent both anions and cations in the graph, according to Ref. [21]. The percentages of meq/L represent water concentrations within the Piper diagram as researchers use the same graph to plot several test results for water classification through hydrochemical facies assessment. Communities and changing patterns over space-time can be tracked effectively through the usage of the Piper diagram. The renormalized concentration format fails to easily accept significant ions that need to be considered beyond the scope of the analysis.

The Durov diagram, an alternative to the Piper diagram, shows the significant ions as percentages. The two triangles of the diagram contain data points whose values are set to 100 % total cations and anions before projection onto perpendicularly placed square grids. Large groups of samples can benefit from this plot because it reveals data clusters that show samples with analogous compositions. Measurement through the Durov diagram requires data for specific sample groups or complete dataset samples.

4. Results and discussion

4.1. Hydrochemical analysis of borehole water samples

Table 1 presents the results of cation analysis in BH1 to BH10 water samples. The analytical procedure assessed the levels of Calcium (Ca), Magnesium (Mg), Sodium (Na), and Potassium (K). The measured Calcium levels in the samples extended between 29.95 mg/L in BH3 to 64.50 mg/L in BH9. Analytical data revealed that BH8 contained 9.50 mg/L Magnesium, but BH6 showed 14.20 mg/L. The water sample from BH3 contained the lowest sodium level at 14.80 mg/L, while the water sample from BH1 had the highest sodium level at 22.70 mg/L. The analytical results showed that potassium existed in measured concentrations of 4.80 mg/L (BH4) to 10.20 mg/L (BH9). Cations show different concentration levels among sampling areas, which indicates distinct hydrochemical features and possibly different hydrological conditions along with dissimilar mineral sources.

The anion concentrations for the ten borehole samples (BH1 to BH10) were analyzed and are summarized in Table 2. The anions measured include Chloride (Cl), Bicarbonate (HCO_3), Sulfate (SO_4), and Nitrate (NO_3). Chloride concentrations ranged from 39.50 mg/L (BH5) to 52.70 mg/L (BH10). Bicarbonate levels varied between 17.80 mg/L (BH8) and 22.80 mg/L (BH4). Sulfate concentrations were lowest in BH1 (18.76 mg/L) and highest in BH10 (31.20 mg/L). Nitrate levels ranged from 16.78 mg/L (BH3) to 30.70 mg/L (BH4). These variations in anion concentrations indicate diverse hydrochemical characteristics across the sampled locations, suggesting different sources of contamination and varying geochemical processes.

The trace metal concentrations for the ten borehole samples (BH1 to BH10) were analyzed and are

Table 1. Cation concentrations in borehole samples.

Sample code	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)
BH1	52.600	11.700	22.700	7.500
BH2	44.700	11.720	18.100	6.600
BH3	29.950	10.870	14.800	5.800
BH4	37.560	9.670	17.300	4.800
BH5	34.850	13.200	19.400	7.500
BH6	45.870	14.200	20.300	8.200
BH7	37.550	12.700	19.600	9.300
BH8	41.870	9.500	20.100	8.400
BH9	64.500	9.820	20.200	10.200
BH10	41.900	12.600	16.700	9.200

Table 2. Anion concentrations in borehole samples.

Sample code	Chloride (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Nitrate (mg/L)
BH1	39.800	21.800	18.760	17.500
BH2	42.800	22.100	19.760	21.800
BH3	50.200	19.600	21.900	16.780
BH4	45.600	22.800	30.800	30.700
BH5	39.500	19.800	28.900	29.800
BH6	45.780	18.700	26.600	25.400
BH7	49.900	20.000	30.400	19.600
BH8	39.780	17.800	28.900	18.700
BH9	45.800	18.900	27.850	22.400
BH10	52.700	22.700	31.200	26.500

summarized in Table 3. The trace metals measured include Lead (Pb), Copper (Cu), Zinc (Zn), and Manganese (Mn). Lead concentrations ranged from 0.092 mg/L (BH6) to 0.127 mg/L (BH8). Copper levels varied between 0.132 mg/L (BH1) and 0.231 mg/L (BH4). Zinc concentrations were lowest in BH3 (0.179 mg/L) and highest in BH5 (0.219 mg/L). Manganese concentrations ranged from 0.087 mg/L (BH2) to 0.124 mg/L (BH8). These variations in trace metal concentrations indicate diverse geochemical conditions across the sampled locations, which could be influenced by both natural mineralogy and anthropogenic activities.

4.2. Statistical analysis of borehole water samples

The water samples were analyzed for cation concentrations of four key minerals: calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K). The results are summarized in Table 4.

As shown by measurements, the water samples contain a typical amount of calcium because their mean measurement (43.14 mg/L) matches natural water standards. Sample data shows heavy variability because the standard deviation measures 9.80 mg/L, and the range extends to 34.55 mg/L. Water management techniques and differences in geological water formation create variability that affects the results. The negative correlation between calcium and magnesium amounts to −0.19, indicating that calcium slightly reduces the magnesium concentration levels in the solutions. Mineral dissolution and precipitation processes inhibit the competitive interaction between these cations [22]. The typical magnesium content in natural water is 11.60 mg/L, which demonstrates consistent levels, as shown by a slight standard deviation of 1.61 mg/L. The minimal relationship between magnesium and calcium, along with sodium and potassium, demonstrates independent change in magnesium content compared to these other mineral concentrations. The sodium levels in the water reached 18.92 mg/L while demonstrating a moderate positive statistical relation with both calcium at 0.62 and potassium at 0.45. The measurements of sodium

Table 3. Trace metal concentrations in borehole samples.

Sample code	Lead (mg/L)	Copper (mg/L)	Zinc (mg/L)	Manganese (mg/L)
BH1	0.106	0.132	0.182	0.097
BH2	0.098	0.198	0.198	0.087
BH3	0.104	0.212	0.179	0.095
BH4	0.103	0.231	0.211	0.107
BH5	0.093	0.198	0.219	0.107
BH6	0.092	0.167	0.196	0.121
BH7	0.102	0.194	0.189	0.118
BH8	0.127	0.167	0.186	0.124
BH9	0.122	0.213	0.208	0.112
BH10	0.124	0.230	0.192	0.119

Table 4. Correlation analysis for cation concentrations in borehole samples.

	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)
Calcium (mg/L)	1.00			
Magnesium (mg/L)	−0.19	1.00		
Sodium (mg/L)	0.62	0.14	1.00	
Potassium (mg/L)	0.56	0.21	0.45	1.00

levels show minimal variation across the samples because their standard deviation is low at 2.24 mg/L. Sodium shows linkages with calcium because either the same dissolution processes unite them or water-softening operations replace magnesium along with calcium with sodium ions. Potassium concentrations in the samples reach 7.75 mg/L on average and spread over 1.67 mg/L, which represents some variability between the samples. The 0.56 and 0.45 values of correlation between calcium and sodium indicate that similar elements or distribution methods affect these mineral concentrations. Water hardness, measured through the amounts of calcium and magnesium, affects both industrial production systems and home water utilization. Selections from the article show that elevated sodium levels can affect people following restricted sodium intakes [23]. Monitoring potassium consumption remains crucial for preventing adverse health effects, although people need to take small doses of it. The correlation analysis helps researchers understand the geochemical processes that control water chemistry patterns. The moderate positive relationship between calcium and sodium ions implies that both substances originate from equivalent geological areas or experience related anthropogenic factors [24].

Table 4 above presents the correlation coefficients among the concentrations of the four minerals.

