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Lithological and Seasonal Controls on Trace Element Distribution and Groundwater Quality in Crystalline Basement Aquifers of Oyo Town, Southwestern Nigeria

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Abstract

Groundwater in crystalline basement terrains serves as a critical water resource in southwestern Nigeria but is often influenced by lithological and seasonal controls that affect its quality. This study evaluates the lithological and seasonal influences on trace element distribution in groundwater from Oyo Town. A total of 80 groundwater samples were collected during wet (n = 40) and dry (n = 40), alongside representative rock samples for petrographic and geochemical analyses using X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS). Results indicate that migmatite gneiss-dominated lithologies, rich in feldspars and ferromagnesian minerals, exert a primary geogenic control on groundwater chemistry. Elevated concentrations of Fe (0.02–4.52 mg/L in the wet season; 0.07–22.77 mg/L in the dry season), Mn (0.006–7.12 mg/L), Al (0.07–1.95 mg/L in the wet season; 0.49–42.7 mg/L in the dry season), and Pb (0.03–0.06 mg/L in the wet season; 0.01–0.23 mg/L in the dry season) are more pronounced during the dry season due to increased residence time and intensified water–rock interaction. Spatial distribution patterns and inter-element relationships further support a dominant lithogenic origin for most trace elements. The results demonstrate that groundwater chemistry is primarily controlled by lithology and seasonal variation, with limited evidence of anthropogenic influence. This integrated approach provides improved understanding of groundwater quality evolution in basement aquifers and highlights the need for continuous monitoring and sustainable groundwater management.

Keywords: Basement aquifer, Trace metals, Lithological control, Seasonality, Hydrogeochemistry,

1. Introduction

Groundwater in crystalline basement terrains constitutes a major source of water supply for domestic, agricultural, and industrial activities across many tropical regions, particularly in Sub-Saharan Africa (Hamma et al., 2024). In Nigeria, especially in the southwestern region, surface water resources are often seasonal and unreliable, making groundwater stored within weathered and fractured basement aquifers the principal source of water for domestic and agricultural use (Adelana & MacDonald, 2008; MacDonald et al., 2012; Nwankwo et al., 2020; Odukoya & Ifarajinmi, 2021; Markus et al., 2022; Jolaosho et al., 2024). These aquifers typically occur within weathered regolith and fractured zones developed in crystalline rocks such as migmatite gneiss, granite gneiss, and schists. Although these lithologies are characterized by low primary porosity, secondary porosity generated through weathering and fracturing significantly enhances groundwater storage and transmission (Rahaman, 1988; Gibbs, 1970). Consequently, groundwater chemistry in basement terrains is largely controlled by lithological characteristics and water–rock interaction processes.

The hydrogeochemistry of crystalline basement aquifers is primarily governed by mineral dissolution, silicate weathering, and ion exchange reactions occurring within the weathered and fractured rock matrix (Li et al., 2018; Nwankwo et al., 2020; Jolaosho et al., 2024). These processes facilitate the release of trace elements such as Fe, Mn, Zn, and Ni into groundwater systems (Nwankwo et al., 2020; Kayode et al., 2024). Recent studies have increasingly highlighted the importance of geogenic controls on groundwater chemistry in basement terrains, emphasizing the role of mineralogical composition and weathering intensity in regulating trace element mobility (Akinlalu et al., 2023;

Kayode et al., 2024; Jolaosho et al., 2024). In such settings, trace elements are predominantly derived from geogenic sources, while anthropogenic contributions are generally localized and less significant except in areas of intense human activity (Guo et al., 2024). The dissolution of ferromagnesian minerals, accessory sulfides, and oxide phases within basement lithologies plays a critical role in controlling trace element concentrations in groundwater.

Seasonal variability further exerts a strong influence on groundwater chemistry and trace element mobility. During the rainy season, increased recharge enhances chemical weathering and promotes the mobilization of trace metals from the weathered and fractured rock matrix into the aquifer system (Kayode et al., 2024). In contrast, the dry season is characterized by reduced recharge, increased residence time, and evaporative concentration, which collectively lead to elevated dissolved ion concentrations and changes in redox conditions (Abidemi et al., 2019). Recent investigations in southwestern Nigeria have demonstrated that the interaction between lithological heterogeneity and seasonal hydrological processes significantly controls the spatial distribution and concentration of trace elements in basement aquifers (Akinlalu et al., 2023; Jolaosho et al., 2024). However, the relative contribution of lithology versus seasonal processes remains insufficiently constrained in many local settings.

Despite these advances, previous hydrogeochemical studies in Oyo Town and similar basement complex environments have largely focused on major ions, water quality indices, and general hydrochemical characterization, with limited emphasis on trace elements and their direct linkage to lithological sources. Furthermore, few studies have integrated petrographic evidence, whole-rock geochemistry, and groundwater chemistry to explicitly establish geogenic controls on trace element distribution across contrasting seasonal conditions. This limitation constrains a comprehensive understanding of the processes governing trace element occurrence and mobility in shallow basement aquifers.

Therefore, this study integrates petrographic analysis, rock geochemistry, and groundwater hydrochemistry to evaluate the lithological and seasonal controls on trace element distribution in Oyo Town. The specific objectives of this study are to: (1) Characterize the mineralogical and geochemical composition of the host rocks; (2) Assess the spatial distribution and seasonal variability of trace elements in groundwater; (3) Elucidate the dominant geochemical processes controlling trace element occurrence and mobility. By linking rock composition with groundwater chemistry across seasons, this study provides new insights into geogenic controls on groundwater quality and contributes to improved understanding and management of crystalline basement aquifer systems.

2. Study Area and Sampling

The study area is located in Oyo Town, southwestern Nigeria, within the Precambrian Basement Complex. It lies approximately between latitudes 7°45′N–7°55′N and longitudes 3°50′E–4°00′E (Figure 1). The area is accessible via major road networks and is characterized by a mix of residential, agricultural, and small-scale commercial activities, all of which depend largely on groundwater for water supply.

Geologically, the area is underlain predominantly by crystalline basement rocks, including migmatite gneiss, granite gneiss, biotite schist, and quartzite, with minor intrusions of pegmatites and granitoids. These lithologies form part of the Nigerian Basement Complex and are known to host weathered and fractured aquifer systems (Rahaman, 1988). The weathering profile typically consists of a lateritic overburden underlain by a saprolitic zone and fractured bedrock, which collectively constitute the main groundwater-bearing units. Groundwater occurrence is therefore largely controlled by the thickness of the weathered layer and the degree of fracturing within the bedrock.

