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ORIGINAL ARTICLE

Evaluation of Groundwater Suitability for Drinking and Irrigation in Kaiama, North-Central Nigeria: Hydrochemical Characteristics and Health Risk Assessment

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ABSTRACT: Groundwater quality is a vital concern for human health and agricultural productivity, particularly in regions where this resource is a primary source of drinking water and irrigation. This study evaluates groundwater quality in the study area using various indices: the Water Quality Index, the Irrigation Water Quality Index, and the Human Health Risk Assessment. The assessment included 19 locations and hydrochemical analysis showed that the predominant water type was Ca-Mg-HCO3. The hydrogeochemical modeling revealed that the groundwater is characterized by cation exchange, while rock–water interactions and silicate weathering are heavily involved in the geochemical processes. The groundwater water quality index values ranging from 25.34 to 58.72 indicated that the water was suitable for drinking. For irrigation purposes, the mean value of various indices such as sodium percent (22.15%), sodium absorption ratio (0.21meqL–1), and Kelley's index (0.31) indicated suitability for irrigation. However, the magnesium hazard (65.65%) and residual sodium carbonate (9.1meqL–1) demonstrated that prolonged application of groundwater for irrigation needs soil management to avoid soil compaction and decrease crop productivity. A Human Health Risk Assessment was conducted to evaluate nitrate (NO_3^-) exposure. The ingestion Hazard Quotient exceeded 1.0 in several samples for children, indicating significant non-carcinogenic risks, while dermal exposure remained below 1.0 for all groups. However, heavy metals analysis should be considered to ascertain the threshold values of the concentration in the groundwater resource in the study area.

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INTRODUCTION

Water is indispensable for human survival, hence the confirmation of the term "Water is life". It is a crucial component of the environment. Unfortunately, geogenic and anthropogenic activities have long deteriorated groundwater and surface water. Geogenic activities influencing water quality include hydrogeological, atmospheric, climatic, mineral compositions of underlying rocks, and topographical and lithological factors [1; 2]. Anthropogenic activities include mining, livestock farming, waste disposal (industries, municipal, agricultural), sediment run-off, oil seepage/spillage [3], and heavy metal pollution [4]. Access to safe drinking water is a critical global issue, where over 1 billion people worldwide face challenges in accessing clean water (source). Groundwater is a crucial resource, supplying water to over

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1.5 billion people and supporting 40% of global irrigation needs [5]. However, over-extraction and contamination from natural processes and human activities threaten groundwater quality, ecological balance, and human well-being [6; 7].

Groundwater availability depends on quantity and quality, shaped by geological and hydrological processes [8]. Contaminants like fluoride, chlorides, bicarbonates, nitrates, and heavy metals compromise water quality and pose health risks [9]. Effective water quality assessments are essential for resource management, reducing treatment costs, and enhancing agricultural productivity [10]. Addressing groundwater contamination requires efficient monitoring and management methods to ensure sustainability and safeguard human health [11].

Traditional water quality assessments compare hydrochemical parameters with national and international criteria. Parameters such as pH, TDS, nitrate, and fluoride are critical in evaluating groundwater quality, while indices like the Water Quality Index (WQI) provide a holistic evaluation by simplifying complex data into a single value [12]. WQI ratings range from excellent to poor, reflecting overall water quality status [13]. Also, it involves evaluating potential health hazards posed by groundwater contaminants and assessing the probability of adverse health effects in exposed populations. Various tools such as the human health risk assessment (HHRA) model, average daily intake (ADI), hazard quotients (HQs), and hazard index (HI) play a vital role in this process, providing invaluable insights into potential health risks [14]. Groundwater contamination poses significant health risks, especially in developing countries, contributing to waterborne diseases and emphasizing the need for risk assessments to protect public health [15].

Groundwater is a vital source of drinking water for many rural communities in Kaiama, a local government area in Kwara State, Nigeria. However, groundwater quality in these regions is threatened by various geogenic and anthropogenic factors, such as geology, weathering, land use, pollution, and overexploitation. These factors are related to the causes of tooth coloration (fluorosis) among consumers. Despite the critical importance of groundwater in Kaiama, there is a significant gap in systematic and comprehensive assessments of its quality, which impedes effective management and protection of this vital resource. This study aims to fill this gap by evaluating the groundwater quality in Kaiama and its surrounding areas, specifically focusing on its suitability for drinking, assessing potential health risks, and determining its safety for other domestic uses. This research utilizes water quality indices as key indicators to provide a detailed understanding of the groundwater conditions in the region

Study Area

Kaiama, the provincial capital of Kaiama Local Government Area, is located in the northwestern part of Kwara State, Nigeria within the Federal Survey map of Nigeria Sheet 158, Kaiama SE, the area spans approximately 770 km² (Figure 1). Defined by Latitude N09°30'00" to N09°45'00" and Longitude E03°45'00" to E04°00'00", Kaiama is a border town, approximately 60 km from the international boundary with Benin Republic. Niger State bounded Kiama to the north, Oyo State to the south, and Baruten LGA of Kwara State to the west.

The study area is characterized by a temperate climate with two distinct seasons: the rainy and the dry season. The rainy season starts from May to September and is marked by cool temperatures ranging from 20°C to 35°C. In contrast, the dry season which spans from October to April, is characterized by hot and dry conditions. The study area's terrain is characterized by moderate relief in parts, with flood plains in others, relative to the surrounding hills. The major rock exposures are hills, with the highest elevation reaching 419 m above sea level and the lowest point being 289 m above sea level. The geology of Kaiama district in Kwara State is characterized by its position within Nigeria's Basement Complex, consisting primarily of older granite and undifferentiated basement complex rocks. These rocks have undergone significant weathering, resulting in the formation of sandy clay lenses and weathered sand pockets across the area. The region is predominantly underlain by granites, syenites, and andesite, which occur as intrusions and are often associated with pegmatites. The mechanical weathering of rocks has also led to the accumulation of significant sandstone deposits, further defining the geological landscape. Hydrogeologically, this weathered layer forms the primary aquifer, allowing for groundwater storage and movement, though the fractured basement rocks below also contribute to water flow, particularly through fractures and joints.

