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Hydro-geochemical Characterization and Groundwater Quality Assessment of Mariri Aquifer, Kano, Nigeria

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Abstract: The chemical composition of groundwater, which reflects its quality, is a product of natural and anthropogenic factors that affect its use for different purposes. This study characterizes the groundwater chemistry of the Mariri aquifer using the Piper Diagram, Chadha Diagram, and Gibbs Plot. The suitability of the groundwater for irrigation was assessed using some irrigation quality parameters such as Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP or %Na), Permeability Index (PI), Residual Sodium Bicarbonate (RSBC), Magnesium Adsorption Ratio (MAR), Wilcox Diagram, and Irrigation Water Quality Index (IWQI). In contrast, a weighted arithmetic water quality index was used to evaluate its suitability for drinking. The results show that the groundwater is hard freshwater of Ca-Mg-HCO_3. The major process governing groundwater chemistry is the dissolution of carbonate rock. The Irrigation water quality parameters also indicate that the groundwater has excellent permeability with low to medium salinity, which, as shown by the IWQI, can be used for irrigation with moderate restrictions. The drinking water quality index also indicated "good" to "poor" water quality. The composition of the groundwater shows that it can be used for irrigation and drinking, but with some measure of restraint. The results of the study will benefit water resource managers and policymakers.

Keywords: Irrigation water quality, groundwater, hydrochemistry, WQI, Parameters, Piper

Introduction

Water quality is related to life quality, as its use for various purposes depends on its quality. Worldwide, groundwater accounts for 98% of domestic water usage and 43% of irrigation water, with over 20% of the global population relying on it for drinking water (Kim and Park, 2016). According to reports by Eyinla and Oladunjoye (2014), 35 – 45% of the global food supply comes from irrigated agriculture, with groundwater accounting for over 80% (Diouf et al., 2022). This is more in arid and semiarid regions, owing partly to its availability and less contamination than surface water (Al-Shaibani, 2008; Hossain *et al*., 2024). In Nigeria, about 6 x 10^{18} m^3 of groundwater is abstracted daily for various uses (Adewumi *et al*., 2018). Groundwater is contained in geologic formations known as aquifers.

Although the aquifer is less prone to anthropogenic pollution than surface water, groundwater quality is significantly affected by anthropogenic activities such as industrial activities, agricultural activities, domestic effluents, etc. (Venugopal *et al*., 2009; Ravikumar *et* *al*., 2015; Onoyima and Onoyima, 2023). In addition, dissolved substances acquired from the geological environment of the aquifer significantly influence groundwater quality (Gusikit *et al*., 2020; Mokoena *et al*., 2020; Hossain *et al*., 2024). Geochemical processes influencing groundwater quality include rock weathering, dissolution, precipitation, and ion exchange reactions (Todd, 1980; Sanchez-Martos *et al*., 1999). These processes are influenced by bedrock type, topography, soil, climate, aquifer recharge, residence time, etc. (Andre et al., 2005; Ravikumar *et al*., 2015). As a vital tool for understanding these processes, geochemical characterization of groundwater has been widely used to provide critical insight into the chemical composition of groundwater and its suitability for various uses (Xu *et al*., 2016; Zhou *et al*., 2020; Araga and Gnanachandrasamy, 2021; Diouf *et al*., 2022; Ghimire et al., 2025). Each groundwater system has a unique chemical composition due to the differing geologic conditions and geochemical processes.

Mariri is located in the semi-arid region of Kano, Nigeria. Agriculture is the major economic activity in the area. The relatively flat land favours mechanized farming, and the area is an important food source for the country. Because of the scarcity of surface water and the short period of rainfall, groundwater abstracted from wells is a critical resource for agriculture through irrigation in the area (Eduvie and Musilim, 2024). Many of the population also depend on groundwater for drinking and other domestic uses. However, there is limited research on the groundwater quality, specifically for irrigation, leaving a gap in understanding the potential risks and implications for agricultural practices in the region.

The quality of the irrigation water is a function of the quantity and nature of the dissolved substances it contains, which has a direct effect on soil properties and crop yield (Zaman *et al*., 2018; Adegbola *et al*., 2019; Al Yousif, and Chabuk, 2023; Dey *et al*., 2024). Poor irrigation water can destroy soil structure, affect permeability, and negatively impact plant growth and crop yield (Bashir *et al*., 2013). The problems associated with irrigation water can be categorized as salinity hazards, alkalinity hazards, permeability or infiltration hazards, or specific ion toxicity (toxicity hazards) (Simsek and Gunduz, 2007; Dey *et al*., 2024). Water quality for irrigation depends on the relative concentration of one ion over the other (Gautam and Rai, 2023). Hence, different indices have been widely used to evaluate the suitability of water for irrigation, including Electrical conductivity (EC), Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP or %Na), Permeability Index (PI), Residual Sodium Bicarbonate (RSBC), Magnesium Adsorption Ratio (MAR), Wilcox Diagram, etc. (Chaudhar and Satheeshkumar, 2018; Mokoena *et al*., 2020; Xia et *al*., 2021; Sharma *et al*., 2021; Nawrin *et al*., 2022). Irrigation water quality index (IWQI) has also been used to reflect the composite influence of numerous water quality parameters on the overall water quality (Abbasnia *et al*., 2018; Al-Hadithi *et al*., 2018; M'nassri *et al*., 2022; Hussein *et al*., 2024).

Because groundwater is abundantly available and relatively free from contamination (compared to surface water), it is a source of drinking water for an estimated one-third of the global population (UNEP, 2005; Hossain *et al*., 2024). This is even more so in developing countries such as Nigeria, where about 59% of the population depends on groundwater for domestic purposes (FGN, 2007). Groundwater quality affects the management of water resources and their suitability for different uses (Paternoster *et al.*, 2021). Hence, there is a need for regional groundwater quality assessment and monitoring to ensure its suitability for various purposes. This study aims to characterize the groundwater hydrochemistry of Mariri in Kano State, Nigeria, and to evaluate its suitability for drinking and irrigation. Regional groundwater assessment and hydrochemical characterization provide useful information for water resource managers and policymakers. This research will play a key role in protecting public health, enhancing agricultural practices, and ensuring the sustainable use of this essential resource.

Materials and Methods

Study area

The study area (Figure 1) was Mariri, Kano State, Northwestern Nigeria, located approximately at Latitude 11° 56'N to 11° 57'N and longitude 08° 36'E to 08° 34'E. The area's climate is semi-arid with two distinct seasons: the rainy and dry seasons. The annual rainfall ranges from 800 mm to 1000 mm, while the temperature is between 26 ^{O}C to 33^{O}C. The area falls within the Sudan savannah vegetation belt, characterized by flat-topped hills, granite inselbergs, and low regions with alluvial deposits. The region's geology is mainly of the weathered and fractured basement of complex rocks made up of granite, gneiss, schist, and quartzite. Groundwater in the study area occurs in the aquifer of fractured basement rocks and sandy alluvial deposits along river courses, with water tables generally less than 20 m (Ismail and Yola, *2012)*. The area is about 20 km^2 with a population of approximately 39837. It is mainly a residential area with an adjoining vast agricultural land, with residents primarily engaged in the cultivation of staple crops such as millet, sorghum, maize, and rice. Groundwater is the main water source for domestic and agricultural use for the people in the area.