The study area experiences a tropical climate characterized by distinct wet and dry seasons. The wet season typically spans from April to October, while the dry season extends from November to March. Mean annual rainfall ranges between 1200 and 1500 mm, with peak precipitation occurring between June and September. Average temperatures range from 25°C to 32°C, with relatively high humidity during the rainy season. These climatic conditions play a significant role in groundwater recharge, chemical weathering, and seasonal hydrogeochemical processes.

Hydrogeologically, groundwater occurs under unconfined to semi-confined conditions within the weathered regolith and fractured basement rocks. Shallow hand-dug wells, typically less than 30 m deep, constitute the primary means of groundwater abstraction. These shallow aquifers are highly susceptible to seasonal variations, including recharge dilution during the wet season and concentration effects during the dry season due to increased residence time and evaporation.

The spatial distribution of sampling locations across the major lithological units is presented in Figure 2. The integration of geological, climatic, and hydrogeological characteristics makes the study area suitable for investigating the lithological and seasonal controls on trace element distribution in groundwater.

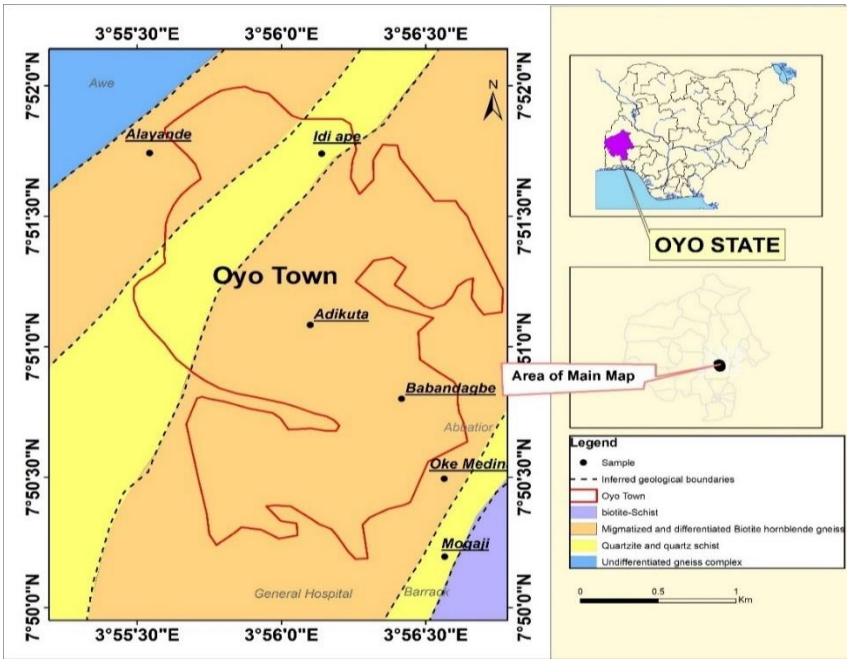


Figure 1: Geological Map of Oyo Town showing rock sampling point (Modified after NGSA, 2006)

3.Materials and Methods

3.1 Sampling Design and Strategy

A total of eighty (80) groundwater samples were collected from shallow wells across the study area (Fig. 2), comprising forty (40) samples during the wet season and forty (40) during the dry season. The sampling strategy was designed to capture both spatial variability across major lithological units and temporal (seasonal) variations in groundwater chemistry. Sampling locations were systematically distributed across the dominant lithologies, including migmatite gneiss, granite gneiss, schist, and quartzite, to ensure adequate representation of geological controls on groundwater composition. Shallow wells (typically <30 m depth) were selected due to their susceptibility to seasonal recharge fluctuations, water–rock interaction processes, and potential surface influences.

In addition, six (6) representative rock samples were collected from outcrops within the vicinity of sampled wells (Fig. 1) to establish the geogenic relationship between host lithology and groundwater trace element composition.

3.2 Sample Collection and Preservation

Groundwater samples were collected in pre-cleaned 1 L high-density polyethylene (HDPE) bottles following standard protocols (APHA, 2017). Prior to sampling, wells were purged for 10–15 minutes to obtain fresh aquifer water representative of in-situ conditions. Samples for trace element analysis were filtered in the field using 0.45 µm membrane filters and acidified immediately to pH < 2 using ultra-pure nitric acid (HNO_3) to prevent metal precipitation and adsorption onto container walls. All samples were stored at 4°C in ice-packed coolers and transported to the laboratory for analysis within 48 hours.

Rock samples were collected as fresh, unweathered specimens, labeled, and prepared for petrographic and geochemical analyses.

3.3 Petrographic studies of rock samples

Six representative rock samples were prepared as thin sections and examined under a polarizing microscope to determine mineralogical composition, textural characteristics, and alteration features. Particular attention was given to identifying ferromagnesian minerals, feldspars, and accessory phases that may act as sources of trace elements in groundwater.

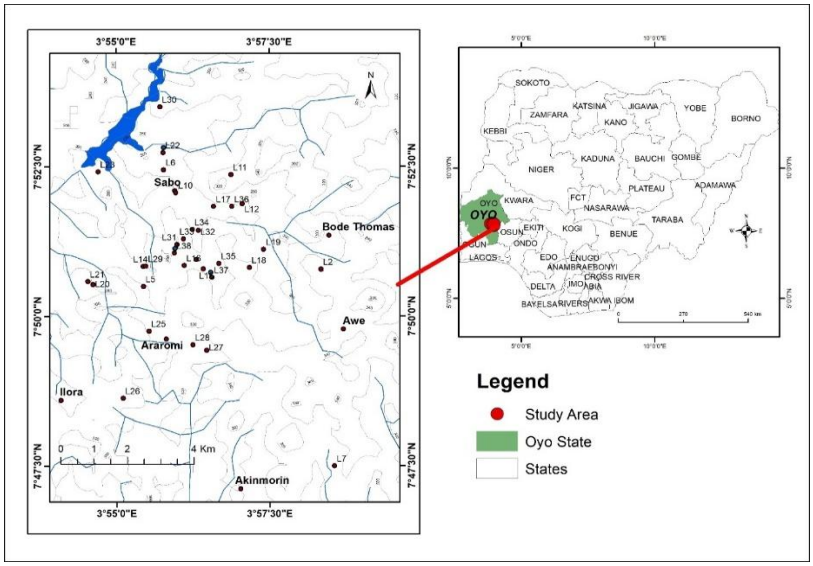


Figure 2: Map of Oyo Town showing groundwater sampling locations points.

3.4 Geochemical Analysis

3.4.1 X-ray Fluorescence (XRF)

Major element compositions of rock samples were determined using X-ray fluorescence (XRF) spectrometry. Pulverized samples were fused into glass discs to ensure homogeneity prior to analysis. The XRF instrument was operated at 4 kW and 60 kV (160 mA), and calibrated using certified reference materials. Major oxides analyzed include SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2, and P_2O_5.