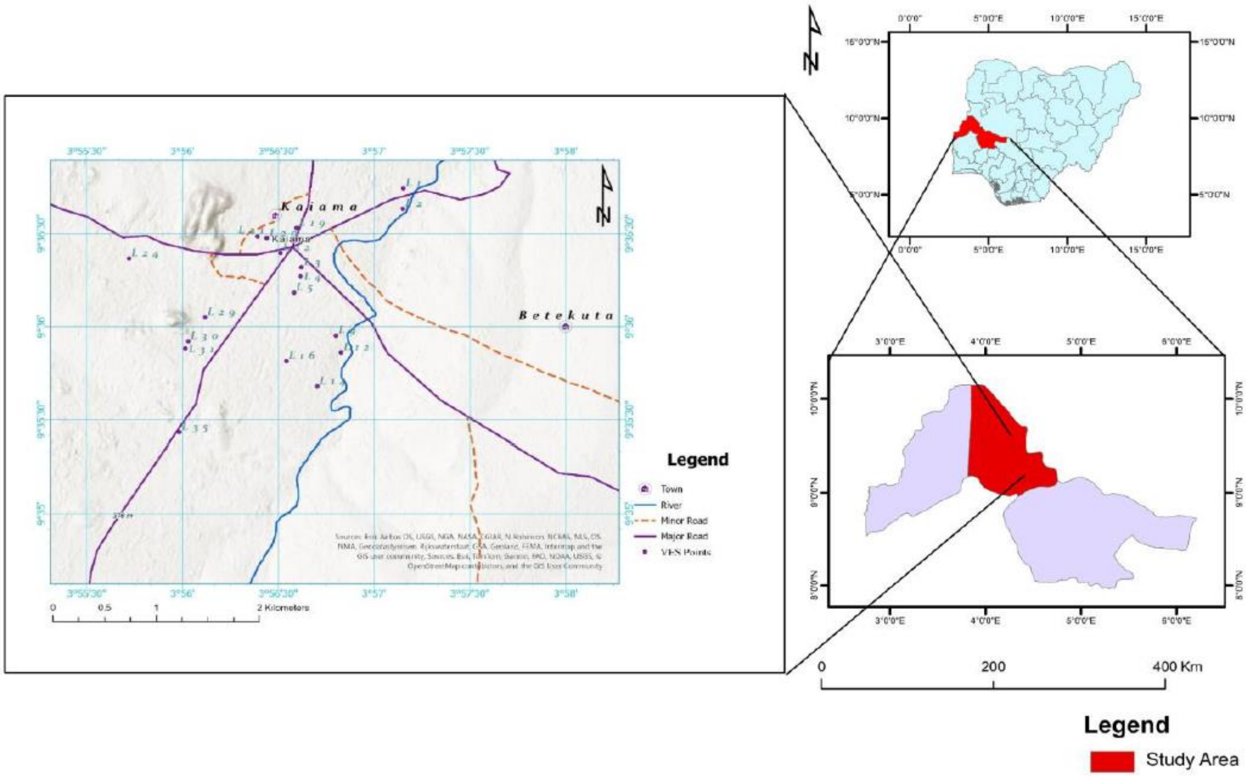


Figure 1. Location map of the Study area

MATERIALS AND METHODOLOGY

Nineteen (19) water samples were taken from different wells (Borehole & Hand dug well) in Kiama town, northwest of Kwara state in the early period of January 2024, the sampling locations were marked out with the Global Positioning System (GPS), and was plotted and digitized using ArcMap 10.7. Water samples were collected randomly and on each water sample, in-situ parameter tests such as pH, Electrical Conductivity (EC) Us/cm, Total Dissolved Solid (TDS) ppm, Salt (ppm), Salinity (%), Specific Gravity (SG), Oxidations-Reductions Potential (ORP) mv, was conducted on it. Water samples from different sources were analyzed to assess the various physicochemical parameters as described by the (30) standard methods.

The digested cations and undigested anions samples were sent to the University of Ilorin Central Research Laboratory for Atomic Absorptions Spectrophotometer (AAS) analysis using the BUCK Scientific ACCUSYS 230 Absorptions Spectrophotometer model for cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) test. Sulphate (SO_4^{2-}) analysis was carried out using the Ultraviolent (UV) Spectrophotometer Analitik Jena Specord 200 Plus model. Alkalinity (CO_3^{2-} & HCO_3) test, Chloride (Cl^{-}) test, and %Nitrates test were also carried out. In addendum, 19 digested water samples were sent to Agilent Technologies Lagos, for heavy metal and trace metals (Ag, As, Cd, Ca, Cs, Co, Ga, etc.) analysis.

Groundwater Quality Assessment for Drinking

Groundwater quality was assessed to determine its suitability for drinking purposes. Weights (wi) were initially assigned to various parameters on a scale of A to E (Table 1), based on the severity of their impact on human health (5). The relative weights (Wi) were then calculated using the formula:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad \text{(i)}$$

Wi represents the relative weight, Wi is the assigned weight of each parameter, and n denotes the total number of parameters

Table 1. Rating of water quality according to this WQI

WQI Value	Rating of Water Quality	Grading
0-25	Excellent water quality	A
25-50	Good water quality	B
51-75	Poor water quality	C
76-100	Very poor water quality	D
Above 100	Unsuitable for drinking purposes	E

Next, the quality rating scale (qi) for each water quality parameter was determined using the formula:

$$q_i = \left[\frac{C_i}{S_i}\right] \times 100\% \quad \text{(ii)}$$

Where Ci is the observed concentration (mg/L) of each parameter, and Si is the corresponding WHO standard limit. Finally, the sub-index (SI) was calculated to obtain the Water Quality Index (WQI) using:

$$SI = W_i \times q_i \quad \text{(iii)}$$

Groundwater Quality Assessment for Irrigation

Kaiama plays a vital role in agriculture, requiring a specific volume of water for effective irrigation. However, quantity and quality are critical factors that influence soil health, crop growth, and yield. Using poor-quality groundwater for irrigation can lead to soil degradation and decreased crop productivity, underscoring the importance of high-quality water for sustainable agriculture [16]. Therefore, assessing groundwater suitability for irrigation is essential for promoting sustainable agricultural development. This assessment involves calculating various indices including (Na%), (SAR), and (RSC) etc. (Table 2)

Table 2. Indices used for estimating the suitability of groundwater resources for irrigation practices.

Indices	Formula	Scale	Interpretation
Sodium Percentage	$Na\% = \frac{Na^+ + K^+}{Na^+ + K^+ + Ca^{2+} + Mg^{2+}} \times 100\%$	<60% >60%	Suitable Unsuitable
Kelly's Index	$KI = \frac{Na^+}{Ca^{2+} + Mg^{2+}}$	<1 >1	Good Bad
Magnesium Hazard	$MH = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}}$	<0.5 >0.5	Suitable Unsuitable
Sodium Adsorption Ratio	$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$	0 – 10 11 -17 - 26 >26	Excellent Good Doubtful Unsuitable
Residual Sodium Carbonate	$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+})$	<0 0 – 1.25 > 1.25	Suitable doubtful Unsuitable

Identification of Hydrogeochemical Processes

To identify the hydrogeochemical processes influencing groundwater chemistry, several analytical tools were used, including the Piper diagram [17], Gibbs diagrams [18], Stiff pattern plots [19], and Schoeller diagrams [29; 20]. Additionally, ratios of major cations and anions, along with the saturation indices of key minerals, were employed to provide a comprehensive understanding of the processes controlling groundwater chemistry.

Human Health Risk Assessment (HHRA)

The Human Health Risk Assessment (HHRA) model was used to estimate the non-cancer risk of exposure to groundwater pollutants through ingestion and dermal contact for residents in the study area [21; 22]. This model is widely preferred because it offers a comprehensive framework for evaluating health risks associated with exposure to contaminants across various environmental media, including air, water, soil, and food.

