


## ORIGINAL RESEARCH ARTICLE

## Multivariate Hydrogeochemical Assessment of Urban Groundwater Quality in Kano Metropolis, Nigeria

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### ABSTRACT

Groundwater is the primary source of domestic water in Kano Metropolis, yet its quality is increasingly threatened by rapid urbanization and anthropogenic activities. This study evaluated the spatiotemporal variation in groundwater quality using systematic sampling and multivariate statistical approaches. Forty-eight water samples (24 boreholes and 24 wells) were purposely collected across eight Local Government Areas during dry and wet seasons (Feb–Sept 2023). Physicochemical parameters were analyzed in line with WHO standards. Results indicated significant seasonal differences, with higher contamination observed during the dry season. Chloride concentrations peaked at 579.38 mg L<sup>-1</sup>, turbidity at 8.01 NTU, and total dissolved solids (TDS) at 538 mg L<sup>-1</sup>, both exceeding WHO permissible limits and posing potential risks of salinity-related health effects. Principal Component Analysis (PCA) identified four key factors explaining 76.1% of the total variance, attributed to salinity and mineralization, carbonate buffering, organic contamination, and sulphate enrichment. Agglomerative Hierarchical Clustering (AHC) distinguished boreholes, which showed relative stability, from wells, which were highly susceptible to surface contamination. Hydrochemical facies plots from Piper diagrams revealed dominance of Ca–Mg–SO<sub>4</sub>–Cl and Ca–Mg–Cl–SO<sub>4</sub> water types, reflecting both geogenic and anthropogenic influences. The findings demonstrate that groundwater in Kano is vulnerable to deterioration from industrial effluents, poor sanitation, and unregulated land-use practices. To mitigate contamination risks, the study recommends an integrated groundwater management strategy that includes continuous monitoring, stricter waste disposal regulations, improved well and borehole siting, and community education on water safety. These interventions are critical to ensuring long-term groundwater sustainability and safeguarding public health in the metropolis.

### ARTICLE HISTORY

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Groundwater quality, PCA, Cluster Analysis, Seasonal variation, GIS mapping, Kano Metropolis, Physicochemical parameters



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### INTRODUCTION

Groundwater resources, despite their critical role in sustaining human and ecological systems, are increasingly under threat from both natural and anthropogenic pressures. Population growth, urban expansion, unregulated waste disposal, agricultural intensification, and industrialization are among the leading drivers of human-induced contamination worldwide (Ashraf et al., 2017; Lapworth et al., 2022). In developing countries, particularly across Sub-Saharan Africa, these risks are exacerbated by weak institutional capacity, ineffective land-use planning, inadequate waste management practices, and limited public awareness of the environmental and health implications (Balogun et al., 2021).

In Nigeria, groundwater is the dominant and, in many areas, the only reliable source of drinking water. This dependence is particularly pronounced in urban and peri-urban communities where municipal water supply systems are often inadequate or entirely absent (Talabi, 2018; Tukur et al., 2018). The Nigerian Ministry of Water Resources reports that only 39% of the population has access to safely managed drinking water, forcing most households to rely on boreholes, hand-dug wells, and other informal groundwater abstraction systems (Omole, 2018). Such heavy reliance, compounded by weak quality control mechanisms and minimal water safety awareness, significantly heightens the risks of public health hazards (Lapworth et al., 2017; Shaikh & Birajdar, 2024).

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The physicochemical integrity of groundwater serves as a key determinant of its suitability for drinking, domestic, agricultural, and industrial purposes. Parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), nitrates, chlorides, sulphates, fluoride, iron, and heavy metals provide vital insights into both natural hydrogeological processes and contamination from human activities. Exceedances of World Health Organization (WHO) thresholds pose serious health consequences, ranging from methemoglobinemia and skeletal damage to kidney dysfunction, neurological disorders, and cancer (WHO, 2019).

Rapid urbanization in Nigerian cities further amplifies risks to groundwater quality (Aliyu & Amadu, 2017). Kano Metropolis, Northern Nigeria's largest and most industrialized urban center, exemplifies this challenge. With a population exceeding four million, the city's water demand far outpaces its municipal supply, forcing households, industries, and small-scale enterprises to rely on shallow wells and boreholes for their daily water needs (Ibrahim, 2019; Shawai et al., 2019). However, many of these abstraction points are located dangerously close to pollution hotspots such as fuel stations, dumpsites, abattoirs, pit latrines, and informal industries (Tukur et al., 2018; Mukhtar, 2021).

The region's fractured basement complex geology and permeable formations further intensify aquifer vulnerability by accelerating the infiltration of contaminants (Dauda & Ali, 2024). Combined with uncontrolled land-use practices, this hydrogeological sensitivity exacerbates risks to public health and ecosystems. Kano State's recurring cholera outbreaks, recorded annually since 1970 with high case fatality ratios between 4.98% in 2010 and 5.10% in 2018, highlight the urgent intersection of water contamination and disease burdens (NLM, 2021).

### Research Questions

- How do the primary sources of contamination such as salinity, organic waste, sulphate differ between borehole water and open well water in Kano Metropolis?
- To what extent does seasonal variation (dry vs. wet season) affect the concentration of key pollutants like chloride, nitrate, and turbidity in the groundwater?

## MATERIALS AND METHODS

### Description of the Study Area

Kano Metropolis comprises eight Local Government Areas (LGAs): Dala, Fagge, Gwale, Municipal, Nassarawa, Tarauni, Kumbotso, and Ungogo. The metropolis covers approximately 499 km<sup>2</sup> and is situated at an altitude of 472 meters above sea level. It lies between latitudes 11°05'N and 12°07'N, and longitudes 8°23'E and 8°47'E. The

metropolis is bordered to the northeast by Minjibir LGA, to the east by Gezawa LGA, to the southeast by Dawakin Kudu LGA, and to the west by Madobi and Tofa LGAs (Figure 1). Kano Metropolis has experienced significant urban growth and transformation in recent decades, characterized by increased human activities, rapid land-use changes, and the convergence of various socio-environmental challenges (Barau et al., 2015). It is Nigeria's second-largest commercial hub after Lagos and the most prominent urban center in the Hausa region. Historically, it has played a vital role as a major commercial center in the Sudan region and has maintained a long-standing sedentary population organized under a traditional emirate system (Boyi et al., 2017).

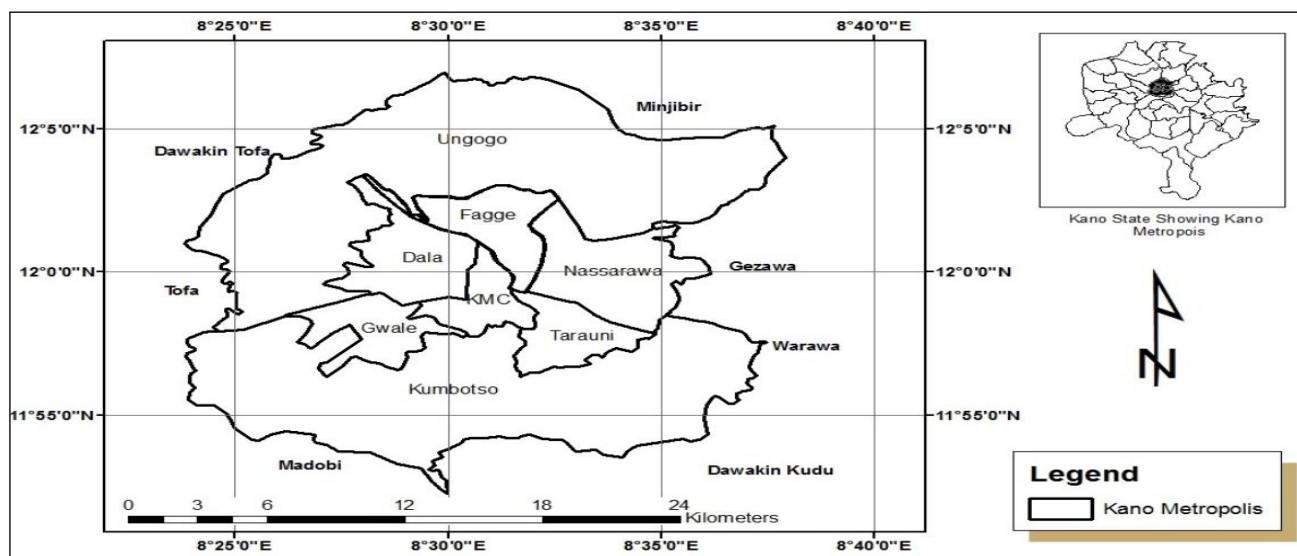
The study area lies within the semi-arid region of northern Nigeria and falls predominantly within the Sudan savannah vegetation zone. However, the southern fringes of the state extend into the Guinea savannah zone. Other localized vegetation types exist, especially along river channels and floodplains, where dense vegetation flourishes. Savannah woodlands are preserved in areas like the Falgore Game Reserve (Ali, 2012). The climate of the study area is classified as tropical wet and dry. The wet season spans approximately four to five months, typically from May to September, with peak rainfall occurring in August. Annual rainfall ranges between 250 mm and 850 mm, and is largely influenced by the Intertropical Convergence Zone (ITCZ) (Olofin and Tanko, 2002; Boyi et al., 2017). Drainage in the area is controlled by topography and features several rivers, including the Jakara, Challawa, Watari, and Kano Rivers. The Jakara River constitutes the most extensive drainage network within Kano Metropolis (Mustapha et al., 2013). The Challawa River is fed by several tributaries such as Magaga, Takwami, Guzu-guzu, Kutumbulu, and Iyaka. Drainage density in the area has been reported to influence groundwater quality due to the dynamics of surface runoff and infiltration (Rilwanu, 2014). Land use in the metropolis is diverse and comprises residential, commercial, agricultural, institutional, educational, and industrial zones. Industrial activities are concentrated in designated layouts such as Dakata, Sharada, and Bompai, which host steel rolling mills, food and beverage plants, packaging facilities, and rice processing industries. Commercial activities are distributed throughout the metropolis, with notable markets including Sabon-Gari, Kantin-Kwari, Singer, Dawanau, and Yankaba markets (Isa et al., 2016; Haruna et al., 2019).