The correlation examination reveals critical information about water sample mineral content and possible mineral interactions. There exists a weak negative correlation between calcium and magnesium (−0.19), indicating competitive effects in mineral dissolution alongside precipitation, which influences water mineral concentrations. Geochemical processes or sources appear to affect sodium (0.62) and potassium (0.56) because their correlation with calcium is moderate and optimistic. Either natural forces such as rock weathering or human activities from agriculture lead to increased mineral levels in water, together with other determining factors. The measurement between sodium and potassium (0.45) confirms that these ions potentially share familiar sources or influencing elements. Water sources become contaminated with nutrients sodium and potassium when these chemicals appear together in fertilizers. The low positive correlations of magnesium show that its concentration remains independent of influencing variables that affect calcium and sodium as well as potassium measurement [25].

The water laboratory examined chloride, bicarbonate, sulfate, and nitrate anions within the water samples and presented their results in Table 5. The borehole samples demonstrate a normal distribution of chloride levels because chloride concentrations showcase mean and median values matching at 45.19 mg/L and 45.69 mg/L, respectively. The measurement variability confirms that some borehole samples show diverse mineral levels (13.20 mg/L range), while the standard deviation stands at 4.73 mg/L. The identification and management of seawater intrusion alongside road salt utilization and industrial runoff require close monitoring because high chloride levels can develop from these agencies [26]. Empirically, data indicates that bicarbonate exhibits reduced sample variability because its 20.42 mg/L mean concentration has a minor 1.79 mg/L standard deviation. The bicarbonate measurement spread across all samples remains narrow at only 5.00 mg/L. Water bicarbonate stems from carbonate mineral dissolution, such as calcite and dolomite, which indicates that geological formations influence water chemistry [27]. Sulfate shows a mean level of 26.51 mg/L yet presents a higher standard deviation value of 4.66 mg/L and a range of 12.44 mg/L, which indicates higher variability between samples. Several varied sources, such as natural mineral dissolution and agricultural activities, including sulfate-based fertilizer use and industrial activities, likely explain this variability. Water with high sulfate content produces an undesirable taste, and excessive intake might lead to diarrhea, according to research [28]. The assessment of anions reveals that nitrate concentrations demonstrate the highest levels of variability because they show a 22.92 mg/L mean value and a 4.99 mg/L standard deviation value. The data shows possible contamination sources through agricultural runoff septic systems and industrial waste because of the wide range (13.92 mg/L) and highest measurement (30.70 mg/L).

Table 5 above presents the correlation coefficients among the anion concentrations. The correlation analysis reveals essential relationships that exist between anion concentrations found in borehole

Table 5. Correlation analysis for anion concentrations in borehole samples.

	Chloride (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Nitrate (mg/L)
Chloride (mg/L)	1.000			
Bicarbonate (mg/L)	0.214	1.000		
Sulfate (mg/L)	0.325	−0.119	1.000	
Nitrate (mg/L)	0.002	0.336	0.578	1.000

water samples. Bicarbonate and sulfate anions, along with chloride, show weak positive relationships (0.214 and 0.325, respectively) because these ions share natural mineral dissolution patterns and anthropogenic or geologic influencing factors. The minute correlation value of 0.002 between chloride and nitrate demonstrates that these two anions maintain separate sources of pollution. The weak negative correlation between bicarbonate and sulphate (−0.119) and weak positive correlation between bicarbonate and nitrate (0.336) shows that different geochemical processes affect its concentration. Farming operations potentially contribute to overlapping pollution sources, which justify the weak to moderate positive relationship between chloride and nitrate. Data shows that sulphate and nitrate share an established positive relationship, which indicates their synchronized increases due to typical causes such as industrial operations and agricultural runoff. The robust association between areas having elevated sulphate concentrations shows that these regions often experience significant nitrate levels, which creates water pollution hazards. The strong data correlations between sulphate and nitrate demonstrate familiar environmental factors that affect anion chemical concentrations through agricultural runoff activities. Other anions show weak correlations, indicating that geochemical processes and sources for water pollution are diverse and complex. Chloride and nitrate exist independently from each other, which suggests that separate management strategies should be considered for these contaminants [29].

A report about the trace metal concentrations found in water samples has been developed in Table 6. Borehole water analysis of trace metal content provides a critical understanding of both water quality status and sources of contamination. The study showed lead amounts at 0.107 mg/L as the mean concentration, together with 0.104 mg/L as the median. Results from the data demonstrate reasonable variability throughout the analyzed samples due to their standard deviation (0.013 mg/L) and range value (0.035 mg/L). The lead values in the samples demonstrate low variability because the minimum count reached 0.092 mg/L while the maximum reached 0.127 mg/L. Contaminated lead amounts in water occur mainly through corroded pipes industrial wastewater releases, and various human-made sources. The health dangers due to low lead concentrations in drinking water affect children and pregnant women substantially. The average copper content in the samples amounts to 0.194 mg/L, and the central measurement value is 0.198 mg/L. The variance among measurements of this metal shows wider dispersion than other studied elements. The standard deviation stands at 0.031 mg/L, and the measurements span over 0.099 mg/L. Drinking water contains different copper traces from 0.132 mg/L to 0.231 mg/L because mining systems, along with industrial procedures, allow copper to escape into the water supply. The essential nutrient status of copper at regular levels supports human health, while high exposure creates gastrointestinal problems that become significant health threats. Statistical assessments show zinc concentrations at 0.196 mg/L as the mean value and 0.194 mg/L as the median value. The samples exhibit low variability because their standard deviation reaches 0.013 mg/L while their range amounts to 0.040 mg/L. Natural deposits, together with industrial sources and plumbing materials, contribute to zinc contamination, which makes the concentrations measure between 0.179 and 0.219 mg/L. Consuming too much water containing zinc as a trace element leads to the development of nausea and anemia, along with other health issues. Manganese levels examine 0.110 mg/L as both their mean and median value. The findings indicate moderate variability in the study data because the standard deviation measures 0.012 mg/L while the range extends to 0.037 mg/L. The intensity of zinc content in water remains between 0.087 mg/L and 0.124 mg/L.

Table 6 above presents the correlation coefficients among the trace metal concentrations. The correlation examination reveals vital knowledge about the relationships existing between trace metals detected in borehole water specimens. Results indicate the existence of either familiar sources or identical geochemical characteristics because the relationship between lead and copper reaches 0.15, and lead and manganese reach 0.40. The weak negative coefficient of −0.26 between zinc and lead shows two

Table 6. Correlation analysis for trace metals concentrations in borehole samples.

	Lead (mg/L)	Copper (mg/L)	Zinc (mg/L)	Manganese (mg/L)
Lead (mg/L)	1.00			
Copper (mg/L)	0.15	1.00		
Zinc (mg/L)	−0.26	0.43	1.00	
Manganese (mg/L)	0.40	0.00	0.05	1.00

different origins of elements or the existence of zinc-lead competitive interactions. The moderate positive correlation of 0.43 between copper and zinc in the borehole water samples reflects similar industrial contamination and plumbage system rusting processes as possible sources. The absence of correlation between manganese (0.00) indicates separate geochemical mechanisms that govern both metals, as well as distinct sources of origin. The slight positive relation between zinc and manganese showed no meaningful association (0.05), even though there are multiple reasons for this neutral relationship. The small quantity of lead in the water requires strict regulatory measures as an essential public health safety measure. Assessments for water quality must be consistent since both essential nutrients, zinc and copper, can become hazardous at specific concentration levels. Manganese shows health risks to human beings when present in excessive quantities, which highlights the critical need for continuous monitoring programs.

4.3. Spatial analysis of borehole water samples

4.3.1. Spatial analysis of borehole water samples for selected cations

The spatial map of calcium concentration across the study area, shown in Fig. 2, provides a visual representation of the variation in calcium levels in borehole water samples.