HHRA considers multiple exposure pathways, such as ingestion, inhalation, and skin contact, allowing for a more detailed risk assessment. It factors in exposure duration, frequency, and contaminant concentration levels to estimate the potential health impacts. The model is adaptable to different scenarios and populations, making it a versatile tool for diverse contexts. Additionally, the results are often presented in a clear format, aiding policymakers, stakeholders, and the public in making informed decisions about risk management. The HHRA model's thorough approach, flexibility, and practicality make it an effective tool for assessing and mitigating health risks from environmental exposures.

RESULTS AND DISCUSSION

Physicochemical Characteristics of Groundwater

A statistical summary of the groundwater's physicochemical parameters reveals variations in water quality across the sampled sites (Table 3). The pH of the water ranged from 4.2 to 6.68, with an average of 5.89, indicating that the groundwater in the study area is slightly acidic, falling below the WHO-recommended range of 6.5 to 8.5 for safe drinking water. This suggests that local geology and interactions between the groundwater and host rock may influence the water's pH.

Electrical conductivity (EC), which indicates the water's ability to conduct electrical current and reflects the concentration of dissolved salts, ranged from 217 to 1531 µS/cm, with an average of 659.72 µS/cm. Around 30% of the sites exceeded the WHO threshold of 1000 µS/cm, suggesting moderate salt enrichment, which could impact soil and plant health if used for irrigation.

The total dissolved solids (TDS) values ranged between 108 and 765 mg/L, with an average of 331 mg/L, classifying the groundwater as fresh (TDS < 1000 mg/L). Higher TDS levels at some locations could result from prolonged water-rock interactions, mineral dissolution, or anthropogenic influences. Although all values fell within the WHO limit of 1000 mg/L, areas with elevated TDS may indicate potential issues for agricultural use, particularly for crops sensitive to salinity.

The hardness of groundwater, which results from dissolved calcium and magnesium salts, varied from 58 to 500 mg/L, with an average of 285.8 mg/L. The groundwater in this region is classified as moderately hard to very hard. Hardness can affect water usability for both domestic and industrial purposes, as well as soil and plant health if used for irrigation.

The groundwater's major ion chemistry provides further insights into its composition and potential geochemical processes. The major cations calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) exhibited varying concentrations across the study area. Calcium levels ranged from 1.15 to 9.09 mg/L (average: 3.3 mg/L), magnesium from 5.62 to 6.85 mg/L (average: 6.25 mg/L), sodium from 2.57 to 3.91 mg/L (average: 2.78 mg/L), and potassium from 1.06 to 7.26 mg/L (average: 2.93 mg/L). The order of abundance of these cations is $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$.

High levels of bicarbonate (HCO_3^-) were observed, ranging from 58.15 to 956.12 mg/L (average: 469.95 mg/L), indicating significant carbonate dissolution in the groundwater, which is a common process in areas with carbonate-rich geology. Chloride (Cl^-) levels ranged from 15 to 202 mg/L, with an average of 63.52 mg/L, while sulfate (SO_4^{2-}) concentrations were relatively low, ranging from 0.0721 to

0.1814 mg/L. Nitrate (NO_3^-) concentrations remained minimal, with values between 0.0775 and 0.4652 mg/L, suggesting limited contamination from agricultural runoff or sewage.

The water samples were classified as fresh based on their TDS values, and the abundance of the major cations and anions follows the order $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$, respectively. These patterns are consistent with groundwater systems where carbonate dissolution and ion exchange processes dominate, leading to the observed ion distribution.

Table 3. Statistics summary of the groundwater physicochemical properties.

Parameters	pH	EC (µS/cm)	TDS (ppm)	Ca (mg/l)	Mg (mg/l)	Na (mg/g)	K (mg/l)	HCO_3^- (mg/l)	SO_4^{2-} mg/l)	Cl^- (mg/l)	NO^-_3 (mg/l)
Min	4.2	217	108	1.1455	5.6235	2.571	1.061	58.15	0.0721	15	0.0775
Max	6.68	984	765	9.089	6.847	3.9155	7.26	956.12	0.1814	202	0.4652
Ave	5.89	659.72	331	3.2963	6.2469	2.7841	2.9346	469.955	0.1057	63.52	0.2257
WHO (2022) [23]	6.5 - 6.8	1000	1000	75	50	200	12	500	250	250	45

Hydrochemical Facies of Groundwater

The hydrochemical facies of groundwater were determined using a Piper trilinear diagram, which highlights the dominant cations and anions in the water samples. As depicted in Figure 2, all samples fell within the Ca-Mg-HCO_3 facies, indicating that the groundwater in the study area is predominantly of the calcium-magnesium-bicarbonate type. This water type is primarily characterized by the dominance of alkaline earth metals, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), along with bicarbonate (HCO_3^-) as the primary anion.

According to [24], the presence of Ca^{2+}, Mg^{2+}, and HCO_3^- ions in groundwater typically corresponds to pH levels ranging from 6.5 to 7.8, which aligns with the slightly acidic to near-neutral pH observed in the study area. This water type is commonly associated with transitory hardness, as noted by various studies, and is characteristic of freshwaters formed through processes such as incongruent weathering of silicate minerals or dissolution of carbonate rocks.

The Ca-Mg-HCO_3 facies are often prevalent in recharge zones, where groundwater is in the early stages of its geochemical evolution. This indicates limited interaction with the surrounding rock matrix, suggesting that the groundwater in the studied aquifer is relatively young and has undergone minimal chemical alteration. Such a facies is typical of regions where aquifer recharge is driven by recent precipitation, leading to water that is generally low in dissolved solids and retaining its initial chemical signature from the recharge environment.

