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Full Length Research

Seasonal variation in quality of rural groundwater in Kachi, Dutse Local Government Area, Jigawa State, based on physicochemical characteristics and water quality index

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ABSTRACT: Groundwater is a key source of water for domestic and rural use, yet its quality is highly influenced by seasonal fluctuations and local geochemical processes. This study provides a comprehensive assessment of seasonal groundwater quality in the study area by integrating physico-chemical parameters, Water Quality Index (WQI), Pollution Index (PI), and Principal Component Analysis (PCA). Water samples were collected from selected boreholes during wet and dry seasons and analysed using standard laboratory procedures, with results compared against WHO drinking water guidelines. Seasonal variation was pronounced: pH ranged from 7.10 (wet) to 7.54 (dry), while electrical conductivity (EC) varied significantly from 426 µS cm^{-1} (dry) to 2645 µS cm^{-1} (wet). Major ions such as Na^{+} (55.78–767.97 mg L^{-1}), K^{+} (62.24–799.12 mg L^{-1}), Ca^{2+} (875.60–911.86 mg L^{-1}), Mg^{2+} (139.66–447.29 mg L^{-1}), Cl^{-}, SO_4^{2-}, PO_4^{3-}, and HCO_3^{-} frequently exceeded permissible limits in multiple wells. WQI (68.5–414.8 dry; 185.5–596.3 wet) and PI confirmed that the majority of samples were unsuitable for drinking, with more severe deterioration during the wet season due to surface runoff, recharge, and solute mobilisation. PCA revealed that dry season water chemistry was largely controlled by salinity enrichment and mineral dissolution, whereas wet season patterns reflected ion redistribution and increased nutrient influence, indicating the combined effect of geogenic and anthropogenic factors. These results highlight significant spatial and seasonal heterogeneity in groundwater quality and emphasise the urgent need for routine monitoring, appropriate treatment strategies, and sustainable management practices to ensure safe water supply and protect public health in rural communities.

Keywords: Groundwater, Water Quality Index (WQI), Borehole water, Major ions, Drinking water standards, Groundwater management, Wet and dry seasons.

INTRODUCTION

Freshwater resources are under growing global pressure due to population growth, urbanisation, industrialisation, and climate change. Over 2 billion people worldwide face water scarcity at least one month per year, while pollution from human activities, agricultural runoff, mining and inadequate waste management increasingly threaten water quality (Mekonnen and Hoekstra, 2016; Joshua *et al*., 2025). Globally, water-related challenges manifest as scarcity, excess, or contamination, all of which have significant implications for human health, agriculture, and sustainable development (Hamidu *et al*., 2017).

In Africa, semi-arid and arid climates, highly seasonal rainfall, and rapidly growing populations exacerbate water resource challenges. Groundwater remains the primary source of potable water for many rural communities, yet contamination from agricultural chemicals, domestic waste, and industrial effluents is increasingly common (Coker *et al*., 2020). Seasonal climate variations further influence groundwater recharge, physicochemical characteristics, and overall suitability for domestic and

agricultural use.

In Nigeria, rural populations heavily depend on groundwater, particularly during the long dry season when surface water sources such as ponds, streams, and small dams diminish. Human activities, unsustainable agricultural practices, and inadequate waste management increasingly compromise groundwater quality (Abdullahi *et al*., 2021; Garba *et al*., 2016). Semi-arid regions, including Jigawa State, experience pronounced seasonal fluctuations in rainfall and temperature, which affect groundwater availability and physicochemical parameters. The hydrogeology of the area, comprising both sedimentary and Basement Complex aquifers, further influences groundwater occurrence and quality, with weathering, fracturing, and permeability controlling water storage and flow (Garba *et al*., 2016).

Kachi, a rural community in Dutse Local Government Area of Jigawa State, exemplifies these challenges. Groundwater is the primary water source for domestic, agricultural, and livestock use, yet it is vulnerable to contamination from human and agricultural activities. Despite the critical reliance on groundwater, few studies have examined how seasonal climatic and hydrogeological factors jointly influence groundwater quality at the community level (Tukur *et al*., 2019; Tahir *et al*., 2022; Ahmed *et al*., 2023). Integrating physicochemical analyses with the Water Quality Index (WQI) allows for a comprehensive assessment, consolidating multiple parameters into a single numerical score to evaluate water suitability.

This study investigates seasonal variations in groundwater quality in Kachi, Dutse LGA, Jigawa State, with a focus on implications for domestic water supply and sustainable resource management. By quantifying temporal changes in key water quality parameters, the research provides evidence-based insights for safe and sustainable groundwater management in rural Nigeria and offers lessons applicable to similar semi-arid regions across Africa and globally.

MATERIALS AND METHODS

Study area

Kachi is a rural village in Dutse Local Government Area of Jigawa State, north-western Nigeria, located between latitudes 11°67′N and 11°74′N and longitudes 9°32′E and 9°36′E, and bordered by Limawa, Jigawar Tsada, and Madobi communities (Figure 1). The area is predominantly agrarian, with subsistence farming, livestock rearing, and small-scale trading as the main livelihoods, all strongly shaped by seasonal climatic conditions. Kachi lies within the semi-arid Sudan–Sahel ecological zone, characterised by a long dry season and a short wet season, with generally hot temperatures throughout the year. Mean annual temperature is about 25°C, ranging from approximately 21°C in the coolest months (December–January) to around 31°C in May. Rainfall is highly seasonal, occurring mainly between June and September, with annual totals of about 600–800 mm and peak rainfall in August, while the extended dry season from October to May increases dependence on groundwater resources. Relative humidity also varies significantly, reaching 60–80% during the wet season but dropping to 20–30% in the dry Harmattan period, which enhances evaporation, reduces surface water availability, and further intensifies reliance on groundwater for domestic and agricultural needs.

Geology and hydrogeology

Geologically, Kachi lies within the Hadejia–Yobe Basin, a structurally triangular basin forming the south-western arm of the Lake Chad Basin in Nigeria (Hamidu *et al*., 2017). The area is underlain by a mixture of crystalline Basement Complex rocks and sedimentary formations, producing an undulating landscape with Basement outcrops in several locations and sedimentary deposits dominating the low-lying zones (Figure 2). Elevation generally ranges between 500 and 600 m above sea level (Garba *et al*., 2016). This geological setting gives rise to two main aquifer systems: sedimentary aquifers, which typically have higher permeability and storage capacity, and Basement Complex aquifers, where groundwater occurrence is largely controlled by the extent of weathering and fracturing (Garba *et al*., 2016). Recharge occurs mainly from rainfall, with additional inputs from irrigation return flow and localised infiltration from rivers, ponds, seasonal streams, and small dams (Garba *et al*., 2016; Coker *et al*., 2020). Groundwater is discharged primarily through hand-dug wells and boreholes, which serve as the main domestic water sources, particularly during the long dry season when surface water becomes scarce. Consequently, the strong seasonal variations in climate significantly influence groundwater recharge and availability, placing increased stress on wells and boreholes during dry months and underscoring the importance of sustainable groundwater management in the area (Coker *et al*., 2020; Alao *et al*., (2024)

Data sources

Primary data for this study were obtained through field sampling of groundwater sources (wells and boreholes) within the study area. A preliminary survey identified a total of 23 wells and boreholes, of which only six were functional at the time of sampling. Geographically referenced coordinates of all sampling points were recorded using a hand-held Global Positioning System (GPS) receiver to ensure accurate spatial representation.

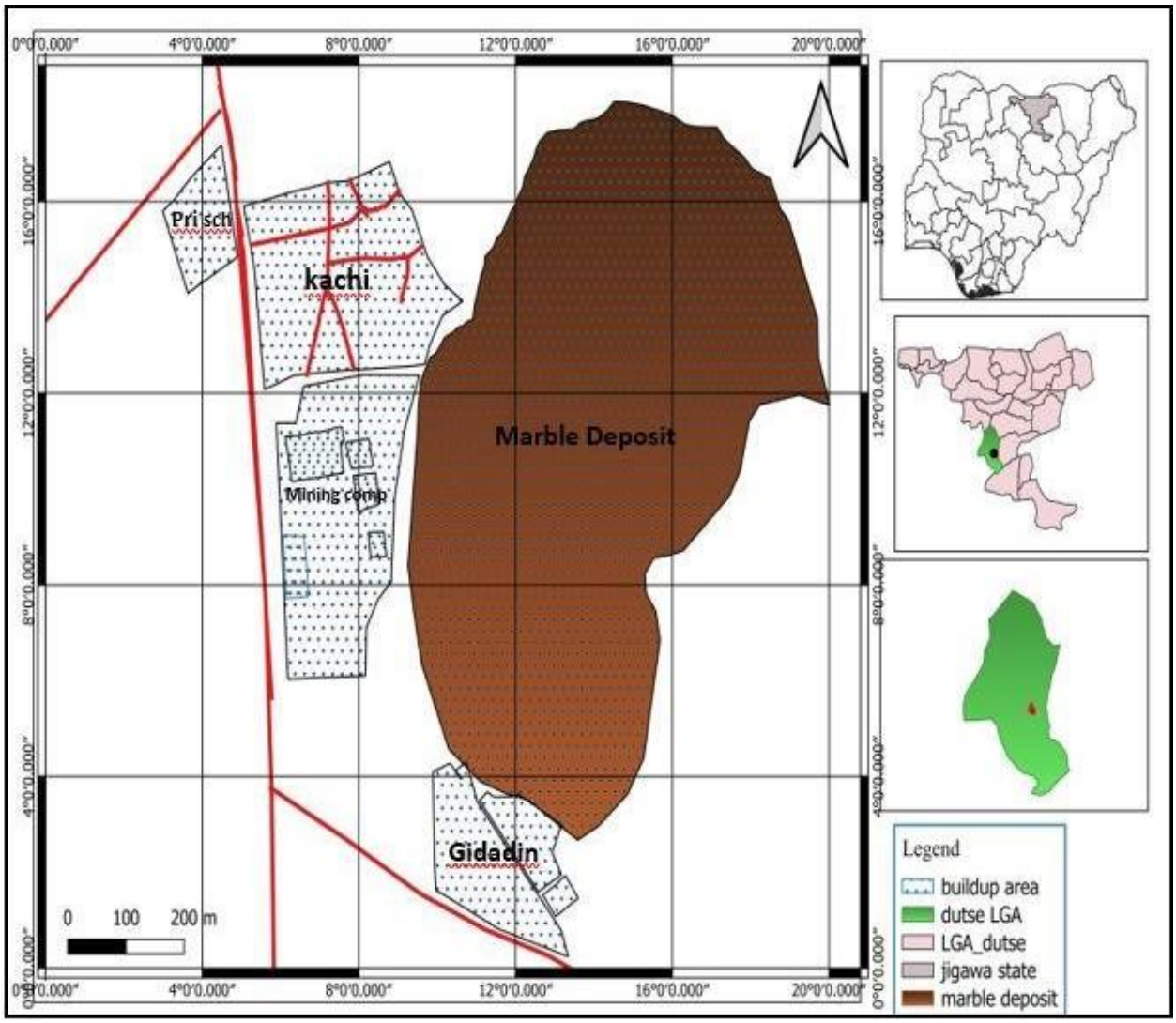

Figure 1. Map of the study area (Source: GIS Laboratory, Federal University, Dutse, 2023).