The middle portion of the study grounds demonstrates typical calcium contents. Natural water sources across the studied region show typical calcium levels that match these representative values without any abnormal readings. Water bodies located near regions have elevated calcium content. The groundwater calcium levels are affected when calcium-rich minerals from the surrounding geological structures dissolve into water bodies and then travel to the groundwater [6,30]. Such areas typically accumulate more minerals because groundwater meets surface water sources. Groundwater from borehole BH9 located in the southeastern section exceeds other parts by displaying calcium content above 51.75 mg/L. An elevated mineral presence in water leads to water hardness, and even though such conditions do not generally result in immediate harm, they can affect household water operations and manufacturing activities. The presence of hard water leads to mineral deposits inside pipes that degrade the operation of appliances by shortening their operational life. Local geologic characteristics, as well as hydrologic patterns, influence the average concentration of calcium in water samples. High calcium content indicates the existence of limestone deposits or

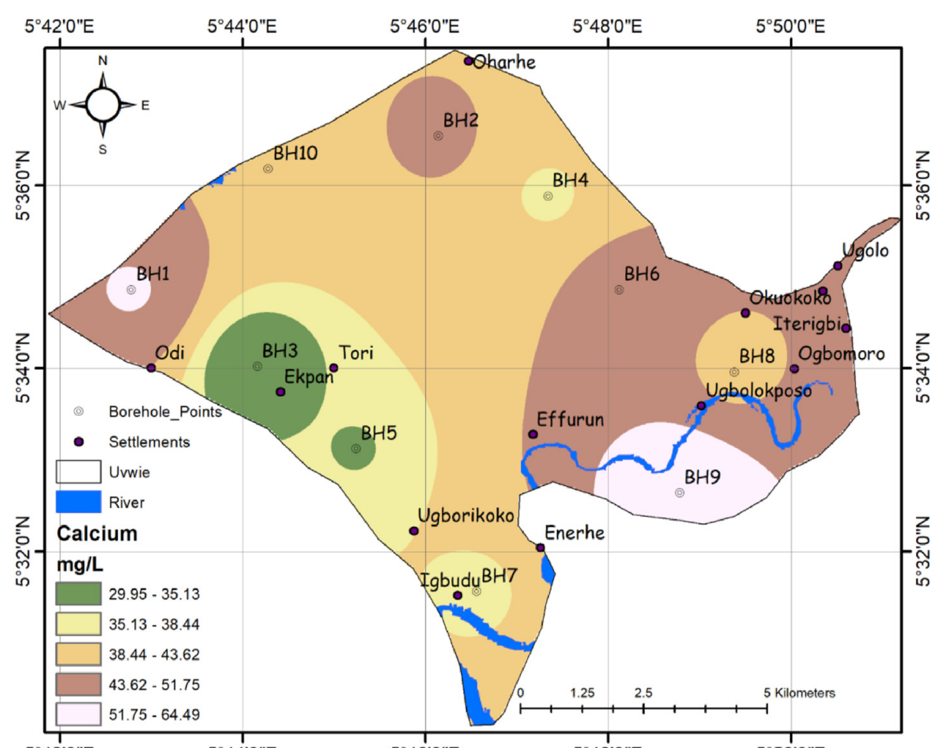

Fig. 2. Spatial map of calcium in the study area.

other rock formations with mineral calcium present underneath the surface [8,31].

The examination area shows prominent differences in magnesium content levels between various regions, according to Fig. 3.

High magnesium values appear in both the southern and northwestern areas where water bodies exist. The magnesium content in Boreholes BH7 and BH10 in these areas reaches high levels since the minerals containing magnesium dissolve from geological structures and through interactions with surface water. Although BH8 and BH9 have locations adjacent to water bodies, they show magnesium concentrations that measure less than 11.10 mg/L. These areas exhibit mineral composition differences in the geology probably because of distinctive water-rock interaction properties. The magnesium levels in the northeastern area of the study region stand lower than values found in both the western and southern parts. The unequal magnesium levels between different parts of the study area demonstrate that geological formations show diverse mineral compositions across their regions. Water contamination by these minerals has shown to be an essential magnesium source in the groundwater system. Areas consisting of carbonate or dolomite rocks tend to release magnesium when these rocks start to weather, thus causing this natural process [8,10,32]. Surface water might interact with groundwater because the sites in southern and northwestern areas are near water bodies. The surrounding environment releases minerals into surface water that causes elevated magnesium concentrations in these sections. The interaction affects boreholes BH7 and BH10 because they exhibit significantly elevated magnesium levels. The nearness of boreholes BH8 and BH9 to water sources does not always lead to high magnesium content in groundwater since local geology determines water composition. Geological conditions in the northeastern section of the study prove essential because they lead to diminished magnesium water content when compared to western and southern areas. The study area shows important spatial variations of magnesium content across different areas, which are influenced by both geological strata and surface water elements. Groundwater composition in the southern plus northwestern parts that contain elevated magnesium values demonstrates how geology, together with hydrology, alters the chemical makeup of water reserves.

4.3.2. Spatial analysis of borehole water samples for selected anions

The spatial distribution of chloride in the study area, as depicted in Fig. 4, shows a notable pattern of chloride concentrations across different regions.

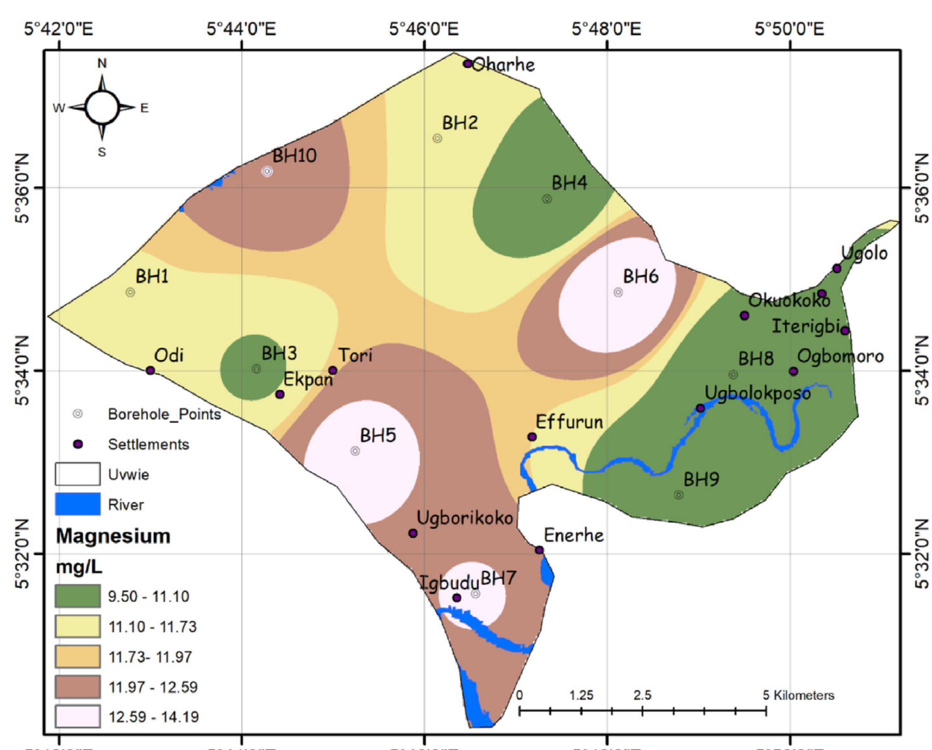

Fig. 3. Spatial map of magnesium in the study area.