### Methods

An experimental research design was adopted, combining systematic field sampling, laboratory analysis, and statistical modeling. Kano Metropolis, covering approximately 499 km<sup>2</sup>, was stratified into representative zones to ensure adequate spatial coverage. Groundwater samples were collected in triplicate at each site across seasons to minimize variability. Standard quality assurance and quality control (QA/QC) protocols, including field blanks, duplicates, and instrument calibration logs, were strictly observed. Detection limits for trace major ions

were maintained in line with the specifications of AAS and ion chromatography. This design ensured reliable

assessment of groundwater quality, contaminant transport, and seasonal dynamics.



**Figure 1: Map of Kano Metropolis, Kano State**  
 Source: Cartography Lab Geography Department BUK (2024)

The study was carried out across the eight Local Government Areas in Kano Metropolis (Nassarawa, Tarauni, Fagge, Kumbotso, Ungoggo, Gwale, Municipal, and Dala). Due to the large geographic scope of the study area, it was not feasible to cover every location. Therefore, a systematic random sampling technique was used. A total of 48 groundwater samples (borehole and open well) were collected. The sampling approach involved purposive sampling, where triplicate sampling points were selected from densely populated areas. Groundwater samples were collected in both the dry and rainy seasons, resulting in a total of forty-eight water samples to estimate the variability caused by the sampling and analytical procedures. The sampling points were identified using satellite images. The samples were selected to represent various geological formations and land-use patterns. The sample selection was based on the sources of water within the area. The technique was also used due to the homogeneous nature of the study area; the sources of water in the streets, roads, and wards in the study area are almost the same. This sampling method was chosen to ensure an even distribution across the population, which was crucial for mapping and modeling.

In order to attain (APHA) standard, before embarking on any sampling exercise, the water containers (polyethylene bottles) was subjected to an acid wash with 5% nitric acid (HNO<sub>3</sub>) and rinsed with distilled water. For every sampling point, the water level was measured, followed by emptying the tube well three times or pumping the water out of the borehole for at least 10 minutes before taking water samples (Isa *et al.*, 2012). This is to guarantee that the samples collected are truly represent the groundwater and not the stagnant water. A total of 48 sampling sites (24 boreholes and 24 open wells) were utilized in this research work. Sampling exercises were carried out for a period of eight consecutive months, during which triplicates of groundwater samples were collected from

each of the 8 Local Government Areas. The samples collected were used for the analysis of physicochemical and microbial contaminants.

In-situ parameters, including dissolved oxygen (DO), pH, Electrical conductivity (EC), temperature (Temp), and turbidity (Tur), were measured in the field during sample collection. The pH of the water samples was determined using a portable Hanna microprocessor pH meter. Electrical Conductivity was analyzed using a Jenway conductivity meter (model 4510). Total dissolved solids (TDS), Turbidity, and Temperature were measured using a multi-parameter WP600 series meter. Other parameters, such as Biochemical Oxygen Demand (BOD) and Dissolved Oxygen (DO), were analyzed using a water quality meter by standard methods outlined in the World Health Organization (WHO, 2011). All of which will be measured in situ because they change within a short time (Dayyabu *et al.*, 2025).

Major anions like bicarbonate (HCO<sub>3</sub>) and chloride (Cl) were analyzed through titration within the shortest possible time, while NO<sub>3</sub> and SO<sub>4</sub> were analyzed using a HACH (DR/2000) meter with 25 mL samples (APHA, 2005). The samples were filtered using a 0.45 µm filter paper (Whatman Milipores, Clifton, NJ, USA), and HNO<sub>3</sub> acid was added to bring the pH below 2 (Belkhiria *et al.*, 2012; APHA, 2005). The samples were stored at 4 °C and then transported to the laboratory for analysis of the major cations (Ca, Mg, Na, and K) using an atomic absorption spectrophotometer (AAS) (Kura *et al.*, 2018).

The risk assessment approach followed the US EPA method for non-carcinogenic risk evaluation. The Hazard Quotient (HQ) was computed as:

$$HQ = \frac{C}{RfD}$$

**Table 1: Spatial Variation of Groundwater Quality Parameters ANOVA and Duncan Multiple Range Test Analysis**

Parameters	Locations								WHO
	Tarauni	Gwale	Dala	Nassarawa	Fagge	Ungogo	KMC	WHO	
Temp (°C)	25.38 ± 2.82 <sup>a</sup>	25.82 ± 1.99 <sup>a</sup>	26.52 ± 2.16 <sup>a</sup>	25.83 ± 1.98 <sup>a</sup>	25.96 ± 1.79 <sup>a</sup>	25.37 ± 2.30 <sup>a</sup>	25.40 ± 2.51 <sup>a</sup>	-	
pH	7.35 ± 0.64 <sup>bc</sup>	7.18 ± 0.27 <sup>abc</sup>	6.70 ± 0.31 <sup>a</sup>	7.34 ± 0.55 <sup>bc</sup>	7.54 ± 0.68 <sup>c</sup>	7.40 ± 0.48 <sup>c</sup>	7.08 ± 0.29 <sup>abc</sup>	6.5-8.5	
DO (mg/l)	5.55 ± 0.55 <sup>bc</sup>	5.34 ± 0.31 <sup>ab</sup>	5.41 ± 0.28 <sup>abc</sup>	5.12 ± 0.39 <sup>a</sup>	5.71 ± 0.37 <sup>bc</sup>	5.11 ± 0.38 <sup>a</sup>	5.77 ± 0.58 <sup>c</sup>	8-May	
BOD (mg/l)	1.32 ± 0.22 <sup>bc</sup>	1.39 ± 0.40 <sup>bc</sup>	1.32 ± 0.35 <sup>bc</sup>	1.28 ± 0.54 <sup>b</sup>	1.61 ± 0.26 <sup>c</sup>	1.14 ± 0.34 <sup>b</sup>	1.23 ± 0.25 <sup>b</sup>	30-May	
TDS (mg/l)	315.63 ± 204.79 <sup>a</sup>	315.63 ± 204.79 <sup>a</sup>	315.63 ± 204.79 <sup>a</sup>	315.63 ± 204.79 <sup>a</sup>	315.63 ± 204.79 <sup>a</sup>	315.63 ± 204.79 <sup>a</sup>	315.63 ± 204.79 <sup>a</sup>	500-1500	
Turb (NTU)	2.84 ± 1.42 <sup>abc</sup>	4.86 ± 2.19 <sup>d</sup>	5.88 ± 1.03 <sup>de</sup>	4.08 ± 1.69 <sup>bc</sup>	6.37 ± 1.84 <sup>e</sup>	3.53 ± 1.25 <sup>abc</sup>	4.84 ± 1.94 <sup>cd</sup>	<5	
EC (µS/cm)	240.89 ± 57.72 <sup>ab</sup>	277.88 ± 78.57 <sup>b</sup>	233.24 ± 73.16 <sup>ab</sup>	196.50 ± 116.72 <sup>a</sup>	230.65 ± 91.56 <sup>ab</sup>	216.92 ± 77.30 <sup>ab</sup>	238.54 ± 51.97 <sup>ab</sup>	-	
NO3 (mg/l)	3.06 ± 3.08 <sup>b</sup>	1.70 ± 0.68 <sup>a</sup>	1.44 ± 0.44 <sup>a</sup>	1.40 ± 0.54 <sup>a</sup>	1.54 ± 0.64 <sup>a</sup>	1.40 ± 0.35 <sup>a</sup>	1.52 ± 0.88 <sup>a</sup>	<50	
Cl (mg/l)	392.20 ± 211.55 <sup>b</sup>	318.73 ± 178.56 <sup>ab</sup>	241.37 ± 62.98 <sup>a</sup>	306.98 ± 207.73 <sup>ab</sup>	272.49 ± 161.83 <sup>ab</sup>	297.08 ± 98.40 <sup>ab</sup>	374.05 ± 156.15 <sup>ab</sup>	250	
HCO3 (mg/l)	210.35 ± 268.49 <sup>b</sup>	101.58 ± 62.06 <sup>a</sup>	70.51 ± 29.37 <sup>a</sup>	132.13 ± 62.77 <sup>ab</sup>	150.02 ± 81.63 <sup>ab</sup>	163.85 ± 67.27 <sup>ab</sup>	154.80 ± 73.04 <sup>ab</sup>	< 200	
SO4 (mg/l)	0.61 ± 0.13 <sup>ab</sup>	0.77 ± 0.46 <sup>b</sup>	0.60 ± 0.37 <sup>ab</sup>	0.59 ± 0.20 <sup>ab</sup>	0.36 ± 0.15 <sup>a</sup>	0.81 ± 0.93 <sup>b</sup>	0.33 ± 0.23 <sup>a</sup>	500	
Ca (mg/l)	0.74 ± 0.25 <sup>d</sup>	0.65 ± 0.20 <sup>cd</sup>	0.59 ± 0.22 <sup>bcd</sup>	0.69 ± 0.24 <sup>d</sup>	0.42 ± 0.19 <sup>ab</sup>	0.49 ± 0.09 <sup>abc</sup>	0.45 ± 0.13 <sup>ab</sup>	-	
Mg (mg/l)	0.40 ± 0.10 <sup>a</sup>	0.34 ± 0.13 <sup>a</sup>	3.22 ± 9.57 <sup>a</sup>	0.31 ± 0.13 <sup>a</sup>	0.45 ± 0.04 <sup>a</sup>	0.28 ± 0.08 <sup>a</sup>	0.46 ± 0.06 <sup>a</sup>	-	
Na (mg/l)	0.32 ± 0.08 <sup>a</sup>	1.57 ± 4.35 <sup>a</sup>	0.30 ± 0.17 <sup>a</sup>	0.35 ± 0.10 <sup>a</sup>	0.30 ± 0.09 <sup>a</sup>	0.23 ± 0.19 <sup>a</sup>	0.29 ± 0.14 <sup>a</sup>	-	
K (mg/l)	0.59 ± 0.36 <sup>ab</sup>	0.62 ± 0.23 <sup>ab</sup>	0.55 ± 0.36 <sup>a</sup>	0.56 ± 0.15 <sup>a</sup>	0.44 ± 0.18 <sup>a</sup>	0.85 ± 0.42 <sup>b</sup>	0.73 ± 0.46 <sup>ab</sup>	<12	