Sampling design and sample collection

Purposive sampling was adopted to select six (6) groundwater sampling locations in areas where mining activities are prevalent. Selection was based on the proximity of water sources to mining sites in order to assess possible contamination gradients.

Water samples were collected during both the dry and wet seasons (March representing the dry season and August representing the wet season). Samples were obtained in 750 mL plastic containers, which were thoroughly rinsed with deionised water prior to collection to minimise contamination. Each bottle was properly labelled according to its respective sampling location for accurate identification and traceability, following standard water sampling procedures (APHA *et al.,* 2024). pH, conductivity, temperature, and turbidity were measured at the sampling sites in accordance with the standard protocols and methods prescribed by the American Public Health Association using different calibrated standard instruments (APHA *et al*., 2024).

Sample preservation and preparation

Water samples were disinfected with sodium hypochlorite and subsequently neutralised using sodium thiosulfate. Sample digestion was performed with a mixture of hydrochloric acid (HCl) and nitric acid (HNO_3) at elevated temperature until the solution became clear. The digest was then filtered through Whatman No. 42 filter paper into a 50 mL volumetric flask and diluted to the mark with deionised water to obtain a prepared sample solution for chemical constituent analysis. This approach follows standard procedures for groundwater chemical analysis as used in recent hydrogeochemical studies (Onoyima *et al*., 2025).

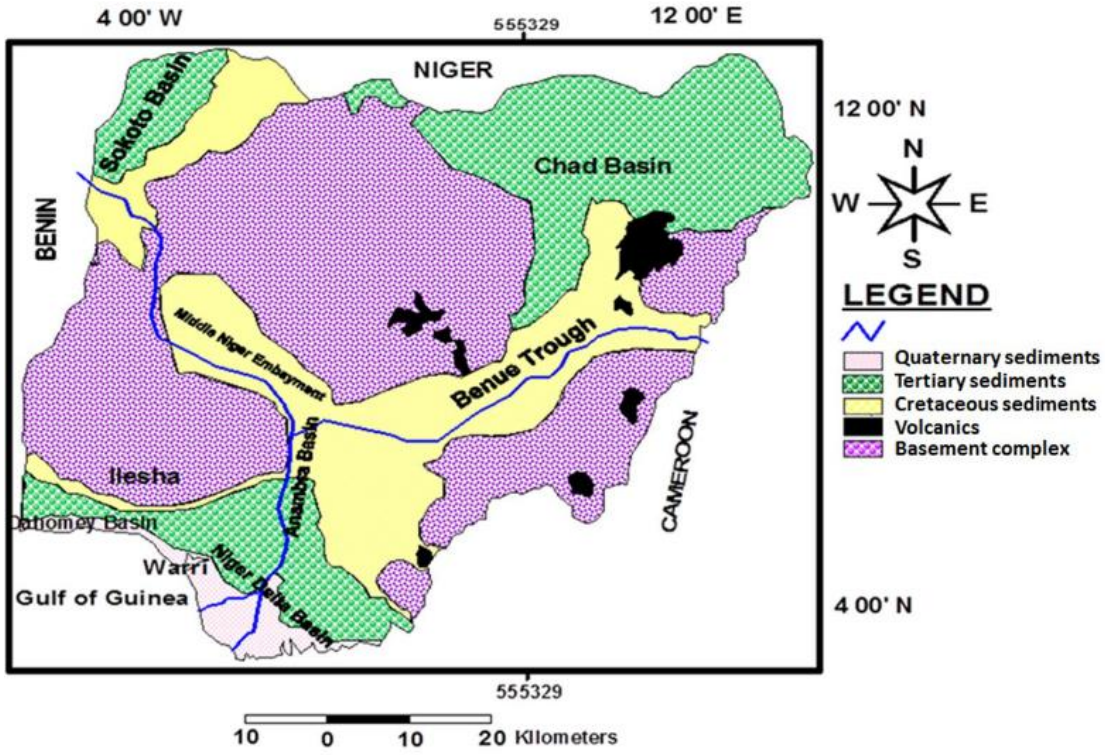

Figure 2. Geological map of Nigeria showing Basement Complex and Sedimentary formations **(Source:** Ologe *et al*., 2014).

Physicochemical analysis

Physicochemical parameters, including pH, electrical conductivity, temperature, and turbidity, were measured in situ at the sampling sites using calibrated field instruments. Conductivity was measured with a conductivity meter, turbidity with a portable turbidity meter, and pH with a digital pH meter calibrated using standard buffer solutions of pH 4 and pH 7. Temperature was measured using a mercury thermometer. All measurements were carried out following standard protocols outlined by APHA *et al. (*2024).

Determination of major cations

The cations analysed in this study are Calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na), and potassium (K^{2+}). Analysis was carried out using an Atomic Absorption Spectrophotometer (Perkin–Elmer Analyst 400) in accordance with the methods described by Mahmud *et al*. (2024).

Determination of major anions

For anion analysis, the concentration of Sulphate (SO_4^{2-}) in the groundwater samples was determined using the turbidimetric method, which is based on the formation of barium sulphate in the presence of acidified barium chloride (HCl). The reaction was enhanced by the addition of glycerol and other organic compounds, and the absorbance of the resulting colloidal solution was measured against a standard using a UV–Visible spectrophotometer (Mgbeojedo and Al-Naimi, 2018). Phosphate content was determined using the molybdate blue method. Chloride (Cl^-) concentration was measured by titration, while bicarbonate (alkalinity) was determined by titrating 100 mL of the sample with 0.01 mol dm^{-3} H_2SO_4, using phenolphthalein and methyl orange indicators, with pH monitored until a final value of 4.5 was reached (Hassan and Iliyasu, 2021).

A paired t-test was used to determine whether groundwater physicochemical parameters differed significantly between the wet and dry seasons. This test was appropriate because samples were collected from the same locations in both seasons, allowing seasonal changes to be assessed through paired comparisons. SPSS version 25.0 and Microsoft Excel were used for the t-test, p=0.5 was used to determine the significant differences in seasonal variation of groundwater physicochemical parameters. The mean value of observed parameters in the groundwater samples was compared with the WHO and NSDWQ using a simple comparison method (Table 1).

WQI was determined using various parameters such as

Table 1. Comparison of mean concentration of the physicochemical parameters of the assayed water samples with standards.

Parameters	Dry Season			Wet Season			WHO (2011)	NSDWQ (2007)
	Min	Max	Mean	Min	Max	Mean		
Temperature	32	32.4	32.22	26.7	26.8	26.75	NA	NA
pH	7.47	7.61	7.54	7	7.2	7.1	6.5-8.5	6.5-8.5
Conductivity (*μ*S/cm)	710	747	426	444	5060	2645.33	1250.00	1000.00
TDS	454.4	4780.8	2762.67					
Turdidity (NTU)	2.56	1.78	1.99	1.66	4.13	2.69	5.00	5.00
Calcium (mg/L)	79.308	1763.42	875.6	507.9	1245.36	911.86	75.00	75.00
Magnesium (mg/L)	184.58	953.67	447.29	28.47	241.36	139.66	50	30.00
TH as (CaCo3)(mg/L)	1110.53	8319.42	3863.23	706.84	4104.48	2322.75	≤ 500	500
Sodium (mg/L)	300.31	1575.49	767.97	6.16	101.14	55.78	200.00	200.00
Potassium (mg/L)	64.14	2026.54	799.12	8.77	115.71	62.24	55.00	200.00
Sulphate (mg/L)	0.57	2.25	1.43	9.09	15.16	11.32	500	100.00
Phosphate (mg/L)	9.7	12.12	10.70	0.54	0.87	0.73	5.0	NA
Chloride (mg/L)	532.5	4082.5	2012.3	355	8875	2869.58	250	NA
Bicarbonate (mg/L)	27.45	100.65	69.64	11.44	22.88	19.06	600	NA

pH, turbidity, electrical conductivity, calcium, magnesium, sodium, potassium, chlorides, sulphate, phosphate and bicarbonate. This provides a single numerical value that expresses the overall water quality at a certain location and time based on several parameters (Mathur *et al*., 2024).

The method has been widely used by various scientists, and the calculation of WQI was made by using the following equation:

$$WQI = \frac{\sum_{i=1}^{n} Q_i W_i}{\sum_{i=1}^{n} W} \quad \text{i}$$

Where: Q_i= quality rating of the i-th water quality parameter, W_i= weight assigned to the i-th parameter, n= total number of parameters considered

The quality rating scale (Qi) for each parameter is calculated by using this expression:

$$Q_i = 100 \times \frac{V_i - V_0}{S_i - S_0} \quad \text{ii}$$

Where: Q_i= quality rating for the i-th water quality parameter, V_i= measured value of the i-th parameter, S_i= standard permissible value of the i-th parameter (WHO or NSDWQ), V_0= ideal value of the parameter in pure water (typically 0 for most parameters except pH, which is 7).

The unit weight ($W\ i$) for each water quality parameter is calculated by using the following formula:

$$W_i = \frac{K}{S_i} \quad \text{iii}$$

Where: K = Proportionality constant and can also be calculated by using the following equation:

$$\mathrm{K} = \frac{1}{\sum 1/Si} \quad \text{iv}$$

The rating of water quality according to this WQI is given in Table 1 (Boah *et al*., 2015). To further validate the results, the Water Quality Index (WQI) analysis was compared with the Groundwater Pollution Index (PIG), allowing cross-verification of seasonal water quality assessments. Pollution Index (PI) for Groundwater was used by integrating multiple physicochemical parameters into a single index. The pollution index (PI) was calculated in is a five-steps. In the first step, the relative weight (Rw) was assigned to selected parameters on a scale of 1 to 5 (Subba Rao, 2012). The second step involves the calculation of the weight parameter (Wp) for each selected element of groundwater using Eq. ii (Table 1). After that, the concentration status (Sc) for each selected element has been calculated using Eq. iii in step three, where C represents the concentration of each variable in the groundwater sample and Ds represents the standard limit. For this, standard limits (Ds) set by the Standard Organisation of Nigeria (SON, 2015), Nigerian Standard for Drinking Water Quality (NSDWQ), and World Health Organisation standards (WHO, 2017) have been used. The fourth step involves the calculation of the overall quality (Ow) for each element using Eq. iv. Finally, the PIG is determined using Eq. v by the summation of the overall water quality (Ow) values of all selected elements for each sample.

$$PI_i = \frac{C_i}{S_i} \quad \text{v}$$

Where: PI_i = pollution index of the (i)-th parameter, C_i = measured concentration of the parameter in groundwater, S_i = standard permissible limit of the parameter (e.g., WHO/IS:10500).

Each parameter is assigned a weight W_i based on its relative importance (Table 5), and the overall Pollution Index (RPI) is computed as a weighted average:

$$PI = \frac{\sum_{i=1}^{n} W_i \cdot PI_i}{\sum_{i=1}^{n} W_i} \quad \text{vi}$$

Where: *PI* = overall groundwater pollution index, W_i= weight assigned to the (i)-th parameter, *n* = total number of parameters considered.