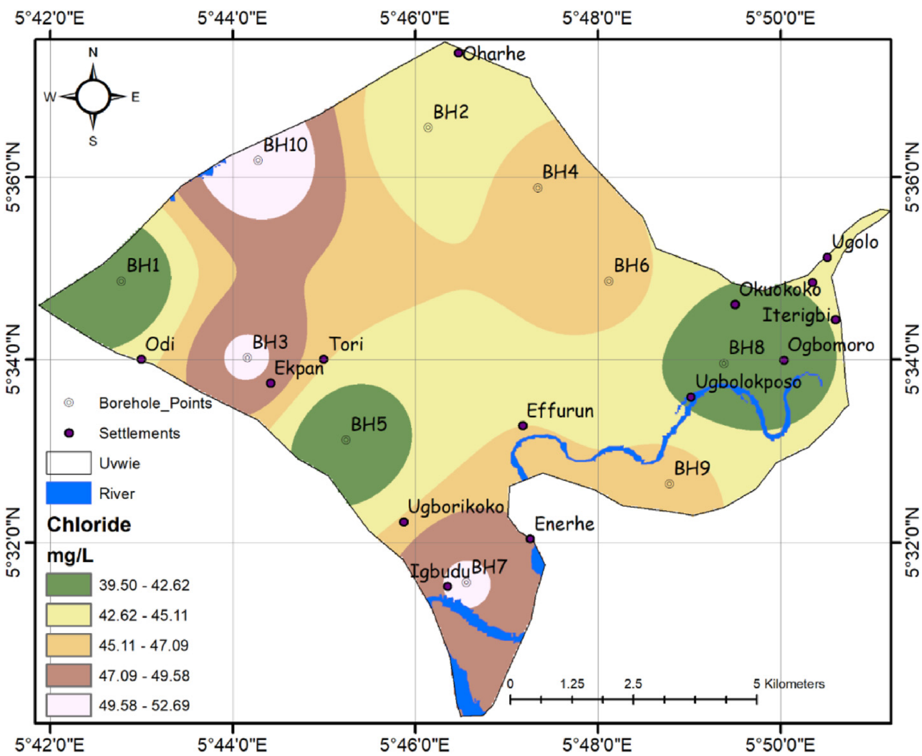

Fig. 4. Spatial map of chloride in the study area.

The high chloride values become noticeable throughout the southern region where borehole BH7 is located. Bruce Head area shows significantly higher chloride concentrations throughout its extent when compared to the rest of the study zone. The concentration range of chloride at borehole BH1 in the western section reaches from 29.50 to 42.62 mg/L. The chloride concentrations of the northern area measured at borehole BH2 range from 42.62 mg/L to 45.11 mg/L. The chloride measurements in both the western and northern parts show medium levels of water salinity. The chloride measurements throughout the study territory display an even distribution because the highest values only appear at the southern boundary. A spatial representation of chloride shows fundamental information about chloride distribution and sources in the study site that serves as essential knowledge for groundwater quality assessment and management. Multiple conditions, including agricultural runoff, industrial operations, and geologic elements, contribute to the increased chloride content located at the southern point near BH7 as also reported by Ref. [15]. Local groundwater contains excessive chloride levels because this highly soluble substance enters water systems from different human-made sources. Chloride levels found in both BH1 and BH2 sites indicate that chloride input remains steady in their respective locations of the western and northern tips. Groundwater chloride levels stem from normal, natural mineral processes, small amounts of agricultural fluid emissions, and minor industrial emissions. The study site displays a balanced chloride distribution because uniform various chloride sources exist across its entire domain. The even distribution of chloride across the study region stems from agricultural practices that remain steady and geological conditions that share similarities throughout the study area, according to Refs. [24,33]. Excessive chloride levels develop problems in water quality that include pipe deterioration alongside tasting issues in drinking water supplies despite chloride serving as an essential human health component.

The analysis of bicarbonate distributions in the study region displays notable spatial variations throughout different parts of the area (Fig. 5).

The geographic areas near BH1, BH2, BH4, and BH5 exhibit elevated bicarbonate levels throughout their northern area. The research areas show more elevated bicarbonate concentrations than other zones of the study site. The bicarbonate levels within the central and southern borehole region (BH3, BH5, and BH7) span between 19.02 and 20.65 mg/L. The bicarbonate levels in these zones show a middle range according to measurement results. The bicarbonate levels appear lower in the

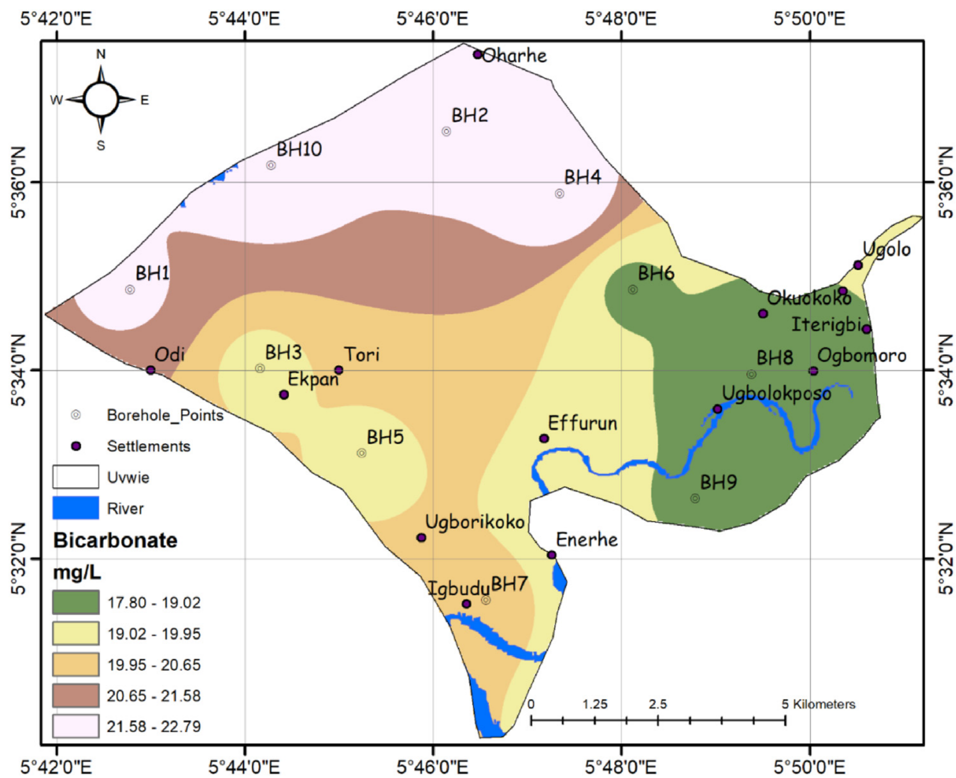

Fig. 5. Spatial map of bicarbonate in the study area.

eastern sector, where BH6, BH8, and BH9 are located. The study area contains these areas where bicarbonate maintains the lowest concentrations. The bicarbonate spatial map creates vital knowledge about how bicarbonates disperse and which sources feed bicarbonate levels across the study site for groundwater quality assessment and resource management decisions. The high bicarbonate levels in the northern areas surrounding BH1, BH2, BH4, and BH5 may stem from carbonate mineral dissolution in subterranean materials within the aquifer section. Geological substrata containing limestone or carbonate rocks heavily affect this process. The presence of elevated bicarbonate levels in groundwater suggests both natural geologic weathering operations and agricultural practices that produce bicarbonate chemicals in the drinking water. Bicarbonate concentrations in BH3, BH5, and BH7 in the central and southern regions indicate that geochemical stability maintains a steady pace of bicarbonate input. Proof of natural mineral dissolution and minimal human activities maintain a stable bicarbonate amount in these regions. The eastern groundwater areas containing BH6, BH8, and BH9 have lower bicarbonate levels, which suggests that significant carbonate mineral sources, along with geochemical reactivity, are either nonexistent or less active in these regions. Different hydrological characteristics and composition of geologic materials alongside agricultural activity influence bicarbonate levels because the substances are limited to accumulating in specific environments [17,34]. Bicarbonates act as essential pH buffers in groundwater, where they govern water alkalinity and stability—the high levels of bicarbonate work to defend pipes and infrastructure from corrosive, acidic environments.