Values are mean ± SD of the parameters in the various LGAs. Mean values with different superscripts across the rows differ significantly (p<0.05).

**Table 2: Temporal Variability of Groundwater Quality Parameters using Paired Sample t-Test**

Parameter	Wet Season (Mean ± SD)	Dry Season (Mean ± SD)	t-value	p-value	HQ (Wet)	HQ (Dry)
Temp (°C)	24.20 ± 0.96	27.42 ± 1.82	-9.834	0.000**	n/a	n/a
pH	6.90 ± 0.42	7.46 ± 0.60	-6.004	0.000**	n/a	n/a
DO (mg/l)	5.68 ± 0.40	5.11 ± 0.39	11.241	0.000**	1.136	1.022
BOD (mg/l)	1.23 ± 0.35	1.31 ± 0.43	-1.354	0.182	0.246	0.262
TDS (mg/l)	183.60 ± 82.16	454.01 ± 202.39	-13.336	0.000**	0.367	0.908
Turb (NTU)	4.05 ± 1.35	4.64 ± 2.50	-2.094	0.042**	0.810	0.928
EC (µS/cm)	272.32 ± 85.67	197.71 ± 48.32	6.183	0.000**	n/a	n/a
NO <sub>3</sub> (mg/l)	1.00 ± 0.26	2.29 ± 1.58	-5.672	0.000**	0.020	0.046
Cl (mg/l)	296.25 ± 162.89	324.00 ± 153.51	-2.112	0.040**	1.185	1.296
HCO <sub>3</sub> (mg/l)	201.25 ± 130.89	63.87 ± 26.80	7.406	0.000**	1.006	0.319
SO <sub>4</sub> (mg/l)	0.66 ± 0.58	0.44 ± 0.20	2.935	0.005**	0.001	0.001
Ca (mg/l)	0.64 ± 0.22	0.47 ± 0.21	6.334	0.000**	n/a	n/a
Mg (mg/l)	0.33 ± 0.10	1.10 ± 4.79	-1.112	0.272	n/a	n/a
Na (mg/l)	0.25 ± 0.10	0.65 ± 2.18	-1.264	0.212	n/a	n/a
K (mg/l)	0.70 ± 0.36	0.51 ± 0.26	4.643	0.000**	0.058	0.043

\*\* Significantly differ at 0.05 level of significance

**Table 3: Factor Loadings after Varimax Rotation**

Variables	Components			
	F1	F2	F3	F4
Temp	0.278	-0.852	0.026	-0.105
pH	0.458	-0.564	-0.216	0.347
DO	0.397	0.658	0.477	-0.184
BOD	-0.505	-0.211	0.634	0.308
TDS	0.706	-0.556	-0.170	-0.141
Turb	0.542	-0.013	0.670	0.083
EC	0.632	0.481	-0.095	-0.021
NO <sub>3</sub> <sup>-</sup>	0.424	-0.743	-0.009	0.232
Cl <sup>-</sup>	0.901	0.059	-0.122	-0.128
HCO <sub>3</sub> <sup>-</sup>	0.122	0.850	0.153	0.126
SO <sub>4</sub> <sup>2-</sup>	0.568	0.281	-0.262	0.628
Ca <sup>2+</sup>	0.623	0.500	0.027	0.340
Mg <sup>2+</sup>	0.538	-0.318	0.561	-0.192
Na <sup>+</sup>	0.477	-0.231	0.405	-0.090
K <sup>+</sup>	0.612	0.313	-0.375	-0.415
Eigenvalue	4.502	3.921	1.890	1.100
Variability (%)	30.007	26.139	12.598	7.335
Cumulative %	30.007	56.146	68.744	76.079

Where C is the mean concentration (mg/L) and RfD is the WHO reference dose or permissible limit. For parameters with WHO ranges, the lower limit was used for calculation. For parameters with no WHO guideline (e.g., Temperature, EC, Ca, Mg, Na), HQ was not computed. The Hazard Index (HI) was obtained by summing the HQs for each season. An HI > 1 indicates a potential health concern, while HI < 1 suggests a negligible risk.

**Data Analysis**

Descriptive statistics (mean, standard deviation, range) were computed. Sample adequacy was verified using the Kaiser–Meyer–Olkin test (KMO > 0.60) and Bartlett’s test of sphericity (p < 0.05). Principal Component Analysis (PCA) extracted key contamination factors based on eigenvalues greater than 1 and scree plot criteria. Cluster Analysis employed Agglomerative Hierarchical

Clustering with Ward’s linkage and squared Euclidean distance.

**RESULT AND DISCUSSION**

The paired sample t-test revealed significant temporal variability in groundwater quality, with most parameters exhibiting differences between the wet and dry seasons. The higher concentrations of TDS, turbidity, and chloride during the dry season may be linked to reduced dilution effects and increased evaporation, consistent with findings by [Ezea et al. \(2022\)](#) in Nigeria, who observed seasonal influences on spring water quality using WHO standards. Elevated bicarbonate and dissolved oxygen in the wet season reflect enhanced recharge and aeration from rainfall, in line with [Adimalla and Qian \(2019\)](#), who reported similar patterns in agricultural groundwater systems of South India.

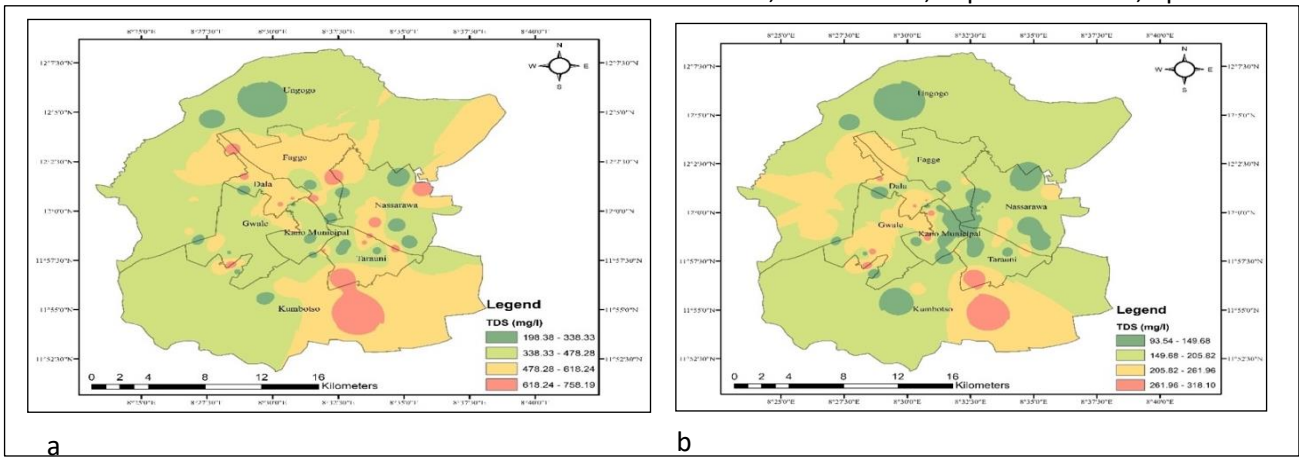


Figure 2: Spatial Distribution of Groundwater TDS (a) in Wet Season (b) in Dry Season