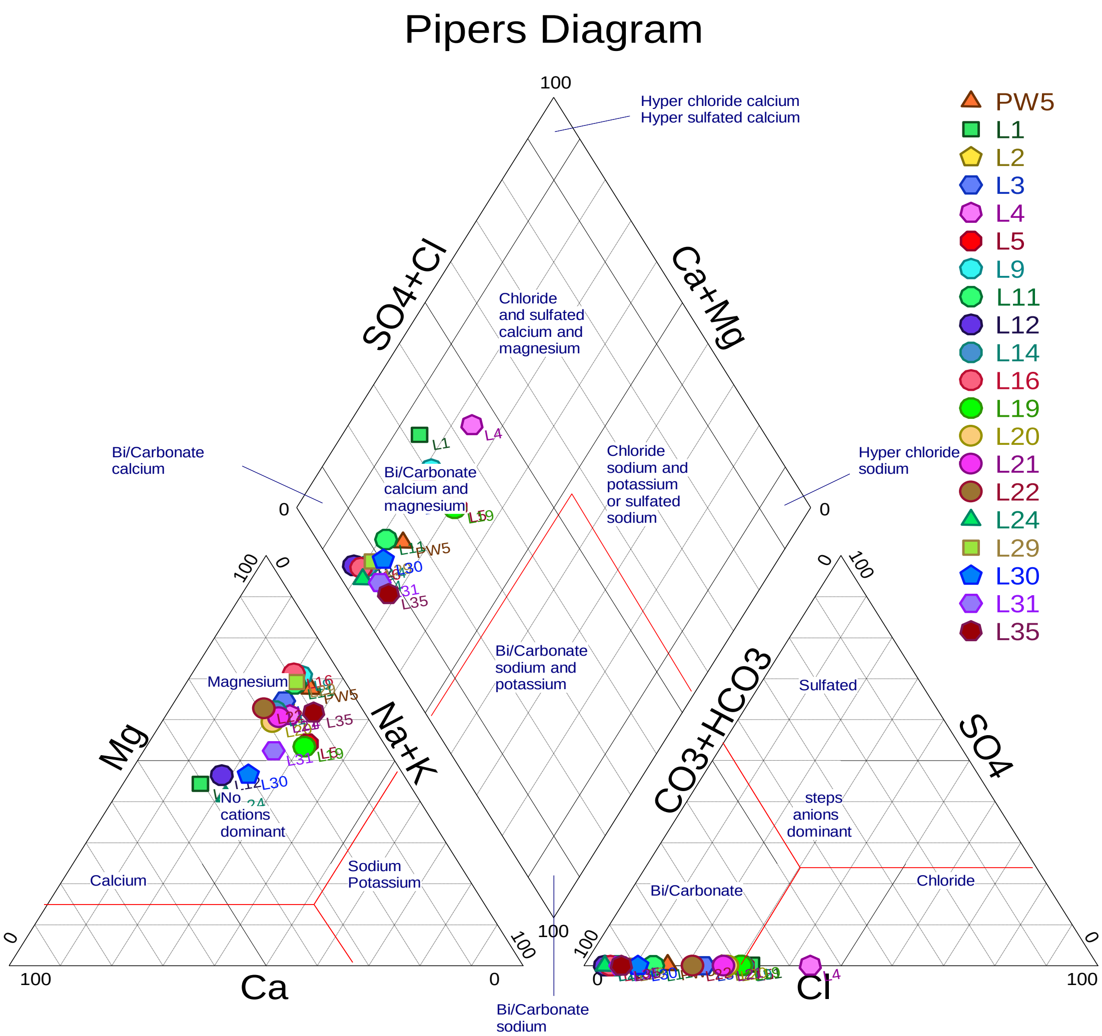


Figure 2. Piper Trilinear diagram showing the water types and hydrogeochemical facies of groundwater

Hydrogeochemical Processes

To understand the hydrogeochemical processes influencing the groundwater chemistry in the study area, Gibbs, Stiff, and Schoeller diagrams were utilized. These diagrams help to identify the primary factors contributing to the groundwater's ionic composition, such as rock-water interaction, precipitation, and evaporation. The Gibbs diagrams illustrate that the majority of the groundwater samples fall within the rock-weathering domain (Figure 3), signifying that the dominant process influencing groundwater chemistry is the interaction between the water and the host rock. This suggests that the primary source of major ions, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-), results from the dissolution of minerals in the aquifer as the groundwater moves through the subsurface.

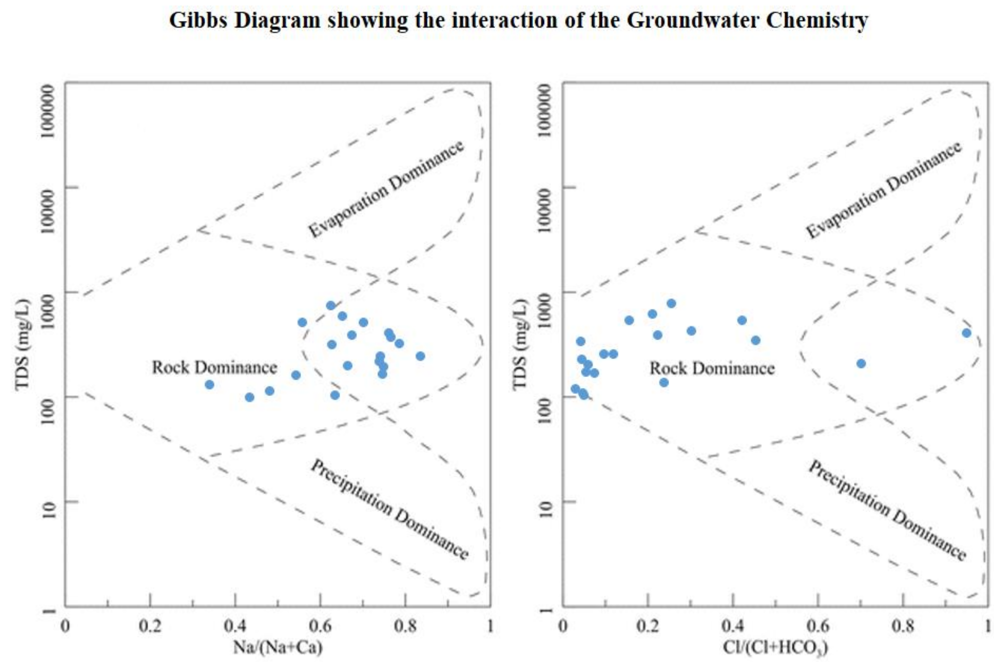
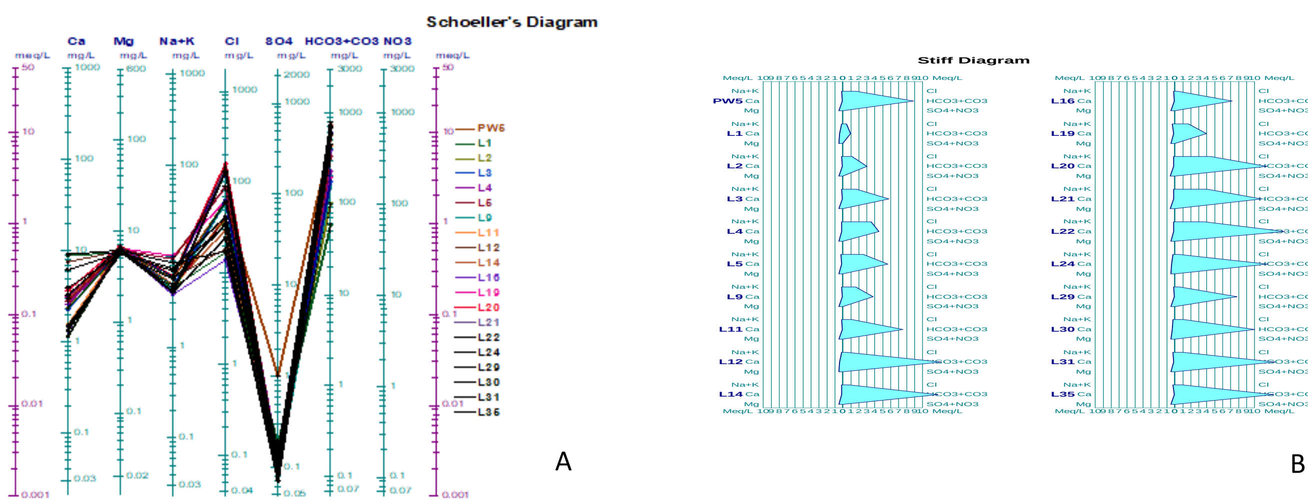


Figure 3. Gibbs diagram showing the dominant factor controlling groundwater chemistry

Additionally, Stiff and Schoeller diagrams were employed to further characterize the water chemistry (Figures 4 A & B). These diagrams visually depict the relative concentrations of cations and anions, reaffirming the dominance of calcium and magnesium ions, along with bicarbonates, consistent with the Ca-Mg-HCO_3 water type identified earlier. This pattern supports the conclusion that rock weathering, particularly of carbonate minerals, is the predominant process shaping the groundwater chemistry in the area.