The PIG was used to classify groundwater quality into categories (e.g., excellent, good, moderate, poor, very poor), facilitating a comprehensive and practical assessment of water pollution levels (Table 6).

Additionally, the Groundwater Pollution Index (PIG) results were interpreted alongside Principal Component Analysis (PCA) to identify key contributing parameters and sources of groundwater contamination, providing a comprehensive understanding of water quality dynamics. PCA was performed on dry and wet season groundwater data using SPSS 23. PCs with eigenvalues ≥1 were extracted, and varimax normalised rotation was applied to obtain interpretable loadings. Parameter loadings were classified as strong (>0.75), moderate (0.50–0.75), and weak (0.40–0.50), with loadings <0.40 considered insignificant. Laboratory data were normalised by their maximum values prior to PCA. The PCs were interpreted to identify natural processes (e.g., mineral dissolution, carbonate buffering) and anthropogenic influences (e.g., nutrient input, urban runoff), consistent with seasonal variations in groundwater chemistry (Arıman *et al*., 2024; Abdulsalam *et al*., 2022; Pitchaimani *et al*., 2024). Parameters were standardised using:

$$Z_{ij} = \frac{X_{ij} - \bar{X}_J}{\sigma_j} \quad \text{vii}$$

Where: X_{ij}= value of variable $j$in sample i, $\bar{X}_J$= mean of variable j, and σ_j= standard deviation of variable j.

After standardisation, each variable has a **mean = 0** and a **variance = 1**, so PCA is not biased by units. The covariance matrix was computed, which shows how variables vary together.

$$C_{jk} = \text{cov}(Z_j, Z_k) \quad \text{viii}$$

RESULTS AND DISCUSSION

Physicochemical parameters of groundwater samples

The results of physicochemical parameters of groundwater in Kachi show variation both spatially and seasonally (Table 1). A comparison of the analysed physicochemical properties of the water samples with the World Health Organisation (WHO) standards, along with the water quality index for each sample location, is presented in Table 1. The spatial and temporal variation in physicochemical analysis of the six selected water samples are depicted in Figures 3 to 15.

Temperature

The analysis shows a clear seasonal contrast in groundwater temperature, with higher average values observed in the dry season (32.22°C) and lower values during the wet season (26.75°C) (Figure 3). This pattern can be attributed to intensified solar radiation, minimal cloud cover, and reduced groundwater recharge in the dry period, while rainfall, increased cloudiness, and atmospheric cooling exert a moderating effect during the wet season. Related findings were also recorded in Zaria, Kaduna State, where temperature fluctuations were linked mainly to prevailing climatic conditions rather than human-induced influences (Eneogwe *et al*., 2022). Similar seasonal trends have been observed globally, such as in coastal aquifers in Spain, where dry periods coincide with groundwater warming (Yanes *et al*., 2025), and in shallow aquifers affected by climate-driven warming trends (Benz *et al*., 2024). Although regulatory standards do not specify permissible limits for water temperature, elevated values in the dry season may accelerate chemical reactions and stimulate biological processes within aquatic systems.

pH

The pH of the groundwater samples varied between 7.47 and 7.61 in the dry season and from 7.0 to 7.2 during the wet season (Figure 4). The highest pH value was recorded at GWS-4 and GWS-5 during the dry season with pH values of 7.96 and 7.99, respectively, while the lowest pH value of 7.0 was recorded at GWS-1, GWS-4 and GWS-6, respectively (Table 3). In both periods, the water exhibited neutral to slightly alkaline conditions, with values falling within the permissible limits recommended by the World Health Organisation and the Nigerian Standard for Drinking Water Quality (6.5–8.5) (Table 1). The slightly elevated pH observed in the dry season may be linked to evaporative concentration effects and increased bicarbonate levels, whereas the marginal reduction in the wet season is likely due to dilution and the introduction of weak organic acids from surface runoff. This corresponds with seasonal consistency in groundwater pH documented in Onitsha Metropolis, Anambra State, where seasonal variations were minimal and largely governed by the buffering capacity of the aquifer system (Okolo *et al*., 2023). Comparable trends have also been reported in Ilorin, Kwara State, indicating that groundwater pH in many Nigerian hydrogeological environments is relatively stable despite seasonal fluctuations (Dauda and Shuaib-

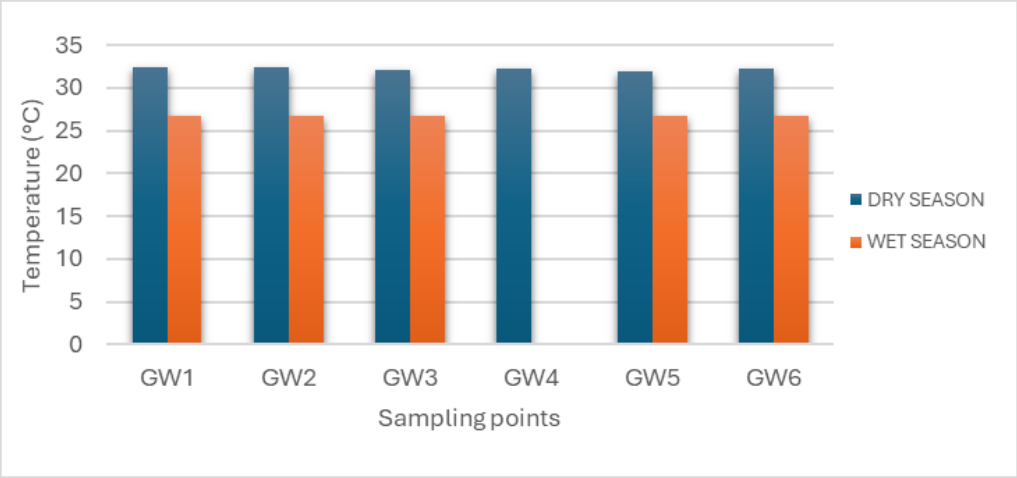

Figure 3. Seasonal variation of temperature of groundwater.

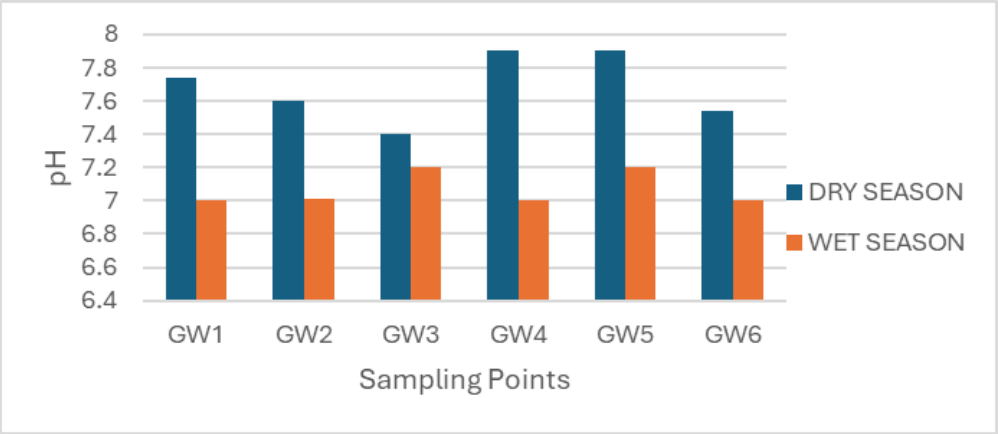

Figure 4. Seasonal variation of pH in groundwater.

Na'Allah, 2021). Similar patterns of neutral to slightly alkaline groundwater with minor seasonal variation have been reported globally; for example, in Central Asian aquifers, groundwater pH was generally higher during dry or winter periods and lower in wetter months due to recharge and water–rock interaction processes (Du *et al*., 2025)

Electrical conductivity (EC)

Electrical conductivity exhibited marked seasonal variation, with higher values recorded during the dry season compared to the wet season (Figure 5). In the dry season, EC ranged from 710 to 7470 µS cm^{-1}, averaging 4260 µS cm^{-1}, while in the wet season, values ranged from 444 to 5060 µS cm^{-1}, with a mean of 2645.33 µS cm^{-1} (Table 1). The lowest conductivity of 710µS cm-1 was observed at sampling site GWS-5, and the highest 7470µS cm^{-1} was observed at GWS-1 during the dry season. There is a slight reduction in the conductivity during raining season, the highest recorded for this period was 5060µS cm-1 GWS-1), and the lowest was 444µScm-1 at GWS-4, as presented in Table 3. The elevated dry-season EC reflects the concentration of dissolved ions due to limited recharge, evaporation, and the accumulation of salts, whereas the comparatively lower wet-season values result from dilution by rainfall. Similar seasonal patterns have been observed in Idemili South and Nnewi North, Anambra State, where runoff and ion mobilisation during rainfall events significantly influenced groundwater EC (Akukwe *et al*., 2025). In coastal regions like Bonny Island, Rivers State, seasonal EC fluctuations have been attributed to increased mixing between freshwater and saline sources during the wet season (Okoli *et al*., 2024). Seasonal EC fluctuations have also been reported in the central plains of Punjab, India, where higher dry-season conductivity corresponded with reduced dilution and enhanced mineral

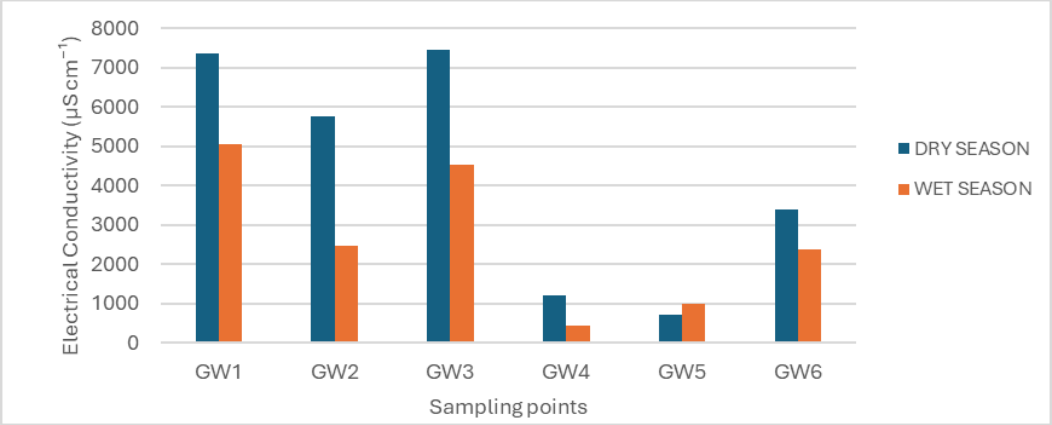

Figure 5. Seasonal variation of electrical conductivity of groundwater.