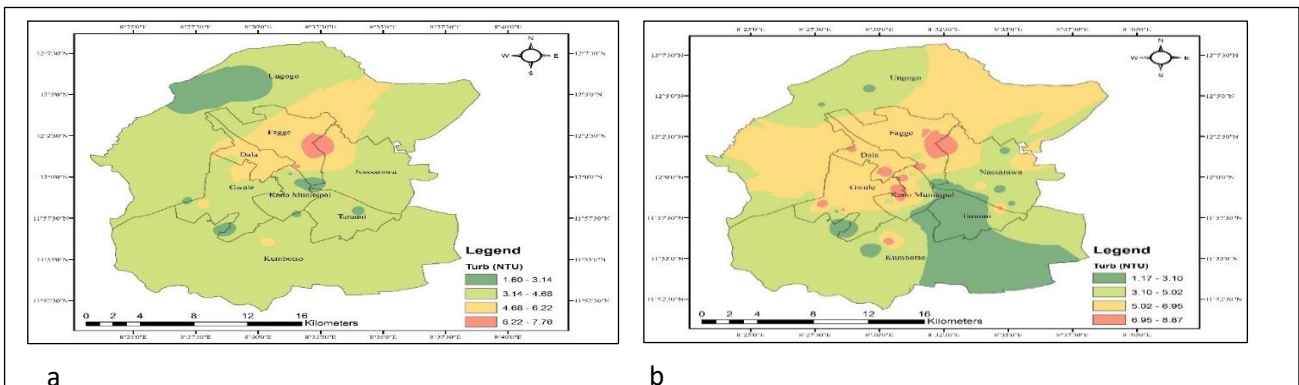


Figure 3: Spatial Distribution of Groundwater Turbidity (a) in Wet Season (b) in Dry Season

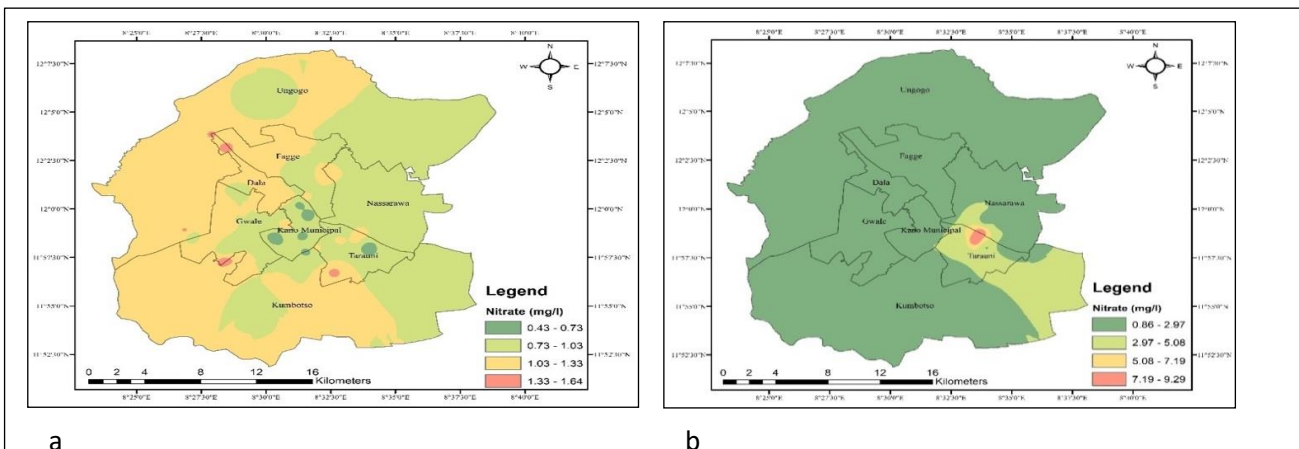


Figure 4: Spatial Distribution of Groundwater Nitrate (a) in Wet Season (b) in Dry Season

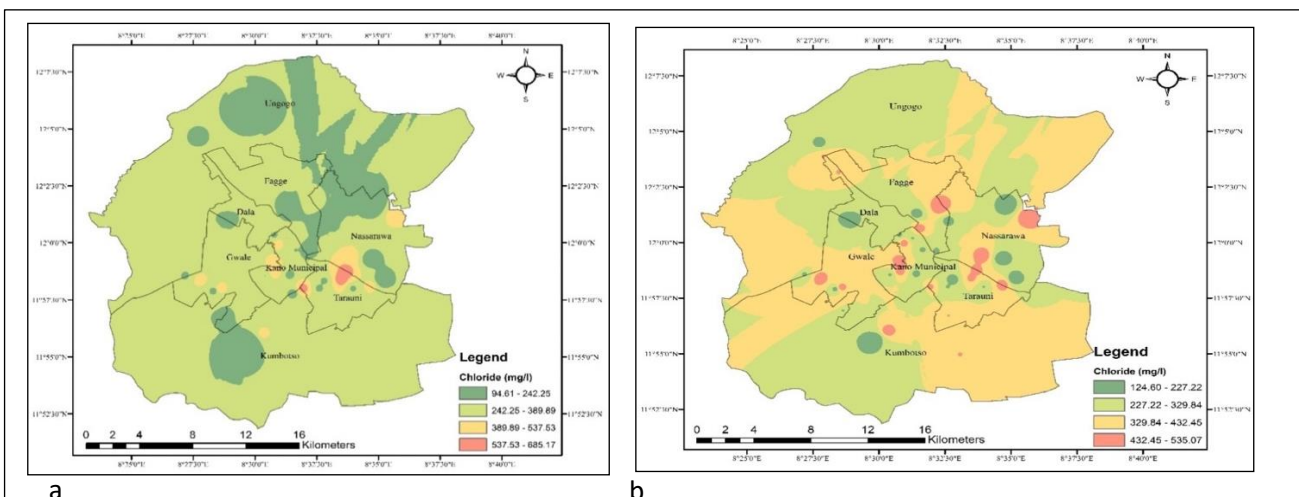


Figure 5: Spatial Distribution of Groundwater Chloride (a) in Wet Season (b) in Dry Season

**Table 4: Kaiser-Meyer-Olkin measure of sampling adequacy**

Parameter	Sampling adequacy
TEMP	0.688
pH	0.738
DO	0.586
BOD	0.542
TDS	0.663
TURB	0.645
EC	0.620
No <sub>3</sub>	0.658
Cl	0.571
HCO <sub>3</sub>	0.683
SO <sub>4</sub>	0.472
Ca	0.718
Mg	0.386
Na	0.102
k	0.593
KMO	0.606

by Chakraborty et al. (2022), who highlighted bicarbonate and nitrate enrichment as critical factors in seasonal water quality assessments. Although BOD, Mg, and Na did not vary significantly, their values remained within permissible limits, suggesting minimal impact on water safety. Overall, the study highlights the seasonal influences on hydrochemistry, with water from the dry season exhibiting greater contamination stress. This aligns with global evidence that climatic factors and anthropogenic inputs significantly influence groundwater quality dynamics, underscoring the importance of continuous monitoring and sustainable management.

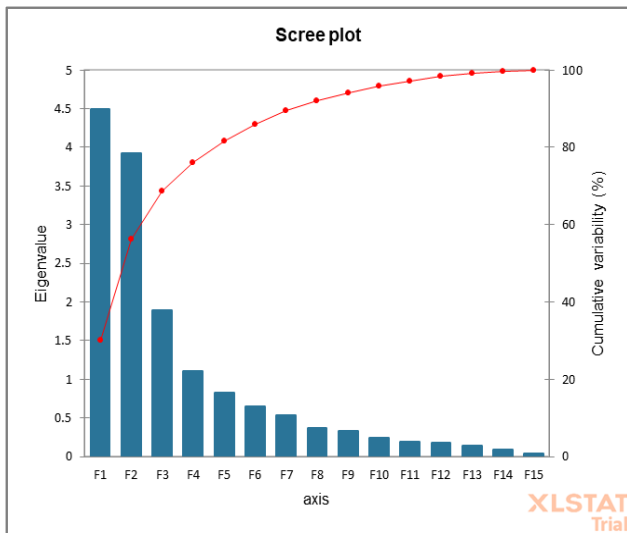
The Hazard Quotient (HQ) results indicate that chloride, dissolved oxygen, and bicarbonate are the primary contributors to non-carcinogenic risks, particularly in the dry season when contamination stress intensifies, highlighting the seasonal influence of hydrogeochemistry. This finding aligns with Chakraborty et al. (2022), who emphasized the importance of bicarbonate and nitrate enrichment in seasonal water quality dynamics. It also aligns with the findings from Cherif et al. (2020) in Morocco and Jain et al. (2021) in India, where seasonal and anthropogenic factors were found to govern HQ outcomes. Therefore, continuous monitoring and sustainable management are crucial for mitigating groundwater risks.

Total Dissolved Solids (TDS) levels were significantly higher in the dry season ( $454.01 \pm 202.39$  mg/l) compared to the wet season ( $183.60 \pm 82.16$  mg/l), as indicated by the high t-value of -13.336 ( $p = 0.000$ ). The negative t-value reflects the direction of the change, with higher TDS levels during the dry season. This increase is likely due to evaporation concentrating dissolved salts and reduced dilution from rainfall during the dry season. The large magnitude of the t-value underscores the significant seasonal effect on TDS, highlighting the role of evaporation in altering groundwater salinity.

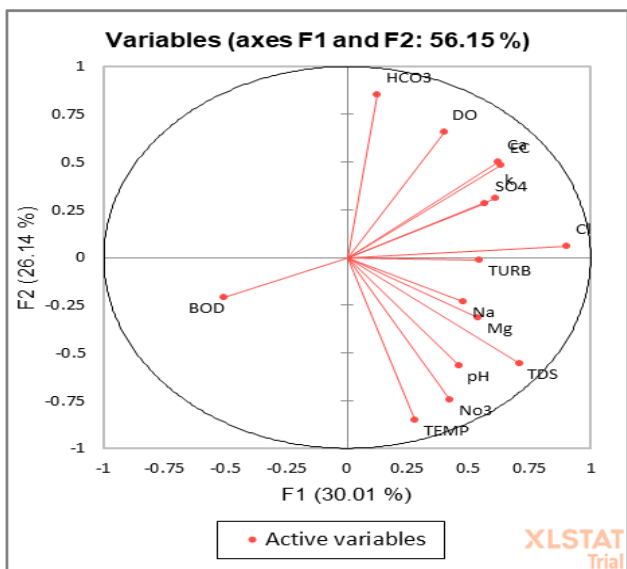
Turbidity (Turb) was significantly higher in the dry season ( $4.64 \pm 2.50$  NTU) compared to the wet season ( $4.05 \pm 1.35$  NTU), with a t-value of -2.094 ( $p = 0.042$ ). The negative t-value indicates an increase in turbidity during the dry season. This increase may result from reduced water flow and increased suspended solids from erosion or anthropogenic activities during the dry season. The moderate t-value suggests a noticeable but less pronounced seasonal effect on turbidity.