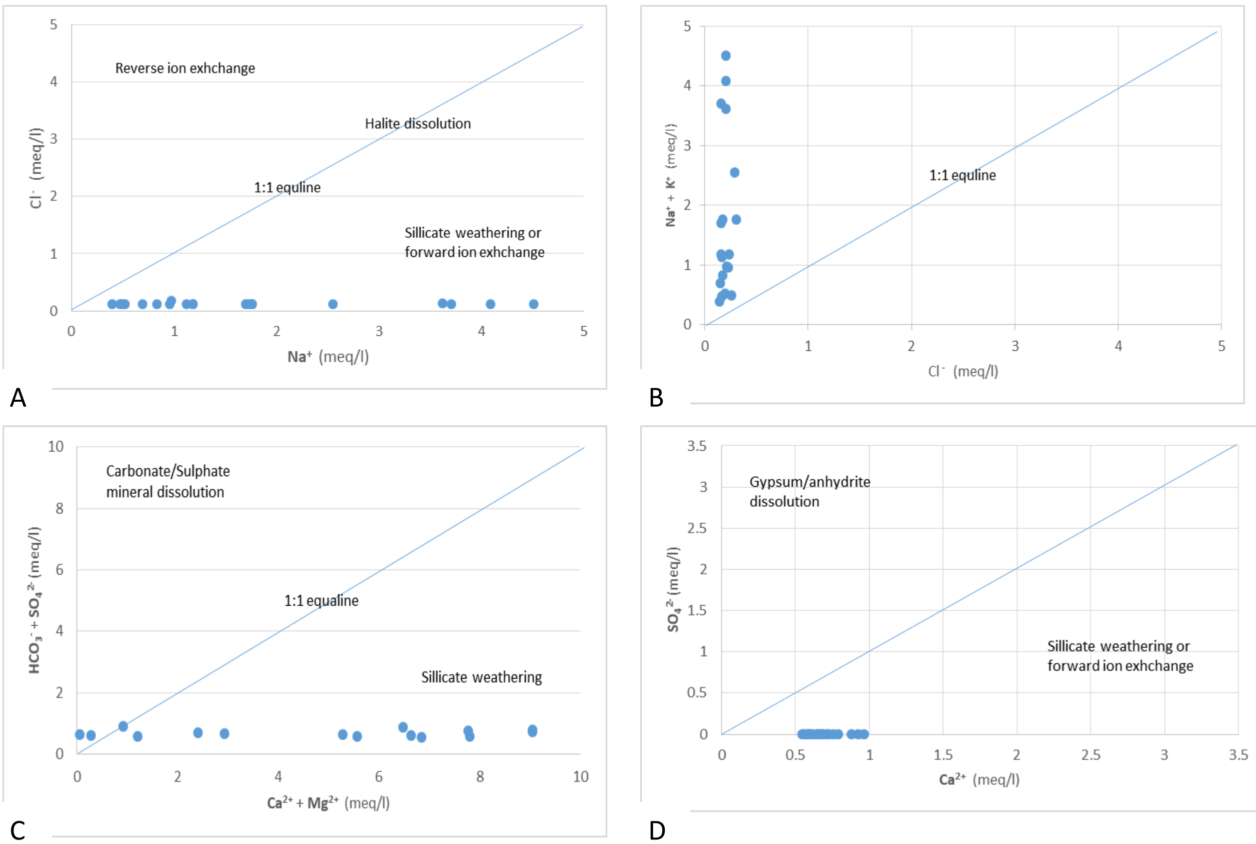


Figures 4A. & 4B. Stiff and Schoeller diagrams showing groundwater evolution

Evaporation, on the other hand, appears to play a minimal role in altering groundwater chemistry, as suggested by the relatively stable sodium-to-chloride (Na/Cl) ratio across different electrical conductivity (EC) values. This stability implies that while groundwater may be influenced by rock-water interactions, evaporation is not a significant contributor to its geochemical evolution in this region.

Groundwater evolution/Weathering and dissolution

The hydrogeochemical characteristics of an aquifer system are shaped by various ion exchange mechanisms and geochemical processes, which play a significant role in determining groundwater quality [31]. In this study, the interionic ratios and interactions among the chemical ions were analyzed and are illustrated in Figure 5.



Figures 5 (A-D). Scatter plots that display the relationships between various chemical ions in the groundwater samples.

Figure 5a demonstrates the linear correlation between sodium (Na^+) and chloride (Cl^-), which primarily results from mineral dissolution. The concentrations of Na^+ and Cl^- in groundwater suggest no halite dissolution, as these ions typically plot below the 1:1 equiline (2). However, in this study, the groundwater samples plot well below the equiline due to the higher Na^+ levels compared to Cl^-, indicating silicate weathering and forward ion exchange as the dominant processes [32; 34]. Elevated Na^+ concentrations, relative to Cl^-, may also arise from anthropogenic activities or the introduction of Na^+ via ion exchange processes. Figure 5b, which depicts the correlation between Cl^- and ($Na^+ + K^+$), shows that 100% of the samples fall above the equiline, suggesting an excess of cations. This could be due to the formation of alkali salts, alkali carbonates, or sulfates in the region. This result is consistent with findings from the Piper trilinear plot.

The scatter plot in Fig. 5c illustrates the relationship between bicarbonate (HCO_3^-) + sulfate (SO_4^{2-}) and calcium (Ca^{2+}) + magnesium (Mg^{2+}), highlighting ionic exchange processes. When sample plots shift left (reverse ion exchange) or right (forward ion exchange) of the equiline, ionic exchange is evident. Samples above the equiline suggest dissolution of gypsum, calcite, and dolomite in the aquifer, while those below the 1:1 line indicate silicate weathering as the source. In this study, all samples plot to the right and below the equiline, confirming the predominance of ionic exchange processes driven by silicate dissolution rather than carbonate mineral weathering [34; 32]. Figure 5d, which explores the relationship between sulfate (SO_4^{2-}) and calcium (Ca^{2+}), reveals that all samples fall within a 1:1 ratio, confirming that silicate weathering, rather than anhydrite or gypsum dissolution, is the main process influencing hydrogeochemical ions in the aquifer. The consistently low concentrations of silicate ions such as chloride (Cl^-), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), and nitrate (NO_3^-) further corroborate the anoxic hydrogeological conditions of the study area.

