

Hydrochemical Characterization and Pollution Assessment of Groundwater in Yendogo and Its Environs, Sokoto Basin, Northwestern Nigeria

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ABSTRACT

Groundwater is the principal source of water for domestic and agricultural activities in Yendogo and its environs, Sokoto Basin, northwestern Nigeria. Assessing its hydrochemical characteristics and pollution status is essential for sustainable groundwater management under changing climatic conditions. This study assessed the hydrochemical characteristics, pollution status, and suitability of groundwater for domestic use. Field investigations, groundwater sampling, and in-situ measurements of pH, temperature, electrical conductivity (EC), and total dissolved solids (TDS) were carried out. Laboratory analyses were conducted to determine major ions and selected heavy metals, while the analytical data were processed using AquaChem, Microsoft Excel, and Surfer software and compared with World Health Organization (WHO) drinking water guidelines. Groundwater was generally fresh, slightly acidic, and moderately mineralized, with temperature ranging from 28.0–31.8°C, pH 4.78–5.90, EC 159–772 $\mu\text{S/cm}$, and TDS 112–360 mg/L. Hydrochemical analysis showed that groundwater is predominantly of the Ca–Mg–HCO₃ hydrochemical facies, indicating that groundwater chemistry is mainly controlled by carbonate dissolution and natural rock–water interactions. Most physicochemical parameters and major ions and the selected heavy metals were within WHO permissible limits. However, lead (Pb) concentrations exceeded the WHO guideline value in some sampling locations, indicating localized contamination and the need for continuous groundwater quality monitoring. Overall, the groundwater is generally suitable for domestic use; however, appropriate treatment is recommended before consumptions in areas where elevated lead concentrations were observed.

Keywords: Groundwater, Hydrochemistry, Pollution Assessment, Heavy Metals, Water Quality, Sokoto Basin, Yendogo.

1.0 INTRODUCTION

Groundwater is one of the most important freshwater resources worldwide, providing a dependable source of water for domestic, agricultural, and industrial uses (Scanlon *et al.*, 2023; UNESCO, 2022). In semi-arid regions, where surface water is often scarce, seasonal, or unreliable, groundwater plays a critical role in sustaining livelihoods and supporting socio-economic development (Gambo *et al.*, 2024). In northwestern Nigeria, particularly within the Sokoto Basin, groundwater serves as the principal source of potable water owing to rapid population growth, urban expansion, and the limited availability of perennial surface water resources (Offodile, 2002; Adelana *et al.*, 2008).

The quality of groundwater is primarily controlled by the interaction between water and the geological formations through which it flows. Processes such as mineral dissolution, ion exchange, rock weathering, and groundwater residence time significantly influence groundwater chemistry (Ekwere *et al.*, 2023; Haman Didier *et al.*, 2023). In addition to these natural processes, anthropogenic activities, including improper waste disposal, agricultural practices, leakage from septic systems, and urban development,

may introduce contaminants into aquifer systems, thereby reducing groundwater quality and posing risks to public health and environmental sustainability (Abanyie *et al.*, 2023; WHO, 2022).

Shallow aquifers within the Sokoto Basin are particularly vulnerable to contamination because of their close interaction with surface-derived inputs and intensive agricultural activities. Previous investigations in the Gidan Gulbi floodplain aquifer have documented physicochemical and heavy-metal contamination and highlighted the potential vulnerability of shallow groundwater resources to anthropogenic pollution (Ibrahim *et al.*, 2020)

Hydrochemical characterization provides valuable information on the chemical composition of groundwater and the geochemical processes controlling its evolution. Similarly, pollution assessment helps identify the extent of groundwater contamination resulting from both natural and human-induced activities. The analysis of physicochemical parameters, major ions, and selected heavy metals enables the classification of groundwater types, evaluation of pollution status, identification of contamination sources, and assessment of groundwater



suitability for domestic use. Such information is essential for the sustainable management of groundwater resources, particularly in regions experiencing increasing water demand and the impacts of climate variability.

The Sokoto Basin is one of Nigeria's major inland sedimentary basins and comprises several important hydrological units, including the Gwandu, Kalambaina, Wurno, Dange, and Rima formations. Among these, the Gwandu Formation is the principal aquifer in many parts of the basin because it consists predominantly of unconsolidated to poorly consolidated sands and gravels with high porosity and permeability, allowing it to store and transmit significant quantities of groundwater. The Kalambaina Formation also serves as an important aquifer where fractured limestone and sandy horizons occur, while the Dange Formation generally has lower groundwater potential due to its shale-rich composition. These aquifer systems provide the major source of groundwater for domestic, agricultural, and livestock uses throughout the Sokoto Basin, including Yendogo and its surrounding communities (Kogbe, 1989; Offodile, 2002; Adelana *et al.*, 2008). Within the basin, Yendogo and its environs depend almost entirely on groundwater obtained from hand-dug wells and boreholes which primarily tap the Gwandu Formation aquifer. In some parts of the study area, particularly where geological boundaries occur, groundwater may also be obtained from the Kalambaina Formation aquifer. These aquifer systems constitute the principal source of water for drinking, domestic activities, livestock production (Offodile, 2002; Kogbe, 1989; Adelana *et al.*, 2008). However, increasing population growth, expanding commercial and agricultural activities, poor sanitation practices, and inadequate waste management have heightened concerns regarding groundwater pollution (Abanyie *et al.*, 2023; Adelana *et al.*, 2008). Furthermore, climate variability, characterized by prolonged dry seasons, irregular rainfall patterns, and rising temperatures, has the potential to affect groundwater recharge and long-term water availability within the basin (Ahmed *et al.*, 2026; IPCC, 2023).

Despite the heavy dependence of local communities on groundwater, hydrochemical information for Yendogo and its environs remains limited. Consequently, there is inadequate baseline information for monitoring groundwater quality, assessing pollution levels, and developing effective groundwater management strategies. In addition, information regarding the occurrence and distribution of potentially toxic heavy metals in groundwater within the area is scarce, making it difficult to properly evaluate potential health risks associated with groundwater consumption.

This study was therefore undertaken to assess the hydrochemical characteristics and pollution status of groundwater in Yendogo and its environs, Sokoto Basin, northwestern Nigeria. Specifically, the study evaluates the physicochemical characteristics of groundwater, determined the concentrations of major ions and selected heavy metals, identified the dominant hydrochemical facies controlling groundwater chemistry, and assessed groundwater quality for domestic use. The findings provide baseline information for groundwater monitoring, environmental management, and evidence-based decision-making aimed at protecting groundwater resources and promoting their sustainable management within the Sokoto Basin.