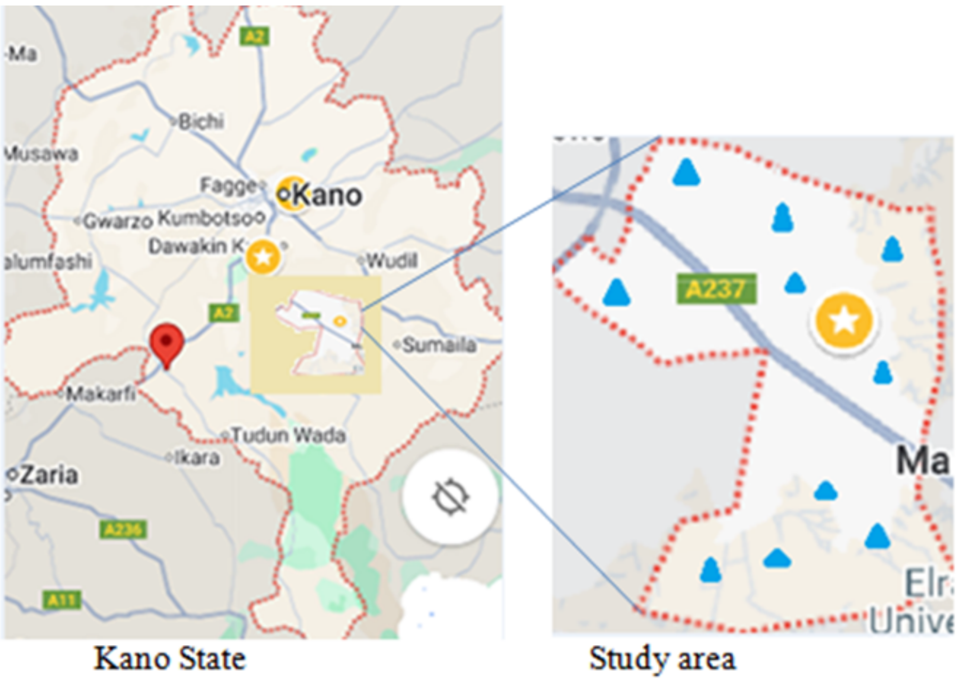

Figure 1: Map of the study area showing the sampling points

Sampling and Analysis

Samples were collected in February, corresponding to the peak of the dry season, when the dependence on groundwater for irrigation and domestic use was also at its peak. Ten groundwater samples were collected from hand-dug wells using a clean, non-reactive bailer and were put into polyethylene bottles (previously washed with 10% nitric acid and rinsed with distilled water). The samples were labeled, air-tight, and immediately transported to the laboratory in a cooler maintained at 4 °C. Some parameters, such as pH, EC, and TDS, were measured on-site using a well-calibrated Hach HQ440d Benchtop Multi-Meter with appropriate probes. Standard sampling procedures were strictly adhered to for accuracy and quality control. The major ions, including $Na^{+,}$ K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and NO_3^-, were analyzed using standard methods (ALPHA, 1995).

For accuracy of data, cation and anion charge balance (CB) was calculated according to the formula:

$$CB = \frac{\sum M_c - \sum M_a}{\sum M_c + \sum M_a} \times 100 \qquad (1)$$

where M_c and M_a are the concentrations of the cations and anions, respectively, in meq/L. The acceptable error range is within ±5% (Ouarani *et al*., 2020).

Hydrochemical Evaluation

Piper diagram, first developed by Hill in 1940 and later modified by Piper (1944), was used to understand the hydrochemical facies and classify the water type in the groundwater. A Microsoft Excel template was used to construct the Piper diagram. All concentrations were in meq/L. A Chadha diagram was used for a deeper insight into the hydrochemistry of the groundwater (Chadha, 1999). This is a modified form of the Piper diagram constructed by plotting the difference in weak acids (HCO_3^- - (Cl^- + SO_4^{2-})) on the y-axis and the difference of the major alkaline and alkali ions ((Mg^{2+} + Ca^{2+}) – (Na^+ + K^+)) on the x-axis, all in meq/L. This was done using Microsoft Excel software. The Gibbs plot was employed as a tool to examine the primary process that governs groundwater chemistry. The Gibbs plot (Gibbs, 1970) has been a common tool used by various researchers to evaluate the relationship between the chemical composition of water and the lithological characteristics of the aquifer. It is a plot of TDS vs the ratio of the cations (Na^+/(Na^+ + Ca^{2+})) or anions (Cl^-/(HCO_3^- + Cl^-)).

Irrigation Water Quality Parameters

The status of irrigation water, which depends on the dissolved ions in the water, can be assessed using some established irrigation water quality parameters. In this study, parameters used include Sodium Adsorption Ratio (SAR) (Richard, 1954), Soluble Sodium Percentage (SSP or %Na) (Todd and May, 2005), Permeability Index (PI) (Doneen, 1964), Residual Sodium Bicarbonate (RSBC) (Gupta and Gupta, 1987), Magnesium Adsorption Ratio (MAR), (Raghunath, 1987) and Irrigation Water Quality Index (IWQI).

The parameters were calculated using the following formula:

$$SAR = \frac{Na}{\sqrt{\frac{Mg^{2+} + Ca^{2+}}{2}}} \qquad (2)$$

Irrigation water is classified as excellent (SAR < 10), good (10 < SAR < 18), doubtful (19 < SAR < 26), and unsuitable (SAR > 26).

$$\%Na = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \qquad (3)$$

Irrigation water can be excellent (< 20%), good (20 – 40%), permissible (40 – 60%), doubtful (60 – 80%), or unsuitable (> 60%)

$$PI = \frac{Na^+ + \sqrt{HCO_3}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \qquad (4)$$

PI classifies irrigation water as good (> 73%), suitable (25 – 75%), or unsuitable (< 25%)

$$RSBC = HCO_3^- - Ca^{2+} \qquad (5)$$

RSBC < 5 meq/L = suitable for irrigation; RSBC > 5 meq/l = unsuitable for irrigation

$$MAR = \frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}} \times 100 \qquad (6)$$

MAR < 50% is suitable while MAR > 50% is unsuitable for irrigation.
The concentrations of all the ions are in meq/L.

Irrigation Water Quality Index (IWQI)

IWQI reflects the composite influence of numerous water quality parameters on the overall water quality. The parameters used for calculating IWQI include EC, Na^+, Cl^-, SAR, and HCO_3^-. The index was calculated using the formula proposed by Miereles *et al.,* (2010):

$$IWQI = \sum_{i=1}^{n} q_i w_i \qquad (7)$$

Where w_i is the relative weights of the parameters as computed by Miereles *et al.,* (2010) (EC = 0.211, Na^+ = 0.204, HCO_3^- = 0.202, Cl^- = 0.194, SAR = 0.189) and q_i is the quality rating for the ith parameter.

q_i was calculated using the formula below:

$$q_i = q_{imax} - \left(\frac{(x_{ij} - x_{inf}) \times q_{iamp}}{x_{amp}}\right) \qquad (8)$$

The limiting values of the parameters are shown in Table 1, where q_{imax} = the maximum value of q_i for the class; x_{ij} = the measured value of the parameter; x_{inf} = the lower limit of the class of the parameter; q_{iamp} = the class amplitude; x_{amp} = the class amplitude of the parameter. The highest value of the measured parameter was considered the upper limit of the last class of each parameter.

The limiting values of q (Table 1) were obtained from the irrigation water quality data from the University of California Committee of Consultants (UCCC) as reported by Ayers and Westcot (1994).

Based on the index, irrigation waters are classified as follows: "no restriction" (85-100), "low restriction" (70-85), "moderate restriction" (55-70), "high restriction" (40-55), and "severe restriction" (40-55).

Table 1. The limiting values of the irrigation water quality parameters (Ayers & Westcot, 1994)

q_i	EC	SAR	Na^+	Cl^-	HCO_3^-
85-100	200≤EC<750	SAR<3	2≤Na<3	Cl<4	1≤HCO_3<1.5
60-85	750≤EC<1500	3≤SAR<6	3≤Na<6	4≤Cl<7	1.5≤HCO_3<4.5
35-60	1500≤EC<3000	6≤SAR<12	6≤Na<9	7≤Cl<10	4.5≤HCO_3<8.5
0-35	EC<200 or EC≥3000	SAR≥12	Na<2 OR Na≥9	Cl≥10	HCO_3<1 or HCO_3≥8.5

Drinking Water Quality Index

The suitability of the groundwater for drinking was evaluated using the weighted arithmetic water quality index (WAWQI). The water quality parameters were first assigned weights, reflecting the parameter's significance for drinking purposes (Douglas *et al.,* 2015; Onoyima *et* *al.,* 2022). Nigeria's reference standards for drinking water were adopted while assigning weights to the water quality parameters. The formula for calculating the WAWQI is as follows:

$$WAWQI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (9)$$

$$W_i = \frac{K}{S_i} \quad (10)$$

$$k = \frac{1}{\sum_{i=1}^{n} \frac{1}{S_i}} \quad (11)$$

$$Q_i = \frac{C_n - C_i}{S_i - C_i} \times 100 \quad (12)$$

Where: W_i = assigned weight, Q_i = the quality rating for the ith parameter, n = number of the parameters, C_n = the concentration of the ith parameter, S_i = the reference value of the ith parameter, K = a proportionality constant, C_i = the ideal value of the ith water quality parameter (C_i for pH = 7, for other parameters, C_i = 0).