The bivariate plot in Fig. 6a shows the relationship between Na^+/Cl^- and electrical conductivity (EC), used to assess the effects of evaporation and ion exchange on groundwater chemistry [31]. In this study, the Na^+/Cl^- molar ratios were majorly above 1, with EC values ranging from 204 to 988.78 µS/cm, all below 1000 µS/cm. This suggests that the dominant process affecting the groundwater chemistry is silicate dissolution, with minimal evaporation effects. Groundwater ions originate from aquifer materials through ion exchange processes occurring in the surrounding environment or during chemical migration [33]. To further analyze the source of these ions and understand the ion exchange occurring in the groundwater, chloro-alkaline indices (CAI) were calculated using the formulas CAI = $[Cl^- - (Na^+ + K^+)/Cl^-]$ (Fig. 6b). Positive CAI values indicate an ion exchange between Na+ and Ca2+, while negative values suggest that Ca^{2+} replaces Na^+ in the groundwater. In this study, all the groundwater samples showed positive CAI values, indicating that reverse ion exchange is the primary mechanism responsible for the release of alkali metals (Na^+ and K^+) into the groundwater system.

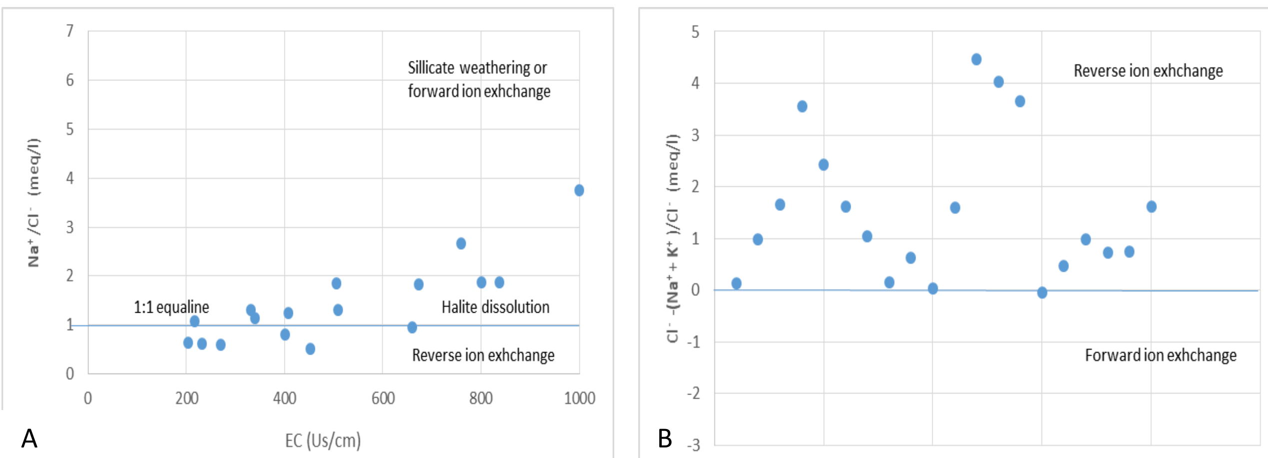


Figure 6A & 6B. Bivariate plots showing the evaporation and ionic exchange reactions in groundwater

Drinking Water Quality

The Water Quality Index (WQI) model was employed to assess the drinking water suitability of groundwater in the study area. The WQI values ranged from 25.34 to 58.72, indicating a range of water quality conditions across different locations. Out of the 19 locations analyzed, the majority of the sites (73.68%) fell under the "Good" water quality category, while two locations (L12 and L22) were classified as "Poor." One location (L5) stood out with an "Excellent" water quality rating, exhibiting the lowest WQI value of 25.34 (Table 4).

Locations such as L12 and L22, which had higher WQI values of 58.72 and 54.99, respectively, suggest that their water quality is less favorable for consumption. These elevated WQI scores likely result from higher concentrations of dissolved ions and potential contaminants. In contrast, sites like L5, with its "Excellent" rating, indicate minimal contamination and suitable drinking water quality. Overall, the assessment suggests that most of the groundwater in the study area is safe for drinking, though certain locations require attention to improve water quality. It is essential to monitor these sites and take necessary actions to ensure safe drinking water for local communities.

Table 4. Calculated WQI of each location and their categories using equations 1-3.

Locations No.	WQIs	Categories
PW5(Control)	39.320	Good
L3	35.395	Good
L4	26.290	Good
L5	25.344	Excellent
L9	27.284	Good
L11	34.377	Good
L12	58.721	Poor
L14	44.362	Good
L16	35.461	Good
L19	36.938	Good
L20	44.514	Good
L21	33.726	Good
L22	54.989	Poor
L24	28.556	Good
L29	36.958	Good
L30	29.252	Good
L31	33.161	Good
L35	39.111	Good

Irrigation Water Quality (IWQ)

Irrigation water quality is a critical factor in evaluating groundwater suitability for agricultural use, as well as its potential impact on human consumption. The quality of water used for irrigation can influence soil health, crop yield, and long-term agricultural productivity. One of the key tools used to assess this suitability is the Irrigation Water Quality Index (IWQI), which provides a comprehensive measure of water quality by considering various physicochemical parameters and their effects on both crops and soil [28; 24; 25].

Sodium percent (Na%)

Sodium Percent (Na%) is an essential parameter for evaluating the suitability of groundwater for irrigation, as high sodium content can negatively affect soil structure, permeability, and plant growth [16]. In this study, Na% values ranged from 14.99% to 30.69%, with an average of 22.15%. Based on the Na% classifications, around 11.11% of samples were excellent, 66.67% fell in the good category, and 22.22% were permissible for irrigation. Elevated sodium levels in some samples may be attributed to the natural weathering of rocks [26]. Wilcox diagram (Figure 7) shows groundwater mainly in excellent (75%) and good (25%) classes. Thus, the classification of groundwater using Wilcox shows the water is primarily within safe limits for irrigation, ensuring soil health and crop productivity [11].