2.0 MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Yendogo and its environs, located within the Sokoto Basin in northwestern Nigeria. The study area is centered approximately at latitude 12°57'27"N and longitude 05°17'28"E, with an average elevation of about 323 m above sea level. The region experiences a semi-arid climate characterized by a short rainy season (May–September) and a prolonged dry season (October–April). Annual rainfall ranges from approximately 500 to 900 mm, while mean daily temperatures vary between 28°C and 40°C (Wali *et al.*, 2025; Adelana *et al.*, 2006).

2.2 Field Investigation and Groundwater Sampling

Field investigations were conducted in August 2025. The study involved geological mapping, hydrogeological surveys, and groundwater sampling. Geological mapping was carried out to identify lithological units, geomorphological features, and structural characteristics of the study area. Geographic coordinates of sampling locations were recorded using a handheld Global Positioning System (GPS) receiver.

Hydrogeological investigations included the identification of hand-dug wells, and documentation of well characteristics and groundwater utilization. A total of sixteen (16) groundwater samples (W1–W16) were collected from selected wells distributed across the study area. Before sampling collection, each well was purged by removing stagnant water to obtain representative groundwater samples. The samples were collected in clean polyethylene bottles, appropriately labeled, and transported under cooled conditions to the laboratory for physiochemical, major ion, and heavy metal analyses.

2.3 Field Measurements

In-situ measurements of temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS) were carried out at each sampling location using portable digital field meters. The Instruments were

calibrated before field measurements in accordance with the manufacturers' instructions to ensure data accuracy and reliability of the measured data.

2.4 Laboratory Analysis

Laboratory analyses were conducted at the Central Laboratory, Bayero University Kano (BUK), Kano, Nigeria, using standard analytical procedures. Prior to analysis, groundwater samples were filtered through 0.45 μm membrane filters. Samples designated for cation and heavy metal determination were preserved with concentrated nitric acid (HNO_3) to maintain a pH below 2, whereas samples intended for anion analysis were stored without acidification.

Major cations, including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+), were determined using standard titrimetric and flame photometric methods. Major anions, including bicarbonate (HCO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}), and nitrate (NO_3^-) phosphate (PO_4^{3-}), and ammonium (NH_4^+), were analyzed using standard titrimetric and spectrophotometric techniques. Selected heavy metals (lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni)) were determined using Atomic Absorption Spectrophotometry (AAS).

2.5 Hydrochemical and Spatial Analysis

Hydrochemical data were processed using Microsoft Excel, AquaChem, and Surfer software. Microsoft Excel was used for data organization, computation of descriptive statistics, and preparation of summary tables. AquaChem software was employed to classify groundwater hydrochemical facies using the Piper trilinear diagram, while Surfer software was used to generate the spatial distribution maps of selected heavy metals.

Groundwater quality was evaluated by comparing the measured physicochemical parameters, major ions, and heavy metal concentrations with the World Health Organization (WHO, 2022) drinking water guidelines.

3.0 RESULTS

3.1 Geological Setting/Geology of the Area

The digitized geological map (Figure 1) shows that the study area is underlain mainly by the Gwandu, Kalambaina, and Dange Formations of the Sokoto Basin, northwestern, Nigeria. Groundwater occurrence in the study area is primarily associated with the Gwandu and Kalambaina aquifer systems, while the Dange Formation generally acts as a confining unit due to its relatively low permeability. Boreholes located within the Dange outcrop may obtain groundwater from the underlying Wurno or Taloka aquifer systems.

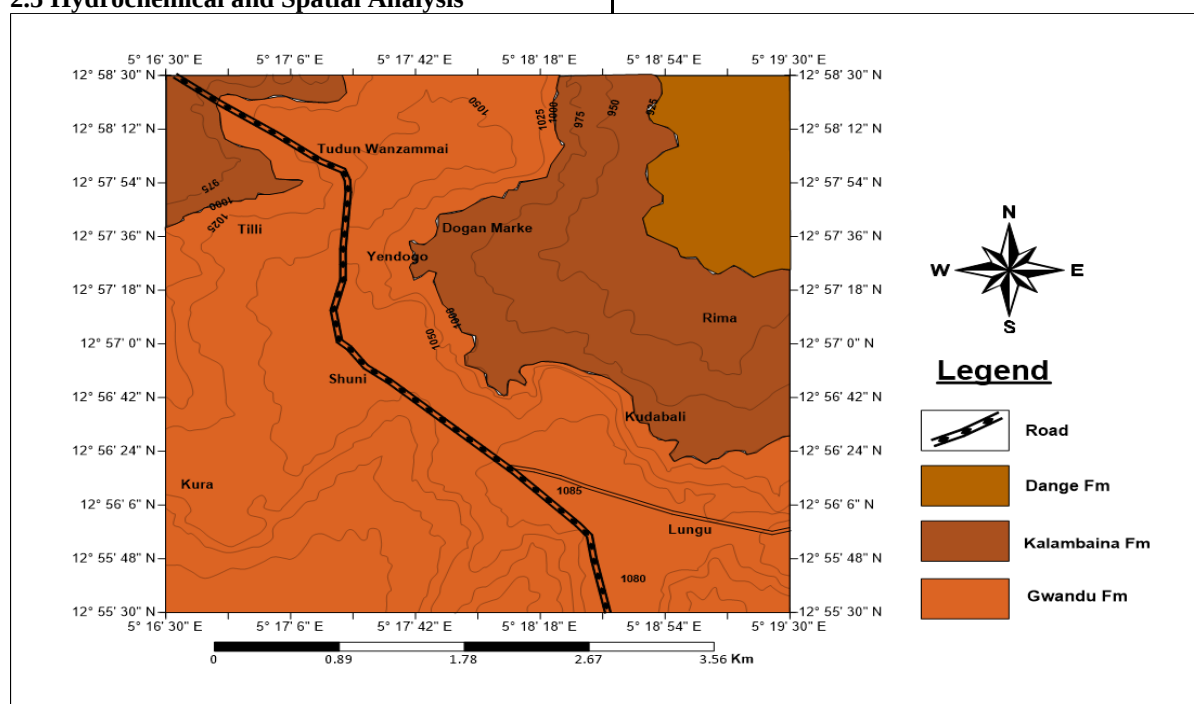


Figure 1: Geological map of the study area

3.2 Physicochemical Characteristics of Groundwater

The physicochemical characteristics of groundwater collected from Yendogo and its environs are presented in Table 1. Groundwater temperature ranged from 28.0 to 31.8°C, with a mean of 30.39°C, indicating little spatial variation across the study area. The pH values

ranged from 4.78 to 5.90, with a mean of 5.39, indicating that the groundwater was generally acidic.