The water quality ratings for the WAWQI are: Excellent (< 25), good (26 – 50), moderate (51 – 75), poor (76 – 100), and very poor (> 100).

Results and Discussion

Groundwater Quality Parameters

The level and nature of dissolved substances in groundwater determine its quality and suitability for different purposes. The descriptive statistics of the water quality parameters of the groundwater of the study area are summarized in Table 2. The pH ranged from 6.70 to 7.30 with a mean of 7.0. pH is a critical parameter in water quality assessment as it has control over other water quality parameters and is often used to assess the overall health of the water (He *et al*., 2017; Adesina *et a*l., 2024). The near-neutral and narrow pH range observed in this study is typical of carbonate rock aquifers. This is a result of the buffering effect of the dissolution of calcite (siliciclastic rock aquifers have a wider pH range, while in addition to this, crystalline rock aquifers have a median or mean pH near 6.0) (Lindsey *et al*., 2006).

EC ranged from 489 µS/cm to 511 µS/cm with a mean of 535 µS/cm. EC is an important parameter for the evaluation of water for irrigation and drinking purposes. TDS measures the levels of dissolved solids in the water and is directly related to EC because conductive ions are part of dissolved solids and inorganic materials (Adesina *et al*., 2024). TDS in the study area ranged from 308 to 337 mg/L. Water can be generally classified as soft (<60 mg/L), moderately hard (60 – 120 mg/L), hard (120 – 180 mg/L), and very hard (> 180 mg/L) (McGowan, 2000). Total hardness in the study area ranged from 150 to 172 mg/L. Groundwater can also fall into any of the nine classes based on hardness and TDS as presented in Figure 2. The result shows that the groundwater is hard-fresh water. Total hardness in groundwater is the combined effect of Ca^{2+} and Mg^{2+} from the dissolution of dolomite and calcite in groundwater (Xu *et al*., 2023; Dey *et al*., 2024).

The major cations are in the following range: Ca^{2+} (38.00 – 45.00 mg/L), Mg^{2+} (14.00 – 17.00 mg/L), Na^{+} (20.00 – 24.00 mg/L), and K^{+} (3.70 – 4.20 mg/L). These cations are in low abundance in the groundwater. Although the abundance of ions in groundwater is a function of many factors, it was reported that the level of Na^{+} in groundwater is mostly controlled by lithogenic minerals (silicate minerals), saline water intrusion, and evaporation processes (Kumar, 2013; Marghade, 2020). The relatively low abundance of this ion in the study area indicates that these processes may not be prominent in the groundwater. Fresh water is also characterized by a lower level of Na^{+} than Ca^{2+} (Mokoena *et al*., 2020).

The anions of the groundwater are in the range Cl^{-} (41.00 – 48.00 mg/L), SO_4^{2-} (17.00 – 20.00 mg/L), HCO_3^{-} (102.00 – 115.00 mg/L), and NO_3^{-} (4.90 – 5.70 mg/L). Cl^{-} in groundwater may be derived from bedrock (through ion exchange), saltwater intrusion, or anthropogenic activities (Bolt and Bruggenwert, 1978; Goswami *et al*., 2022). In addition to anthropogenic activities (such as fertilizer applications), SO_4^{2-} in groundwater originates from the dissolution of gypsum and pyrite (Antibachi *et al*., 2012; Kumar, 2013). On the other hand, elevated nitrate concentration in groundwater indicates anthropogenic influence (Lindsey *et al*., 2006; Mufur *et al*., 2021; Dey *et al*., 2024). From the results of this study, there is no evidence of much anthropogenic impact on the groundwater quality of the study area.

Table 2. The descriptive statistics of the water quality parameters

Parameter	Minimum	Maximum	Mean	Std dev.	Nigerian Std. (Drinking)
pH	6.70	7.30	7.00	0.17	6.5-8.5
EC (μScm^{-1})	489.00	535.00	511.00	12.98	1000
TDS (mgL^{-1})	308.00	337.00	320.60	8.42	500
Hardness (mgL^{-1})	150.00	172.00	163.30	6.17	150
Ca^{2+} (mgL^{-1})	38.00	45.00	41.40	2.11	-
Mg^{2+} (mgL^{-1})	14.00	17.00	15.60	0.92	20
Na^{+} (mgL^{-1})	20.00	24.00	22.00	1.26	200
K^{+} (mgL^{-1})	3.70	4.20	3.96	0.16	-
Cl^{-} (mgL^{-1})	41.00	48.00	44.50	2.01	250
SO_4^{2-} (mgL^{-1})	17.00	20.00	18.70	0.90	100
HCO_3^{-} (mgL^{-1})	102.00	115.00	109.40	3.61	-
NO_3^{-} (mgL^{-1})	4.90	5.70	5.25	0.25	50

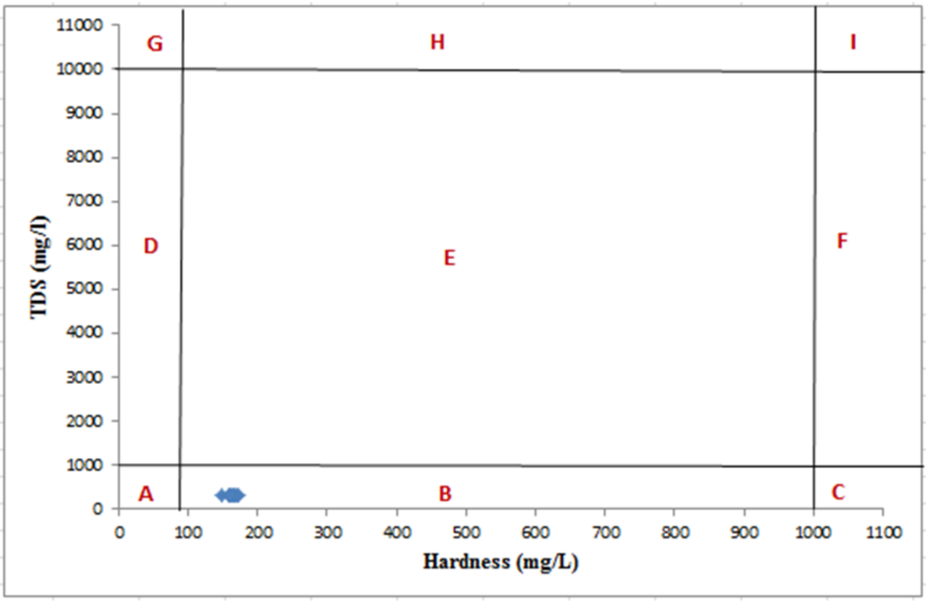

Figure 2: Groundwater classification based on hardness and TDS

Hydrochemistry of the Groundwater

Piper diagram, proposed by Piper in 1940, is a commonly used tool to delineate the hydrochemistry of groundwater. It comprises a triangle for the cations (left), another for the anions (right), and a diamond above the triangles. Each apex of the triangles represents 100% dominance of the cations and anions, while the diamond gives the overall water type. The Piper diagram for the groundwater of the study area is shown in Figure 3. The result shows that all the samples are in the no-dominant cation type, while the dominant anion is the bicarbonate type. From the diamond, the overall water type is the magnesium bicarbonate type. It also shows that alkaline earth metals exceed alkali metals for all the samples, and weak acids exceed strong acids. The dominance of alkaline earth metals over alkali metals may have resulted from the dissolution of alkaline earth minerals or ion-exchange reactions (Adewumi *et al*., 2018).