Nitrate (NO<sub>3</sub>) levels were significantly higher in the dry season ( $2.29 \pm 1.58$  mg/l) compared to the wet season ( $1.00 \pm 0.26$  mg/l), with a t-value of -5.672 ( $p = 0.000$ ). The negative t-value indicates an increase in nitrate concentrations during the dry season. This increase may result from reduced dilution and increased concentration of agricultural or industrial contaminants during the dry season. The significant t-value highlights the role of rainfall in diluting nitrate concentrations.

The Chloride (Cl) levels were significantly higher in the dry season ( $324.00 \pm 153.51$  mg/l) compared to the wet season



**Figure 6: Scree Plot**



**Figure 7: Factor Loadings Plot**

Hazard Quotient analysis indicated that chloride, dissolved oxygen, and bicarbonate contributed most to health risks in both seasons, consistent with observations <https://scientifica.umyu.edu.ng/>

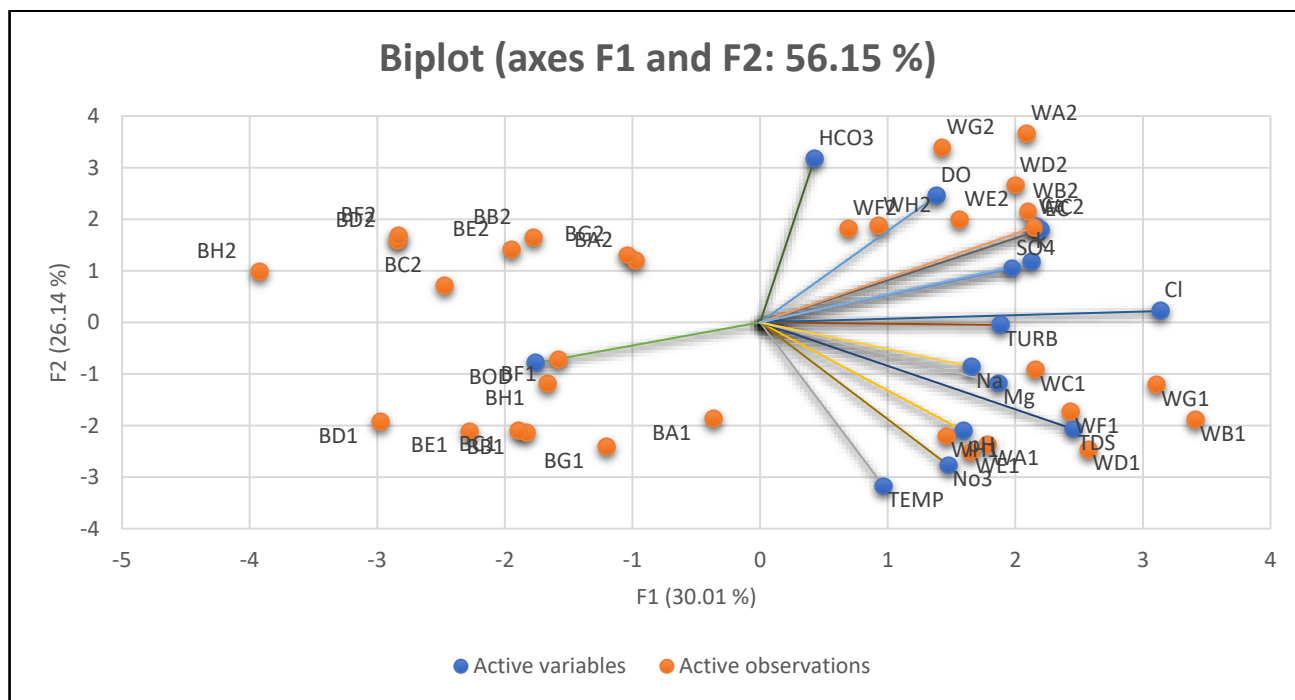
season ( $296.25 \pm 162.89$  mg/l), as indicated by the t-value of -2.112 ( $p = 0.040$ ). The negative t-value reflects the direction of the change, with higher chloride levels during the dry season. This increase is likely due to evaporation

concentrating chloride ions and reduced dilution from rainfall during the dry season. The moderate t-value suggests a noticeable but less pronounced seasonal effect on chloride concentrations.

**Table 5: Communalities**

Variable	Observations	Obs. with missing data	Obs. without missing data	Min	Max	Mean	Std. deviation
TEMP	32	0	32	22.300	29.500	25.813	2.113
pH	32	0	32	6.000	8.600	7.194	0.579
DO	32	0	32	4.600	6.600	5.425	0.458
BOD	32	0	32	0.610	1.930	1.270	0.358
TDS	32	0	32	94.000	759.000	321.775	211.321
TURB	32	0	32	1.380	8.630	4.360	2.046
EC	32	0	32	105.500	392.800	236.831	79.367
No3	32	0	32	0.550	3.540	1.530	0.718
Cl	32	0	32	94.300	687.030	314.076	158.793
HCO3	32	0	32	26.400	652.800	132.933	118.048
SO4	32	0	32	0.050	1.501	0.506	0.305
Ca	32	0	32	0.150	1.140	0.553	0.226
Mg	32	0	32	0.188	22.600	1.066	3.931
Na	32	0	32	0.070	2.810	0.374	0.467
k	32	0	32	0.130	3.183	0.696	0.555

Min: Minimum; Max: Maximum



**Figure 8: Biplot Relationship between Water Quality Parameters and Sampling Points**

**Spatial Distribution of Groundwater Contaminants**

The spatial distribution maps (Figures 2a–5b) present a detailed portrayal of hotspot areas of groundwater quality in Kano Metropolis, comparing seasonal variations between the wet and dry periods. These maps not only reveal the essential geochemical characteristics of the aquifers but also highlight the influence of climatic conditions and anthropogenic activities on groundwater quality.

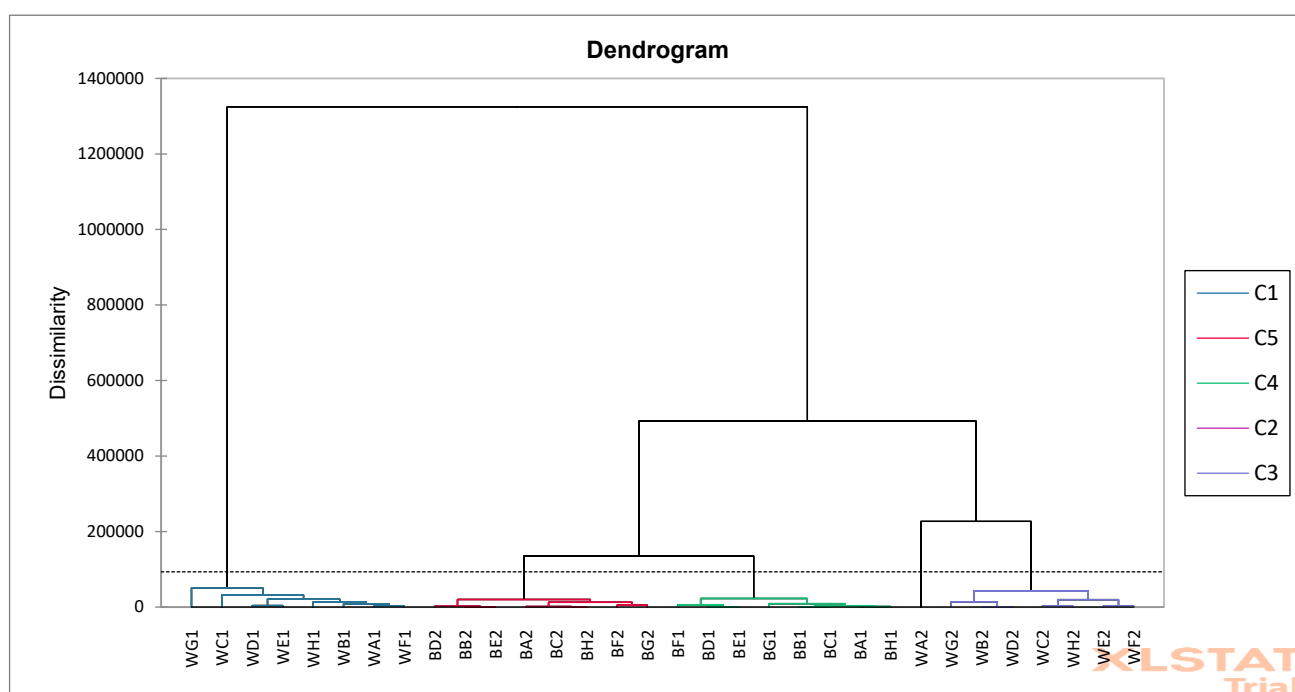
Figures 2a and 2b illustrate the spatial distribution of Total Dissolved Solids (TDS) across the study area. During the wet season, TDS values range from 198.38 to 758.19 mg/L, with most of the area exhibiting values between 338.33 and 618.24 mg/L. Within this season, localized patches show both lower TDS values (198.38–336.33 mg/L) and peak concentrations (618.24–758.19 mg/L). In contrast, the dry season is characterized by lower TDS levels, ranging from 93.4 to 318.10 mg/L, with the majority of the study area falling between 149.66 and

261.96 mg/L. These elevated TDS concentrations during the wet season are indicative of enhanced mineral

dissolution and recharge processes that contribute to the concentration of dissolved solids in the groundwater.