Electrical conductivity (EC) ranged from 159 to 772 $\mu\text{S}/\text{cm}$, with a mean of 494.19 $\mu\text{S}/\text{cm}$, while total dissolved solids (TDS) ranged from 112 to 360 mg/L , with a mean of 248.19 mg/L . These values indicate that

the groundwater is fresh, while the variation in EC reflects differences in the concentration of dissolved ions among the sampled groundwater resources.

Overall, the measured physicochemical parameters were generally within the World Health Organization (WHO, 2022) permissible limits, except for pH, which was below the recommended drinking water range of 6.5–8.5 in all sampled locations.

Table 1: Physiochemical Characteristics of Groundwater Samples

Sample ID	Location	Latitude (N)	Longitude (E)	Elevation (m)	Temp (°C)	pH	EC (µS/cm)	TDS (mg/L)
W1	Shuni 1	12°57'0.45"	5°16'57.53"	316	30.1	5.39	624	340
W2	Shuni 2	12°56'57"	5°16'54"	320	31.0	5.29	654	317
W3	Shuni 3	12°56'0.96"	5°16'58.40"	318	31.8	5.58	772	294
W4	Tilli 1	12°57'42"	5°17'4.84"	314	30.3	5.59	358	201
W5	Yendogo 1	12°57'27"	05°17'29"	323	29.8	5.59	446	201
W6	Shuni 4	12°56'57"	05°16'54"	320	31.0	5.29	652	317
W7	Tilli 2	12°57'42"	05°17'05"	314	30.3	5.90	358	201
W8	Rima	12°57'12"	05°17'21"	323	30.5	5.71	310	155
W9	Rugan Kura 1	12°55'18"	5°15'39"	320	31.4	5.01	244	112
W10	Rugan Kura 2	12°56'04"	5°16'36"	315	28.0	4.78	325	156
W11	Shuni 5	12°56'54"	5°15'54.30"	320	31.0	5.29	625	317
W12	Shuni 6	12°57'00"	5°16'58.40"	318	31.8	5.58	772	294
W13	Rugan Kura 3	12°56'4.46"	5°16'36.54"	315	28.0	4.78	159	165
W14	Yendogo 2	12°57'27"	5°17'28.58"	323	29.8	5.59	446	201
W15	Shuni 7	12°57'0.33"	5°16'57.53"	313	30.1	5.39	624	340
W16	Shuni 8	12°56'32.3"	5°17'16.43"	315	31.4	5.43	538	360
					28.0	4.78	159	112
					31.8	5.90	772	360
Mean					30.39	5.39	494.19	248.19

3.3 Major ion chemistry

The concentrations of major cations and anions are presented in Table 2.

Among the major cations, calcium (Ca^{2+}) and magnesium (Mg^{2+}), were the dominant ions in the groundwater samples, whereas sodium (Na^+) and potassium (K^+) occurred in comparatively lower concentrations. Bicarbonate (HCO_3^-) was the dominant

anion, while chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), phosphate (PO_4^{3-}), and ammonium (NH_4^+) occurred at relatively lower concentrations.

The dominance of calcium, magnesium, and bicarbonate indicates that groundwater chemistry is mainly influenced by the dissolution of carbonate-bearing minerals within the sedimentary formations of the Sokoto Basin.

Table 2: Major Ion Composition of Groundwater

S/ID	Location	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	HCO_3^- (mg/L)	Cl^- (mg/L)	NH_4^+ (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	PO_4^{3-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)
W1	Shuni 1	48.0	37.2	110.0	4.1	2.2	3.0	0.07	0.06	40.0	45.8
W2	Shuni 2	48.0	42.0	120.6	3.8	1.6	2.3	0.03	0.05	34.0	30.0
W3	Shuni 3	70.0	58.8	89.6	4.5	2.0	3.0	0.03	0.03	35.6	40.6
W4	Tilli 1	56.0	40.8	68.4	3.0	1.2	2.4	0.05	0.02	28.0	30.6
W5	Yendogo 1	52.0	42.0	98.0	2.8	1.2	2.6	0.02	0.04	12.0	20.2

W6	Shuni 4	54.0	50.4	86.5	2.2	0.9	2.0	0.02	0.02	15.0	25.0
W7	Tilli 2	46.0	43.2	78.0	3.0	1.4	3.0	0.03	0.03	14.6	18.6
W8	Rima	32.0	38.4	70.0	2.6	1.0	2.2	0.05	0.04	12.4	16.8
W9	Rugan Kura 1	26.0	82.0	64.0	3.0	2.2	3.4	0.04	0.06	24.4	36.8
W10	Rugan Kura 2	48.0	44.4	86.4	3.5	2.6	3.2	0.02	0.05	30.5	45.0
W11	Shuni 5	62.0	64.8	65.0	2.8	1.6	2.8	0.03	0.05	23.4	35.0
W12	Shuni 6	32.0	84.0	90.6	3.8	2.8	3.0	0.04	0.06	32.0	52.0
W13	Rugan Kura 3	66.0	51.6	108.0	3.2	1.8	3.8	0.05	0.04	38.4	48.6
W14	Yendogo 2	34.0	69.6	74.0	2.2	2.4	4.4	0.03	0.04	22.8	40.0
W15	Shuni 7	46.0	58.8	120.0	4.0	1.6	3.4	0.06	0.04	30.0	40.0
W16	Shuni 8	68.0	40.8	88.4	3.6	2.0	2.8	0.04	0.03	35.0	50.0
	Minimum	26.0	37.2	64.0	2.2	0.9	2.0	0.02	0.02	12.0	16.8
	Maximum	70.0	84.0	120.6	4.5	2.8	4.4	0.07	0.06	40.0	52.0
	Mean	49.88	52.80	89.61	3.29	1.79	2.99	0.04	0.04	26.76	36.88

3.4 Hydrochemical Facies

The Piper trilinear diagram (Figure 2) shows that groundwater samples are predominantly of the Ca–Mg–HCO₃ hydrochemical facies.