The Chadha diagram was employed to gain a deeper understanding of the hydrochemistry of the groundwater and to classify the water type (Chadha, 1999). Similar to what was obtained with the Piper diagram, all the groundwater samples are in the Ca-Mg-HCO_3 water type (Figure 4). Gibbs (1970) proposed that three major mechanisms that control the world's water chemistry are rock-water interaction (rock weathering), precipitation, and evaporation-crystallization processes. Gibbs plot, for both cations and anions (Figure 5), shows that rock-water interaction was the major natural process controlling the groundwater chemistry of the aquifer. The rock-water interaction designates the interface between the rock chemistry and the chemistry of the groundwater. Rock-water interaction dominates where there is sufficient time to interact with the lithology and release different ions into the groundwater (Mokoena *et al.,* 2020). The dominance of Ca-Mg-HCO_3 water type of the aquifer indicates the dissolution of carbonate rocks as calcite and dolomite in groundwater react with CO_2 and release Ca^{2+}, Mg^{2+}, and HCO_3^- according to the reaction below:

$$CaMg(CO_3)_2 + 2H_2O + 2CO_2 \longrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-$$

The above reaction is also largely responsible for the observed hardness of the groundwater.

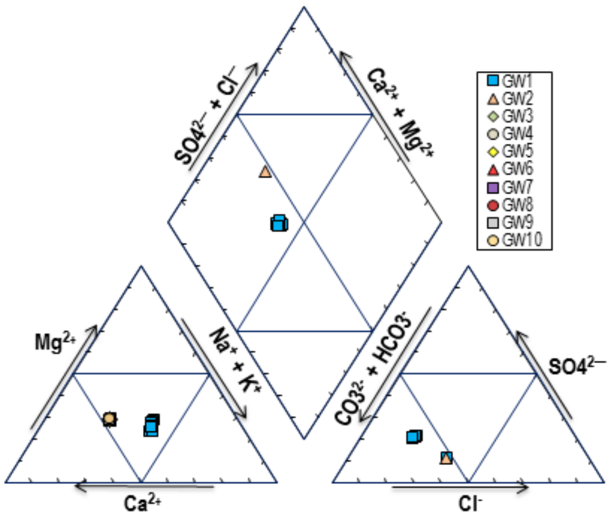

Figure 3: Piper diagram for the groundwater of the area

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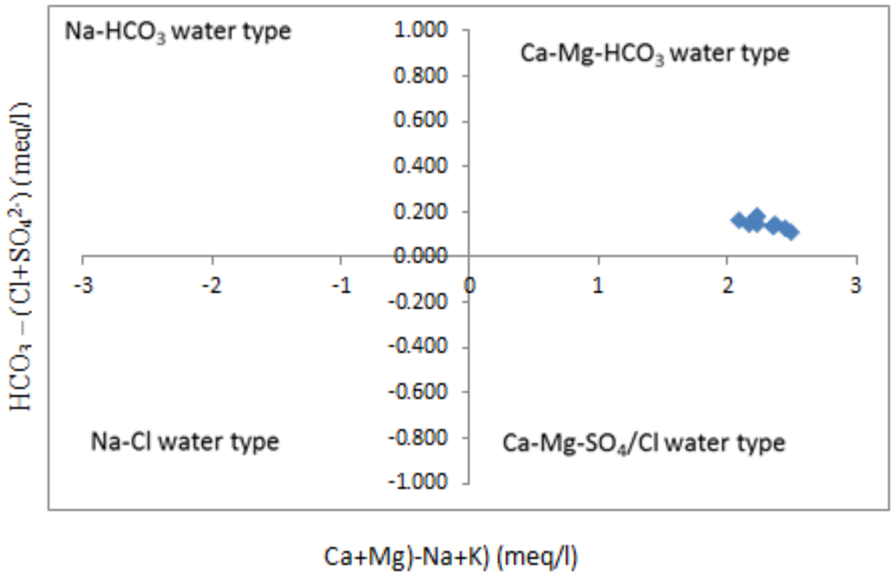

Figure 4: The Chadha diagram of the groundwater of the study area

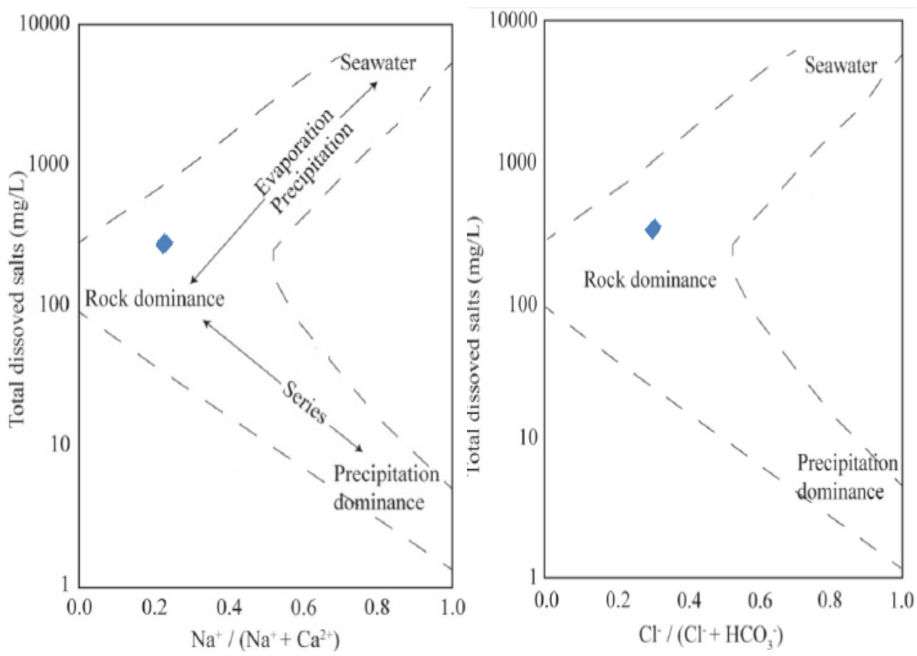

Figure 5: The Gibbs Plot for both cations and anions

Irrigation Water Quality

Irrigation water quality has a direct effect on soil properties and crop yield. The problems associated with irrigation water can be categorized as salinity, permeability, alkalinity, and toxicity hazards (or specific ion toxicity) (Simsek and Gunduz, 2007; Dey *et al*., 2024). Some of the irrigation water quality parameters of the study area are displayed in Table 3. Salinity hazard is a measure of the reduction of the quantity of water and nutrients (Physiological drought) available to plants due to the accumulation of dissolved salts and the consequent increase in osmotic pressure of the soil solution (Hossain *et al*., 2018). The most satisfactory measure of salinity hazard is electrical conductivity (EC), which can be classified into four classes as low salinity (EC < 500 μS/cm), medium salinity (500 – 100 μS/cm), high salinity (1000 – 3000 μS/cm), and very high salinity (EC > 3000 μS/cm) (Tatawat and Chandel, 2008). The result of this study shows that three samples (W2, W7, and W10) representing 30 % of the samples are in the low salinity category, while the rest (70%) are of medium salinity.

Permeability or infiltration hazard, also known as sodium (alkali hazard), measures the ability of irrigation water to alter the soil texture and structure and affect the rate at which the water enters the soil's lower layers. This ability is a function of the relative concentrations of Na^{+}, Mg^{2+}, and Ca^{2+} in water, and is mostly quantified as Sodium Adsorption Ratio (SAR) (Ayers and Westcot, 1994). The results of Table 3 show that the SAR values for all the groundwater samples are in class 1(SAR < 10), indicating the "excellent" category. At high SAR, the Na^{+} in water displaces the Ca^{2+} and Mg^{2+} in the soil, leading to sodic soil with poor soil structure (sodic soil becomes hard and close-packed when dry) and decreased permeability or infiltration of the soil to water with consequent adverse effects to crops and crop yield (Hussain and Rao, 2013; Aragaw and Gnanachandrasamy, 2021). In addition to the reduced permeability, Na^{+} also reacts with CO_3^{2-} and Cl^{-} to form alkaline and saline soils, respectively, which negatively impact plant growth and crop yield (Todd, 1980). High SAR is also associated with pipe scaling, corrosion, and plugging of the emitter in drip irrigation (Anyango *et al.,* 2024).