3.4.2 Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Trace element concentrations in both groundwater and rock samples were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the University of Cape Town, South Africa. Water samples were filtered (0.45 µm), acidified, and analyzed directly, while rock samples were digested using a mixed acid digestion ($HF–HNO_3–HClO_4$) to achieve total dissolution. Calibration was performed using multi-element standard solutions. The ICP-MS detection limits for trace elements were typically in the range of 0.001–0.01 mg/L for water samples. Analytical accuracy was verified using certified reference materials (CRMs), while procedural blanks were used to monitor contamination.

3.5 Quality Assurance and Quality Control (QA/QC)

Quality assurance procedures were implemented to ensure reliability and reproducibility of analytical results. Duplicate samples and replicate analyses were used to assess precision, with relative standard deviations (RSD) generally within ±5%. Analytical accuracy was evaluated using certified reference materials, yielding recovery rates between 90% and 110%. Field blanks and laboratory blanks were analyzed to check for contamination, and all measured concentrations were above detection limits. Instrument calibration was performed regularly using standard solutions to maintain analytical consistency.

3.6 Data Analysis

Descriptive statistical methods were employed to summarize the concentration, distribution, and variability of trace elements in groundwater for both wet and dry seasons. Spearman rank correlation analysis was used to evaluate relationships among trace elements and infer possible geochemical associations.

Spatial distribution maps were generated using QGIS software to visualize the influence of lithology and seasonal variation on trace element distribution. Comparative seasonal analysis was conducted to assess hydrogeochemical evolution between wet and dry periods.

Geogenic contributions to groundwater chemistry were evaluated by integrating petrographic observations, rock geochemistry, and groundwater trace element data to identify dominant sources and controlling processes.

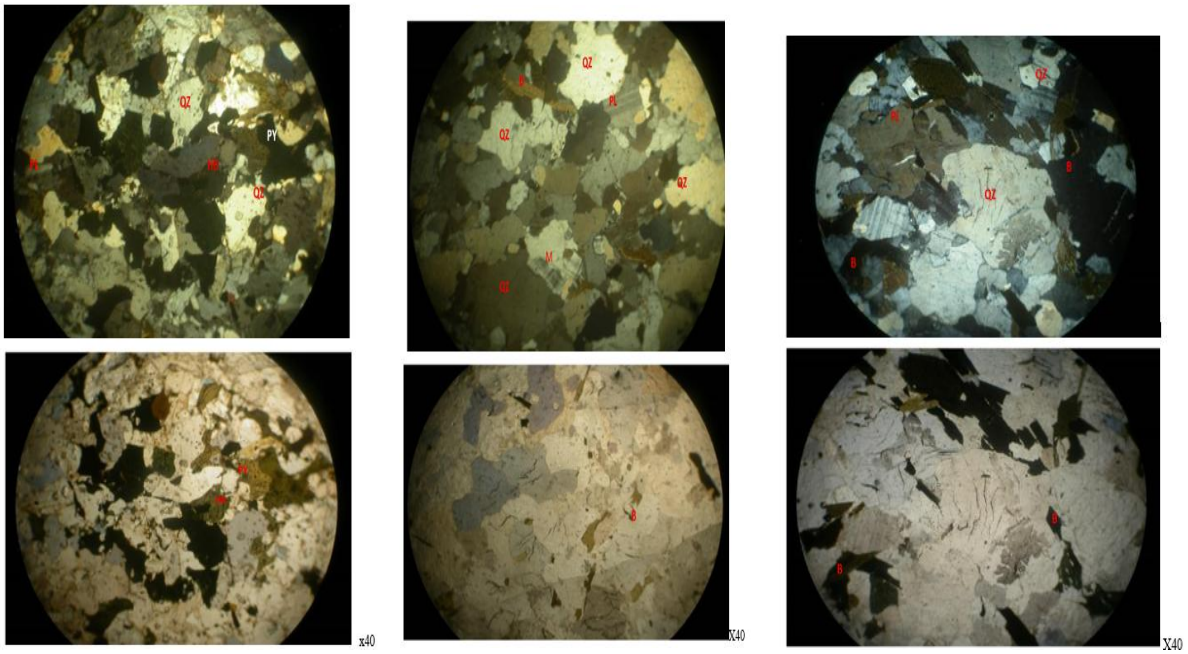
4. Results and Discussion

4.1 Petrographic Characteristics and Implications for Trace elements Sources

Petrographic analysis of rock sample from Alayande, Idi-Ape, Oke-Modina, and Sabo reveals a medium- to coarse-grained, inequigranular texture composed predominantly of quartz, plagioclase feldspar, microcline, muscovite, biotite, hornblende, and minor pyroxene (Figures 3a, b,and c). Quartz grains exhibit undulose extinction, indicating tectonic deformation, while feldspar minerals show varying degrees of alteration, reflecting ongoing weathering processes. Modal composition data (Table 1) indicate that quartz (16–23 vol.%), plagioclase feldspar (19–24 vol.%), and microcline (15–21 vol.%) are the dominant mineral phases, whereas muscovite, biotite, hornblende, pyroxene, and accessory minerals occur in subordinate proportions.

This mineral assemblage is characteristic of crystalline basement rocks in southwestern Nigeria and represents a significant geogenic source of trace elements such as Fe, Mn, Ni, Cr, and Co through mineral weathering and dissolution (Nwankwo et al., 2020; Adeyemi et al., 2022). In particular, the presence of ferromagnesian minerals such as biotite and hornblende is critical, as these minerals release Fe, Mn, and Ca during oxidative weathering processes in shallow aquifer systems (Egbueri & Unigwe, 2020). Similarly, feldspars (plagioclase and microcline), which constitute a substantial proportion of the rock matrix, contribute to the release of Al, Na, Ca, and K through hydrolysis reactions.

The observed mineral alteration and micro-fracturing enhance mineral water interaction, thereby facilitating the mobilization of trace elements into groundwater. These petrographic characteristics indicate that the host lithology functions as an active geochemical reservoir, with its mineralogical composition exerting a primary control on groundwater chemistry, particularly under conditions of prolonged residence time and seasonal variability.