**Table 6: Distances between the Central Objects for Sample Sites**

Variable	Minimum	Maximum	Mean	Std. deviation
TEMP	22.300	29.500	25.813	2.113
pH	6.000	8.600	7.194	0.579
DO	4.600	6.600	5.425	0.458
BOD	0.610	1.930	1.270	0.358
TDS	94.000	759.000	321.775	211.321
TURB	1.380	8.630	4.360	2.046
EC	105.500	392.800	236.831	79.367
No3	0.550	3.540	1.530	0.718
Cl	94.300	687.030	314.076	158.793
HCO3	26.400	652.800	132.933	118.048
SO4	0.050	1.501	0.506	0.305
Ca	0.150	1.140	0.553	0.226
Mg	0.188	22.600	1.066	3.931
Na	0.070	2.810	0.374	0.467
k	0.130	3.183	0.696	0.555



**Figure 9: Dendrogram of Agglomerative Hierarchical Clustering for Groundwater Sample Sites**

Turbidity maps (Figures 3a and 3b) revealed a consistent spatial distribution for both seasons. In the wet season, most groundwater samples exhibit turbidity values ranging from 3.14 to 6.22 NTU, while in the dry season, the values mostly fall between 3.10 and 6.95 NTU.

During the wet season, the lowest turbidity (1.60–3.14 NTU) is observed in the northeastern section of Ungogo, the southern part of Gwale, and near the confluence of Nassarawa, Fagge, Tarauni, and Kano Municipal LGAs. Conversely, the highest turbidity values (6.22–7.76 NTU) appear to the west of Nassarawa and east of Fagge. In the dry season, peak turbidity (6.95–8.87 NTU) is scattered across densely populated LGAs, while the lowest values (1.17–3.10 NTU) are found throughout Tarauni, parts of southern Nassarawa and Fagge, the eastern section of Kano Municipal, and the mid-eastern region of Kumbotso

LGA. Overall, the groundwater in the study area appears generally clear, except in localized zones with elevated turbidity levels.

The spatial distribution of Nitrate (NO<sub>3</sub>), as illustrated in Figures 4a and 4b, exhibits a distinct seasonal variation, with higher concentrations observed during the dry season (0.86–9.29 mg/L) compared to the wet season (0.43–1.64 mg/L). During the wet season, NO<sub>3</sub> concentrations predominantly range between 1.03 and 1.64 mg/L in the western section of the metropolis, while lower values (0.43–1.03 mg/L) are more common in the eastern section. In contrast, the dry season map reveals that a significant portion of the metropolis falls within the lower concentration range of 0.86–2.97 mg/L. Mid-range values (2.97–5.08 mg/L) are concentrated in Tarauni, the

southwestern part of Nassarawa, and the eastern section of Kumbotso LGAs. The highest concentrations (5.08–9.29 mg/L) are recorded in the southwestern part of Nassarawa and the northern section of Tarauni LGAs. However, the observed seasonal variations suggest potential influences from surface activities and hydrogeological processes. The lower NO<sub>3</sub> concentrations

in the wet season may be attributed to dilution effects caused by increased recharge and infiltration of rainwater. Conversely, higher concentrations during the dry season could result from reduced dilution, increased evapotranspiration, and potential leaching of accumulated nitrates from agricultural runoff, sewage, and other anthropogenic sources.

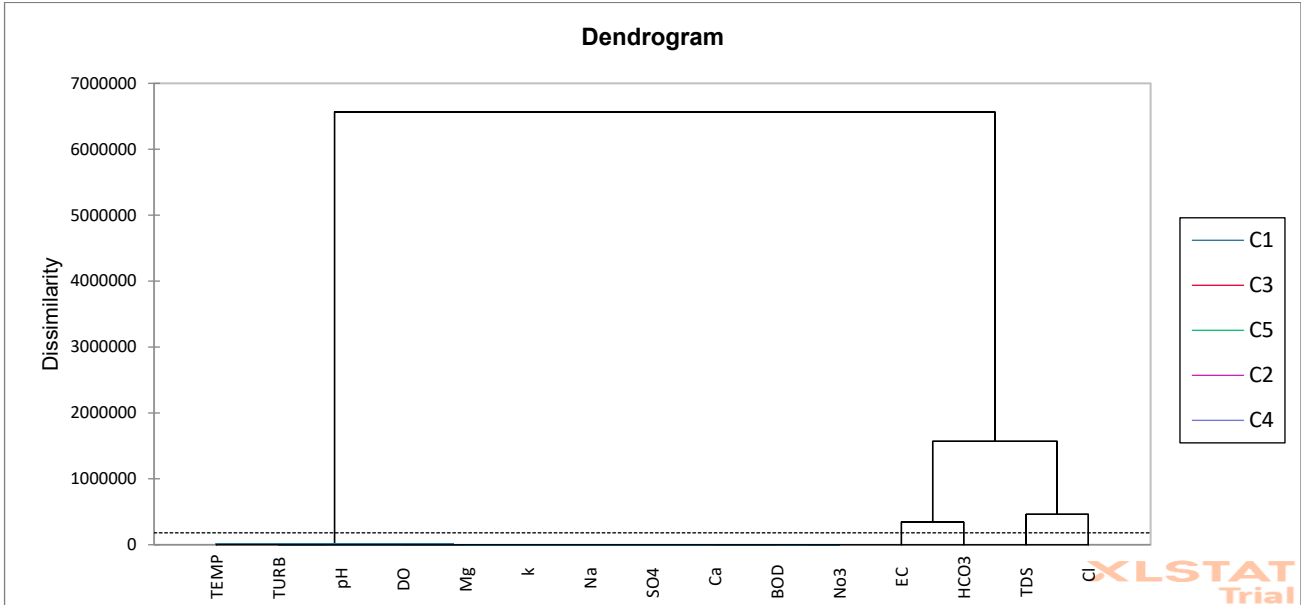


Figure 10: Dendrogram of Agglomerative Hierarchical Clustering for Groundwater Quality Parameters

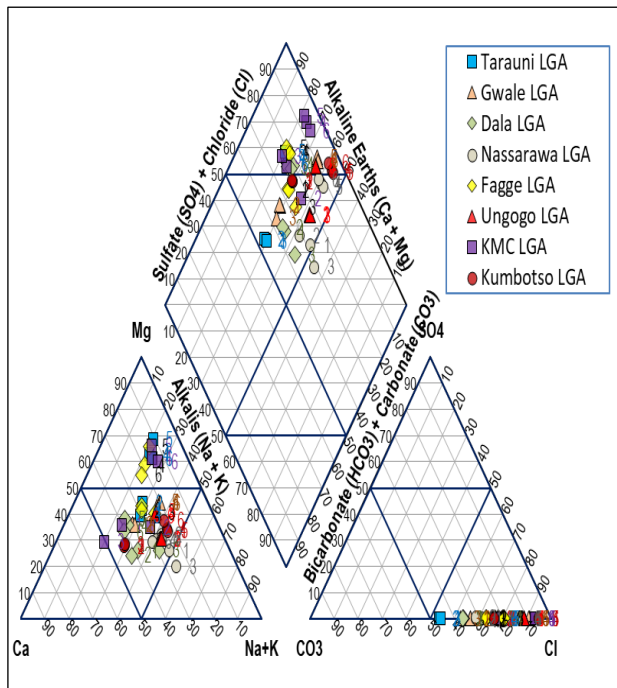


Fig 11: Plot for Dry Season Groundwater Chemistry

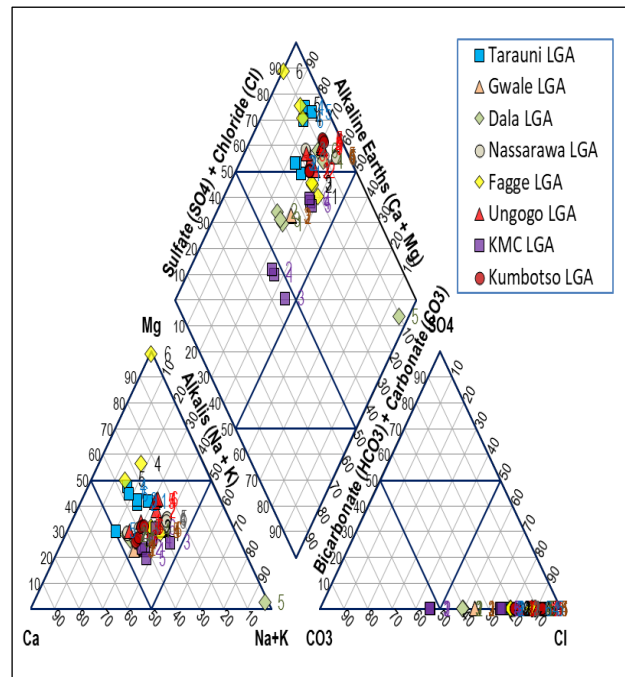


Fig 12: Plot for Wet season Groundwater Chemistry

The spatial distribution of chloride, as illustrated in Figures 5a and 5b, reveals distinct seasonal variations. During the wet season, chloride concentrations range from a low of 94.61 to 242.25 mg/L to a peak of 537.53–685.17 mg/L. In contrast, the dry season exhibits slightly different patterns, with chloride values ranging from 124.60 to 227.22 mg/L at the lower end and peaking at 432.45–535.07 mg/L. In the wet season, the majority of

the study area is dominated by moderate chloride levels between 242.26 and 389.89 mg/L, spanning across all LGAs. The highest concentrations, ranging from 537.53 to 685.17 mg/L, are observed in isolated pockets, particularly at the confluence of Tarauni, Nassarawa, Kumbotso, and Kano Municipal LGAs. During the dry season, most sections of the metropolis exhibit mid-range chloride concentrations, ranging from 227.22 to 432.45 mg/L. The highest values, ranging from 432.45 to 535.07

mg/L, appear sporadically in densely populated areas, likely reflecting anthropogenic influences such as domestic wastewater discharge and industrial activities. This seasonal variation suggests that both natural hydrogeological processes and human activities influence chloride levels.

### Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was applied to the 15 physicochemical parameters and yielded 15 components; however, only components with an eigenvalue greater than 1 were considered to be the most important (O'Rourke et al., 2005; Kura et al., 2013). The scree plot (Figure 2) of the eigenvalues demonstrates a steep decline in variance explained after the fourth component, confirming that only these four factors are necessary for interpretation. The remaining components contribute minimal variance, indicating that they primarily represent less influential processes.

The eigenvalues and cumulative variance, as indicated in Table 1, showed that the first four principal components (F1–F4) collectively explain 76.1% of the total variance in the groundwater dataset. The first component (F1) alone accounts for 30.0% of the total variance, while the second component (F2) explains 26.1%, making them the most dominant factors influencing groundwater quality. The third (F3) and fourth (F4) components contribute 12.6% and 7.3% of the variance, respectively.

The factor loadings offer insight into the specific variables that influence each principal component. The first component (F1), which accounts for 30.0% of the variance, has high positive loadings for chloride (Cl), total dissolved solids (TDS), turbidity, electrical conductivity (EC), sulphate (SO<sub>4</sub>), calcium (Ca), magnesium (Mg), and potassium (K), represents salinity and mineralization in the groundwater.

The PCA results reveal that both natural hydrogeochemical processes and anthropogenic activities shape groundwater quality in Kano Metropolis. The dominance of F1 (34.8%), associated with salinity and mineralization (Na, Cl, TDS, and temperature), highlights the influence of parent rock dissolution and aquifer–rock interactions, a trend also observed by Adimalla & Qian (2019) in South India, where groundwater salinity was primarily linked to water–rock interactions and evaporite mineral dissolution. The additional contribution from industrial effluents and agricultural inputs aligns with the findings of Ezea et al. (2022), who reported that anthropogenic factors significantly affect groundwater salinity in peri-urban Nigerian settings.

The F8 component (26.1%), reflecting the carbonate buffering system (HCO<sub>3</sub>, Ca, DO, EC), demonstrates the role of carbonate dissolution and recharge dynamics. Similar results were presented by Chakraborty et al. (2022), who found that bicarbonate–calcium dominance indicated buffering effects and recharge influence in Indian plateau aquifers. The high DO association here suggests zones of active infiltration, implying groundwater vulnerability to surface contamination. F9 (12.6%), dominated by BOD, turbidity, and Mg, indicates organic and microbial contamination, likely from wastewater, septic leakage, and runoff. This parallels observations by Chakraborty et al. (2022), who found turbidity and BOD as markers of microbial pollution in shallow aquifers.

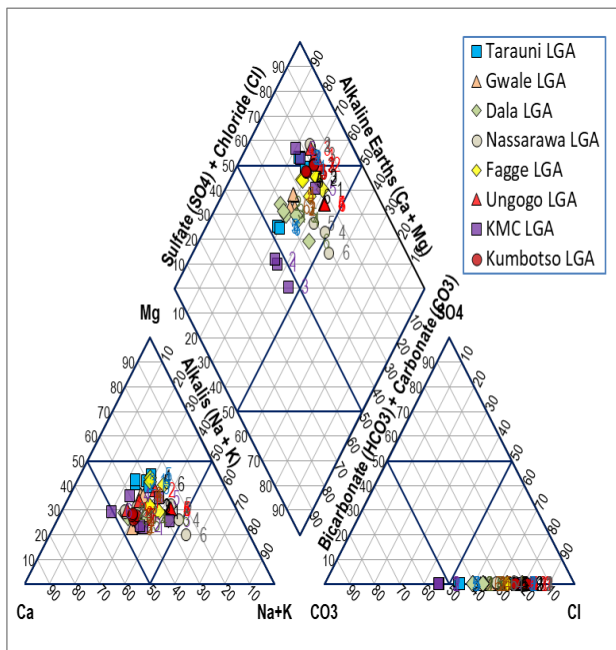


Fig 13: Piper Plots for Boreholes Water Samples

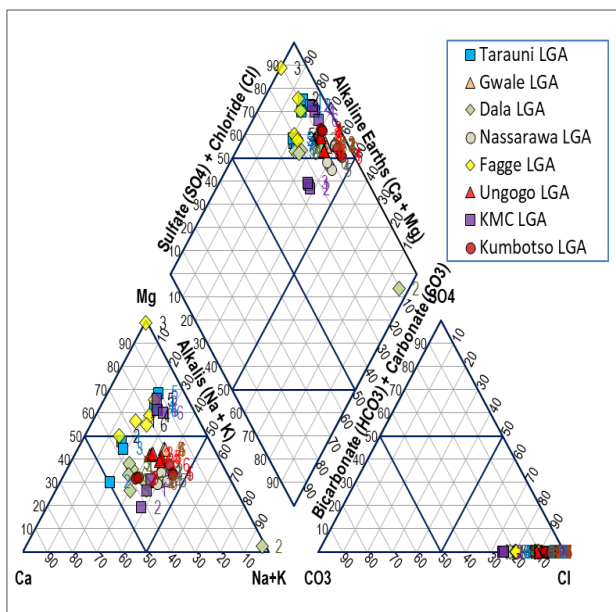


Fig 14: Plots for Wells Water Samples

### Factors Controlling Groundwater Quality in the Study Area

The factors controlling groundwater quality were analyzed using Principal Component Analysis (PCA), and Agglomerative Hierarchical Clustering (AHC) to identify key contamination sources, spatial trends, and relationships among groundwater quality parameters. Also, a Piper trilinear diagram was deployed for the hydrogeochemical characterization of groundwater in the study area.

Finally, F10 (7.3%), with strong sulphate loading, reflects localized contamination from fertilizers and industrial sources. This trend is consistent with [Eze et al. \(2022\)](#), who highlighted sulphate enrichment from fertilizer leaching in Nigerian aquifers. The PCA biplot further demonstrates spatial clustering of sampling sites, distinguishing zones influenced by salinity and anthropogenic stress (WF1, WF2, WC1, WC2, WD1, WD2) from recharge-dominated, better-buffered sites (BH1, BH2, BD1, BE1, BC2). Such spatial differentiation of hydrogeochemical processes has also been reported by [Adimalla & Qian \(2019\)](#), underscoring the strength of PCA in delineating contamination hotspots.

The dispersion of data points along the axes provides insights into the spatial heterogeneity of groundwater quality in the study area. Locations with closely positioned observations, such as BE1 and BE2, or BG1 and BG2, suggest similar physicochemical properties, while those that are widely scattered, such as BC1 and WC1, exhibit diverse water quality characteristics. This differentiation highlights the variability in groundwater sources and the potential impact of both natural and anthropogenic factors. The findings suggest that some groundwater sources are more significantly impacted by salinity, mineral dissolution, and anthropogenic activities, whereas others are influenced by their natural buffering capacity and oxygenation processes. The findings from the biplot indicate that some groundwater sources are more affected by salinity, mineral dissolution, and anthropogenic activities, while others are influenced by natural buffering capacity and oxygenation processes.

### Cluster Analysis

The AHC results reveal strong spatial and seasonal variability in groundwater quality across Kano, with well sources in both dry and wet seasons showing higher variance compared to borehole sources. The high variance of wells, particularly in the dry season, indicates greater susceptibility to surface contamination and fluctuating recharge, consistent with findings by [Edet & Okereke \(2014\)](#) in southeastern Nigeria. The distinct outlier cluster observed in WA2 during the wet season further demonstrates unique geochemical conditions, a pattern also noted by [Ali et al. \(2021\)](#) in Egyptian aquifers where isolated clusters represented less-contaminated sources. Seasonal recharge plays a critical role in shaping variability, as seen in Cluster 3, where increased wet season runoff mobilized contaminants, mirroring observations from [Ibrahim et al. \(2022\)](#) in Abuja. By contrast, borehole clusters displayed lower variance, suggesting more geochemical stability, which aligns with [Wali et al. \(2018\)](#) who reported that deeper aquifers in Sokoto maintained consistent water chemistry compared to shallow wells.