4.3.3. Spatial analysis of borehole water samples for selected trace elements

The distribution chart in Fig. 6 reveals substantial changes in lead levels that affect different parts of the study area, most prominently around water areas.

The lead levels remain elevated at the sites consisting of boreholes BH8, BH9, and BH10, which are situated in proximity to water bodies. The lead concentration in borehole BH7 at Igbudu near a water body stands lower than other sampled facilities near water bodies. Spatial data about lead concentrations enables critical analysis of lead distribution patterns and the origins of pollution from groundwater, which establishes fundamental knowledge for evaluating environmental health risks and setting proper management protocols. Among BH8, BH9, and BH10 near water bodies, the

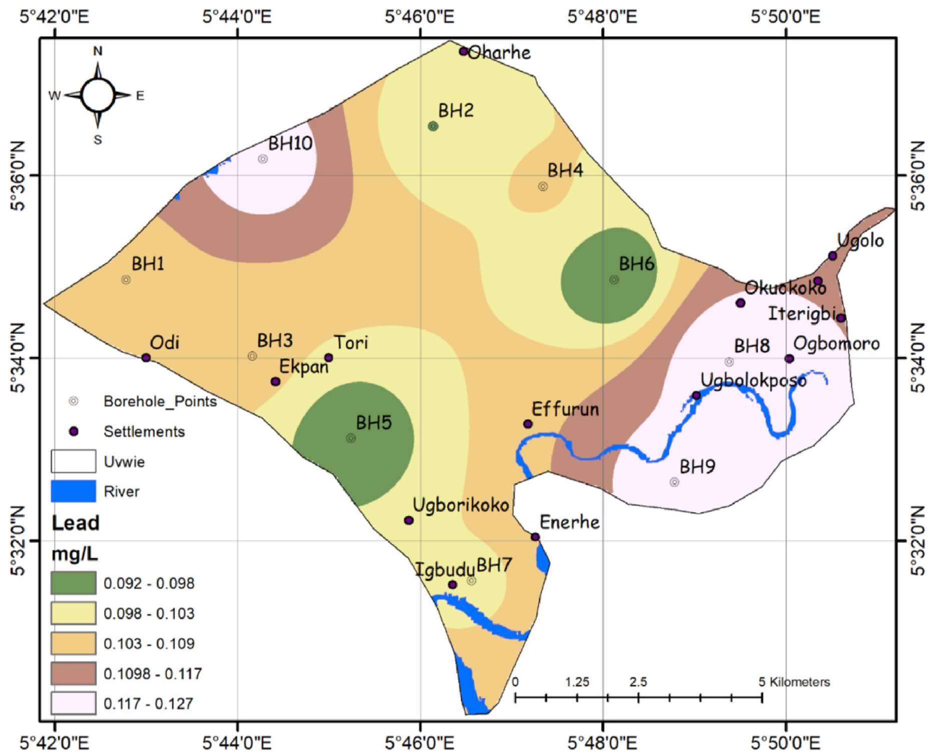

Fig. 6. Spatial map of lead in the study area.

elevated lead levels might originate from multiple environmental elements. The areas suffer runoff from industrial areas together with urban environments and waste disposal locations that harbor lead contaminants.

Water sinks serve as pollutant reservoirs before the substances migrate to the underground water system. The natural lead content in the local geology is released into groundwater by way of weathering processes. Led materials that remained from previous industrial or agricultural operations continue to pollute soil and water areas [8,35]. BH7 shows lower lead concentrations, although it should sit near a water body, leading to distinguishable variations in lead origin or the natural reduction of lead amounts. The BH7 geographic area experiences lower concentrations of industrial runoff compared to those found in BH8, BH9, and BH10. BH7's geological makeup, combined with its soil conditions, supports the natural filtration of lead substances, thus resulting in lower concentrations in the groundwater.

The examination of Fig. 7 shows high copper concentrations throughout most of the study area with specific contrasting regions.

The bulk of copper measurements in the study region fall between 0.161 mg/L and 0.231 mg/L. Borehole BH1 at the western extremity shows lower copper levels than the remaining points. The geographic depiction of copper levels in groundwater shows important information about how contaminated areas are distributed and where copper enters groundwater. The evaluation of environmental health requires this information, together with the development of an effective management strategy. The entire research area displays elevated copper levels due to multiple contributing factors. The geology of the area might have copper-bearing minerals, which cause natural mineral dissolution within groundwater systems.

Both copper-based fertilizers used in agriculture and industrial processes, together with pesticides, can increase copper values in groundwater. Higher copper levels appear within water systems when copper pipes become corroded in old infrastructure systems [36]. Copper measurements at BH1 show a deviation from other sites because geological properties or sources in that area appear to contain less copper naturally. The geological composition of BH1 lacks copper-bearing minerals, which reduces the natural occurrence of copper in the water. The westernmost location of BH1 maintains lower copper contamination levels because it lies outside the influence zone of agricultural and industrial activities in the study area.

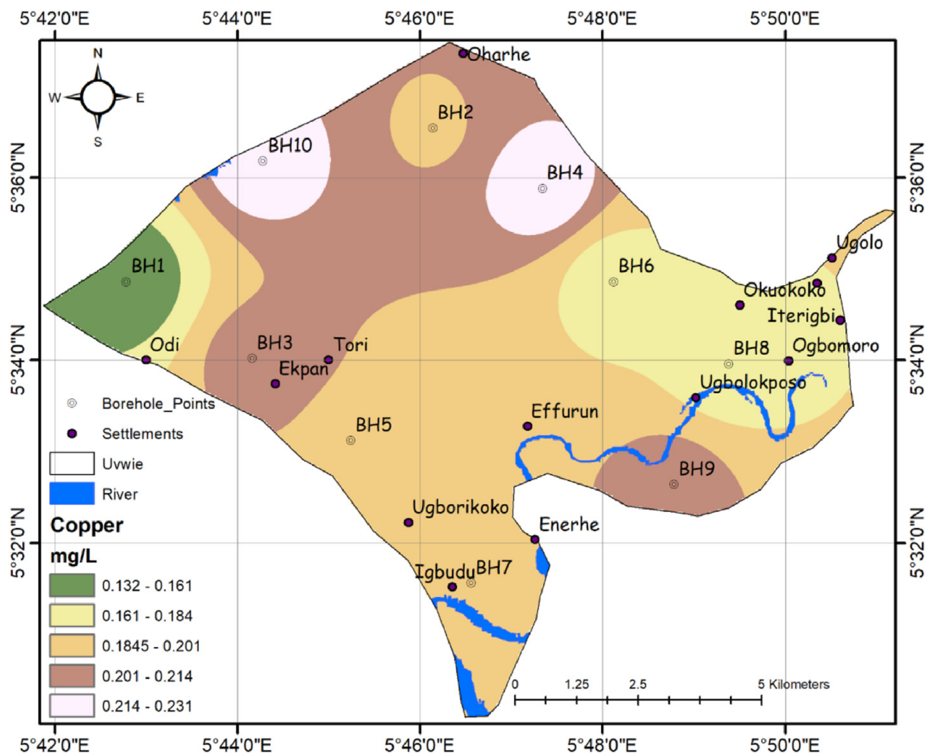

Fig. 7. Spatial map of copper in the study area.