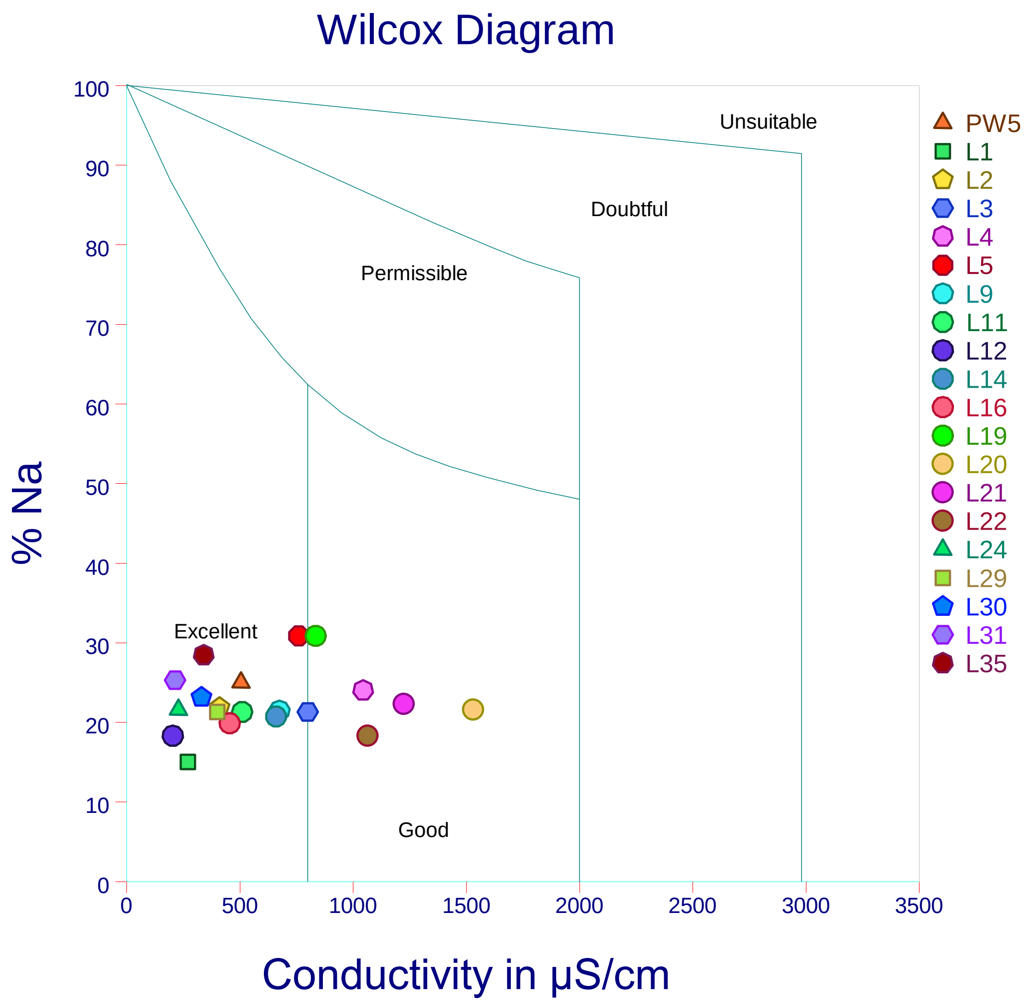


Figure 7. Wilcox diagram classifying water samples into its different categories

Sodium Absorption Ratio (SAR)

SAR is a key indicator used to evaluate the suitability of groundwater for irrigation, as elevated SAR levels can affect soil structure, leading to reduced permeability and crop yield due to sodium accumulation [27]. In this study, SAR values ranged from 0.16 to 0.33, with an average of 0.21 meq/L, classifying all samples as excellent for irrigation use (SAR < 10). No samples exceeded the SAR threshold which could potentially harm soil health, indicating that the groundwater in the study area is well-suited for long-term irrigation (11). Additionally, the USSL diagram (Figure 8) used to assess the relationship between salinity (EC) and SAR places most samples in categories where salinity remains manageable with moderate leaching practices. Thus, groundwater is safe for irrigation with minimal risk of sodium-induced soil compaction.

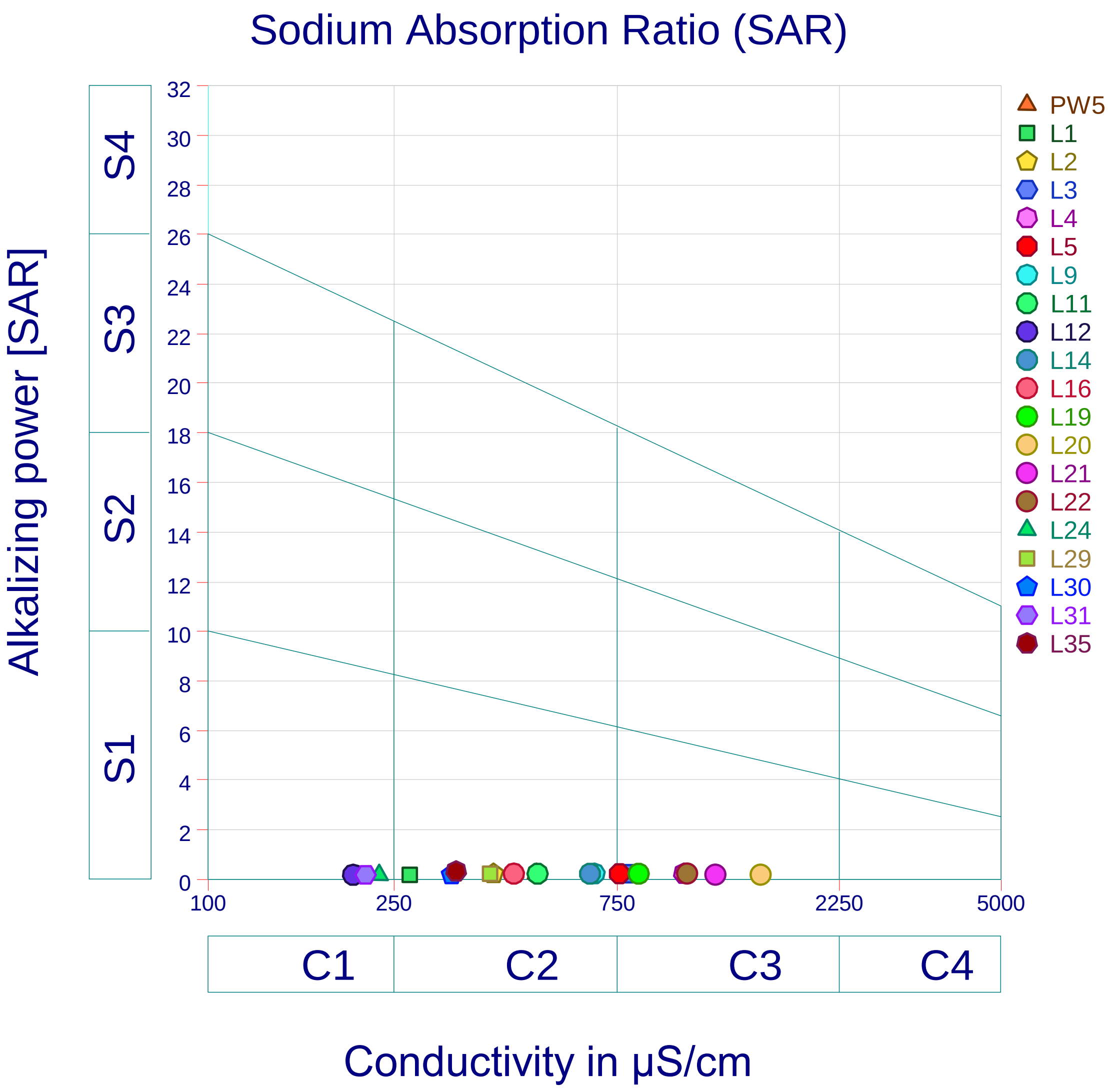


Figure 8. SAR for water samples in the study area

Residual Sodium Carbonate (RSC)