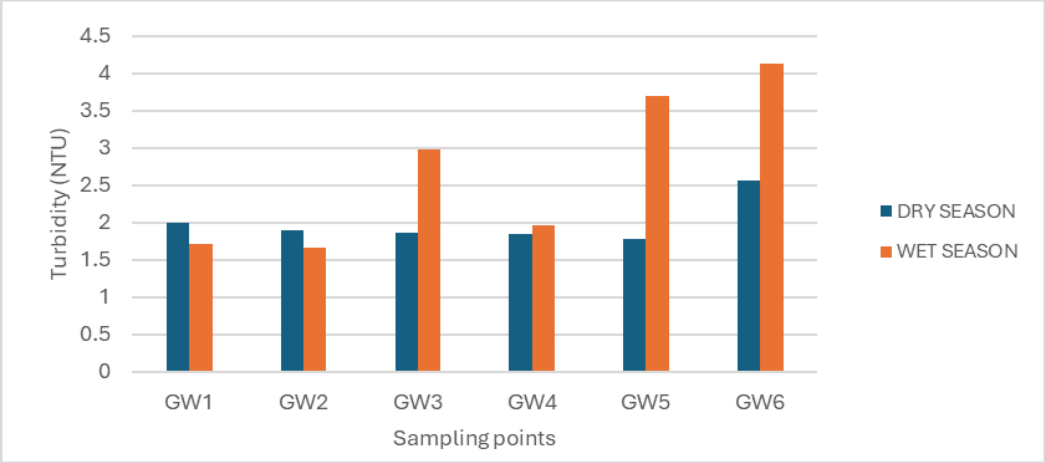

Figure 6. Graphical presentation of seasonal variation of turbidity in groundwater.

dissolution (Singh *et al*., 2023). The occurrence of EC values above recommended limits highlights potential salinity-related water quality challenges in the study area.

Turbidity

Turbidity levels in the groundwater remained within the WHO and NSDWQ recommended limit of 5 NTU in both seasons (Table 1), though slightly higher values were recorded during the wet season. In the dry season, turbidity ranged from 1.78 to 2.56 NTU, with a mean of 1.99 NTU, whereas the wet season showed an increase, with values averaging 4.13 NTU (Figure 6). Very high turbidity values were obtained in the wet season compared to the dry season. A comparatively low water turbidity of 2.56 NTU was found at sample site GWS-6 in the dry season. The highest value of 4.13NTU was found at sample site GWS-6 during the wet season, as shown in Table 3. The higher wet-season turbidity reflects greater sediment mobilisation and transport from surrounding catchment areas during rainfall events. Comparable seasonal turbidity trends have been reported in groundwater and surface water systems in Ado-Ekiti, Ekiti State, where elevated wet-season turbidity was linked to erosion and runoff processes (Akinbile and Yusoff, 2011). Overall, the low turbidity levels suggest minimal particulate contamination and indicate the effectiveness of natural filtration mechanisms within the aquifer system.

Calcium (Ca^{2+})

Calcium concentrations in the groundwater were consistently high across both seasons, exceeding the WHO and NSDWQ guideline limits (Table 1). During the dry season, Ca^{2+} levels ranged from 79.3 to 1763 mg/L, with a mean of 875.5 mg/L, while wet-season concentrations ranged from 507.9 to 1245.36 mg/L, averaging 911.86 mg/L (Figure 7). The highest dry season concentration

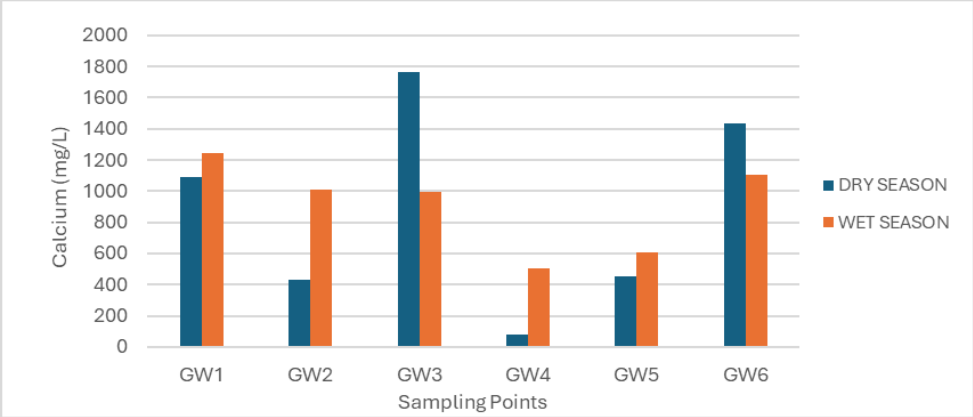

Figure 7. Seasonal variation of Calcium in groundwater samples.

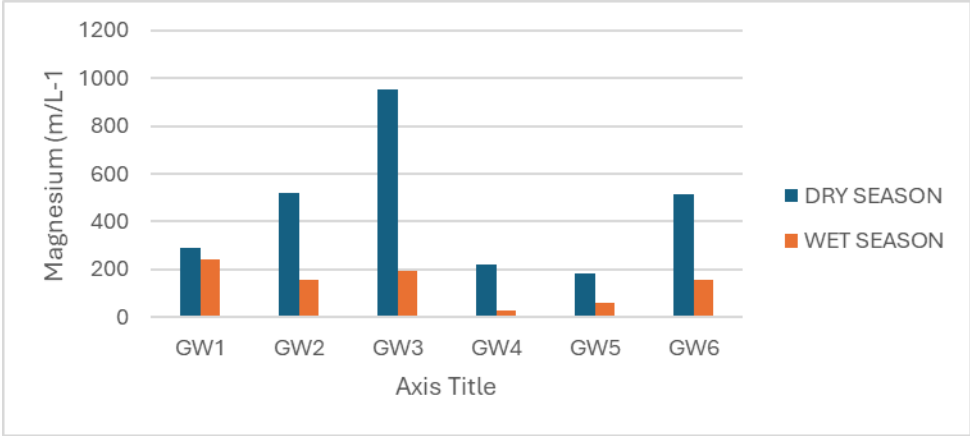

Figure 8. Seasonal variation of Magnesium in groundwater samples.

of 1763 mg/L was observed in GWS-3, while the lowest concentration of 79.3 mg/L is in GWS-4. The lowest wet season concentration of Ca2+ was observed at GWS 4, and the highest concentration was at GWS1 (Table 3). The elevated calcium levels suggest a strong geogenic influence, primarily from the dissolution of calcium-bearing minerals such as calcite and dolomite within the aquifer. Slightly higher dry-season concentrations likely result from evaporative concentration and reduced groundwater recharge, whereas wet-season values reflect partial dilution from rainfall infiltration. Similar patterns of calcium enrichment have been documented in Ilorin, Kwara State, where carbonate mineral weathering was identified as the main source of Ca^{2+} irrespective of season (Dauda and Shuaib-Na'Allah, 2021). Comparable observations were also made in Onitsha Metropolis, Anambra State, where ongoing water–rock interactions maintained elevated calcium levels year-round (Okolo *et al.*, 2023). High calcium concentrations contribute significantly to total water hardness, potentially affecting domestic water use and the longevity of water-related infrastructure. Similar global trends have been reported in Punjab, India, where seasonal hydrochemical analyses revealed that calcium is the predominant cation in groundwater, showing significant seasonal variability associated with monsoon inputs and local geologic conditions (Singh *et al.*, 2023).

Magnesium (Mg^{2+})

Magnesium concentrations were elevated in both seasons, exceeding recommended limits, with higher values observed during the dry season (Table 1). In the dry season, Mg^{2+} ranged from 184.5(GWS 5) to 953.6 mg/L (GWS3), averaging 447.29 mg/L, while wet-season values varied from 28.47 mg/L (GWS4) to 241.36 mg/L (GWS1), with a mean of 139.66 mg/L (Figure 8). This pattern indicates that magnesium primarily originates from the dissolution of ferromagnesian minerals and clay-rich geological formations, with dry-season concentrations amplified by reduced dilution and longer groundwater residence times. Similar seasonal dominance of Mg^{2+}

during dry periods has been reported in Zaria, Kaduna State, where extended water–rock interactions governed hydrochemical evolution (Eneogwe *et al*., 2022). In Ilorin, Kwara State, magnesium was found to significantly contribute to groundwater hardness and exhibited minimal seasonal dilution, further supporting its geogenic origin (Dauda and Shuaib-Na'Allah, 2021). Seasonal hydrochemical studies in Douala, Cameroon, also identified magnesium as a major cation in groundwater, with its relative abundance influenced by rock weathering and ion exchange processes that vary between dry and wet periods (Akoachere *et al*., 2019). Elevated magnesium levels may affect water taste and, at excessive concentrations, could pose mild health risks.

Total hardness (as $CaCO_3$)

Groundwater in the study area exhibited consistently elevated total hardness (TH) across both dry and wet seasons, indicating extremely hard water unsuitable for direct domestic use. TH ranged from 1,110.53 to 8,319.42 mg/L with mean value of 3,863.23 mg/L in the dry season and from 706.84 to 4,104.48 mg/L with mean of 2,322.75 mg/L in the wet season **(**Figure 9), substantially exceeding the 500 mg/L limit recommended by WHO (2017) and NSDWQ (SON, 2015) (Table 1) and classifying the water as "very hard" (>180 mg/L). The highest amount of TH in the water was 830.5mg/L recorded during the dry season at sampling site GWS-3 due to the presence of high content of calcium and magnesium, in addition to chloride in this site. The lowest amount of 184.43mg/L was recorded during the wet season at GWS-4 due to the relatively low concentration of calcium and the dilution effect (Table 3). While high hardness is not a direct health risk, it contributes to scaling, poor taste, and reduced domestic and industrial suitability. Similar high TH levels have been reported in the Gorgan Aquifer, Iran (Faraji and Shahryari, 2024), and seasonal variability in groundwater hardness has been observed in urban Enugu, Nigeria (Ezurike *et al*., 2026). These elevated TH levels likely reflect the influence of geogenic factors, such as the dissolution of calcium- and magnesium-rich minerals, as well as potential anthropogenic contributions from agricultural runoff and industrial activities.

Sodium (Na^+)

Sodium concentrations exhibited pronounced seasonal variation, with substantially higher levels recorded in the dry season compared to the wet season. During the dry period, Na^+ ranged from 300.31 (GWS 5) to 1575.49 mg/L 9GWS3), with a mean of 767.97 mg/L, which exceeded the permissible limit of 200 mg/L (Table 1). Wet-season concentrations of Na^+ were markedly lower, ranging from 6.16 mg/L (GWS 5) to 101.14 mg/L (GWS1), averaging 55.78 mg/L, all within permissible limits of 200 mg/L (Figure 10). The elevated dry-season sodium is attributed to evaporative concentration, reduced aquifer recharge, and potential cation exchange interactions between groundwater and aquifer materials. Similar seasonal enrichment of major ions, including sodium, has also been reported in recent groundwater assessments, where higher dry-season concentrations were linked to evaporation dominance and reduced recharge effects in aquifer systems (Kayode *et al*, 2024). In coastal aquifers of Lagos State, high sodium concentrations have also been linked to saline water intrusion under low freshwater hydraulic gradients (Tijani, 2010). Seasonal groundwater studies in the Amman-Zarqa Basin, Jordan, also reported higher sodium and other major ion concentrations in the dry season, reflecting the influence of recharge patterns and geologic controls (Alomari *et al*., 2023). Exceedances of sodium beyond recommended limits may pose health risks to sensitive groups and can reduce water suitability for irrigation due to sodicity-related concerns.