(a) (b) (c)

Figure 3: Photomicrographs of rock sample at Alayande, Idi-Ape and Oke Modina in thin section and under a plain polarized light showings grain of plagioclase (PL), Horblende (HB) quartz (QZ), pyroxene (PY), microcline (M), and biotite (B)

Table 1: Modal compositions of the rock samples (vol. %) around Oyo town

Minerals	RK1	RK2	RK3	RK4	RK5	RK6
Quartz	16	20	20	23	20	23
Microcline	21	18	15	17	19	18
Plagioclase feldspar	22	19	20	24	19	20
Muscovite	11	14	11	10	15	11
Hornblende	9	8	10	8	7	8
Biotite	9	10	15	8	8	9
Pyroxene	8	8	5	7	8	7
Opaque	3	2	3	2	3	3
Accessory minerals	1	1	1	1	1	1
Total	100	100	100	100	100	100

4.2 Major Oxide Geochemistry of Migmatite Gneiss

The major oxide composition of the rock sample in the study area (Table 2) indicates a siliceous composition, with SiO_2 ranging from 60.96 to 72.34 wt.%, confirming a felsic to intermediate lithology. Al_2O_3 concentrations (13.06–17.30 wt.%) reflect the abundance of feldspar and mica, while Fe_2O_3 values (1.70–6.30 wt.%) correspond to the presence of iron-bearing minerals such as magnetite, hematite, and ilmenite. Elevated CaO and Na_2O concentrations indicate significant plagioclase content and suggest active plagioclase weathering, a key geogenic process influencing groundwater chemistry in crystalline basement aquifers (Kayode et al., 2024).

The relatively low Loss on Ignition (LOI) values (0.16–0.85 wt.%) indicate limited chemical alteration of the parent rock, implying that the system is dominated by ongoing mineral dissolution rather than advanced weathering. This suggests that groundwater chemistry is primarily controlled by active water–rock interaction processes, where primary minerals serve as continuous sources of dissolved ions and trace elements. Such conditions are consistent with similar basement complex environments in Nigeria, where moderate weathering facilitates sustained release of geogenic constituents into groundwater systems (Akinlalu et al., 2023). This geochemical signature reinforces the role of these rocks as a primary source of dissolved constituents, thereby exerting a fundamental control on groundwater composition in the study area

Table 2: Concentration of Major oxides (wt. %) in the Rock Samples

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	Cr_2O_3	N_iO	LOI
RK1	68.65	0.35	15.42	3.64	0.04	0.93	3.24	4.66	1.68	0.12	0.07	0.01	b.d.	0.85
RK2	67.76	0.62	14.68	4.88	0.07	1.03	2.94	3.98	3.11	0.24	0.03	0.01	b.d.	0.37
RK3	60.96	0.74	17.30	6.30	0.08	2.22	4.59	4.86	1.81	0.42	0.01	b.d.	b.d.	0.33
RK4	72.34	0.19	15.29	1.70	0.03	0.32	1.83	4.44	3.75	0.05	b.d.	b.d.	0.01	0.16
RK5	66.51	0.58	13.06	3.69	0.12	0.56	6.45	3.72	1.32	2.45	0.04	0.01	b.d.	0.77
RK6	70.39	0.34	15.10	3.36	0.05	1.00	2.76	4.21	2.29	0.13	0.00	0.01	b.d.	0.32
MIN	60.96	0.19	13.06	1.70	0.03	0.32	1.83	3.72	1.32	0.12	0.01	0.01	b.d	0.16
MAX	72.34	0.74	17.30	4.88	0.12	2.22	6.45	4.86	3.75	2.45	0.07	0.01	b.d	0.85
MEAN	67.77	0.470	15.14	3.93	0.07	1.01	3.64	4.31	2.33	0.57	0.025	0.01	b.d	0.47
S.D	3.91	0.21	1.360	1.55	0.03	0.66	1.64	0.43	0.93	0.93	0.027	0	b.d	0.28

*b.d-below detention limits, *wt. % - Weight percentage

4.3 Chemical Index of Alteration (CIA)

The Chemical Index of Alteration (CIA) was used to evaluate the degree of chemical weathering in the migmatite gneiss samples. The CIA reflects the progressive depletion of mobile cations (Ca^{2+}, Na^{+}, K^{+}) relative to the enrichment of Al during feldspar weathering and secondary clay formation (Nesbitt & Young, 1982). Calculated CIA values range from 43 to 64% (Table 3), with most samples (RK1, RK3, RK4, and RK6) clustering within the moderate weathering range (~60–64%), while RK2 and RK5 show relatively lower values, indicating localized variations in weathering intensity.

These results suggest that the rocks have undergone moderate chemical weathering, typical of crystalline basement environments where primary minerals are only partially altered. Such a weathering regime reflects a balance between mineral stability and dissolution, enabling sustained release of trace elements into groundwater. Importantly, the moderate CIA values indicate that trace element mobilization is not governed solely by weathering intensity but is strongly influenced by hydrogeological controls, particularly groundwater residence time and seasonal recharge dynamics. This interplay between lithology and hydrology underscores the combined controls on groundwater chemistry in the study area.

This further supports the interpretation that groundwater chemistry in the study area is controlled by active water–rock interaction under moderate weathering conditions rather than extreme chemical alteration.

Table 3: Chemical Index of Alteration (CIA) Values for the Rock Samples

Sample	Al_2O_3	CaO	Na_2O	K_2O	CIA (%)
RK1	15.42	3.24	4.66	1.68	62.90
RK2	14.68	2.94	3.98	3.11	57.66
RK3	17.30	4.59	4.86	1.81	60.36
RK4	15.29	1.83	4.44	3.75	63.55
RK5	13.06	6.45	3.72	1.32	43.40
RK6	15.10	2.76	4.21	2.29	60.50

The A–CN–K ternary diagram (Figure 4) corroborates the CIA results, with most samples plotting along the CN–K boundary, indicative of limited progression toward aluminum enrichment characteristic of advanced weathering. Sample RK5's position closer to the CN apex suggests a fresher composition dominated by CaO + Na_2O, which aligns with its lower CIA value and implies lesser chemical alteration. Therefore, the combination of CIA and the A–CN–K plot indicates a moderate degree of chemical weathering in the study area, reflecting both geologic and climatic influences on rock alteration.

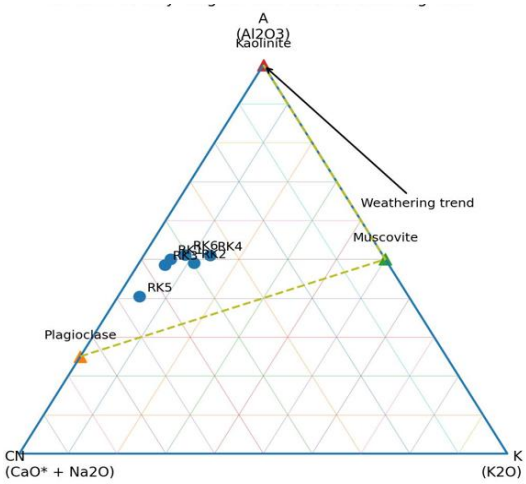


Figure 4: A–CN–K ternary diagram for your rock samples shows the relative positions of each sample based on Al_2O_3, CaO + Na_2O, and K_2O proportions

4.4 Trace Element Composition in the Rock Samples

Trace element concentrations in the rock samples (Table 4) reveal significant enrichment of Zn (49.47–121.5 ppm), Cu (7.29–71.45 ppm), Cr (52.11–78.19 ppm), Ba (356.7–1433 ppm), and Sr (297–7152 ppm). These elements are primarily associated with feldspars, biotite, hornblende, and accessory mineral phases typical of migmatitic basement rocks. The observed enrichment of Ni and Co further reflects the contribution of mafic and ferromagnesian minerals, which are known to host and release these elements during weathering processes.