Soluble sodium percentage (SSP or % Na) is another measure of permeability hazard, but less satisfactory than SAR. From Table 3, all the groundwater samples can be classified as "good" for irrigation (20 < %Na < 40) based on %Na. A similar index, the permeability index (PI), also classified the groundwater as class II irrigation water, indicating "moderate" for irrigation purposes (25 < PI <75).

Residual Sodium Bicarbonate (RSBC) and Magnesium Adsorption Ratio (MAR) are irrigation water quality parameters used to measure the effect of irrigation water on soil alkalinity (alkalinity hazard). High RSBC indicates high irrigation water pH, which can lead to infertile soil due to the deposition of $NaCO_3$ (Udom *et al*., 2019). The results of this study show that the groundwater is safe for irrigation based on RSBC (RSBC < 5). On the other hand, the MAR of all the water samples is less than 50%, indicating no magnesium hazard. MAR > 50% implies more alkaline soil, leading to decreased phosphorus availability (Al-Shammiri *et al.,* 2005; Rawat *et al*., 2018).

The above-discussed indices evaluated various aspects of irrigation water quality, such as salinity hazard, permeability hazard, and alkalinity hazard. This combination of indices is necessary to achieve a more comprehensive understanding of water quality. While the salinity hazard was evaluated with only EC, which, as stated earlier, indicated that 70% of the samples have medium value and 30% have low salinity, the permeability hazard was assessed with three different indices: SAR, SSP, and PI. The results of the SSP and PI agree with each other, with 100% of the samples in the moderate class. SAR presented a less conservative approach concerning soil conservation, as 100% of the samples are in the excellent class. The two indices used to assess alkalinity hazard also agree with each other (safe for irrigation).

Using multiple indices can identify potential issues by reflecting aspects of water chemistry that impact plant growth and soil health, which a single index might overlook. Farmers and agricultural managers benefit from the detailed insights that a combination of indices provides. This enables them to make informed decisions regarding water use, crop selection, and irrigation practice. In this study, 70% of the water samples have medium salinity, while 30% have low salinity. Farmers and agricultural managers can use this information to select crops with salt tolerance in this range. For instance, it has been shown that wheat or barley tolerates higher salinity than rice or corn; on the other hand, irrigation with saline water can even improve the quality of some vegetables (such as sugar content in tomatoes and melons) (Mateo-Sagasta and Burke, 2010).

The results also indicated that there is no need for remediation action against saline or sodic soils. Although constrained by massive energy requirements, desalination of salty groundwater is an available option, while leaching and drainage are required to maintain salt balance in the soil profile and to sustain crop yield (FAO, 2007)

A plot of %Na vs EC, known as the Wilcox diagram (Wilcox, 1955), evaluates irrigation water based on a combined effect of salinity hazard and permeability hazard and has been commonly adopted in assessing the suitability of water for irrigation (Ziani *et al*., 2017; Talib *et al*., 2019; Ouarani *et al*., 2020; Paternoster *et al*., 2021; Hossain *et al*., 2024). The Wilcox diagram for this study (Figure 6) shows that all the groundwater samples are in the "excellent to good" class. This result is in agreement with the results obtained for salinity and permeability hazards. The Wilcox diagram also shows that EC values are parallel with % Na values, indicating that the EC is not dependent on the %Na of the water.

All the irrigation water quality parameters discussed so far focus on salinity, alkalinity, and permeability hazards while paying less attention to specific ion toxicity. These shortfalls necessitate using the Irrigation Water Quality Index (IWQI) proposed by Meireles et al., (2010). It reflects the composite influence of numerous water quality parameters on the overall water quality and uses one numeric value, making interpretation of results easy. This approach simplifies water quality results and addresses the complexity that arises when different indices yield conflicting results regarding the suitability of water for irrigation. The ease of interpretation and wider inclusive parameters also make it ideal for monitoring purposes and crucial for decision-making and managing water resources effectively. The classification of irrigation water is based on the assumption that irrigation is used under average conditions of soil texture, soil infiltration rate, climate, the quantity of irrigation water, and crop salt tolerance (Wilcox, 1955). The result of this study, as presented in Figure 7, indicates that the groundwater can be used for irrigation with moderate restrictions. The water is suitable for soils with moderate to high permeability, with suggested moderate salt leaching. On the other hand, plants with moderate tolerance to salt can be grown with no risk of toxicity.

Table 3. Irrigation Water Quality Parameters

Sample	EC	SAR	PI	SSP	RSBC	MAR
W1	512.00	0.732	52.579	23.666	-0.297	38.535
W2	489.00	0.704	55.147	24.015	-0.228	37.746
W3	535.00	0.773	51.499	23.985	-0.365	38.337
W4	507.00	0.718	54.097	23.808	-0.230	38.163
W5	520.00	0.760	52.725	24.176	-0.315	37.980
W6	515.00	0.732	52.579	23.666	-0.297	38.535
W7	498.00	0.724	54.455	24.138	-0.213	38.762
W8	525.00	0.778	51.925	24.238	-0.332	38.870
W9	510.00	0.747	54.075	24.342	-0.264	37.582
W10	499.00	0.718	54.097	23.808	-0.230	38.163