Potassium (K^+)

Potassium concentrations in the groundwater exhibited pronounced seasonal variation (Figure 11). During the dry season, K^+ ranged from 64.14 mg/L at GWS-5 to 2026.54 mg/L at GWS-3, with a mean of 799.12 mg/L, while wet-season values decreased substantially, ranging from 8.77 to 115.71 mg/L, averaging 62.24 mg/L (Table 1). The presence of potassium in groundwater is largely linked to the weathering of feldspar minerals and may also reflect anthropogenic contributions from agricultural fertilisers and domestic wastewater. Similar patterns of dry-season potassium enrichment have been observed in Ado Ekiti, Ekiti State, where elevated concentrations were attributed to both geogenic and human-derived sources (Kayode *et al*., 2024). Comparable evidence from Tenerife Island, Spain, indicates that potassium, along with other major cations such as sodium and fluoride, is controlled by geological, climatic, and hydrological factors (de Miguel-García and Gómez-González, 2024). While potassium is less strictly regulated than sodium, elevated levels can indicate anthropogenic contamination and declining groundwater quality.

Sulphate (SO_4^{2-})

During the dry season, SO_4^{2-} ranged from 0.57 to 2.25 mg/L, with a mean of 1.43 mg/L. In the wet season, concentrations increased slightly (Figure 12), ranging from 054 to 0.87mg/L, averaging 0.72 mg/L. Sulphate concentrations in the groundwater were low across both seasons and remained well within permissible limits of 500mg/L and 100mg/L by WHO and NSDWQ, respectively (Table 1). The minor wet-season rise may be attributed to

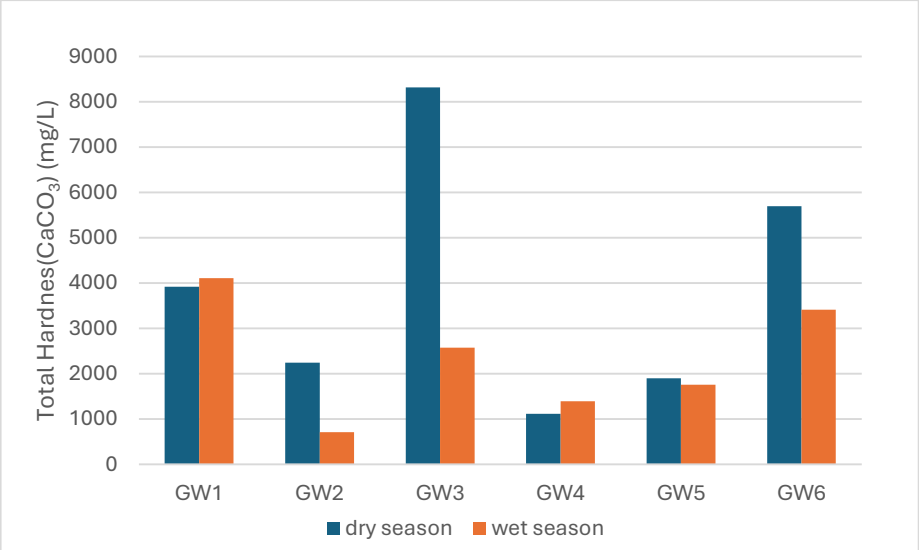

Figure 9. Seasonal variation of total hardness in groundwater samples.

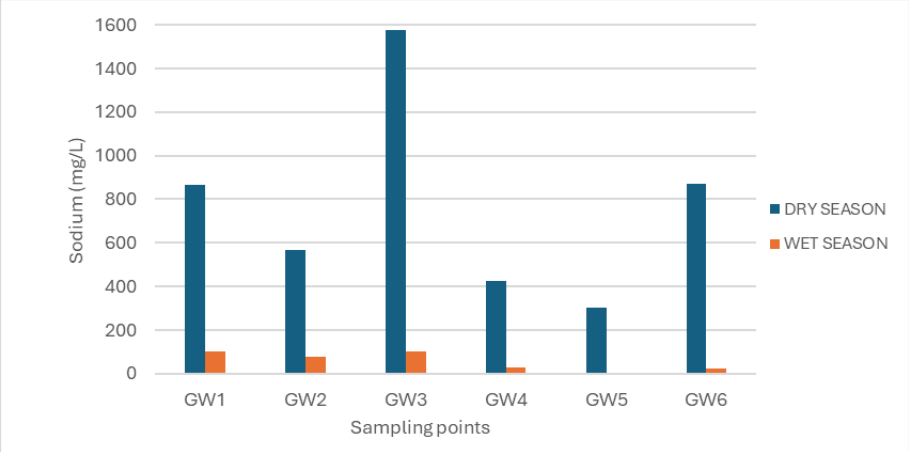

Figure 10. Seasonal variation of Sodium in groundwater samples.

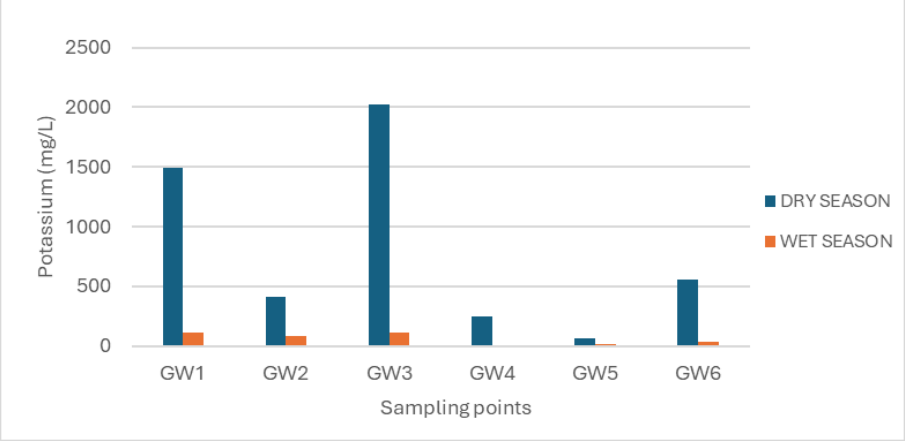

Figure 11. Seasonal variation of Potassium in groundwater samples.

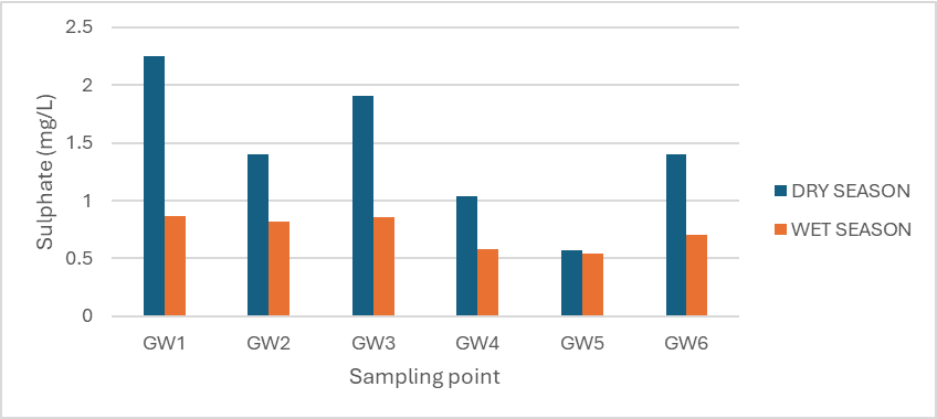

Figure 12. Seasonal variation of Sulphate in groundwater samples.

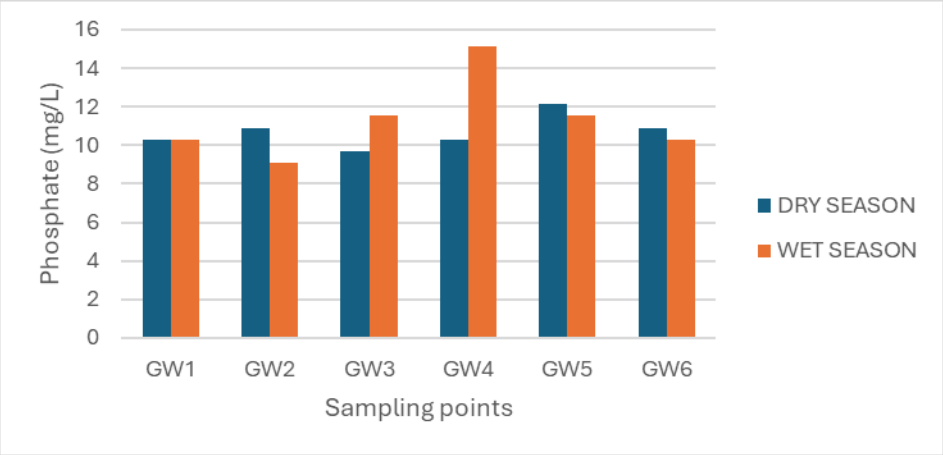

Figure 13. Seasonal variation of Phosphate in groundwater samples.

surface runoff or the oxidation of sulphide-bearing minerals, although overall levels suggest minimal industrial or anthropogenic sulphate influence. Similar low sulphate concentrations have been reported in Zaria, Kaduna State, where the sulphate chemistry was largely governed by natural geological processes (Eneogwe *et al*., 2022). These observations indicate that sulphate poses limited water quality concerns in the study area.

Phosphate (PO_4^{3-})

Phosphate concentrations in the groundwater were higher during the dry season, exceeding recommended guideline values, while wet-season levels were considerably lower (Table 1). During the dry season, PO_4^{3-} ranged from 9.7mg/L (GWS3) to 10.9 mg/L (GWS2 and GWS5), with a mean of 10.70 mg/L, whereas wet-season concentrations varied between 9.09 mg/L (GWS1) and 15.16 mg/L (GWS4), averaging 11.31 mg/L (Figure 13). The dry season phosphate exceeded the permissible limit of 5.0 mg/L by the WHO, while the wet season's concentration remains within the limit. The elevated dry-season phosphate likely results from limited dilution and the accumulation of organic waste and agricultural residues. Similar seasonal trends have been reported in Bonny Island, Rivers State, where wet-season dilution significantly lowered phosphate levels in groundwater (Okoli *et al*., 2024). High phosphate concentrations during the dry season may increase the potential for eutrophication in connected surface water systems.