4.4. Hydrogeochemical plots

The Piper diagram in Fig. 8 below illustrates the hydrochemical facies of groundwater samples from the study area. This diagram helps visualize the chemical composition of groundwater and identify the predominant water types based on major cations (calcium, magnesium, sodium, and potassium) and anions (chloride, bicarbonate, sulfate, and nitrate).

Most water samples contain calcium and sodium as their main cations, alongside significant amounts of magnesium and potassium. Major anions in these samples consist of chlorine and bicarbonate alongside sulfate, along with noticeable amounts of nitrates. The detection of calcium and bicarbonate in water indicates that carbonate rock weathering takes place naturally in most water systems. Ion exchange activities involving clay minerals replace water calcium and magnesium ions with sodium and potassium salts, according to analytical data [37]. Human activities involving agricultural fertilization and wastewater discharge from industrial facilities, along with related processes, raise chloride and nitrate concentrations in water sources. The Piper diagram shows that the study area consists of various hydrochemical facies that mainly include calcium-bicarbonate and sodium-chloride types.

The Durov diagram in Fig. 9 serves as a tool for analyzing the hydrochemical data obtained from groundwater samples. It offers an understanding of both groundwater geochemical process control and major ionic structural elements.

Calcium constitutes the principal water ion, while sodium falls after it, followed by magnesium and potassium. The major anions in the groundwater are chloride and bicarbonate together, while sulfate and nitrate support their composition to a significant extent. Many measured water samples show elevated levels of calcium and bicarbonate, which demonstrates that carbonate minerals contribute to groundwater chemistry. Clay minerals exchange calcium and magnesium with sodium and potassium during possible ion exchange processes, which result in increased sodium and potassium concentrations. Evaporation leads to ion concentration in groundwater, which creates elevated chloride and sulfate levels in certain areas of the study region, as described in Ref. [38]. Possible agricultural pesticide use, along with wastewater and industrial waste, contribute to elevated nitrate amounts in examination results. The presence of high nitrate concentrations indicates that human activities affect water resources, especially agricultural activities [39].

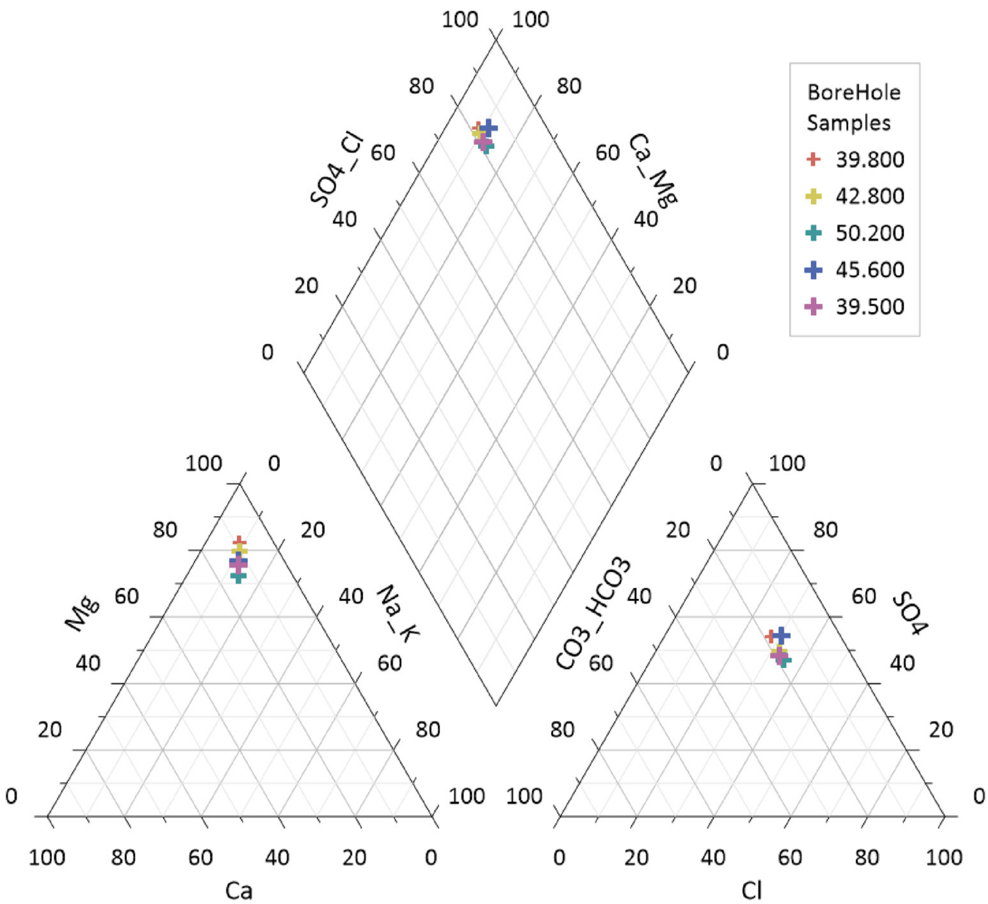

Fig. 8. Piper diagram of the study area.

5. Conclusion

The study of borehole water quality in Effurun, Delta State, revealed significant variations in geochemical patterns due to both natural processes and human activities. Calcium levels ranged from 29.95 to 64.50 mg/L, with an average of 43.14 mg/L, while magnesium remained relatively stable between 9.50 and 14.20 mg/L. The positive correlation between sodium, potassium, and calcium indicated their common origin from rock weathering and ion exchange processes. These cations influence the water's overall hardness, which can affect its suitability for domestic and industrial use. The analysis of anions such as chloride, sulfate, and nitrate highlighted variations in their concentrations. Chloride levels suggested seawater intrusion and industrial discharge as key contamination sources. The elevated sulfate and nitrate concentrations in certain boreholes indicated the influence of agricultural runoff and wastewater infiltration, highlighting the complex interaction between groundwater and surface activities.

One of the most critical findings was the presence of lead in borehole water samples, with concentrations ranging from 0.092 to 0.127 mg/L. These values exceed WHO-recommended limits, raising concerns about potential health risks associated with prolonged consumption. The presence of copper and zinc at variable concentrations indicated contamination from industrial sources and corrosion of aging pipelines. The influence of nearby water bodies was particularly evident in boreholes BH7, BH8, and BH9, where higher levels of lead, chloride, and nitrate were recorded. Lead concentrations were highest in BH8 (0.127 mg/L) and BH9 (0.122 mg/L), while chloride levels reached 49.90 mg/L in BH7 and 45.80 mg/L in BH9. The sulfate and nitrate levels in these boreholes suggested contamination from agricultural activities and wastewater discharge, reinforcing the role of surface-groundwater interactions in shaping water quality.