This hydrochemical facies indicates that groundwater chemistry is primarily controlled by natural rock–water

interaction, particularly the weathering and dissolution of carbonate minerals within the aquifer. The predominance of the Ca–Mg–HCO₃ water type suggests that groundwater is at an early stage of hydrochemical evolution and reflects the natural geochemical characteristics of the Sokoto Basin aquifer.

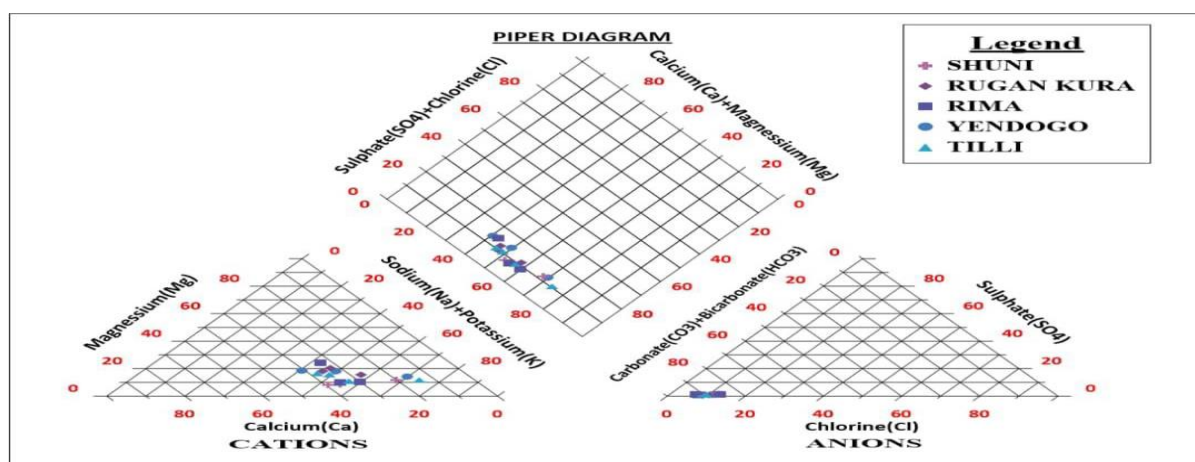


Figure 2: Piper trilinear diagram showing the hydrochemical facies of groundwater

3.5 Heavy Metal Concentrations

The concentrations of cadmium (Cd), nickel (Ni), chromium (Cr), and lead (Pb) in groundwater are presented in Table 3, while the summary statistics are shown in Table 4. Their spatial distributions are illustrated in Figures 3–6.

3.5.1 Cadmium

Cadmium (Cd) concentrations in the groundwater samples ranged from 0.0002 to 0.0026 mg/L, with a mean concentration of 0.0012 mg/L. Figure 3 shows the variation in Cd concentrations across the 16 sampled groundwater locations (W1–W16). The

concentrations varied considerably among the sampling locations, with relatively higher values recorded at W5 and W14, both approximately 0.0026 mg/L, while lower concentrations were observed at locations such as W8 and W12. Despite the observed variations, the Cd concentrations at all the sampling locations remained below the WHO (2022) permissible limit of 0.003 mg/L, represented by the red bar in Figure 3. The highest observed Cd concentration was therefore still below the permissible limit. Overall, the results indicate that cadmium does not pose a significant groundwater quality concern in the study area at the time of sampling.

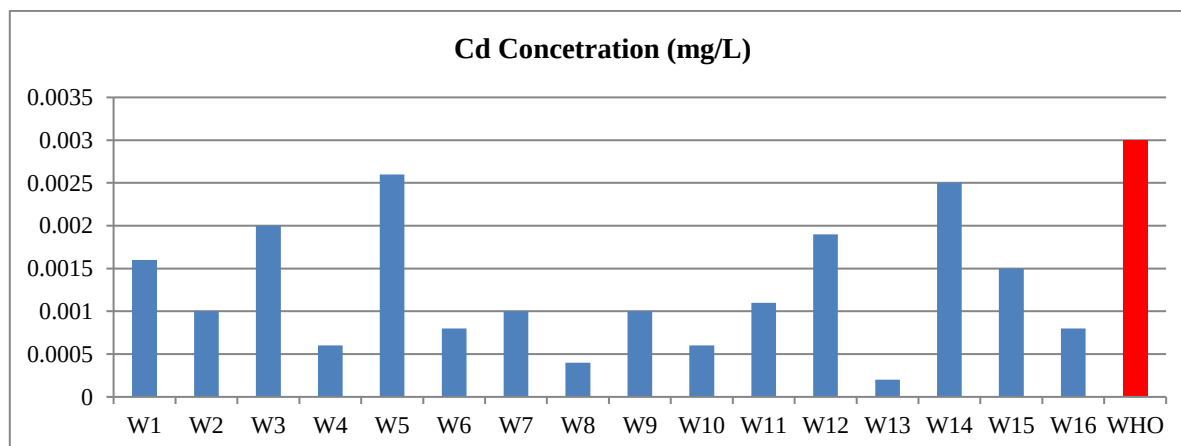


Figure 3: Cadmium (Cd) concentrations across the groundwater sampling locations

3.5.2 Nickel

Nickel (Ni) concentrations in the groundwater samples ranged from 0.0078 to 0.0271 mg/L, with a mean concentration of 0.0150 mg/L. Figure 4 illustrates the variation in Ni concentrations across the 16 groundwater sampling locations. The results show variations in Ni concentration among the sampling locations, with relatively higher concentrations observed at W6, W12, W14 and W16, while comparatively lower concentrations were recorded at

some of the other sampling locations. Despite the observed variations, all the Ni concentrations recorded in the groundwater samples were below the WHO (2022) permissible limit of 0.070 mg/L. The highest measured Ni concentration of 0.0271 mg/L was substantially lower than the permissible limit. Overall, the observed Ni concentrations indicate that nickel does not pose a significant groundwater quality concern in the study area based on the WHO guideline value.