Chloride (Cl^-)

Chloride concentrations in the groundwater were consistently high across both seasons, exceeding WHO guideline values, and suggesting potential saline intrusion or anthropogenic contamination. During the dry season, Cl^- ranged from 532.50 mg/L (GWS 4) to 4082.50 mg/L (GWS 3), with a mean of 2012.0 mg/L, while wet-season values were even higher, ranging from 355.0 mg/l (GWS

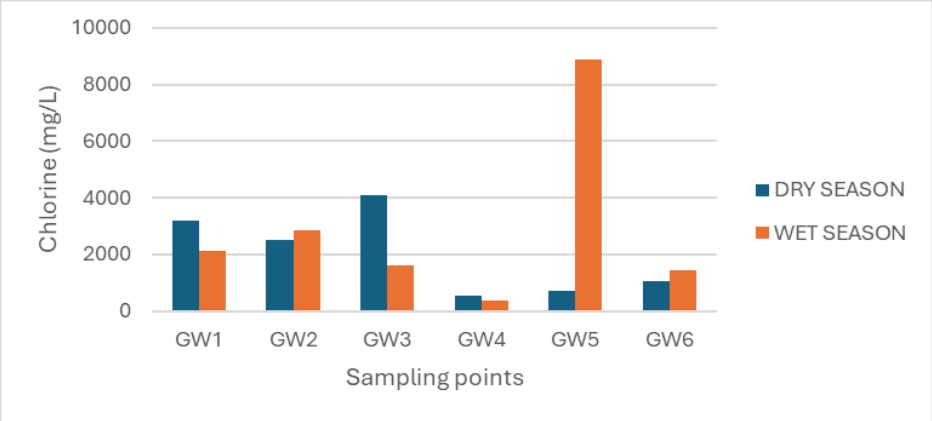

Figure 14. Seasonal variation of chlorine in groundwater samples.

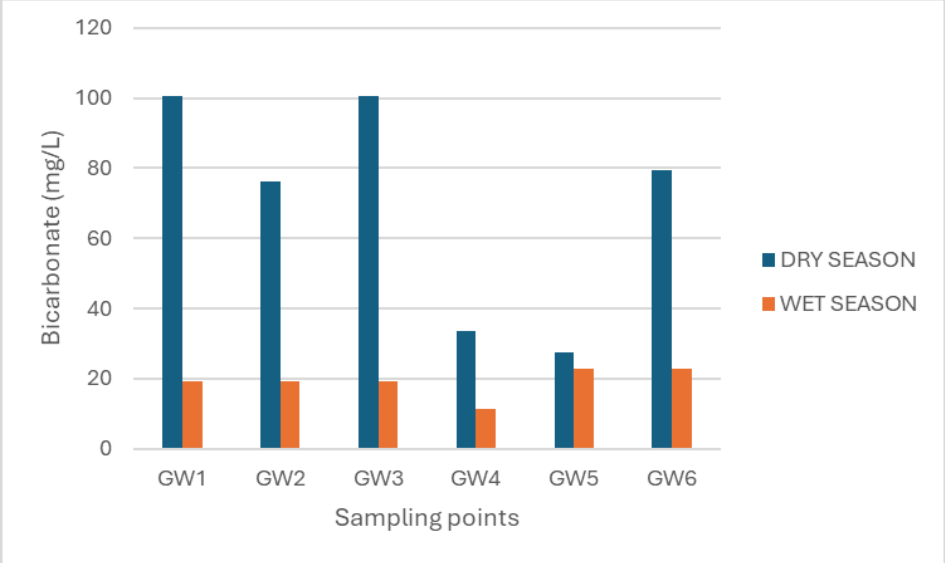

Figure 15. Seasonal variation of Bicarbonate in groundwater samples.

4) to 8875.0 mg/L, with a mean value of 2869.5 mg/L (GWS5) (Figure 14). Compared with the WHO (2017) and NSDWQ (SON, 2015) guideline limit of 250 mg/L (Table 1), chloride concentrations in both seasons far exceeded safe thresholds, rendering the groundwater unsuitable for domestic use without prior treatment. The elevated chloride levels are likely associated with domestic wastewater discharge and leaching from surrounding soils. This pattern is consistent with the studies in southern Ontario, Canada, where chloride concentrations in urban and coastal aquifers exceeded regional water quality guidelines due to both natural and anthropogenic influences (Mackie *et al*., 2025). Similar patterns of chloride enrichment have been documented in coastal and urban aquifers of Lagos State, where saline intrusion and domestic wastewater were identified as major contributing factors (Tijani, 2010).

Bicarbonate (HCO_3^-) and alkalinity

Carbonate was absent in all groundwater samples, indicating that the observed alkalinity is solely attributable to bicarbonate. During the dry season, alkalinity ranged from 27.45mg/L (GWS 5) to 100.65 mg/L (GWS3), with a mean value of 69.44 mg/L, which is well below the recommended guideline limits for drinking water. Alkalinity values were lower in the wet season, ranging from 11.44 mg/L (GWS4) to 22.8 mg/L (GWS5 & GWS6) with a mean of 19.6mg/L (Figure 15), reflecting dilution effects from increased rainfall. Bicarbonate concentrations remained within permissible limits, with slightly higher dry-season values likely due to the dissolution of carbonate minerals. Similar seasonal patterns of bicarbonate have been documented in groundwater systems of Ekiti State, where geochemical weathering was the primary control on

Table 2. Result of t-test showing seasonal variation among physicochemical parameters in the groundwater.

S/N	Parameters	Df	't"	P	Remark
1	Temperature	5	28.245	0.000	Significant
2	pH	5	6.819	0.001	Significant
3	Conductivity	5	2.933	0.033	Significant
4	Turbidity	5	-9.682	0.000	Significant
5	Calcium	5	-0.412	0.689	Not significant
6	Magnesium	5	2.599	0.048	Significant
7	Sodium	5	4.054	0.010	Significant
8	Potassium	5	2.438	0.059	Not significant
9	Sulphate	5	1.581	0.175	Not significant
10	Phosphate	5	-0.652	0.543	Not significant
11	Chloride	5	-0.562	0.598	Not significant
12	Bicarbonate	5	3.934	0.011	Significant

bicarbonate chemistry (Akinbile and Yusoff, 2011).

Seasonal variation in groundwater physicochemical parameters

In order to assess the seasonal variation in groundwater physicochemical parameters Paired t-test was conducted. The results reveal that physical groundwater parameters vary significantly with season at the 0.05 level of significance. Temperature, pH, electrical conductivity, and turbidity all recorded statistically significant differences between the dry and wet seasons, with p-values of 0.000, 0.001, 0.033, and 0.000, respectively (Table 2). This indicates marked seasonal fluctuations in these parameters across the sampling locations. Similar patterns have been documented in Hadejia, Jigawa State, where Garba *et al*. (2016) observed significant seasonal contrasts in key physical water quality indicators.

With respect to major cations, calcium and potassium showed no significant seasonal variation, as reflected by p-values of 0.689 and 0.059, respectively. However, magnesium (p = 0.048) and sodium (p = 0.010) exhibited statistically significant differences between seasons (Table 2). These findings differ from those reported by Nwafor *et al*. (2013) in Akure, Ondo State, who noted higher wet-season concentrations of potassium, iron, and sulphate, alongside increased dry-season levels of magnesium and sodium, underscoring the influence of local geology and hydrogeological conditions on seasonal groundwater chemistry.

Analysis of anionic constituents shows that sulphate, phosphate, and chloride did not vary significantly between seasons, with p-values of 0.175, 0.543, and 0.598, respectively. In contrast, bicarbonate displayed a significant seasonal variation (p = 0.011) (Table 2). This observation aligns with the findings of Ishaku (2011) in Jimeta-Yola, northeastern Nigeria, where sulphate, phosphate, and chloride concentrations remained relatively constant year-round, while bicarbonate showed notable seasonal changes. The seasonal variability in bicarbonate is likely linked to enhanced carbonate mineral dissolution and fluctuations in groundwater recharge associated with wet and dry seasonal cycles.

Groundwater quality evaluation for drinking

The quality of the groundwater has been further examined for its portability, using the Weighted Water Quality Index. The Water Quality Index (WQI) results demonstrate considerable spatial and seasonal variability in groundwater quality across the study area (Table 3). WQI values were interpreted based on the standard classification: 0–25 (excellent, A), 26–50 (good, B), 51–75 (poor, C), 76–100 (very poor, D), and above 100 (unsuitable for drinking, E) (Table 4).

During the dry season, WQI values ranged from 68.5 (GW5, classified as poor) to 414.8 (GW3, unsuitable for drinking), with most sites exceeding 100, indicating unsuitable water quality. High WQI was largely driven by elevated electrical conductivity and major cation concentrations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), as well as chloride, reflecting evaporative concentration and limited aquifer recharge. This pattern is consistent with findings in Zaria, Kaduna State, where dry-season evapoconcentration significantly affected groundwater quality (Eneogwe *et al*., 2022).

In the wet season, WQI values ranged from 185.5 (GWS6) to 596.3 (GWS3), showing greater spatial variability than in the dry season. Sites such as GWS3, GWS2 and GWS1 were classified as unsuitable for drinking, likely due to surface runoff, leaching of anthropogenic contaminants, and mobilisation of dissolved ions during rainfall. Conversely, GWS4 and GWS6, although still above 100, exhibited relatively lower WQI, suggesting moderate dilution and better hydrogeological protection. Similar trends have been reported in Onitsha,

Table 3. Water Quality Index of groundwater samples during wet and dry season.

Parameters	DRY SEASON						WET SEASON					
	GW1	GW2	GW3	GW4	GWS5	GW6	GWS1	GWS2	GWS3	GWS4	GWS5	GWS6
pH	7.74	7.6	7.4	7.9	7.9	7.54	7.0	7.01	7.2	7.0	7.2	7.0
E.C (*μ*S/cm)	7370	5750	7470	1200	1200	3400	5060	1012.27	4530	444	998	2380
TDS	4716.8	3680.0	4780.8	768.0	454.4	2176.0	3238.4	1574.4	2899.2	284.16	638.72	1523.2
Ca (mg/L)	1091.1	43.4	1763.4	79.31	79.3	1433.5	1245.36	156.39	996.75	507.49	606.72	1102.56
Mg (mg/L)	290.1	519.9	953.7	222.5	222.5	512.9	241.36	77.19	19.84	28.47	58.08	157.83
TH (mg/L as $CaCO_3$)	3918.7	2240.6	8319.4	1110.5	1894	5696.1	4104.48	706.84	2573.97	1386.97	1755.47	3408.75
Na (mg/L)	865.3	569.2	1575.5	424.2	424.2	873.3	101.14	80.45	100.44	26.46	6.16	23.28
K (mg/L)	1490.	411.9	2026.5	247.2	247.2	554.1	115.71	0.82	110.39	8.77	19.56	38.58
SO_4 (mg/L)	2.3	1.4	7470	1.04	1.04	1.4	0.87	0.09	0.86	0.58	0.7	0.17
P O_4 (mg/L)	10.3	10.9	1.91	10.3	10.3	10.9	10.31	2840	11.52	15.16	11.52	10.31
Cl (mg/L)	3195	2489	4082.5	532.5	532.5	1065	2130	19.06	1597.5	355	8875	1420
HCO_3 (mg/L)	100.7	76.3	100.7	33.6	33.6	79.3	19.06	19.06	19.06	11.44	22.88	22.88
WQI	298.8	233.6	414.8	180	68.5	303.9	283.6	493.9	596.3	187.5	243.6	185.5
Pollution Index	10.675	4.883	16.583	2.292	1.531	4.345	4.76	15.37	5.92	1.80	2.29	3.36

Anambra State, where wet-season recharge increased solute concentrations and elevated WQI values (Okolo *et al*., 2023).