RSC is another important factor in assessing irrigation water quality, particularly by measuring the balance of carbonates and bicarbonates against calcium and magnesium concentrations. An RSC greater than 2.5 meq/L suggests a risk of sodium buildup, which could lead to calcium and magnesium depletion and soil degradation [19]. In this study, RSC values ranged from 1.9 to 14.4, with an average value of 9.1meq indicating that some locations are at risk of carbonate-induced soil alkalinity, which could negatively affect crop growth. Groundwater from areas with elevated RSC requires careful management, such as regular monitoring and soil amendments, to mitigate potential adverse effects on irrigation suitability.

Kelley index (KI)

The Kelley Index (KI) is an important metric for assessing sodium toxicity in groundwater and its suitability for irrigation. In this study, KI values ranged from 0.17 to 0.55, with an average of 0.31. All groundwater samples had KI values below 1.0, indicating low sodium levels across the study area, making the water highly suitable for irrigation. Since no samples exceeded KI > 1.0, there is no significant risk of sodium-induced soil toxicity. Therefore, the groundwater in the study area is deemed safe for agricultural use without concerns of sodium buildup affecting soil structure or crop growth.

Magnesium hazard (MH)

Magnesium hazard (MH) is a key factor in determining the suitability of groundwater for irrigation. In this study, MH values ranged from 42.6% to 82.4%, with an average of 65.63%. Most groundwater samples exhibited MH values exceeding 50, indicating that most of the samples are not suitable for irrigation purposes. Elevated magnesium concentrations in groundwater can impair soil structure and negatively affect crop growth. The high MH values suggest compromised water quality, which could lead to increased soil alkalinity and reduced agricultural productivity. Addressing the elevated magnesium levels is essential to prevent long-term damage to soil health and ensure sustainable crop yields in the study area.

Human Health Risk Assessment (HHRA)

Human health risk assessment (HHRA) was conducted to evaluate groundwater quality for drinking, specifically focusing on nitrate (NO_3^-) through ingestion and dermal contact. It has been noted that elevated nitrate levels in the body pose a health danger by obstructing the oxygen-hemoglobin connection due to the nitrite generated during its breakdown, which can result in methemoglobinemia and potentially be fatal for young children and babies [35].

This assessment targeted three subpopulations: children, adult females, and adult males. In the study area, ingestion HQ values greater than 1.0 were observed in 56.67% of samples for children, 10% for adult females, and 6.67% for adult males, indicating potential non-cancer risks. However, dermal HQ values remained below 1.0 across all sites and subpopulations, suggesting lower risk through skin contact. The total hazard quotient (THQ) for NO_3^- showed that NO_3^- levels did not exceed 1.0 at any site. Specifically, 50% of sites had THQ > 1.0 for children, while adult females and males exceeded the threshold at 10% and 6.67% of sites, respectively. These findings emphasize the ingestion pathway and NO_3^- exposure as major contributors to non-cancer health risks in the region. This outcome gave a similar result to the study carried out in a dumpsite in residential area around a dumpsite in Lagos, Nigeria [36]. In a similar study carried out [36], the range for the hazard index for ingestion (oral) route (HIoral) was 0.024-0.962, 0.028-1.136 and 0.033-1.3 for male, female and children respectively. The dermal hazard index (HIdermal) shows from Table 2 a range of 0.001-0.026 for male adult, 0.001-0.027 for female adult and 0.002-0,071 for children [36]. According to [37; 38], HItotal values lesser than one (HItotal<1), indicate no significant risk of non-carcinogenic effects while if HItotal value exceeds one (HItotal>1), then there is exposure to non-carcinogenic danger

Children were the most vulnerable group, with average Hazard Index (HI) values of 1.24, compared to 0.59 for adult females and 0.44 for adult males, indicating that children face significantly higher risks. This increased vulnerability among children is likely due to their developing metabolisms and lower body weights. The study highlighted that 56.67% of sites posed potential non-cancer risks to children, while only 10% and 6.67% of sites were risky for adult females and males, respectively. Fluoride levels, in particular, showed a strong positive correlation with HI values, marking it as residents' primary health risk factor. The findings underscore the importance of monitoring NO_3^- concentrations in groundwater, as excessive levels can lead to health issues such as blue baby syndrome, esophageal and gastric cancers, and dental and skeletal fluorosis. The study calls for establishing effective groundwater quality monitoring systems to mitigate these risks and ensure safe water use for the local population.

CONCLUSION

The comprehensive assessment of groundwater quality in the study area reveals significant insights into its suitability for drinking and agriculture. Generally, the groundwater of the study area is dominated by calcium and bicarbonate ions. Ca-Mg-HCO_3 is essentially the dominant hydrochemical facies present in the study area. Interpretation of the hydrochemical data suggests that rock-water interaction, silicate weathering, and ion-exchange processes are responsible for the study area's groundwater chemistry. Water Quality Index (WQI) for drinking, identified varying water quality levels across 19 locations, with the majority classified as "Good quality," and a sample was rated as an "Excellent" quality. However, two locations rated as "Poor quality" highlight critical concerns regarding water safety for consumption, necessitating immediate attention and remedial measures to protect public health.

Furthermore, the Irrigation Water Quality Index (IWQI), revealed that parameters such as Sodium Percent (Na%), Sodium Absorption Ratio (SAR), and Kelley Index (KI) largely indicate favorable conditions for agricultural use, with most samples classified as "excellent" and "good" water quality. Nonetheless, the elevated Magnesium Hazard (MH) values in all samples raise red flags concerning long-term soil health and crop productivity, indicating that rigorous management strategies must be employed to mitigate the risks associated with high magnesium concentrations.

In addition, the Human Health Risk Assessment (HHRA) underscored the potential non-cancer risks associated with nitrate (NO_3^-) exposure, particularly for children, who exhibited the highest vulnerability. With 56.67 % of sites posing ingestion risks for children, local authorities must prioritize groundwater monitoring and establish effective water quality management systems. Given that nitrate levels demonstrated a strong correlation with health risks, addressing fluoride contamination should be a focal point of public health initiatives.

In conclusion, while the assessment indicates that much of the groundwater in the study area is safe for drinking and suitable for irrigation, certain locations require targeted interventions to safeguard human health and ensure sustainable agricultural practices. Establishing monitoring systems and public awareness campaigns will be crucial in mitigating risks and enhancing water quality in the region. The findings of this study serve as a critical reference for stakeholders, including policymakers, public health officials, and agricultural practitioners, in their efforts to manage water resources for sustainable development.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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