The geochemical signature of the rock samples indicates that the migmatite gneiss constitutes a significant geogenic reservoir of trace elements. Under favorable hydrogeochemical conditions—particularly enhanced water–rock interaction, mineral dissolution, and seasonal variability—these elements can be mobilized into the groundwater system. This supports previous findings that lithology exerts a dominant control on trace element availability in basement aquifers (Nwankwo et al., 2020; Egbueri et al., 2021).

Table 4: Concentration of Trace elements (ppm) in rock sample

Sample ID	Cu	Zn	As	Cr	Li	Pb	Ba	Co	Ni	Sr	V	Mo
RK1	23.67	70.50	0.624	63.70	28.01	9.682	674.8	7.883	12.33	442.7	32.69	0.573
RK2	14.82	98.71	1.431	74.54	17.47	19.87	1045	8.823	6.207	423.9	45.63	0.923
RK3	16.09	121.5	0.910	52.91	22.06	10.77	1433	13.83	16.12	723.7	73.51	0.317
RK4	7.294	49.47	0.226	52.11	32.57	22.67	1290	2.451	1.235	742.6	11.23	0.197
RK5	71.45	63.04	0.868	78.19	9.831	32.33	823.5	6.056	9.865	7152	57.38	1.449
RK6	7.467	78.05	0.452	66.82	48.82	18.29	356.7	7.834	9.441	297	41.04	0.284
MIN	7.29	49.47	0.226	52.11	9.831	9.682	356.7	2.451	1.235	297	11.23	0.317
MAX	71.45	121.5	1.431	78.19	48.82	32.33	1433	13.83	16.12	7152	57.38	1.449
MEAN	23.47	80.21	0.75	64.71	26.71	18.94	937.2	7.81	9.20	1630	43.58	0.62

4.5 Trace element Concentrations of Groundwater

Trace element concentrations in groundwater (Table 5) exhibit pronounced spatial and seasonal variability, reflecting the combined influence of lithological composition and hydrogeochemical processes. Iron concentrations range from 0.02–4.52 mg/L in the wet season and 0.07–22.77 mg/L in the dry season, with mean values exceeding WHO and NSDWQ limits at several locations. Similarly, Mn concentrations show significant enrichment during the dry season (0.006–7.12 mg/L). These elevated concentrations are characteristic of basement aquifers and are primarily attributed to the dissolution of Fe–Mn-bearing minerals and the reductive dissolution of Fe–Mn oxides under low-flow conditions (Adeyemi et al., 2022; Kayode et al., 2024).

The marked increase in Fe and Mn concentrations during the dry season reflects reduced recharge, increased groundwater residence time, and limited dilution, which collectively enhance water–rock interaction and promote trace element mobilization. Elevated Al concentrations further support this interpretation and are linked to intensified feldspar hydrolysis under prolonged contact between groundwater and host lithology.

Lead concentrations exceed the WHO guideline value (0.01 mg/L) in both seasons; however, their localized distribution and absence of significant anthropogenic inputs suggest a predominantly lithogenic origin. This is likely

associated with the weathering of accessory sulfide and oxide minerals within the basement rocks, consistent with observations from similar geological settings (Egbueri & Unigwe, 2020).
In contrast, Zn, Cu, and Ni concentrations generally remain within permissible limits despite their presence in the host rocks, indicating selective mobilization controlled by mineral stability, adsorption processes, and groundwater geochemical conditions such as pH and redox state (Smedley & Kinniburgh, 2024).
Overall, the observed seasonal trends demonstrate that while lithology provides the primary source of trace elements, hydrogeological conditions—particularly seasonal recharge and residence time—govern their mobility and concentration in groundwater. This highlights a coupled lithological–seasonal control on groundwater chemistry in the study area.This integrated interpretation provides stronger evidence for geogenic control of groundwater quality than approaches based solely on hydrochemical data.

Table 5: Descriptive statistics of trace elements in groundwater for wet and dry seasons compared with WHO/NSDWQ standards

Parameter	**Min**		**Max**		**Mean**		**SD**		**WHO**	**NAFDAC**
(mg/L)	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**		
Al	0.07	0.49	1.95	42.7	0.49	3.29	0.49	7.08	0.2	0.2
Cd	0.002	0.002	0.003	0.003	0.02	0.001	0.01	0.001	0.003	0.003
Fe	0.02	0.072	4.52	22.77	0.49	1.51	0.94	3.79	0.3	0.3
B	0.04	0.006	0.44	0.10	0.11	0.025	0.06	0.02	0.5	0.5
Ba	0.03	0.076	0.64	1.68	0.19	0.38	0.11	0.41	0.7	0.7
Co	0.02	0.001	0.03	0.125	0.02	0.010	0.01	0.025	-	-
Pb	0.03	0.01	0.06	0.23	0.04	0.012	0.01	0.037	0.01	0.01
Mn	0.05	0.006	1.11	7.12	0.17	0.89	0.22	1.65	0.4	0.4
Cr	0.03	0.001	0.03	0.027	0.03	0.003	0.01	0.063	0.005	0.05
Zn	0.01	0.013	0.93	2.41	0.19	0.19	0.19	0.39	3	3
Cu	0.01	0.008	0.07	0.123	0.05	0.009	0.01	0.020	2	2
Ni	0.003	0.002	0.01	0.06	0.01	0.008	0.01	0.011	0.07	0.07

4.6 Spearman Correlation for Trace element for Dry and Wet season

Spearman rank correlation analysis was applied to assess the degree of association among the analyzed trace elements in groundwater during the dry and wet season (Table 6 and 7).
Spearman correlation analysis reveals distinct seasonal controls on elements distribution in groundwater, with stronger geochemical coherence observed during the wet season compared to the dry season. In the dry season, significant positive correlations among Fe, Mn, Co, Zn, Pb, and Cu ($p < 0.01$), particularly Co–Mn ($\rho = 0.89$) and Zn–Cu/Pb–Cu ($\rho = 0.76$), indicate dominant lithogenic influence through mineral weathering and redox-driven mobilization, with Fe–Mn oxides acting as key scavenging and carrier phases. Moderate associations ($p < 0.05$) and weak correlations involving Ba, Cr, B, and Al suggest secondary controls such as ion exchange, localized lithologic effects, and limited mobility of certain elements. In contrast, the wet season is characterized by very strong correlations among Al–Fe–Cr–Pb ($\rho = 0.80–0.94$, $p < 0.01$), reflecting enhanced co-mobilization under increased recharge, mineral dissolution, and reduced fractionation during transport. Additional moderate relationships (e.g., Ba–Zn, Cd–Pb) indicate partial influence of surface inputs and leaching processes, while Mn maintains significant associations with Fe, Pb, and Cr, highlighting its redox sensitivity. General, the results indicate that groundwater chemistry is primarily controlled by lithogenic processes, with seasonal recharge intensifying metal mobility and introducing variability in geochemical interactions.