Analysis of individual parameters indicates that major cations and EC were the primary contributors to high WQI. For instance, GW3 had the highest dry-season EC (7470 µS/cm) and Ca^{2+} (1763.4 mg/L), corresponding to a WQI of 414.8 (unsuitable for drinking). During the wet season, GWS3 exhibited elevated Na^+ (100.44 mg/L), K^+ (110.39 mg/L), and Cl^- (1597.5 mg/L), leading to the highest WQI of 596.3 (E). Bicarbonate at GWS2 (2460 mg/L) also contributed to elevated wet-season WQI, indicating carbonate dissolution under recharge conditions.

Comparison between seasons shows that some sites (GW3, GW6, GW1) had higher dry-season WQI due to evaporation and ion concentration, whereas others (GWS2, GWS3) were more affected during the wet season because of surface runoff and rainfall-induced leaching. These results align with results reported by Ayoade *et al*. (2015), Eneogwe *et al*. (2022) and Okolo *et al*. (2023), where both geogenic and anthropogenic factors influenced seasonal groundwater quality.

Overall, the WQI assessment indicates that groundwater quality in the study area is predominantly unsuitable for drinking, with significant seasonal and spatial variations (Figure 15).

Pollution Index of Groundwater (PIG)

The Pollution Index of Groundwater (PIG) for the six samples analysed in this study revealed substantial variability in groundwater quality. Specifically, GW1 (5.98), GW2 (7.16), GW3 (4.28), GW5 (2.33) and GW6 (4.13) were classified as very highly polluted (>2.5), indicating significant deviation from permissible water quality standards. Only GW4 (1.72) fell into the highly pollution category (Table 6). These results suggest that the majority of groundwater sources in the study area are subjected to extensive contamination, posing potential risks to human health and domestic use.

The contributions of individual physicochemical parameters to the PIG indicate that Total Dissolved Solids (TDS) and major cations, particularly Na^+ and K^+, were the principal factors elevating pollution scores in GW1, GW3, and GW6. Elevated TDS reflects the accumulation of dissolved ions from both natural mineral weathering and anthropogenic sources such as industrial effluents and agricultural runoff. The high concentrations of Na^+ and K^+ in GW3 (Na 0.897; K 9.632) and GW1 (Na 0.493; K 7.078) are indicative of salinisation processes and fertiliser-related contamination, which are consistent with previously reported sources of groundwater pollution (Shuaibu *et al*.,

Table 4. Water quality rating as per weight arithmetic water quality index method.

WQI Value	Rating of water quality	Grading	No. of samples		% samples	
			Dry	Wet	Dry	Wet
0-25	Excellent	A	0	0	0	0
26-50	Good	B	0	0	0	0
51-75	Poor	C	1	0	17	0
76-100	Very Poor	D	0	0	0	0
> 100	Unsuitable for drinking	E	5	0	83	100

Table 5. Pollution index classification.

PI Value	Pollution Status	Interpretation
< 0.5	Excellent / Safe	Water is of very good quality, suitable for drinking without treatment.
0.5 – 1.0	Good / Slightly Polluted	Minor deviations from standards; water generally safe for consumption.
1.0 – 1.5	Moderate Pollution	Water shows moderate pollution; treatment may be required.
1.5 – 2.0	Poor / Highly Polluted	Significant pollution; water is not recommended for drinking.
> 2.0	Very Poor / Unsuitable	Water is heavily polluted; unsafe for human consumption.

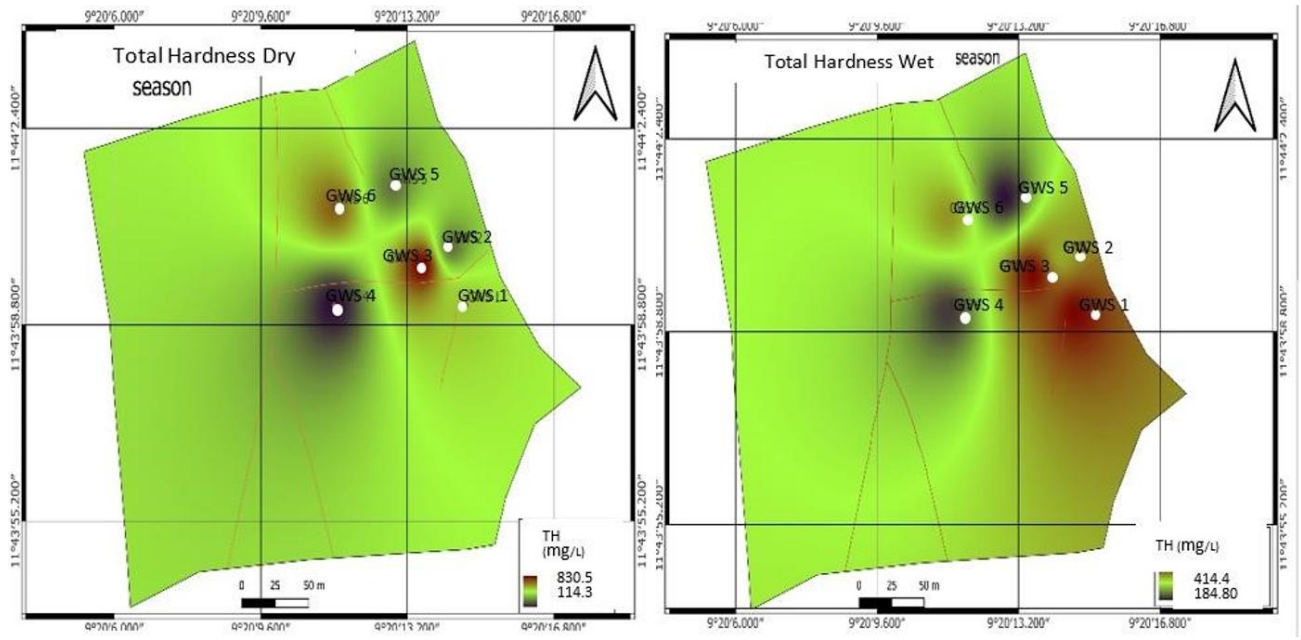

Figure 16. Spatial distribution of the ratings of water quality status in the study area for dry and wet season.

2024).

Anions such as Cl^- and SO_4^{2-} also significantly influenced PIG values. Elevated chloride concentrations in GW1 (1.457), GW2 (1.134), and GW3 (1.860) likely reflect inputs from domestic wastewater or leachates from anthropogenic activities, corroborating findings from recent assessments of groundwater quality in similar hydrogeological settings (Arıman *et al*., 2024). Phosphate and bicarbonate ions, though less prominent in absolute terms, contributed proportionally to the PIG through normalisation, highlighting the sensitivity of the index to even minor deviations from standard limits.

Principal Component Analysis (PCA) and seasonal variation.

Multivariate Principal Component Analysis (PCA) was conducted separately on dry and wet season groundwater datasets to identify the major hydrochemical processes

Table 6. Relative weight and weighted parameters used for PIG computation (Subba Rao, 2012).

Parameter	Observed Value	WHO (2017) Limit	Pollution Rank (1–5)	Relative Weight (Wi = Ri / 36)
pH	7.74	6.5-8.5	1	0.028
TDS (mg/L)	4716.8	1000.00	5	0.139
Ca^{2+} (mg/L)	1091.1	5.00	5	0.139
Mg^{2+} (mg/L)	290.1	75.00	5	0.139
Na^{+} (mg/L)	865.3	30.00	4	0.111
K^{+} (mg/L)	1490	500	5	0.139
SO_4^{2-} (mg/L)	2.3	200.00	1	0.028
PO_4^{3-} (mg/L)	10.3	200.00	4	0.111
Cl^{-} (mg/L)	3195	100.00	5	0.139
HCO_3^{-} (mg/L)	100.7	NA	1	0.028
Total			36	1.00

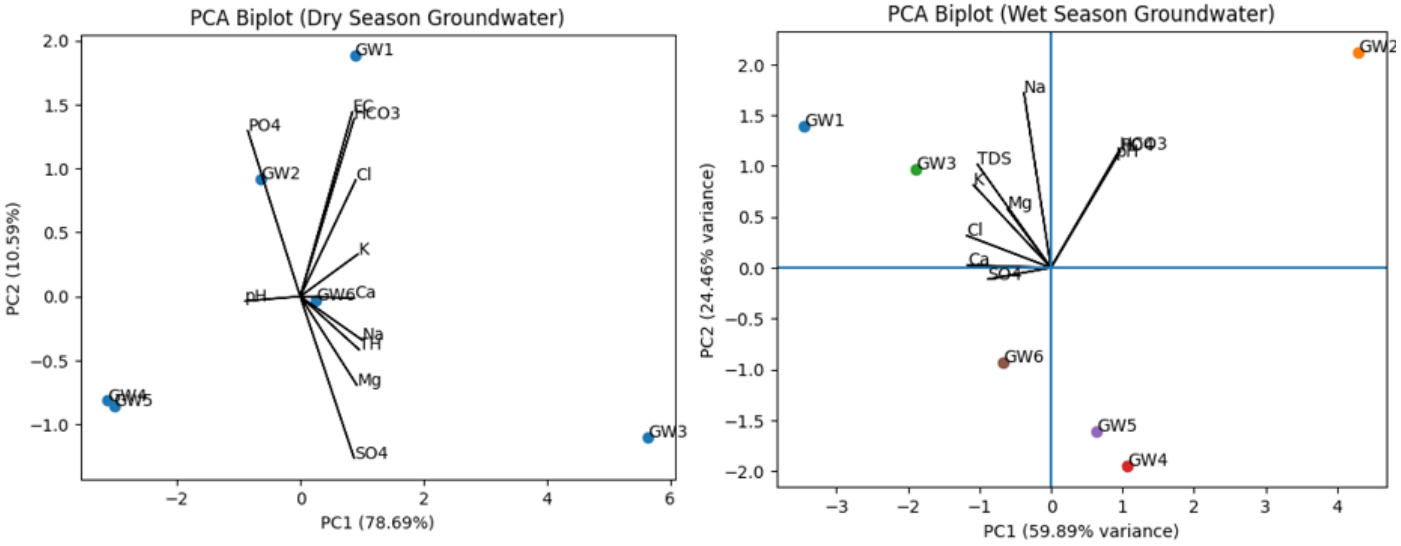

Figure 17. Biplot for dry and wet season Principal Component Analysis.

controlling water quality. Varimax rotation was applied to enhance the interpretability of factor loadings.

For the dry season, PCA extracted multiple significant components, with the first two explaining the majority of the variance. PC-1 accounted for 78.7% of the total variance, showing strong positive loadings of EC, TDS, Ca^{2+}, Mg^{2+}, TH, Na^{+}, K^{+}, Cl^{-}, and SO_4^{2-}. This grouping suggests dominance of salinity and hardness factors, primarily driven by natural water–rock interactions and mineral dissolution processes. Similar patterns have been observed in groundwater hydrochemical studies, where major ions primarily originate from weathering of geological formations and control the bulk of the hydrochemical variation identified through PCA (e.g., salinity and mineralization factors) in semi-arid aquifers (Arıman *et al*., 2024).