Spatial distribution analysis pinpointed the southeastern part of Effurun as a contamination hotspot, emphasizing the need for urgent intervention to manage pollution. Understanding these spatial variations is crucial for implementing effective mitigation strategies. The study's findings

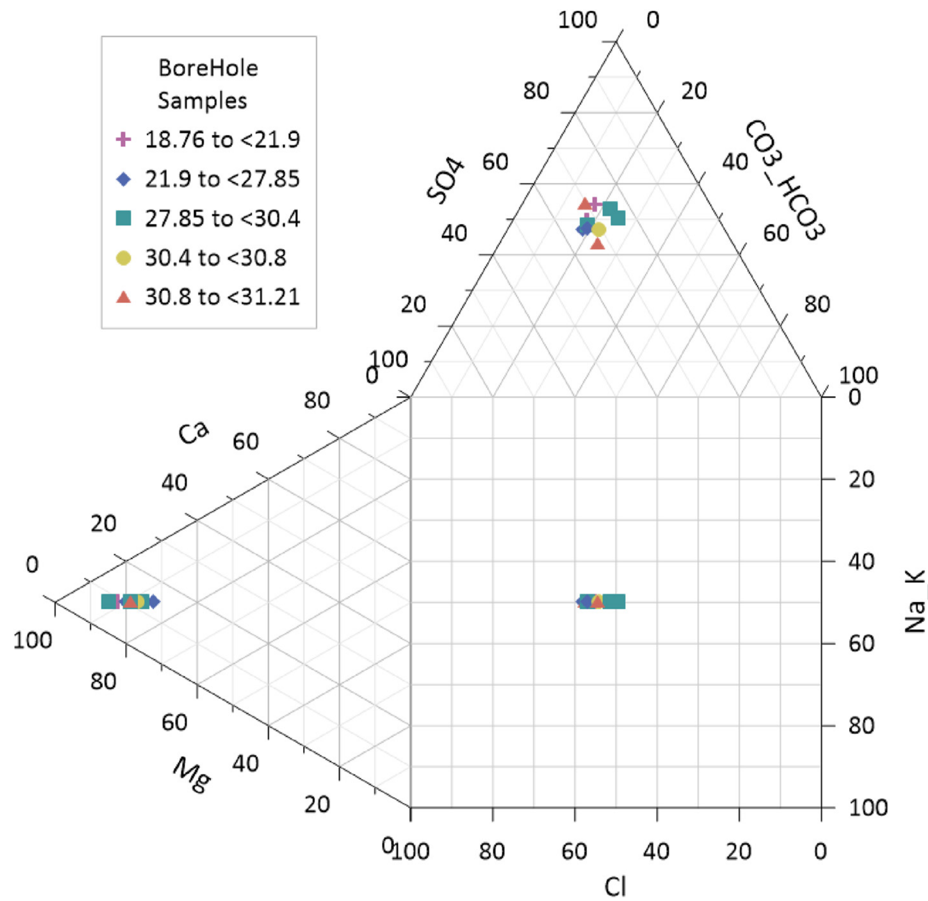

Fig. 9. Durov diagram of the study area.

highlight the importance of continuous water quality monitoring, as seasonal changes and ongoing human activities may further alter groundwater chemistry over time. Future research should focus on longitudinal studies to track variations in contaminant levels across different seasons, while isotopic and tracer studies could help distinguish between natural and anthropogenic pollution sources. Investigating the bioavailability of heavy metals such as lead, copper, and zinc would provide deeper insight into their toxicity risks.

Practical applications of this research include the introduction of stricter pollution control regulations to curb industrial wastewater discharge and agricultural runoff near boreholes. Implementing water treatment solutions such as filtration and ion-exchange systems would help reduce heavy metal concentrations, ensuring safer drinking water. Community engagement and education are essential to promote safe water use practices and raise awareness of contamination risks. The government should establish structured water quality monitoring programs to ensure borehole water safety and provide public access to real-time water quality data. Relocating boreholes away from known contamination zones could further minimize exposure risks, ensuring long-term sustainability of water resources in Effurun.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Ethical Approval

This research did not involve human participants, animal subjects, or sensitive data requiring ethical approval. All procedures conducted in this study comply with institutional, national, and international ethical standards for environmental and water quality research. No experiments were performed on humans or animals, and no personal or identifiable data were collected. The data used were obtained through field sampling and secondary geospatial sources, which are publicly accessible and non-sensitive in nature.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

O.T Ojo conceptualized the study, led the hydrochemical analysis, and drafted the initial manuscript. I.J Chiaka contributed to fieldwork, sample collection, and GIS-based spatial analysis. A.E Okoli performed the statistical analysis and contributed to data interpretation. N.J Inyang supported the hydrogeochemical modeling and assisted in manuscript revision. All authors reviewed and approved the final version of the manuscript.

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References

[1] Talabi A, Abdu-Raheem Y, Afolagboye L, Oguntuase M, Akinola O. Hydrogeochemistry of shallow groundwater in Ado-Ekiti Area, southwestern Nigeria. Groundw Sustain Dev 2020;11:100386. https://doi.org/10.1016/j.gsd.2020.100386.

[2] Adebayo TB, Abegunrin TP, Awe GO, Are KS, Guo H, Onofua OE, et al. Geospatial mapping and suitability classification of groundwater quality for agriculture and domestic uses in a Precambrian basement complex. Groundw Sustain Dev 2021;12:100497. https://doi.org/10.1016/j.gsd.2020.100497.

[3] Smith DN, Ortega-Camacho D, Acosta-González G, Leal-Bautista RM, Fox WE, Cejudo E. A multi-approach assessment of land use effects on groundwater quality in a karstic aquifer. Heliyon 2020;6(5):e03970. https://doi.org/10.1016/j.heliyon.2020.e03970.

[4] Okoli EA, Akaolisa CCZ, Ubechu BO, Agbasi OE, Szafarczyk A. Using VES and GIS-Based DRASTIC analysis to evaluate groundwater aquifer contamination vulnerability in Owerri, southeastern Nigeria. Ecol Quest 2024;35(3):1–27. https://doi.org/10.12775/EQ.2024.031.

[5] Omosuyi GO, Oshodi DR, Sanusi SO, Adeyemo IA. Groundwater potential evaluation using geoelectrical and analytical hierarchy process modeling techniques in Akure-Owode, southwestern Nigeria. Model Earth Syst Environ 2020;7(1):145–58. https://doi.org/10.1007/s40808-020-00915-6.

[6] Raji WO, Abdulkadir KA. Geo-resistivity data set for groundwater aquifer exploration in the basement complex terrain of Nigeria, West Africa. Data Brief 2020;31:105975. https://doi.org/10.1016/j.dib.2020.105975.

[7] Ifeanyichukwu KA, Okeyeh E, Agbasi OE, Moses OI, Ben-Owope O. Using geo-electric techniques for vulnerability and groundwater potential analysis of aquifers in Nnewi, South Eastern Nigeria. J Geol Geogr Geoecol 2021;30(1):43–52. https://doi.org/10.15421/112105.

[8] Akanbi O, Sanni W, Oshin O, Olatunde A. Hydrogeochemical assessment of groundwater of Igboora Area, Southwestern Nigeria. Global J Pure Appl Sci 2020;26(2):99–106. https://doi.org/10.4314/gjpas.v26i2.2.

[9] Ibuot JC, Aka MU, Inyang NJ, Agbasi OE. Georesistivity and physicochemical evaluation of hydrogeologic units in parts of Akwa Ibom State, Nigeria. Int J Energy Water Resour 2022;8(2):111–22. https://doi.org/10.1007/s42108-022-00191-3.

[10] Bolaji TA, Oti MN, Onyekonwu MO, Bamidele T, Osuagwu M, Chiejina L, et al. Preliminary geochemical characterization of saline formation water from Miocene reservoirs, offshore Niger Delta. Heliyon 2021;7(2):e06281. https://doi.org/10.1016/j.heliyon.2021.e06281.

[11] Apuyor SE, Apuyor KE, Okorodudu EO. Hydrochemical assessment of Delta Central (South Southern Nigeria) aquifers. Int J Res Sci Innov 2024;11(9):189–205. https://doi.org/10.51244/IJRSI.2024.1109019.

[12] Ebong DE, Akpan AE, Emeka CN, Urang JG. Groundwater quality assessment using geoelectrical and geochemical approaches: case study of Abi area, southeastern Nigeria. Appl Water Sci 2017;7:2463–78. https://doi.org/10.1007/s13201-016-0439-7.

[13] Ige OO, Ameh HO, Olaleye IM. Borehole inventory, groundwater potential and water quality studies in Ayede Ekiti, Southwestern Nigeria. Discover Water 2021;1:2. https://doi.org/10.1007/s43832-020-00001-z.