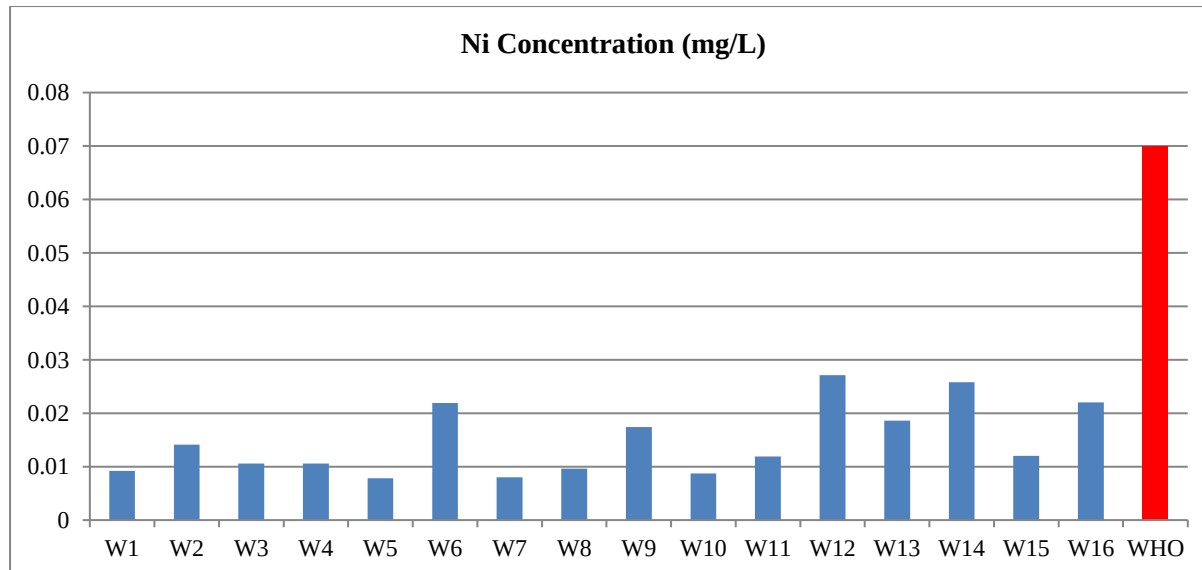


Figure 4: Nickel (Ni) concentrations across the groundwater sampling locations

3.5.3 Chromium

Chromium (Cr) concentrations in the groundwater samples ranged from 0.0095 to 0.0367 mg/L, with a mean concentration of 0.0195 mg/L. Figure 5 illustrates the variation in Cr concentrations across the 16 groundwater sampling locations. The results show clear spatial variations in Cr levels across the sampling sites, with relatively higher concentrations recorded at W6 (0.0367 mg/L) and W12 (0.0298 mg/L), followed

by W10, W15, and W16. Conversely, lower concentrations were recorded at sites such as W11, W13, and W14. Despite these observed spatial fluctuations, all recorded Cr concentrations remained below the WHO (2022) permissible limit of 0.050 mg/L. The maximum detected Cr concentration (0.0367 mg/L at W6) was well within the acceptable threshold. Overall, these findings indicate that chromium does not pose a significant groundwater

quality or public health concern in the study area based on the WHO guideline value.

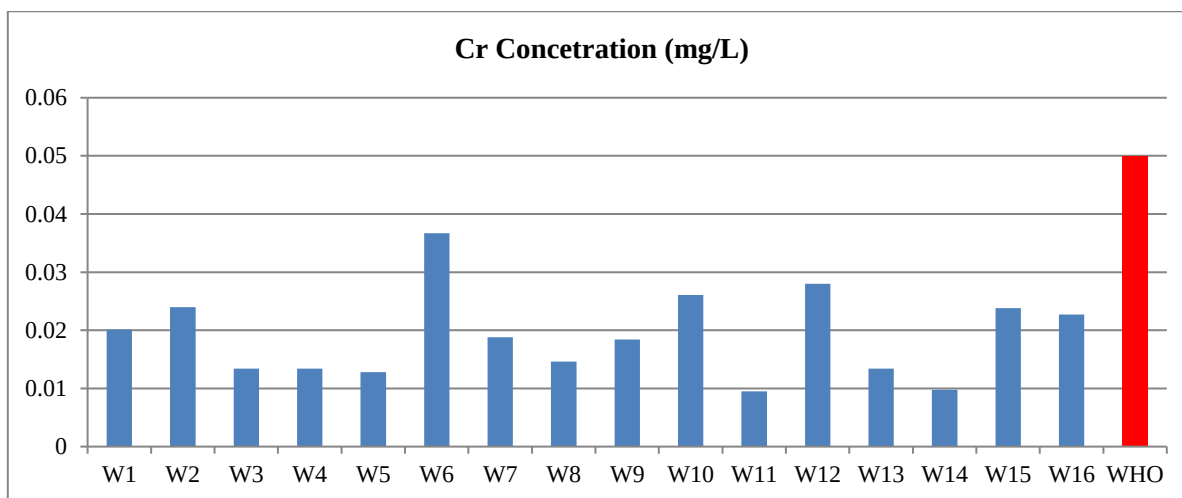


Figure 5: Chromium (Cr) concentrations across the groundwater sampling locations

3.5.4 Lead

Lead (Pb) concentrations in the groundwater samples ranged from 0.0045 to 0.0586 mg/L, with a mean concentration of 0.0302 mg/L. Figure 6 illustrates the variation in Pb concentrations across the 16 groundwater sampling locations (W1–W16). The results reveal significant spatial variation across the study area, with the highest concentration recorded at W8 (0.0586 mg/L), followed by relatively elevated levels at W14, W11, W12, W4, and W2. Conversely, noticeably lower concentrations were observed at locations such as W7 (0.0045 mg/L), W9, and W6.

Unlike the other parameters, almost all sampling locations—with the exception of a few points like W7 and W9—exceeded the WHO (2022) permissible limit of 0.010 mg/L, represented by the red bar in Figure 6. The highest recorded value was nearly six times greater than the regulatory threshold. These widespread elevated lead levels indicate significant contamination across the study area, posing potential health risks to human consumers and underscoring the need for urgent mitigation and continuous monitoring.