Table 6: Spearman Correlation Matrix of Trace Elements in Groundwater Samples during the Dry Season

Parameter(mg/L)	Al	Cd	Fe	B	Ba	Co	Pb	Mn	Cr	Zn	Cu	Ni
Al	1.00**	0.33*	0.92**	−0.00	0.42**	0.27	0.80**	0.60**	0.94**	0.66**	−0.14	0.24
Cd	0.33*	1.00**	0.33*	−0.08	0.45**	−0.05	0.50**	0.09	0.28	0.28	−0.04	−0.08
Fe	0.92**	0.33*	1.00**	−0.07	0.45**	0.35*	0.91**	0.65**	0.93**	0.71**	−0.29	0.33*
B	−0.00	−0.08	−0.07	1.00**	0.03	−0.11	−0.20	0.27	−0.07	0.01	−0.15	0.15
Ba	0.42**	0.45**	0.45**	0.03	1.00**	−0.01	0.50**	0.38*	0.40*	0.57**	−0.30	0.29
Co	0.27	−0.05	0.35*	−0.11	−0.01	1.00**	0.29	0.22	0.30	0.19	0.01	−0.15
Pb	0.80**	0.50**	0.91**	−0.20	0.50**	0.29	1.00**	0.58**	0.89**	0.76**	−0.28	0.20
Mn	0.60**	0.09	0.65**	0.27	0.38*	0.22	0.58**	1.00**	0.63**	0.55**	−0.25	0.18
Cr	0.94**	0.28	0.93**	−0.07	0.40*	0.30	0.89**	0.63**	1.00**	0.70**	−0.22	0.29
Zn	0.66**	0.28	0.71**	0.01	0.57**	0.19	0.76**	0.55**	0.70**	1.00**	−0.40*	0.30
Cu	−0.14	−0.04	−0.29	−0.15	−0.30	0.01	−0.28	−0.25	−0.22	−0.40*	1.00**	−0.37*
Ni	0.24	−0.08	0.33*	0.15	0.29	−0.15	0.20	0.18	0.29	0.30	−0.37*	1.00**

Correlation coefficients marked with * and ** are significant at $p < 0.05$ and $p < 0.01$, respectively

Table 7: Spearman Correlation Matrix of trace elements in Groundwater Sample during the Wet Season

Parameter(mg/L)	Al	Fe	B	Ba	Co	Pb	Mn	Cr	Zn	Cu
Al	1.00	0.17	−0.09	0.01	0.12	0.27	0.10	0.14	−0.05	0.06
Fe	0.17	1.00	0.21	0.22	0.60**	0.66**	0.60**	0.26	0.64**	0.59**
B	−0.09	0.21	1.00	−0.06	0.06	0.38*	0.17	−0.07	0.43**	0.29
Ba	0.01	0.22	−0.06	1.00	0.61**	0.08	0.55**	0.05	0.44**	0.34*
Co	0.12	0.60**	0.06	0.61**	1.00	0.36*	0.89**	0.02	0.59**	0.56**
Pb	0.27	0.66**	0.38*	0.08	0.36*	1.00	0.32*	0.40**	0.67**	0.76**
Mn	0.10	0.60**	0.17	0.55**	0.89**	0.32*	1.00	−0.02	0.54**	0.49**
Cr	0.14	0.26	−0.07	0.05	0.02	0.40**	−0.02	1.00	0.26	0.36*
Zn	−0.05	0.64**	0.43**	0.44**	0.59**	0.67**	0.54**	0.26	1.00	0.76**
Cu	0.06	0.59**	0.29	0.34*	0.56**	0.76**	0.49**	0.36*	0.76**	1.00

Correlation coefficients marked with * and ** are significant at $p < 0.05$ and $p < 0.01$, respectively

4.7 Seasonal Influence of Trace Element Mobilization and Geogenic Dominance in Groundwater

Trace element concentrations in groundwater show clear seasonal variability, reflecting the influence of recharge dynamics and hydrogeochemical conditions. In general, concentrations are lower during the wet season and significantly elevated during the dry season (Table 5). This pattern is primarily controlled by dilution during periods of high recharge and concentration effects during low recharge conditions, as widely reported in basement aquifers of southwestern Nigeria (Kayode et al., 2024; Nwankwo et al., 2020).

During the wet season, increased precipitation enhances groundwater recharge, leading to dilution of dissolved constituents and reduced residence time within the aquifer system. This limits the extent of water–rock interaction and suppresses trace element concentrations. In contrast, the dry season is characterized by reduced recharge, increased groundwater residence time, and higher evaporation rates, which collectively enhance mineral dissolution and trace

element mobilization. Similar seasonal controls have been documented in basement terrains across West Africa, where hydrochemical evolution is strongly influenced by recharge variability (Wannous et al., 2024).

In addition, seasonal variations in redox conditions may further influence trace element behavior. The elevated concentrations of Fe and Mn observed during the dry season are consistent with reductive dissolution of Fe–Mn oxides under low-flow conditions (Adeyemi et al., 2022; Kayode et al., 2024). These results demonstrate that seasonal hydrogeological processes play a critical role in regulating the mobility and concentration of trace elements in the groundwater system.

4.8 Lithological Seasonal Control on Trace Element Distribution

The results of this study indicate that trace element distribution in groundwater is controlled by a coupled lithological–seasonal system, in which lithology determines elemental availability while seasonal processes regulate their mobilization and concentration. Petrographic and geochemical analyses show that the migmatite gneiss host rocks contain significant quantities of trace element-bearing minerals, including feldspars and ferromagnesian phases, which act as primary geogenic sources.

The correspondence between rock geochemistry and groundwater composition, particularly for elements such as Fe, Mn, Pb, and Al, demonstrates a strong lithological control on groundwater chemistry. This is consistent with recent studies in Nigerian basement terrains, where mineralogical composition and weathering processes are identified as dominant controls on groundwater trace element signatures (Nwankwo et al., 2020; Egbueri et al., 2021; Jolaosho et al., 2024).