[14] Manu E, De Lucia M, Kühn M. Hydrochemical characterization of surface water and groundwater in the crystalline basement aquifer system in the Pra Basin (Ghana). Water 2023;15(7):1325. https://doi.org/10.3390/w15071325.

[15] Shuaibu A, Kalin RM, Phoenix V, Banda LC, Lawal IM. Hydrogeochemistry and water quality index for groundwater sustainability in the Komadugu-Yobe Basin, Sahel Region. Water 2024;16(4):601. https://doi.org/10.3390/w16040601.

[16] Ojo OT, Chiaka IJ, Nwokeabia CN. Integrated geophysical and GIS approaches for groundwater potential assessment: a case study of Aladja, Delta State, Nigeria. Water Pract Technol 2024;19(10):4282–302. https://doi.org/10.2166/wpt.2024.254.

[17] Slama T, Sebei A. Spatial and temporal analysis of shallow groundwater quality using GIS, Grombalia aquifer, Northern Tunisia. J Afr Earth Sci 2020;170:103915. https://doi.org/10.1016/j.jafrearsci.2020.103915.

[18] Ijioma UD. Delineating the impact of urbanization on the hydrochemistry and quality of groundwater wells in Aba, Nigeria. J Contam Hydrol 2021;240:103792. https://doi.org/10.1016/j.jconhyd.2021.103792.

[19] Igaz D, Šinka K, Varga P, Vrbičanová G, Aydõn E, Tárník A. The evaluation of the accuracy of interpolation methods in crafting maps of Physical and Hydro-Physical soil Properties. Water 2021;13(2):212. https://doi.org/10.3390/w13020212.

[20] Bu J, Liu W, Pan Z, Ling K. Comparative study of hydrochemical classification based on different hierarchical cluster analysis methods. Int J Environ Res Publ Health 2020;17(24):9515. https://doi.org/10.3390/ijerph17249515.

[21] Eyankware MO, Akakuru OC, Ulakpa ROE, Eyankware OE. Sustainable management and characterization of groundwater resource in coastal aquifer of Niger delta basin Nigeria. Sustain Water Resour Manag 2021;7(4). https://doi.org/10.1007/s40899-021-00537-5.

[22] Mokarram M. Modeling of multiple regression and multiple linear regressions for prediction of groundwater quality (case study: north of Shiraz). Model Earth Syst Environ 2015;2(1). https://doi.org/10.1007/s40808-015-0059-5.

[23] Naser AM, Rahman M, Unicomb L, Parvez SM, Islam S, Doza S, et al. Associations of drinking rainwater with macromineral intake and cardiometabolic health: a pooled cohort analysis in Bangladesh, 2016–2019. NPJ Clean Water 2020;3(1). https://doi.org/10.1038/s41545-020-0067-5.

[24] Malik N, Malik A, Bishnoi S. Assessment of groundwater hydro-geochemistry, quality, and human health risk in arid area of India using chemometric approach. Arabian J Geosci 2021;14(15). https://doi.org/10.1007/s12517-021-07852-3.

[25] Ozoko DC, Onyekwelu IL. Impact of inorganic contaminants from dumpsite leachates on natural waters in the Enugu Metropolis, South Eastern Nigeria. Int J Sci Technol 2020;8(4). https://doi.org/10.24940/theijst/2020/v8/i4/st2004-018.

[26] Ghezelsofloo E, Raghimi M, Mahmoodlu MG, Rahimi-Chakdel A, Khademi SMS. Saltwater intrusion in drinking water wells of Kordkuy, Iran: an integrated quantitative and graphical study. Environ Earth Sci 2021;80(16). https://doi.org/10.1007/s12665-021-09843-9.

[27] Abdrakhmanov RF, Poleva AO, Durnaeva VN. Bicarbonate waters in hydrogeological complexes of the hypergenesis zone of the Southern Cis-Urals. Geol Vestn 2023;1:86–95. https://doi.org/10.31084/2619-0087/2023-1-8.

[28] Nebeokike UC, Igwe O, Egbueri JC, Ifediegwu SI. Erodibility characteristics and slope stability analysis of geological units prone to erosion in Udi area, southeast Nigeria. Model Earth Syst Environ 2020;6(2):1061–74. https://doi.org/10.1007/s40808-020-00741-w.

[29] Torres-Martínez JA, Mora A, Knappett PS, Ornelas-Soto N, Mahlknecht J. Tracking nitrate and sulfate sources in groundwater of an urbanized valley using a multi-tracer approach combined with a Bayesian isotope mixing model. Water Res 2020;182:115962. https://doi.org/10.1016/j.watres.2020.115962.

[30] Ukpai SN, Ezeh HN, Effam SC. Eco-hydrology and the effects on the national economy: case of the eastern region of Abakaliki Anticlinorium, Southeastern Nigeria. Appl Water Sci 2020;10(2). https://doi.org/10.1007/s13201-020-1147-x.

[31] Egbueri JC. Signatures of contamination, corrosivity and scaling in natural waters from a fast-developing suburb (Nigeria): insights into their suitability for industrial purposes. Environ Dev Sustain 2023;23(1):591–609. https://doi.org/10.1007/s10668-020-00597-1.

[32] Ige OO, Owolabi TA, Fatoyinbo IO, Ayodele OE, Obasaju DO. Characterization of factors influencing water quality in Federal University of agriculture abeokuta and its environ, southwestern Nigeria. Int J Energy Water Resour 2020;5(2):205–18. https://doi.org/10.1007/s42108-020-00093-2.

[33] Badmus GO, Akinyemi OD, Gbadebo AM, Oyedepo JA. Hydrochemical analysis of groundwater quality along the coastal aquifers in part of Ogun Waterside, Ogun State, southwestern Nigeria. Heliyon 2020;6(12):e05661. https://doi.org/10.1016/j.heliyon.2020.e05661.

[34] Kayode O, Aizebeokhai A, Odukoya A. Geophysical and contamination assessment of soil spatial variability for sustainable precision agriculture in Omu-Aran farm, North-central Nigeria. Heliyon 2022;8(2):e08976. https://doi.org/10.1016/j.heliyon.2022.e08976.

[35] Kumar M, Nagdev R, Tripathi R, Singh VB, Ranjan P, Soheb M, et al. Geospatial and multivariate analysis of trace metals in tubewell water using for drinking purpose in the upper Gangetic basin, India: heavy metal pollution index. Groundw Sustain Dev 2018;8:122–33. https://doi.org/10.1016/j.gsd.2018.10.001.

[36] Galarce C, Fischer D, Díez B, Vargas IT, Pizarro GE. Dynamics of biocorrosion in copper pipes under actual drinking water conditions. Water 2020;12(4):1036. https://doi.org/10.3390/w12041036.

[37] Krishan G, Sejwal P, Bhagwat A, Prasad G, Yadav BK, Kumar CP, et al. Role of ion chemistry and hydrogeochemical processes in aquifer salinization—a case study from a semi-arid region of Haryana, India. Water 2021;13(5):617. https://doi.org/10.3390/w13050617.

[38] Owamah H. A comprehensive assessment of groundwater quality for drinking purpose in a Nigerian rural Niger delta community. Groundw Sustain Dev 2019;10:100286. https://doi.org/10.1016/j.gsd.2019.100286.

[39] Chinye-Ikejiunor N, Iloegbunam GO, Chukwuka A, Ogbeide O. Groundwater contamination and health risk assessment across an urban gradient: case study of Onitsha metropolis, south-eastern Nigeria. Groundw Sustain Dev 2021;14:100642. https://doi.org/10.1016/j.gsd.2021.100642.