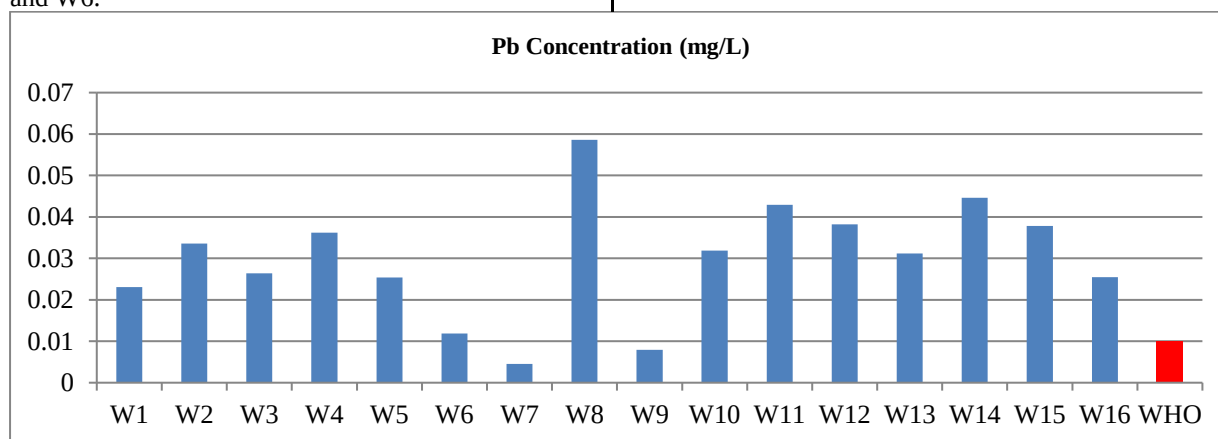


Figure 6: Lead (Pb) concentrations across the groundwater sampling locations

The spatial distribution map indicates relatively higher concentrations of lead around Shuni and some neighboring locations, whereas cadmium, nickel and

chromium showed generally low concentrations throughout the study area.

Table 3: Heavy Metal Concentrations in Groundwater Samples

Sample ID	Location	Cd (mg/L)	Cr (mg/L)	Ni (mg/L)	Pb (mg/L)
W1	Shuni 1	0.0016	0.0201	0.0092	0.0231

W2	Shuni 2	0.0010	0.0240	0.0141	0.0336
W3	Shuni 3	0.0020	0.0134	0.0106	0.0264
W4	Tilli 1	0.0006	0.0134	0.0106	0.0362
W5	Yendogo 1	0.0026	0.0128	0.0078	0.0254
W6	Shuni 4	0.0008	0.0367	0.0219	0.0119
W7	Tilli 2	0.0010	0.0188	0.0080	0.0045
W8	Rima	0.0004	0.0146	0.0096	0.0586
W9	Rugan Kura 1	0.0010	0.0184	0.0174	0.0079
W10	Rugan Kura 2	0.0006	0.0261	0.0087	0.0319
W11	Shuni 5	0.0011	0.0095	0.0119	0.0429
W12	Shuni 6	0.0019	0.0280	0.0271	0.0382
W13	Rugan Kura 3	0.0002	0.0134	0.0186	0.0312
W14	Yendogo 2	0.0025	0.0098	0.0258	0.0446
W15	Shuni 7	0.0015	0.0238	0.0120	0.0378
W16	Shuni 8	0.0008	0.0227	0.0220	0.0255
	Minimum	0.0002	0.0095	0.0078	0.0045
	Maximum	0.0026	0.0367	0.0271	0.0586
	Mean	0.0012444	0.0195389	0.0150111	0.0301556
	WHO (2022)	0.003	0.05	0.07	0.01

Table 4: Summary Statistics of Heavy Metal Concentrations in Groundwater Samples

Parameter	Minimum (mg/L)	Maximum (mg/L)	Mean (mg/L)	WHO (2022) Permissible Limit (mg/L)	Remark
Cadmium (Cd)	0.0002	0.0026	0.0012	0.003	Within permissible limit
Nickel (Ni)	0.0078	0.0271	0.0150	0.070	Within permissible limit
Chromium (Cr)	0.0095	0.0367	0.0195	0.050	Within permissible limit
Lead (Pb)	0.0045	0.0586	0.0302	0.010	Exceeds WHO permissible limit in most sampling locations

Table 5: Pearson Correlation Analysis of Heavy Metals

	<i>Cd</i>	<i>Cr</i>	<i>Ni</i>	<i>Pb</i>
<i>Cd</i>	1			
<i>Cr</i>	-0.21285	1		
<i>Ni</i>	0.124425	0.294423	1	
<i>Pb</i>	0.01709	-0.3562	0.042887	1

Pearson correlation analysis was performed using Microsoft Excel to assess the relationships among the concentrations of cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb) in the 16 groundwater samples. The correlation coefficients ranged from -0.3562 to 0.2944, indicating generally weak relationships among the investigated heavy metals. Cadmium showed a weak negative correlation with chromium ($r = -0.2129$) and a very weak positive correlation with nickel ($r = 0.1244$). Chromium exhibited a weak positive correlation with nickel ($r = 0.2944$), indicating a slight tendency for the

concentrations of both metals to vary together. Lead showed a negligible positive correlation with cadmium ($r = 0.0171$) and nickel ($r = 0.0429$), while it exhibited a weak negative correlation with chromium ($r = -0.3562$). Overall, the weak correlation coefficients indicate limited linear relationships among the investigated heavy metals. This suggests that the distribution of Cd, Cr, Ni, and Pb in the groundwater may be influenced by different sources and/or geochemical processes, rather than being predominantly controlled by a single common source.