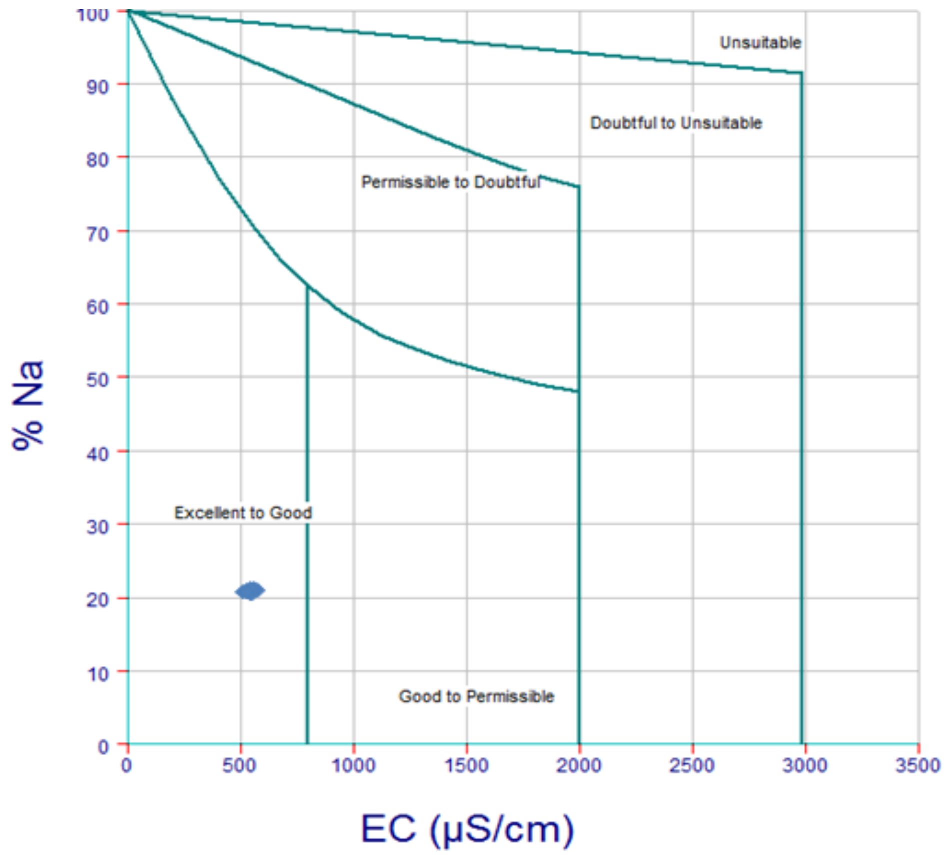

Figure 6: Wilcox Diagram for Groundwater Classification

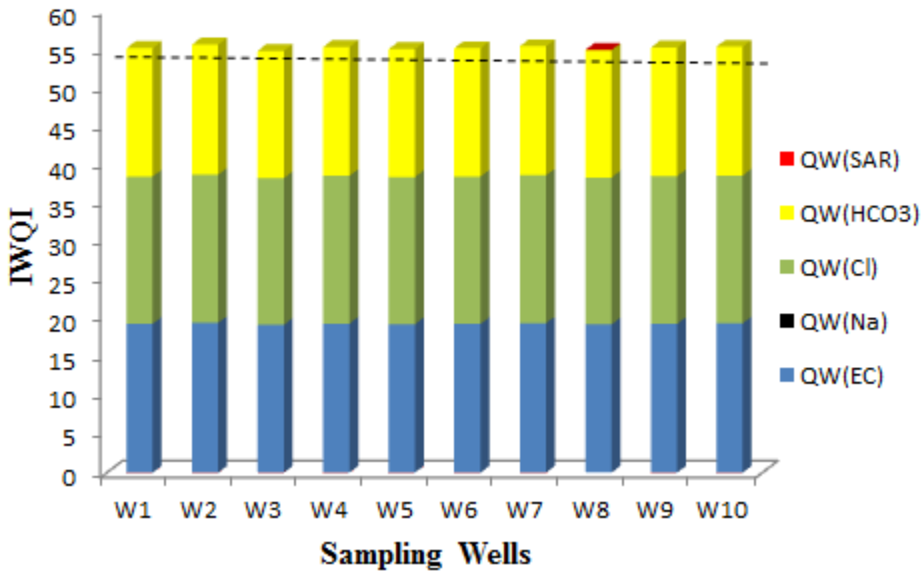

Figure 7: Results of the Irrigation Water Quality Index

Drinking Water Quality

The suitability of the groundwater for drinking purposes was evaluated using the weighted arithmetic water quality index method. From the result shown in Figure 8, W2 and W7 are in the "poor" class (50 < WAWQI < 75) while the rest of the samples are in the "good" class (25 < WAWQI < 50). Although this result indicates that the majority of the groundwater samples are good for drinking, it should be noted that the assessment did not include contaminants like heavy metals, pesticides, polyaromatic hydrocarbons, and other contaminants of emerging concern, which are frequently of health concern to both surface and groundwater. The study also did not consider the seasonal variation in the levels of the water quality parameters.

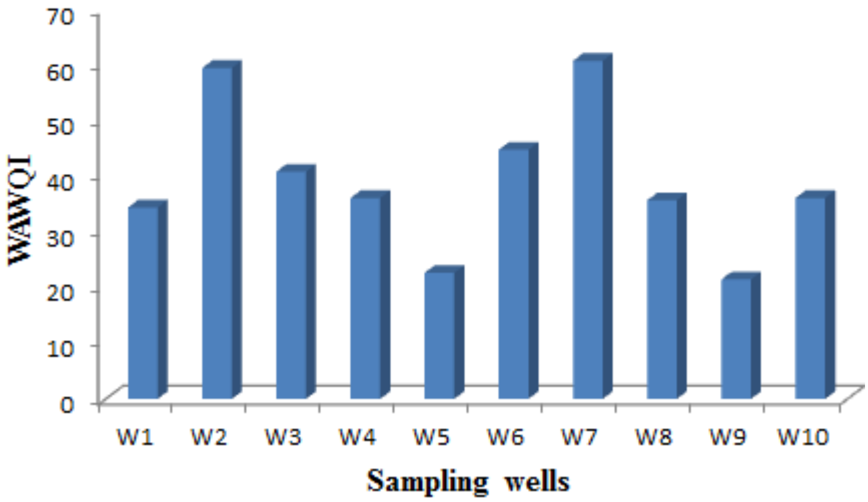

Figure 8: Drinking Water Quality Index

Conclusion

This study explored the impact of the natural and anthropogenic factors on the groundwater chemistry of the Mariri aquifer using the Piper diagram, Chadha diagram, and Gibbs plot to effectively characterize the groundwater quality. The findings show that the groundwater is hard freshwater, with Ca-Mg-HCO_3 as the dominant water type and the dissolution of carbonate rocks as the major processes governing the water chemistry. This geochemical characterization is useful for understanding the suitability of the groundwater for various purposes, especially in a region with limited rainfall and surface water availability.

The use of different irrigation water quality indices such as EC, SAR, SSP or %Na, PI, RSBC, and MAR, suggest that the groundwater has excellent to moderate permeability and low to medium salinity levels with safe alkalinity levels; on the other hand, the irrigation water quality index (IWQI) indicates that the groundwater can be used for irrigation with moderate restrictions, thus making it a viable resources for agricultural practice in the semi-arid region. The results show that combining different indices enhances the accuracy and reliability of irrigation water quality assessments, ultimately supporting sustainable agriculture and effective water management practices.

In addition, the drinking water quality index (WQI) reflects a range from “good” to “poor”, highlighting the need for continuous monitoring and careful management to ensure safe drinking water for the local population. There is also a need for further study on the level of contaminants like heavy metals, pesticides, polyaromatic hydrocarbons, etc. in the groundwater to ascertain its true drinking status.

The research also revealed a limited impact of anthropogenic activities on groundwater quality, suggesting effective natural filtration processes. However, continuous monitoring is needed to detect any change in water quality due to increased human activities or environmental stressors.

This research contributed valuable data to water resource managers in the region. By integrating hydro-geochemical characterization with irrigation and drinking water quality data, stakeholders can improve agricultural productivity and ensure safe drinking water for the local population. The findings provide a foundation for further research and action towards sustainable groundwater management in semi-arid environments.

References

Abbasnia, A., Radfard, M., Mahvi, A.H., Nabizadeh, R., Yousefi, M., Soleimani, H., & Alimohammadi, M. (2018). Groundwater quality assessment for irrigation purposes based on irrigation water quality index and its zoning with GIS in the villages of Chabahar, Sistan and Baluchistan, Iran. *Data in Brief*, 19, 623–631. https://doi.org/10.1016/j.dib.2018.05.061

Adegbola, G.A., Dauda, M., & Aluko, T,O. (2019). Assessment of the suitability of water quality for irrigation in Ogbomoso, Oyo State. *GSC Biological and Pharmaceutical Sciences*, 9(2), 21-31. https://doi.org/10.30574/gscbps.2019.9.2.0191

Adesina, O.B., Paul, E.D., Nuhu A.A., Onoyima, C.C. & Okibe, F.G. (2024). Dynamics of Physicochemical Parameters as Indicator of Water Quality: A Study of Ogun River, Nigeria. *Indonesian Journal of Chemical Analysis*, 07(02), 12-25. DOI:10.20885/ijca.vol7.iss2.art2

Adewumi, A.J., Anifowose, A.Y.B., Olabode, F.O., & Laniyan, T.A. (2018). Hydrogeochemical Characterization and Vulnerability Assessment of Shallow Groundwater in Basement Complex Area, Southwest Nigeria. *Contemporary Trends in Geoscience*, 7(1), 72-103 DOI: 10.2478/ctg-2018-0005

ALPHA. (1995). Standard methods for the examination of water and wastewater. 19 edn., American Public Health Association, Washington, DC. USA.

Al-Hadithi, M., Hasan, K., Algburi, A., & Al-Paruany, K. (2019). Groundwater Quality Assessment Using Irrigation Water Quality Index and GIS in Baghdad, Iraq. *Jordan Journal of Earth and Environmental Sciences*, 10 (1), 15-20.

Al-Shaibani, A.M. (2008). Hydrogeology and hydrochemistry of a shallow alluvial aquifer, Western Saudi Arabia. *Hydrogeology Journal*, 16, 155-165.

Al-Shammiri, Al-Saffar, M.A., Bohamad, S., & Ahmed, M. (2005). Wastewater quality and reuse in irrigation in Kuwait using microfiltration technology in treatment. *Desalination*, 185(1–3), 213–225.

Al Yousif, M.A. & Ali Chabuk, A. (2023). Assessment of Water Quality Indices of Surface Water for Drinking and Irrigation Applications – A Comparison Review. *Journal of Ecological Engineering* 2023, 24(5), 40–55. https://doi.org/10.12911/22998993/161194

Andre L., Franceschi P., Pouchan P., & Atteia O. (2005) Using geochemical data and modeling to enhance the understanding of groundwater flow in a regional deep aquifer, Aquitaine Basin, southwest of France. *Journal of Hydrology*, 33, 50-62, https://doi.org/10.1016/j.jhydrol.2004.08.027

Antibachi, D., Kelepertzis E. & Kelepertis, A. (2012). Heavy metals in agricultural soil of Mouriki-Thiva area (central Greece) and environmental impact implications. *Soil Sediment Contamination International Journal*, 21, 434-450.