However, the extent to which these elements are expressed in groundwater is modulated by seasonal hydrogeological conditions. During the wet season, recharge-driven dilution reduces observable concentrations, whereas in the dry season, increased residence time and intensified water–rock interaction enhances trace element accumulation. This interaction between lithology and seasonal dynamics aligns with recent hydrogeological studies emphasizing the combined influence of geological framework and recharge processes in basement aquifers (Akinlalu et al., 2023; Kayode et al., 2024).

Therefore, neither lithology nor seasonality alone sufficiently explains the observed patterns; rather, it is their interaction that governs trace element dynamics. By integrating petrographic data, rock geochemistry, and seasonal groundwater chemistry, this study provides a more robust framework for understanding geogenic controls on groundwater quality in crystalline basement terrains.

4.9 Geospatial Interpretation of Trace Metal Distribution

The geospatial distribution maps of Al, Fe, Pb, Zn, and Mn for the wet and dry seasons reveal distinct spatial clustering and seasonal amplification patterns across the study area (Figures 5a–5e). These patterns reflect the combined effects of lithological heterogeneity, shallow aquifer hydrogeology, and seasonal recharge dynamics, rather than widespread anthropogenic inputs.

During the wet season. Hydrolysis of feldspar minerals in feldspar-rich crystalline rocks (e.g., gneiss and migmatites) is a major mechanism releasing Aluminium (Figure 5a) and other dissolved ions into groundwater, particularly under prolonged water–rock interaction and seasonal concentration effects (Appelo & Postma, 2005; Olasehinde & Ogundana, 2020). Seasonal intensification during the dry period reflects reduced dilution and longer groundwater residence time, which enhances mineral dissolution processes in shallow basement aquifers (Akinlalu et al., 2023; Kayode et al., 2024).

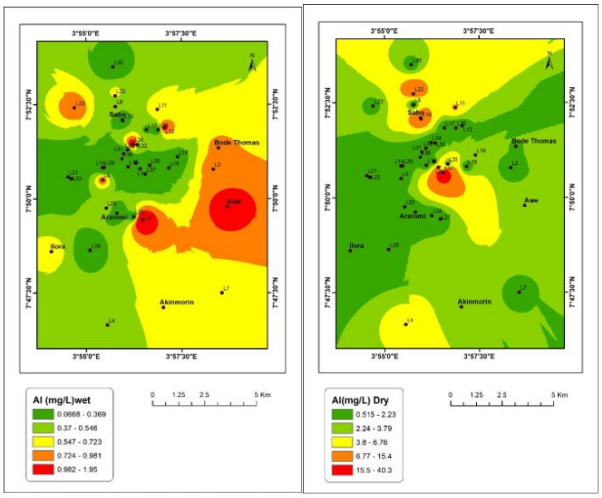
Fe shows pronounced spatial heterogeneity, with persistent high-concentration clusters observed in both seasons but with greater spatial extent during the dry season (Figure 5b). These Fe-enriched zones spatially coincide with biotite- and hornblende-bearing lithologies, indicating a predominantly geogenic origin controlled by the weathering and dissolution of ferromagnesian minerals within crystalline basement rocks (Oladunjoye et al., 2024; Ekeleme et al., 2026). The seasonal increase in Fe concentrations is attributed to intense rock–water interaction and possible reductive dissolution of Fe-bearing minerals under low-flow conditions, a characteristic feature of shallow crystalline aquifers (Adeyemi et al., 2022; Egbueri & Unigwe, 2020).

The localized Pb hotspots observed, particularly during the dry season (Figure 5c), show no clear spatial continuity, indicating point-source lithogenic control likely associated with accessory sulfide and oxide minerals in basement rocks rather than diffuse anthropogenic contamination (Appelo & Postma, 2005; Gaillardet et al., 2014; Adimalla & Li, 2019). Similar spatially restricted Pb enrichment has been documented in basement aquifers where fracture density and mineralogical composition control Pb mobility (Nwankwo et al., 2020; Adeyemi et al., 2022).

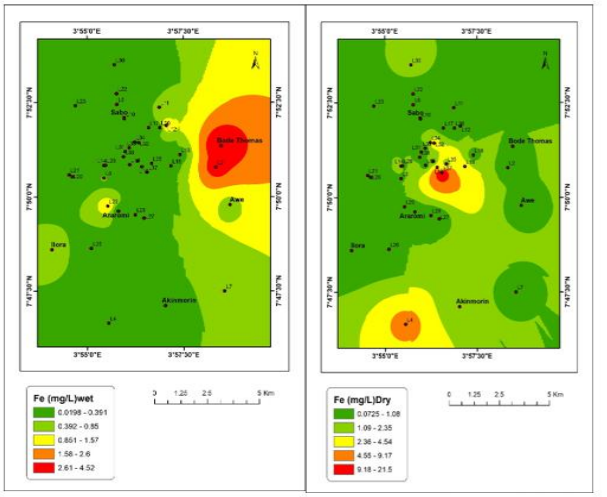
In contrast, Zn displays relatively uniform spatial distribution in both seasons, with concentrations generally remaining below regulatory limits (Figure 5d). Despite moderate Zn concentrations in the host rocks, its limited spatial variability suggests low mobility in groundwater, likely controlled by adsorption onto mineral surfaces and incorporation into stable secondary phases. (Appelo & Postma, 2005; Sposito, 2008; Alloway, 2013). This behavior is consistent with observations from other basement aquifers, where Zn is less sensitive to seasonal hydrogeochemical changes than Fe and Mn (Smedley & Kinniburgh, 2024).

Mn shows clear seasonal spatial expansion, with relatively restricted enrichment zones during the wet season and broader high-concentration areas during the dry season (Figure 5e). Mn enrichment is spatially associated with mafic mineral-rich zones and reflects redox-sensitive mobilization, were reduced conditions during prolonged residence time enhanced Mn dissolution. Such seasonal Mn behavior is typical of shallow crystalline aquifers subjected to fluctuating recharge regimes (Kayode et al., 2024; Nwankwo et al., 2020).