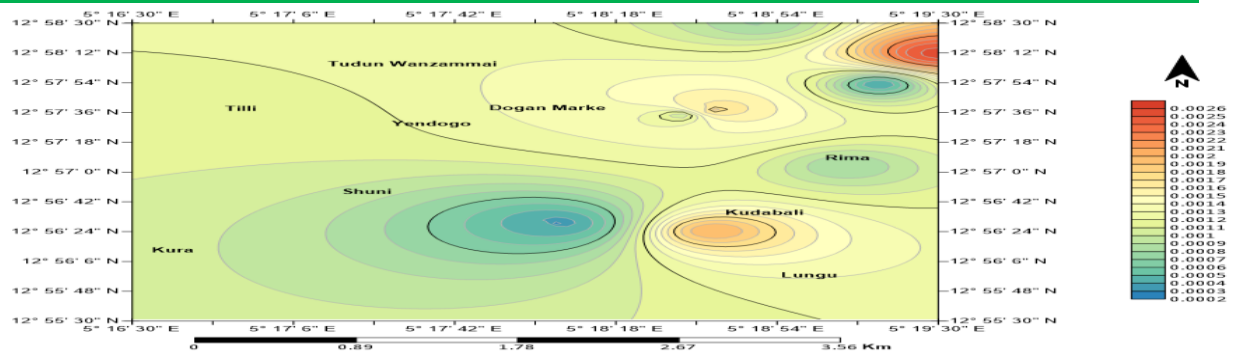


Figure 7: Spatial distribution of cadmium (Cd) concentration

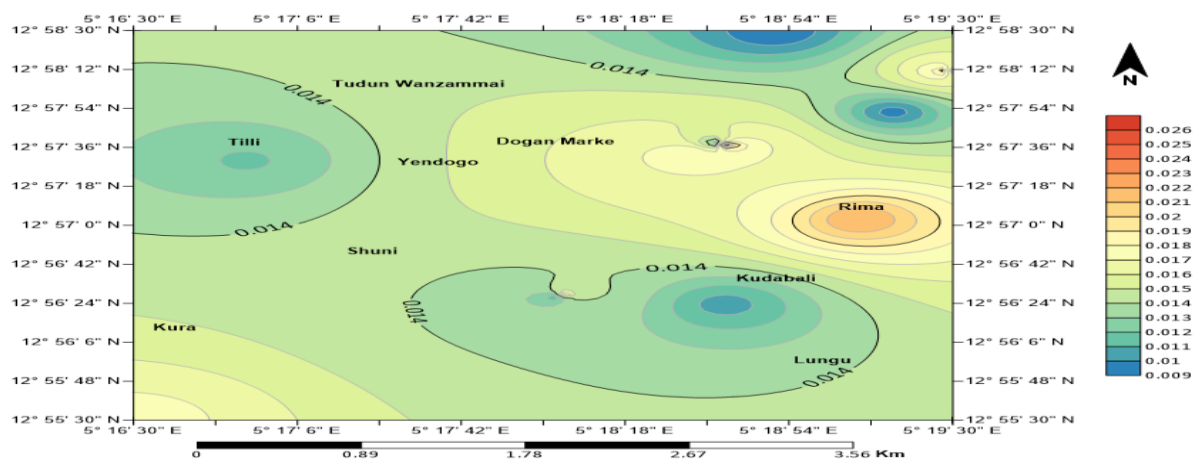


Figure 8: Spatial distribution of nickel (Ni) concentration

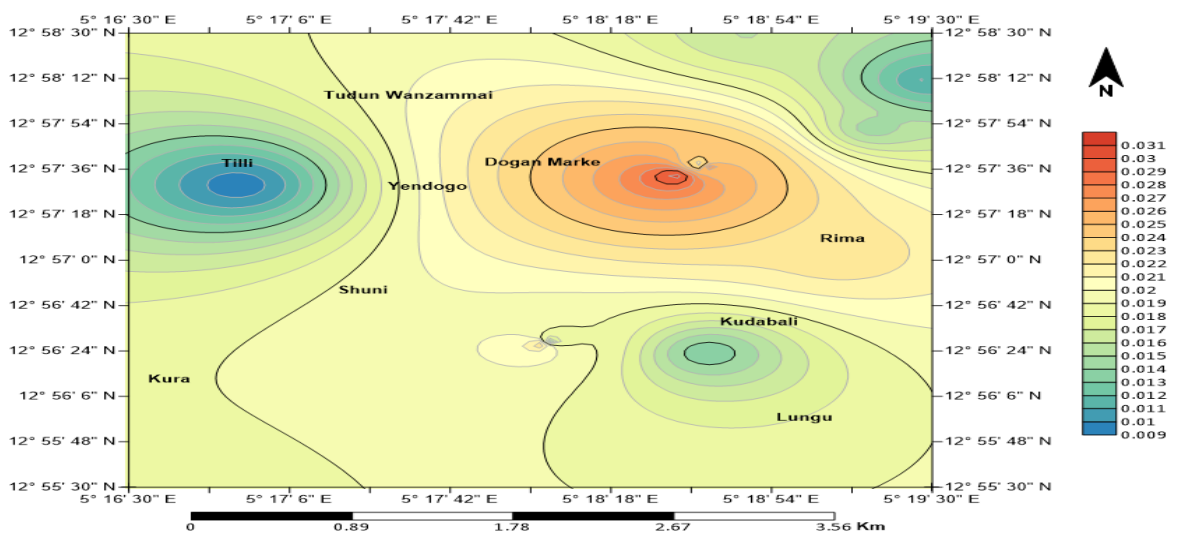


Figure 9: Spatial distribution of chromium (Cr) concentration

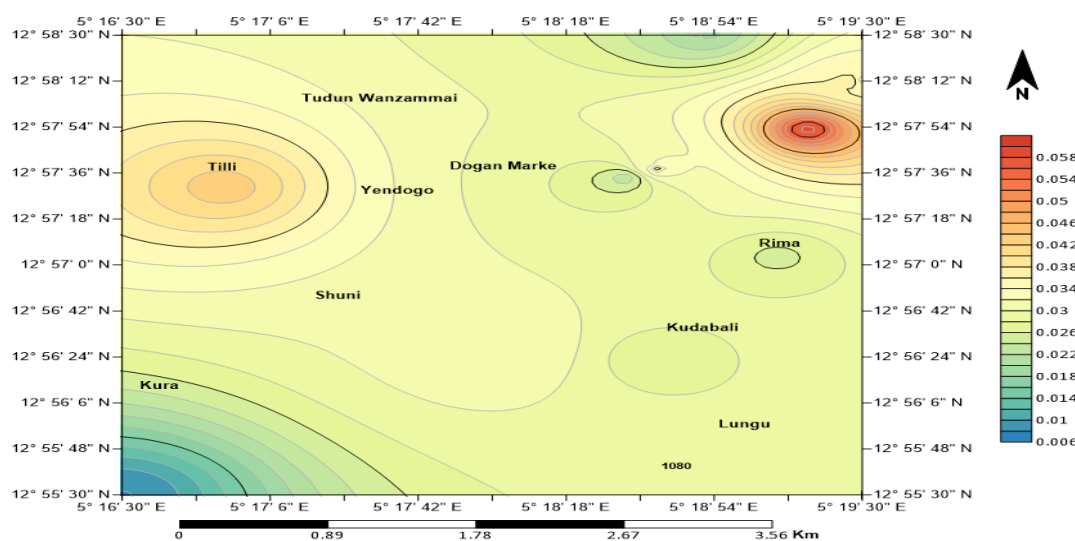


Figure 10: Spatial distribution of lead (Pb) concentration

4.0 DISCUSSION

4.1 Physicochemical Characteristics of Groundwater

The physicochemical characteristics of groundwater in Yendogo and its environs indicate that the groundwater is generally fresh and moderately mineralized. The recorded total dissolved solids (TDS) values range from 112–360 mg/L, while electrical conductivity (EC) range from 159–772 $\mu\text{S}/\text{cm}$. These values are within the World Health Organization (WHO) permissible limits for drinking water, suggesting that groundwater contains relatively low concentration of dissolved salts. According to WHO (2022), groundwater with TDS values below 1,000 mg/L is classified as fresh water, which agrees with the findings of this study.