Anyango, G.W., Bhowmick, G.D., & Bhattacharya, N.S. (2024). A critical review of irrigation water quality index and water quality management practices in micro-irrigation for efficient policy making. *Desalination and Water Treatment*, 318, 100304. https://doi.org/10.1016/j.dwt.2024.100304

Aragaw, T.T. & Gnanachandrasamy, G. (2021). Evaluation of groundwater quality for drinking and irrigation purposes using GIS-based water quality index in the urban area of Abaya-Chemo sub-basin of Great Rift Valley, Ethiopia. *Applied Water Science*, 11, 148. https://doi.org/10.1007/s13201-021-01482-6

Ayers, R.S. & Westcot, D.W. (1994). Water quality for agriculture: FAO Irrigation and Drainage Paper 29, Revision 1, 1-130.

Bashir, E., Naseem, S., & Pirzada, T. (2013). Geochemical study of groundwater of Uthal and Bela areas, Balochistan and its appraisal for drinking and irrigation water quality. *International Journal of Agriculture and Environment*, 2, 1–13.

Bolt G.H. & Bruggenwert, M.G.M. (1978). Soil Chemistry. A: Basic elements, Elsevier, Amsterdam, Netherlands.

Chadha, D.K. (1999). A proposed new diagram for geochemical classification of natural waters and interpretation of chemical data. *Hydrogeology Journal*. 7, 431–439.

Chaudhary, V. & Satheeshkumar, S. (2018). Assessment of groundwater quality for drinking and irrigation purposes in arid areas of Rajasthan, India. *Applied Water Science*, 8, 218. https://doi.org/10.1007/s13201-018-0865-9

Dey, S., Singh, S., Raju, N.J., & Mall, R.K. (2024) Hydrogeochemical characterization for groundwater quality and risk assessment in part of central Gangetic alluvium, India. *Groundwater for Sustainable Development*, 25, 101108. https://doi.org/10.1016/j.gsd.2024.101108

Diouf, O.C., Sarr, H.K., Diedhiou, M., Weihermüller, L., Dieng, N.M., Faye, S.C., Vereecken, H., & Faye, S. (2022). Groundwater Quality for Irrigation Purposes in the Diass Horst System in Senegal. *Water*, 14, 3002. https://doi.org/10.3390/w14193002

Douglas, K.B., Stephen, B., & Kenneth, B. (2015). Mathematical Computation of Water Quality Index of Vea Dam in Upper East Region of Ghana. *Environmental Science*, 3(1), 11-16

Doneen, L. D. (1964). Water Quality for Agriculture, Department of Irrigation.University of California, Davis, 48.

Eduvie, M.O. & Musilim, I. (2024). Groundwater Recharge, Rainwater Harvesting and Regulations for Sustainable Water Resources Development in Nigeria. In: Saha Dipankar, Villholth, K.G., SM (Eds.), Managed Groundwater Recharge and Rainwater Harvesting: Outlook from Developing Countries. Springer Nature Singapore, Singapore, pp. 59–73

Eyinla, D. & Oladunjoye, M.A. (2014). Improving quality agricultural practices in tropical environments through integrated geophysical methods. *IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)*, 2(5), 128–139.

FAO. (2007). Guidelines and computer programs for the planning and design of land drainage systems. FAO irrigation and drainage paper 62, Rome.

FGN (2007). Legal Notice on Publication of the 2006 Census Report. Federal Government of Nigeria official Gazette, 4 (94), 1–8.

Gautam. A. & Rai, S.C. (2023). Hydrogeochemical characterization and quality assessment of groundwater resources in the Upper-Doab region of Uttar Pradesh, India. *Frontiers in Environmental Science*, 11, 1193979. doi: 10.3389/fenvs.2023.1193979

Gibbs R.J. (1970) Mechanisms controlling world water chemistry. *Science*, 170, 3962, 1088-1090, DOI:10.1126/science.170.3962.1088

Goswami, R., Neog, N., & Thakur, R. (2022). Hydrogeochemical assessment of groundwater quality for drinking and irrigation in Biswanath and Sonitpur district of the Central Brahmaputra Plain, India. *Front. Water*, 4, 889128. doi: 10.3389/frwa.2022.889128

Gupta, S.K. & Gupta, I.C. (1987). Management of Saline Soils and Water, Oxford and IBM Publ. Co, New Delhi.

Gusikit, R.B., Haruna, A.I., Dibal, H.U., Yakubu, J.A., & Diyelmak, V.B. (2020). Identification of Hydrogeochemical Processes in Part of the Middle Benue Trough, North Central Nigeria. *World Wide Journal of Multidisciplinary Research and Development*, 6(7), 43-51.

He, B.N., He, J.T., Wang, J., Li, J., & F. Wang, F. (2017). Abnormal pH elevation in the Chaobai River, a reclaimed water intake area. *Environmental Science: Processes and Impacts,* 19(2), 111–122. https://doi.org/10.1039/C6EM00535G

Hossain, M.A., Barma, R.K., Kashem, M.A., Milufarzana, Hasan, M.M. & Rahman, M.S. (2018). Quality Assessment Of Irrigation Water Of Birganj Upazilla Under Dinajpur District. *Tech. J. River Res. Inst*. 14(1), 77-85, 2018.

Hossain, M.S., Nahar, N.,, Shaibur, M.R., Bhuiyan, M.T., Siddique, A.B., Al Maruf, A., & Abu-Khan, S. (2024). Hydro-chemical characteristics and groundwater quality evaluation in southwestern region of Bangladesh: A GIS-based approach and multivariate analyses. *Heliyon*, 10, 2024, e24011. https://doi.org/10.1016/j.heliyon.2024.e24011

Hussain, M. & Rao, D.P. (2013). Assessment of the groundwater quality and its suitability for drinking and irrigation purposes: a case study of Patancheru, Andhra Pradesh, India. *Archive of Applied Science Research*, 5(6), 232–238

Hussein, E.E., Derdour, A., Zerouali, B., Almaliki, A., Wong, Y.J., Ballesta-de, M., Minh, P., Hashim, M.A., & Elbeltagi, A. (2024). Groundwater Quality Assessment and IrrigationWater Quality Index Prediction Using Machine Learning Algorithms. *Water*, 16, 264. https://doi.org/10.3390/w16020264

Ismail, A.Y. & Yola, A.L. (2012). Geoelectrical Investigation of Groundwater Potential of Dawakin Tofa Local Government Area of Kano State Nigeria. American *International Journal of Contemporary Research*, 2(9), 188-197.

Kim, H. & Park, S. (2016). Hydrogeochemical Characteristics of Groundwater Highly Polluted with Nitrate in an Agricultural Area of Hongseong, Korea. *Water*, 8(8), 345. https://doi.org/10.3390/w8080345

Kumar, P.J.S. (2013). Interpretation of groundwater chemistry using Piper and Chadha´s diagrams: a comparative study from Perambalur Taluk. *Elixir Geoscience*, 54, 12208-12211.

Lindsey, B.D., Falls, W.F., Ferrari, M.J., Zimmerman, T.M., Harned, D., Sadorf, E., & Chapman, M. (2006). Factors affecting occurrence and distribution of selected contaminants in groundwater from selected areas in the Piedmont Aquifer System, eastern United States, 1993-2003: U.S. Geological Survey Scientific Investigations Report 2006-5104, 72 p.

Marghade, D. (2020). Detailed geochemical assessment and indexing of shallow groundwater resources in the metropolitan city of Nagpur (western Maharashtra, India) with potential health risk assessment of nitrate-enriched groundwater for sustainable development (2020) Chemie der Erde. *Geochemistry*, 80, 125627. doi: 10.1016/j.chemer.2020.125627

Mateo-Sagasta, J. & Burke, J. (2010). Agriculture and water quality interactions: a global overview. Food and Agriculture Organization (FAO), SOLAW Background Thematic Report - TR08.