The clustering of parameters further illustrates contamination pathways and geochemical controls in Kano groundwater. TEMP, pH, DO, BOD, turbidity, and nutrients such as nitrate and sulfate are grouped together, highlighting organic and agricultural contamination sources. This finding aligns with [Babika & Tukur, \(2022\)](#),

who attributed similar clustering in Kano peri-urban wells to sewage infiltration and fertilizer use. Conversely, parameters such as TDS, EC, chloride, and bicarbonate formed distinct clusters, reflecting the influence of salinity and buffering processes on lithological interactions, similar to those observed by [Li et al. \(2019\)](#) in northern China. The higher centroid distances observed for organic and microbial indicators relative to salinity parameters confirm stronger variability in anthropogenic pollution, a finding consistent with [Obiora et al. \(2019\)](#) in Enugu, where nitrate and turbidity dispersed widely while EC and chloride remained stable.

The Agglomerative Hierarchical Clustering (AHC) analysis has provided significant insights into the spatial and seasonal variability of groundwater quality in Kano Metropolis. The results revealed five distinct clusters of groundwater sampling points, reflecting differences in water sources (boreholes and wells) and seasonal influences. Borehole water samples exhibited relatively stable quality, while well water samples demonstrated greater seasonal variability, indicating a higher susceptibility to surface contamination. The clustering of physicochemical parameters further highlighted key contributors to groundwater quality degradation, with salinity-related factors (TDS, EC, Cl) forming distinct clusters separate from organic pollutants (BOD, turbidity, NO<sub>3</sub>) and industrial contaminants (SO<sub>4</sub>, Na, Mg).

### Hydrogeochemical Classification of Groundwater Using Piper Trilinear Diagrams

The hydrogeochemical characterization of groundwater in Kano Metropolis was conducted using Piper trilinear diagrams, which provide insights into the dominant cation-anion compositions and hydrogeochemical facies of the sampled water. Piper diagrams are widely used in groundwater studies to classify water types and identify geochemical processes influencing water quality ([Igbah and Tanko, 2019](#); [Changsheng et al., 2022](#)). The analysis was performed for both dry and wet seasons, as well as for boreholes and wells, to assess seasonal and source-related variations. This classification helps in understanding aquifer geochemistry, evaluating potential contamination sources, and tracing the evolution of groundwater chemistry over time ([Siddha and Sahu, 2022](#)).

### Piper Plot for Dry Season Groundwater Chemistry

The Piper diagram for dry season groundwater samples ([Figure 7](#)) illustrates the distribution of major cations and anions. The left ternary diagram (cation plot) shows a predominance of alkaline earth metals (Ca<sup>2+</sup> and Mg<sup>2+</sup>) over alkali metals (Na<sup>+</sup> and K<sup>+</sup>), indicating that groundwater in Kano Metropolis is primarily hard water. This composition suggests that the water chemistry is strongly influenced by the dissolution of carbonate and sulphate minerals, which are common in sedimentary rock formations. The dominance of calcium and magnesium points to the presence of limestone, dolomite, and

gypsum, which release these ions into the groundwater through water-rock interactions (Yan *et al.*, 2024).

The right ternary diagram (anion plot) reveals that sulphate ( $\text{SO}_4^{2-}$ ) and chloride ( $\text{Cl}^-$ ) are the dominant anions, surpassing bicarbonate ( $\text{HCO}_3^-$ ) and nitrate ( $\text{NO}_3^{2-}$ ). The elevated levels of sulphate and chloride indicate that groundwater chemistry is influenced by evaporation effects, industrial discharges, agricultural runoff, and potential contamination from urban sources. High chloride concentrations are commonly linked to sewage infiltration, waste disposal, and leachates from industrial activities (Hu *et al.*, 2024).

The diamond plot, which integrates cationic and anionic compositions, classifies most groundwater samples as belonging to the Ca-Mg-SO<sub>4</sub>-Cl facies. This water type is commonly found in semi-arid regions, where high evaporation rates result in increased solute concentrations in groundwater. The dominance of sulphate implies fertilizer application or natural gypsum dissolution, while the strong presence of chloride reinforces the role of industrial and domestic waste contributions (Sharma and Kumar, 2020; Dou *et al.*, 2022).

The observed hydrogeochemical patterns align with the climatic conditions of Kano Metropolis, where intense evaporation leads to increased mineralization of groundwater, especially during the dry season (Tukur *et al.*, 2018). The Piper diagram results suggest that water-rock interactions, anthropogenic influences, and climatic effects are the primary drivers of groundwater chemistry in this period.

#### Piper Plot for Wet Season Groundwater Chemistry

The Piper diagram for wet-season groundwater samples (Figure 8) exhibits a similar cationic composition to that of the dry season, with  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  remaining dominant. However, the anion distribution shows a relative increase in bicarbonate ( $\text{HCO}_3^-$ ) due to rainfall recharge and surface water infiltration, which enhances carbonate dissolution.

This dilution effect results in a slight reduction in chloride and sulfate concentrations, as observed in other recharge-dominated aquifers (Amroune *et al.*, 2020). The central diamond plot for wet season samples indicates a predominant Ca-Mg-Cl-SO<sub>4</sub> hydro chemical facies, similar to the dry season but with a more clustered distribution. This suggests that rainfall recharge helps moderate solute concentrations in groundwater, reducing the degree of mineralization observed in the dry season. However, the persistence of chloride-rich water types suggests that anthropogenic influences, such as domestic wastewater, urban runoff, and industrial discharges, continue to impact groundwater quality, even during the wet season (Sahoo *et al.*, 2024).

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The seasonal variation observed in the Piper diagrams highlights the impact of hydrogeochemical processes and anthropogenic activities on groundwater chemistry. While wet-season recharge helps dilute solute concentrations, the persistence of sulfate and chloride dominance indicates continued contamination risks from human activities. The Piper diagram results suggest that water-rock interactions, anthropogenic inputs, and seasonal variations are the key drivers shaping groundwater chemistry in the study area. This finding is in agreement with those of Mustapha *et al.* (2021), who concluded that water-rock interaction processes and anthropogenic influences impact groundwater quality in the downstream section of the Kano-Challawa River system.

#### Piper Plot for Boreholes and Wells Groundwater Chemistry

The Piper diagram analysis also highlights variations in borehole and well water chemistry, influenced by aquifer depth, recharge sources, and anthropogenic activities (Akhtar *et al.*, 2021). The groundwater samples from both boreholes and wells, as indicated in Figures 9 and 10, predominantly fall under the Ca-Mg-SO<sub>4</sub>-Cl facies, reflecting the strong influence of alkaline earth metals and sulfate-chloride-dominant anions. However, distinct variations exist between boreholes and wells, suggesting differences in hydrogeological conditions and susceptibility to contamination. Borehole samples exhibit a more stable Ca-Mg-SO<sub>4</sub>-Cl water type, which is indicative of deeper groundwater flow, prolonged water-rock interactions, and reduced vulnerability to surface contamination. In contrast, well water samples exhibit greater dispersion in cationic composition, indicating a stronger influence from local lithology, leaching from sediments, and anthropogenic activities such as agricultural runoff and infiltration of domestic waste.

Groundwater chemistry in both boreholes and wells undergoes significant seasonal fluctuations. During the wet season, increased precipitation enhances aquifer recharge, leading to the dilution of dissolved ions in shallow wells. However, increased surface infiltration can introduce contaminants, including nitrates, microbial pollutants, and organic matter, raising potential health risks. Conversely, during the dry season, reduced recharge and increased evaporation lead to higher ion concentrations, particularly in wells, where water levels

may drop, causing enhanced mineral dissolution. Boreholes, due to their greater depth and confined nature, exhibit more stable hydrochemical characteristics with minimal seasonal variation. However, slight increases in sulfate and chloride concentrations suggest a prolonged water residence time and possible contributions from anthropogenic sources.

The hydrogeochemical variations observed in boreholes and wells have important implications for groundwater quality management in Kano Metropolis. Boreholes generally provide a more reliable and chemically stable water source for domestic and agricultural use (Lapworth *et al.*, 2017), though elevated sulphate ( $\text{SO}_4^{2-}$ ) and chloride ( $\text{Cl}^-$ ) concentrations in some borehole samples may indicate potential salinity issues due to rock-water interactions and anthropogenic inputs. On the other hand, well water is more susceptible to seasonal variations and external contamination, with higher  $\text{Na}^+$  and  $\text{K}^+$  concentrations in some samples indicating potential sewage infiltration, fertilizer leaching, and other human-induced influences. Generally, the classification of groundwater facies using Piper diagrams provided crucial insights into the hydrogeochemical evolution of groundwater in the study area. The observed trends suggest that water-rock interactions, evaporation, recharge processes, and human activities collectively shape the groundwater chemistry of Kano Metropolis. This is similar to the report by Mshelia (2023) in a study on spatiotemporal variations of physicochemical parameters of water quality in Kano Metropolis.

## CONCLUSION

This study demonstrates that both natural hydrogeochemical processes and anthropogenic activities significantly influence groundwater quality in Kano Metropolis. Seasonal variations are pronounced, with the dry season showing elevated concentrations of salinity-related parameters (TDS, Cl) due to reduced dilution and increased evaporation. The primary contamination sources identified are salinity/mineralization, carbonate dissolution, organic pollution, and industrial/agricultural inputs. Boreholes generally offer more stable water quality than open wells, which are highly vulnerable to surface contamination. The persistent exceedance of Hazard Quotients for chloride and other parameters indicates a potential non-carcinogenic health risk. To mitigate these risks, it is imperative to establish and enforce legally mandated sanitary protection zones around all public boreholes and wells, and to implement a mandatory quarterly groundwater quality monitoring program, focusing on chloride and nitrate levels in vulnerable open wells. These actions are crucial first steps toward safeguarding public health and ensuring the sustainability of this vital resource.

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