PC-2 (10.6% variance) exhibited strong positive loadings of HCO_3^{-}, PO_4^{3-}, and pH, indicating carbonate buffering and nutrient enrichment. Bicarbonate and pH reflect carbonate equilibrium reactions, while phosphate could be mobilised from soil and anthropogenic sources such as agricultural runoff, even in dry conditions. Studies applying PCA to assess groundwater chemistry have similarly interpreted components dominated by pH, bicarbonate, and nutrient parameters as reflecting geochemical buffering and seasonal influences on nutrient mobilisation (Abdulsalam *et al*., 2022).

Minor components (PC-3 to PC-5) each explained relatively small proportions of variance and likely represented localised or compound processes such as trace metal mobilisation or minor anthropogenic inputs, but these had limited influence compared to the dominant geogenic factors.

In the wet season analysis, the first principal component (PC-1) explained ~72.0% of the total variance with strong positive loadings of TDS, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, and

SO_4^{2-}. This pattern is consistent with hydrochemical salinity and mineralisation, implying that rock–water interactions remain a principal factor in groundwater chemistry even under increased rainfall. Seasonal dilution effects during the wet season often reduce overall ion concentrations and variance explained by salinity factors compared to the dry season (Arıman *et al*., 2024).

PC-2 (12.0% variance) revealed positive loadings of HCO_3^-, PO_4^{3-}, and pH, indicating enhanced nutrient mobilisation and carbonate equilibrium during rainfall events. The relatively higher phosphate loading during the wet season suggests increased leaching and surface runoff input of nutrients from agricultural and urban areas. A similar seasonal influence of nutrient parameters in groundwater PCA was reported in coastal and tropical aquifers, reinforcing the role of recharge and surface processes in mobilising phosphate and bicarbonate during wet periods (Multivariate studies in Trivandrum district).

Subsequent components (PC-3 to PC-5) explained less than ~10% of the variance collectively. These minor components likely captured secondary influences such as trace metals or seasonal anthropogenic impacts, which were not dominant compared to salinity and buffering factors.

Comparing the seasonal PCA results reveals consistent hydrochemical controls across seasons, with natural geogenic processes, such as mineral dissolution and rock–water interaction, dominating in both dry and wet conditions. This reflects findings in other groundwater chemometric studies, where major ion groupings commonly represent the primary hydrochemical processes controlling aquifer chemistry (Arıman *et al*., 2024).

However, seasonal variability is evident in the explained variance and loading strength. The dry season exhibited a higher variance explained by the primary component, indicating stronger control by salinity and hardness factors under low recharge conditions. In contrast, the wet season showed reduced dominance by salinity components and elevated influence of nutrient parameters (PO_4^{3-}) and bicarbonate, demonstrating increased surface influence and nutrient mobilization during rainfall events. This aligns with broader hydrochemical studies that find seasonal differences in groundwater controls due to recharge, dilution, and surface runoff impacts (Pitchaimani *et al*., 2024)

These findings indicate that while the fundamental geochemical processes remain similar across seasons, rainfall introduces additional variability, particularly in nutrient dynamics.

Evaluation of dry and wet season PCA

Principal Component Analysis (PCA) revealed marked seasonal contrasts in groundwater hydrochemistry. During the dry season, PC1 exhibited uniformly positive loadings for EC (0.282), Ca^{2+} (0.293), Mg^{2+} (0.307), TH (0.318), Na^+ (0.335), K^+ (0.313), SO_4^{2-} (0.291), Cl^- (0.300), and HCO_3^- (0.292), with a negative loading for pH (−0.298) (Table 7), indicating a dominant mineralization–salinity control driven by evaporative concentration and water–rock interaction. PC2 showed moderate positive contributions from EC (0.480), HCO_3^- (0.464), PO_4^{3-} (0.432), and Cl^- (0.303), suggesting secondary carbonate weathering and nutrient inputs. In contrast, the wet season demonstrated a redistribution of hydrochemical controls: Mg^{2+} loaded strongly on PC3 (0.706), TH on PC2 (0.574), and pH on PC5 (0.705), while EC (−0.343), Ca^{2+} (−0.391), Na^+ (−0.361), and Cl^- (−0.393) (Table 7) showed negative loadings on PC1, reflecting dilution effects and reduced evaporative concentration. Similar dry-season enrichment patterns have been widely reported in semi-arid and mining-influenced aquifers, where evaporation and extended residence time enhance rock–water interaction (Anjali *et al*., 2025; Hembrom and Kumari, 2026). Likewise, Kayode *et al*. (2024) observed that mineralisation processes overwhelmingly controlled groundwater chemistry in Nigerian hard-rock aquifers during low-flow conditions, with PC1 explaining most of the variance.

PC2 during the dry season displayed moderate positive loadings for EC, HCO_3^-, PO_4^{3-}, and Cl^-, suggesting the influence of carbonate weathering combined with nutrient inputs. This pattern reflects a mixed geogenic–anthropogenic signal. Comparable relationships between bicarbonate and phosphate have been documented in karst and peri-urban aquifers, where carbonate dissolution coincides with surface-derived nutrient mobilisation (Zhang *et al*., 2026). Similarly, Ferreira *et al*. (2024) identified a secondary PCA component linked to nutrient enrichment from surface activities, reinforcing the interpretation that anthropogenic inputs may superimpose on natural buffering reactions.

Overall, six principal components explained approximately 95% of the dry-season variance, with PC1 alone accounting for 78.69%. This high percentage confirms the dominant role of mineral dissolution and evaporative enrichment. Recent hydrochemical studies across India and West Africa have reported comparable PC1 contributions exceeding 70%, attributing groundwater composition during dry periods mainly to carbonate and silicate weathering processes intensified by evaporation (Anjali *et al*., 2025; Kayode *et al*., 2024). The identification of GW3 as a highly mineralised groundwater type further highlights spatial heterogeneity, likely influenced by lithology and groundwater residence time. Similar localised mineralised facies have been reported in mining-affected terrains in eastern India (Hembrom and Kumari, 2026). In the present case, mineralisation appears more strongly controlled by natural geogenic processes than by distinct anthropogenic inputs.

In contrast, the wet season reflects a redistribution rather than a replacement of hydrochemical controls. Although six components again explained a substantial proportion

Table 7. PCA Loadings for dry season and wet season.

Parameters	DRY SEASON						WET SEASON					
	PC1	PC2	PC3	PC4	PC5	PC6	PC1	PC2	PC3	PC4	PC5	PC6
pH	-0.29819	-0.01184	-0.39116	-0.5081	0.168156	0.127533	0.304	0.366	-0.183	0.088	0.705	0.428
EC	0.281559	0.480334	-0.22748	0.137952	0.091789	-0.34477	-0.343	0.339	-0.044	0.206	0.053	-0.439
Ca	0.292585	-0.00423	0.457578	-0.48505	-0.38895	-0.49712	-0.391	0.009	0.218	0.342	0.081	0.122
Mg	0.30659	-0.2312	0.101923	0.493199	-0.09662	0.078887	-0.204	0.194	0.706	-0.578	0.074	0.217
TH	0.318312	-0.13847	0.345831	-0.16663	0.855651	-2.2E-05	-0.126	0.574	-0.214	-0.018	-0.551	0.333
Na	0.334894	-0.11363	0.05946	-0.15446	-0.19707	0.470797	-0.361	0.272	-0.172	0.121	0.008	0.185
K	0.313311	0.11066	-0.2776	-0.41471	-0.0672	0.17238	-0.294	-0.038	-0.554	-0.675	0.180	-0.155
SO4	0.291483	-0.42151	-0.28672	0.036461	-0.05367	0.041128	-0.294	-0.038	-0.554	-0.675	0.180	-0.155
PO4	-0.28376	0.431976	0.349128	0.049882	0.044079	0.158363	0.324	0.383	0.097	-0.076	-0.032	-0.147
Cl	0.299943	0.303115	-0.39125	0.129837	0.120879	-0.2482	-0.393	0.106	0.123	0.131	0.388	-0.254
HCO3	0.291745	0.463877	0.134565	-0.00123	-0.08808	0.521323	0.321	0.388	0.106	-0.067	0.001	-0.553

of total variance (~93%), the contribution of PC1 declined to approximately 72%. This reduction suggests dilution effects associated with recharge, a phenomenon widely observed in monsoon-dominated aquifers (Bisht *et al*., 2025). Despite this dilution, PC1 remained strongly associated with TDS and major ions, indicating that mineral dissolution continues to govern groundwater chemistry even during rainfall periods. Similar persistence of geogenic signatures during wet seasons has been reported in both Indian and West African aquifer systems (Ferreira *et al*., 2024; Hembrom and Kumari, 2026).

The negative loadings of EC, Ca^{2+}, Na^{+}, and Cl^{-} during the wet season further support the interpretation of reduced ionic strength due to recharge. Bisht *et al*. (2025) described comparable seasonal inversions, where recharge attenuated ion concentrations without fundamentally altering the geochemical regime. This suggests that rainfall acts primarily as a moderating force, diluting concentrations but not disrupting the underlying lithogenic framework.

PC2 in the wet season (~12% variance) remained characterised by strong loadings of HCO_3^{-}, PO_4^{3-}, and pH, similar to the dry season configuration. However, phosphate exhibited relatively stronger influence during the wet season, indicating enhanced nutrient mobilisation through runoff and soil leaching. Ferreira *et al*. (2024) similarly observed increased wet-season phosphate concentrations linked to surface-derived inputs, while Chen *et al*. (2024) reported intensified nutrient transport during rainy periods due to stronger surface–groundwater connectivity.

Overall, the PCA demonstrate that groundwater chemistry in both seasons is fundamentally governed by geogenic mineralisation processes. The consistent dominance of major ions in PC1 across seasons confirms the resilience of lithological control. Seasonal changes primarily influence concentration intensity and nutrient transport rather than the overall hydrochemical regime. The dry season amplifies mineralisation through evaporation and limited dilution, whereas the wet season moderates ion concentrations and enhances nutrient mobility. These findings align with recent studies showing that seasonal recharge modifies groundwater chemistry quantitatively but does not fundamentally restructure the governing geochemical processes (Anjali *et al*., 2025; Bisht *et al*., 2025; Hembrom and Kumari, 2026).

Conclusion

The combined analysis of groundwater using physicochemical measurements, Water Quality Index (WQI), Pollution Index (PI), and Principal Component Analysis (PCA) shows that much of the water in the study area is not safe for drinking. During the dry season, high levels of EC, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, PO_4^{3-}, and HCO_3^{-} indicate strong salinity and mineralisation, while the wet season brought some dilution, redistributing ions and increasing variability across sites. WQI and PI confirmed that several wells are heavily impacted, and PCA highlighted that natural geochemical processes largely shape groundwater quality, though localised human activities also play a role. Seasonal changes and spatial differences

show how evaporation, rainfall, and nutrient movement affect water chemistry.

Based on these findings, people should avoid drinking untreated groundwater, especially during the dry season, and use simple household treatment methods such as boiling or filtration. Local authorities should focus on regularly monitoring water quality and addressing contamination in the most affected areas. Policymakers should put in place rules to control pollution sources and promote sustainable groundwater management. Taking these steps will help protect public health and ensure safe, reliable water for communities in the region.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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