McGowan, W. (2000). Water processing: residential, commercial, light-industrial, 3rd ed. Lisle, IL, Water Quality Association.

Meireles, A.C.M., Andrade, E.M.D., & Chaves, L.C.G. (2010). Frischkorn, H.; Crisostomo, L.A. A new proposal of the classification of irrigation water. *Rev. Ciência Agronômica*, 41, 349–357.

M'nassri, S., Amri, A.E., Nasri, N., & Rajouene Majdoub, R. (2022). Estimation of irrigation water quality index in a semi-arid environment using a data-driven approach. Water Supply, 22(5), 5161-5175. doi: 10.2166/ws.2022.157

Mokoena, P., Kanyerere, T., & Donker, J.V. (2020). Hydrogeochemical characteristics and evaluation of groundwater quality for domestic and irrigation purposes: a case study of the Heuningnes Catchment, Western Cape Province, South Africa. *SN Applied Sciences*, 2:1548. https://doi.org/10.1007/s42452-020-03339-0

Mufur, A.M., Awah, M.T., Tamfuh, P.A., Agendia, M.A., Ngambu, A.A., & Kabeyene, V.K. (2021). Groundwater resources for domestic and irrigation purposes in Melong (Littoral Region, Cameroon): hydrogeochemical constraints. *African Journal of Environmental Science and Technology*, 15, 270–281. doi: 10.5897/AJEST2021.3027

Nawrin, N., Junayed, T.R., Khan, M.R., Alam, M.J., Mia, M.B., & Ahmed, K.M. (2022). A Hydrogeochemical Characterization and Quality Assessment of Groundwater from the Sadar Upazila, Khagrachhari District, Bangladesh for Irrigation and Drinking Uses. *Water*, 14, 3052. https://doi.org/10.3390/w14193052

Onoyima, C.C., Okibe, F.G., Ogah, E., & Dallatu, Y.A. (2022). Use of Water Quality Index to Assess the Impact of Flooding on Water Quality of River Kaduna, Nigeria. *Journal of Applied Science and Environmental Management*, 26 (1), 65-70. https://dx.doi.org/10.4314/jasem.v26i1.10

Onoyima, C.C. & Onoyima, N.E. (2023). Pollution Status and Pollution Source Identification in the Groundwater of Yar-Dalla in Wudil, Kano, Nigeria. *Eureka: Life Sciences*, 4, 12-21. DOI: 10.21303/2504-5695.2023.003034

Ouarani, M., Bahir, M., Mulla, D.J., Ouazar, D., Chehbouni, A., Dhiba, D., Ouhamdouch, S., & El Mountassir, O. (2020), Groundwater Quality Characterization in an Over allocated Semi-Arid Coastal Area Using an Integrated Approach: Case of the Essaouira Basin, Morocco. *Water*, 12, 3202. doi:10.3390/w1211320

Paternoster, M., Buccione, R., Canora, F., Buttitta, D., Panebianco, S., Rizzo, G., Sinisi, R., Summa, V., & Mongelli, G. (2021). Hydrogeochemistry and Groundwater Quality Assessment in the High Agri Valley (Southern Italy). *Hindawi Geofluids*, 2021, 6664164. https://doi.org/10.1155/2021/6664164

Piper, A.M. (1994). A graphic procedure in the geochemical interpretation of water-analyses. *Transactions of the American Geophysical Union*, 25, 914–928. doi:10.1029/TR025i006p00914

Raghunath, H.M. (1987). Groundwater, Wiley, New Delhi.

Ravikumar, P., Somashekar, R.K., & Prakash, K.L. (2015). A comparative study on the usage of Durov and Piper diagrams to interpret hydrochemical processes in groundwater from the SRLIS river basin, Karnataka, India. *Elixir Earth Science*, 80, 31073-31077.

Rawat, K.S., Singh, S.K., & Gautam, S.K. (2018). Assessment of groundwater quality for irrigation use: a peninsular case study. *Appl. Water Sci*., 8, 233. doi: 10.1007/s13201-018-0866-8

Richard, L.A. (1954). Diagnosis and Improvement of Saline and Alkali Soils. Edit. US Department of Agriculture, Agricultural Handbook n◦60, Washington, DC, 160. doi:10.1097/00010694-195408000-00012

Sanchez-Martos F, Bosch, A.P., & Calaforra, J.M. (1999). Hydrogeochemical processes in an arid region of Europe (Almeria, SE Spain). *Applied Geochemistry*, 14, 735–745.

Sharma, N., Vaid, U., & Sharma, S.K. (2021). Assessment of groundwater quality for drinking and irrigation purposes using hydrochemical studies in Dera Bassi town and its surrounding agricultural area of Dera Bassi Tehsil of Punjab, India. *SN Applied Sciences*, 3, 245. https://doi.org/10.1007/s42452-021-04199-y

Simsek, C., & Gunduz, O. (2007). IWQ index: A GIS integrated technique to assess irrigation water quality. *Environmental Monitoring and Assessment,* 128, 277–300.

Talib, M.A., Tang, Z., Shahab, A., Siddique, J., Faheem, M., & Fatima, M. (2019). Hydrogeochemical Characterization and Suitability Assessment of Groundwater: A Case Study in Central Sindh, Pakistan. *International Journal of Environmental Research and Public Health*, 16, 886.

Tatawat, R.K. & Chandel, C.P.S. (2008). A hydrochemical profile for assessing the groundwater quality of Jaipur City. *Environmental Monitoring and Assessment*, 143, 337–343. doi: 10.1007/s10661-007-9936-3

Todd, D.K. (1980). Groundwater hydrology. Wiley, New York

Todd, D.K. & Mays, L.W. (2005). Groundwater Hydrology, Wiley, New York, 3rd edition.

Udom, E.A., Ekpo, A.E., & Oluka, S.L. (2019). Assessment of Irrigation Water Qualities of Abak River, Abak, Akwa Ibom State, Nigeria. *Global Journal of Pure And Applied Sciences*, 25, 135-144. https://dx.doi.org/10.4314/gjpas.v25i2.2

UNEP. (2005). Vital Water Graphics. Found at: Unep.org

Venugopal, T., Giridharan, L., Jayaprkash M., & Periakali, P. (2009). Environmental impact assessment and seasonal variation study of the groundwater in the vicinity of River Adyar, Chennai, India. *Environmental Monitoring and Assessment*, 149, 81-97.

Wilcox, L.V. (1955). Classification and Use of Irrigation Water; USDA Circular No. 969: Washington, DC, USA, 1–19.

Xia, C., Liu, G., Xia, H., Jiang. F., & Meng, Y. (2021). Influence of saline intrusion on the wetland ecosystem revealed by isotopic and hydrochemical indicators in the Yellow River Delta, China. *Ecological Indicators*, 133, 108422. https://doi.org/10.1016/j.ecolind.2021.108422

Xu, P., Feng, W., Qian, H., & Zhang, Q. (2016). Hydrogeochemical Characterization and Irrigation Quality Assessment of Shallow Groundwater in the Central-Western Guanzhong Basin, China. *International Journal of Environmental Research and Public Health*, 16, 1492; doi:10.3390/ijerph16091492

Xu, F., Li, P., Wang, Y., & Du, Q. (2023). Integration of hydrochemistry and stable isotopes for assessing groundwater recharge and evaporation in pre-and post-rainy seasons in the Hua County, China. *Natural Resources Research*, 32(5), 1959–1973.

Zaman, M., Shahid, S.A., & Heng, L. (2018). Irrigation water quality. In Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques; Springer: Berlin/Heidelberg, Germany, pp. 113–131.

Zhou, Y., Li, P., Xue, L., Dong, Z., & Li., D. (2020). Solute geochemistry and groundwater quality for drinking and irrigation purposes: a case study in Xinle City, North China. Geochemistry, 80(4), 125609. https://doi.org/10.1016/j.chemer.2020.125609

Ziani, D., Boudoukha, A., Boumazbeur A., & Benaabidate, L. (2017). Water quality assessment for drinking and irrigation using major ions chemistry in the semiarid region: case of Djacer spring, Algeria. *Asian Journal of Earth Science*, 10, 9-21. DOI:10.3923/ajes.2017.9.21