The pH values ranged from 4.78 to 5.90, indicating that the groundwater is acidic and falls below the WHO recommended range of 6.5–8.5. The acidic nature of the groundwater may be attributed to the dissolution of carbon dioxide in infiltrating rainwater, decomposition of organic matter within the soil profile, and natural geochemical interactions between groundwater and the sedimentary formations of the Sokoto Basin. Similar observations have been reported in previous groundwater studies within northwestern Nigeria (Abdullahi et al., 2025; Wali et al., 2025).

4.2 Hydrochemical Facies and Geochemical Processes

The Piper trilinear diagram shows that groundwater in the study area is predominantly of the Ca–Mg– HCO_3^- hydrochemical facies. This water type is typical of recently recharged groundwater and indicates that groundwater chemistry is primarily controlled by natural geochemical processes, particularly rock–water interaction (Piper, 1944).

The dominance of calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) suggests that carbonate weathering is the principal process influencing groundwater composition. The dissolution of limestone and other carbonate-rich rocks within the Kalambaina and associated sedimentary formations contributes significantly to the observed ionic concentrations. The relatively low concentrations of chloride, sulphate, nitrate, and phosphate further indicate limited influence from evaporite dissolution and agricultural activities.

Overall, the hydrochemical characteristics demonstrate that groundwater evolution in the study area is primarily governed by rock–water interaction within the sedimentary aquifer system.

4.3 Heavy Metal Concentrations

The heavy metal analysis revealed varying concentrations of cadmium (Cd), nickel (Ni), chromium (Cr), and lead (Pb) in groundwater samples collected from the study area.

Cadmium concentrations ranged from 0.0002 to 0.0026 mg/L, with a mean concentration of 0.0012 mg/L. All groundwater samples were below the WHO (2022) permissible limit of 0.003 mg/L, indicating that cadmium contamination is not currently a significant groundwater quality concern in the study area.

Nickel concentrations ranged from 0.0078 to 0.0271 mg/L, while chromium concentrations ranged from 0.0095 to 0.0367 mg/L. The concentrations of both metals were below the WHO (2022) permissible limits, suggesting that their occurrence is mainly controlled by natural geological processes, particularly the weathering of aquifer materials.

Lead (Pb) concentrations ranged from 0.0045 to 0.0586 mg/L, with a mean concentration of 0.0302 mg/L.



Although a few sampling locations recorded lead concentrations below the WHO (2022) permissible limit of 0.010 mg/L, most samples exceeded the guideline value, indicating widespread lead contamination within the study area. Elevated lead concentrations in groundwater may be associated with anthropogenic activities such as improper waste disposal, automobile repair activities, battery wastes, metal scraps, and other urban-related sources (Owamah et al., 2023; WHO, 2022). The spatial distribution maps also indicate relatively higher concentrations of lead around Shuni and nearby communities.

4.4 Groundwater Suitability for Domestic Use

The measured physicochemical parameters indicate that groundwater in the study area is generally suitable for domestic use based on most of the analyzed physiochemical characteristics. Electrical conductivity and total dissolved solids were within the World Health Organization (WHO, 2022) permissible limit, indicate relatively low mineralization of the groundwater.

Most major ions also fall within WHO recommended limits for drinking water. However, the elevated concentrations of lead observed in several groundwater samples indicate that water from the affected locations should be treated before domestic consumption. Long-term exposure to elevated lead concentrations may result in adverse health effects, including neurological disorders, kidney damage, and developmental problems, particularly in children (WHO, 2022).

Therefore, although groundwater quality is generally acceptable with respect to most physiochemical parameters and major ions, continuous monitoring and appropriate treatment are recommended, especially in areas where elevated lead concentrations were detected.

4.5 Implications for Climate Resilience and Sustainable Groundwater Management

Groundwater represents the primary source of freshwater in Yendogo and its environs and plays a critical role in supporting domestic water supply, agriculture, and other socio-economic activities. The predominance of the Ca–Mg–HCO₃ hydrochemical facies, together with the general low salinity, and moderate mineralization of the groundwater, suggests that the aquifer currently maintains good groundwater quality under the prevailing environmental conditions.

However, increasing population growth, urban expansion, poor waste management, and changing climatic conditions may threaten groundwater quality and its long-term sustainability (IPCC, 2023). Protecting groundwater recharge zones, improving sanitation practices, regulating waste disposal, and implementing regular groundwater quality monitoring

programmes are essential for ensuring the sustainable management of groundwater resources in the study area.

The findings of this study provide important baseline information for groundwater resource planning, environmental management, and future hydro-geochemical investigations within the Sokoto Basin. These findings can also support the development of sustainable groundwater management strategies aimed at safeguarding groundwater resources under changing environmental and climate conditions.

5.0 CONCLUSION

This study assessed the hydrochemical characteristics and pollution status of groundwater in Yendogo and its environs, Sokoto Basin, northwestern Nigeria, with the aim of evaluating its suitability for domestic use and its implications for sustainable groundwater management under changing climatic conditions.

The results indicate that groundwater in the study area is generally fresh, slightly acidic, and moderately mineralized. Most physicochemical parameters, including electrical conductivity (159-772 μ S/cm), total dissolved solids (112-360 mg/L), and the concentrations of major ions, were within the World Health Organization (WHO) permissible limits for drinking water. However, groundwater Ph ranged from 4.78 to 5.90, which is below the WHO recommended range. Hydrochemical analysis showed that groundwater is dominated by the Ca–Mg–HCO₃ facies, indicating that groundwater chemistry is primarily controlled by natural rock–water interactions, particularly the weathering and dissolution of carbonate-bearing rocks within the Sokoto Basin.

The heavy metal assessment revealed that nickel (Ni) and chromium (Cr) concentrations were within WHO guideline values. Cadmium (Cd) concentrations also remain within the WHO permissible limit in all sampled locations. However, lead (Pb) concentrations exceeded the WHO permissible limit in several sampling locations, indicating localized groundwater contamination that may require appropriate treatment before domestic consumption.

Overall, the findings provide valuable baseline information for groundwater quality assessment and sustainable groundwater resource management in the Sokoto Basin. Continuous groundwater quality monitoring and appropriate treatment are recommended in areas where elevated lead concentrations were detected to safeguard public health.

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