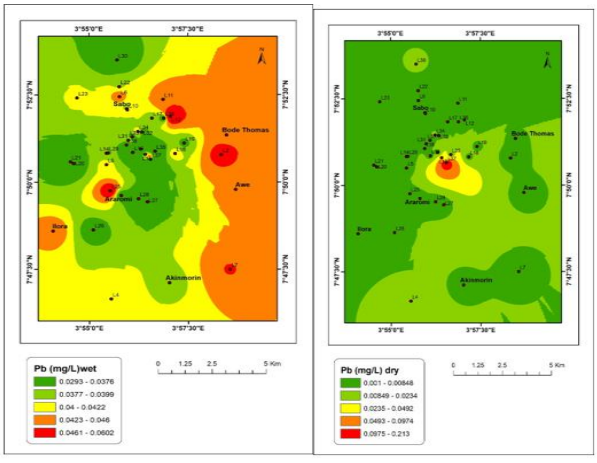
Generally, the integrated geospatial patterns demonstrate that trace metal distribution in groundwater is dominantly controlled by lithology and structurally influenced groundwater flow paths, while seasonal variation primarily governs concentration intensity rather than source origin. The recurrence of high-concentration zones across seasons strongly supports a geogenic origin for the observed trace metal enrichment. These findings emphasize the necessity of incorporating spatial analysis and geological context into groundwater quality assessments, particularly in basement terrains where natural background levels may locally exceed drinking water guidelines.



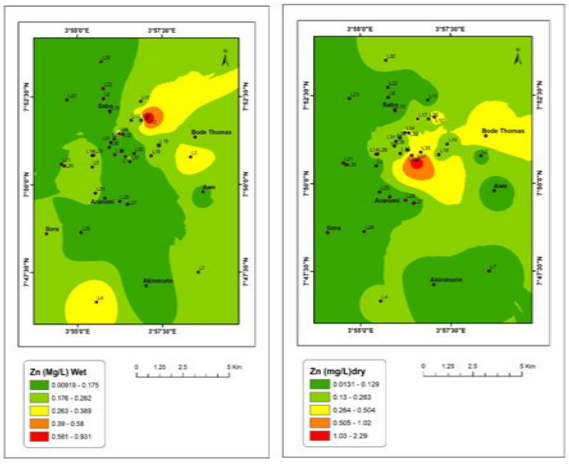
(5a)



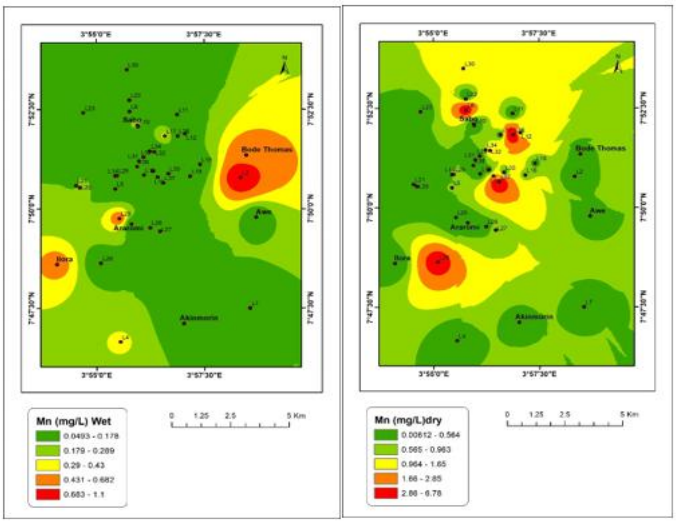
(5b)



(5c)



(5d)



(5e)

Figure 5a, b, c, d, e: Spatial distribution maps showing seasonal variations in Aluminum, Iron, Lead, Zinc, and Manganese concentration (mg/L) in groundwater across the study area.

5. Conclusion

Groundwater quality in Oyo Town is predominantly controlled by lithological characteristics and seasonal variability. The dominance of migmatite gneiss, composed mainly of feldspars and ferromagnesian minerals, exerts a strong geogenic influence on trace element distribution through mineral weathering and water–rock interaction processes. Petrographic and geochemical evidence confirm that the bedrock serves as the principal source of trace elements such as Fe, Mn, Al, and Pb in the groundwater system. Seasonal variations further modulate groundwater chemistry, with relatively lower concentrations observed during the wet season due to recharge-induced dilution, and elevated concentrations during the dry season as a result of increased residence time and intensified mineral dissolution. This seasonal contrast reflects a progressive shift from dilute to more mineralized groundwater conditions.

Although most trace elements are geogenic in origin, concentrations of Fe, Mn, Al, and Pb exceed recommended drinking water limits in several locations, indicating potential health risks and the need for regular monitoring. The strong correspondence between rock composition and groundwater chemistry suggests lithology as the primary control on groundwater quality in the study area. This study provides valuable baseline data and demonstrates the importance of integrating geological and seasonal factors in groundwater quality assessment and management within crystalline basement terrains. To ensure sustainable groundwater utilization, continuous monitoring, improved well construction practices, and effective land-use management are strongly recommended.

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Statements and Declaration

We declare that this manuscript titled “Lithological and Seasonal Controls on Trace Element Distribution and Groundwater Quality in Crystalline Basement Aquifers of Oyo Town, Southwestern Nigeria” is original, has not been published previously, and is not under consideration for publication elsewhere.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request. The data supporting the findings of this study include the geological, mineralogical, geochemical, and/or analytical datasets generated during field investigations and laboratory analyses, as applicable. Relevant supplementary data, including analytical results, sampling information, geochemical measurements, and other supporting datasets, may also be made available to interested researchers subject to reasonable restrictions relating to data integrity, ongoing research activities, and institutional requirements. Where applicable, publicly available geological maps, satellite imagery, and other secondary datasets used in this study were obtained from their respective recognised sources and are appropriately acknowledged in the manuscript. The authors confirm that no data necessary to understand or reproduce the principal findings have been intentionally withheld. Requests for access to the underlying datasets should be directed to the corresponding author. Additional information concerning data processing, analytical procedures, quality control, and interpretation is provided within the manuscript and its supplementary materials.

Conflict of Interest Statement

The authors declare no conflict of interest regarding the publication of this paper.

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Authors' Contributions

Authors' Contributions

- Oyebode Odunayo Jumoke: Conceptualization, Field Work, Laboratory Experiment, Data Acquisition and Analysis and Writing of Original Draft.
- Jimoh Mustapha Taiwo: Fieldwork, Laboratory Experiment, Reviewing and Editing of original manuscript.
- Adewoye Abosede Olufunmilayo: Reviewing and Editing of original draft.

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Ethics

The research was conducted in accordance with accepted ethical principles and applicable institutional guidelines. Ethical considerations were observed throughout the study, including responsible data collection, analysis, interpretation, and reporting. The authors ensured research integrity , transparency, confidentiality, and respect for all relevant participants, stakeholders, and intellectual property rights.

Consent to participate

Participation in this research was voluntary. All participants were adequately informed about the study's purpose, procedures, potential benefits, and risks before participation. Participants provided informed consent and were assured that their information would remain confidential and be used solely for research and academic publication purposes.

Consent to publish

The authors confirm that consent was obtained for the publication of this research work and its associated findings, data, tables, figures, and other relevant materials. All information presented has been reviewed and approved by the authors. The authors agree to publication in the selected journal and accept responsibility for its content.