

Hydrogeochemical and microbial assessment of groundwater quality in a basement complex terrain of Uke, North Central Nigeria

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ABSTRACT: This study presents an integrated hydrogeochemical and microbial assessment of groundwater quality in Uke and its environs, a Basement Complex terrain in North Central Nigeria, where boreholes and hand-dug wells constitute the principal source of domestic water supply. Fifteen groundwater samples, comprising ten boreholes and five hand-dug wells, were collected during the dry season (December) and analysed for physicochemical parameters, major ions, five heavy metals (Fe, Cr, Pb, Hg, As), and the bacteriological indicators Total Coliform and *Escherichia coli*. Results were evaluated against World Health Organisation (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) guidelines. Most physicochemical parameters were within the selected guideline values, although EC, TDS, turbidity, potassium, and pH showed localised departures: EC exceeded 1000 $\mu\text{S}/\text{cm}$ at four sites, TDS exceeded 500 mg/L at six sites, turbidity exceeded 5 NTU at four sites, potassium exceeded 10 mg/L at twelve sites, and pH fell below 6.5 at three sites. Piper, Durov, and Schoeller diagrams indicate that groundwater is predominantly of Ca-Mg-HCO_3 type, consistent with silicate weathering and carbonate dissolution within the crystalline aquifer, with a minority of samples showing a Ca-Mg-Cl or Ca-Na-HCO_3 signature suggestive of localised cation exchange; this facies interpretation is indicative rather than definitive, as major-ion charge-balance errors for two-thirds of the samples exceed $\pm 20\%$ in a verified dataset (full sample-by-sample values reported in the main text). Pearson correlation indicated a strong EC-TDS relationship in both borehole ($r = 0.998$) and hand-dug well ($r = 0.997$) samples, consistent with dissolved ionic load as a principal control on conductivity. Iron exceeded the guideline at BH5, while lead exceeded the guideline at BH5 and BH6; arsenic remained within or equal to the applicable guideline at all sites, and chromium and mercury were not detected. All computed Heavy Metal Evaluation Index values were below 10, and all Heavy Metal Pollution Index values were below 100, indicating that none of the sampled sources falls in the unsafe heavy-metal pollution category, though BH5 and BH6 are identified as priority sites for confirmation sampling. All 15 groundwater sources contained Total Coliform, and *E. coli* was detected in 14 of 15 samples, indicating that none of the sampled sources is suitable for direct consumption without treatment; although sampling occurred during the dry season, the persistence of contamination suggests it may be sustained by structural deficiencies, stored contamination, or hydraulic connection with shallow polluted zones rather than seasonal surface infiltration alone. The findings indicate that groundwater in Uke is broadly acceptable on physicochemical grounds but is bacteriologically unsafe for direct consumption, underscoring an urgent need for wellhead protection, water-point rehabilitation, and routine disinfection across the study area.

Keywords: Basement complex, dry season, groundwater quality, heavy metal pollution index; hydrogeochemistry, microbial contamination; Nigeria.

INTRODUCTION

Groundwater, abstracted through boreholes and hand-dug wells, is the primary source of domestic water supply for

most rural and peri-urban communities in Nigeria, where centralized treatment and piped-water infrastructure

remain limited. The suitability of groundwater for human consumption depends jointly on its chemical composition, which is governed by aquifer lithology and residence time, and its microbiological safety, which reflects the degree of protection from surface and near-surface contamination sources such as pit latrines, waste dumps, and agricultural runoff (Abanyie *et al.*, 2023; WHO, 2021). Nigeria's heavy reliance on self-supplied groundwater, and the geological and hydrogeological diversity that governs its occurrence and quality nationwide, have been documented in detail elsewhere (Adelana *et al.*, 2008; Abanyie *et al.*, 2023).

In Uke and its environs, North Central Nigeria, groundwater is drawn from a crystalline Basement Complex aquifer system in which storage and flow are controlled by weathering depth, fracture density, and structural discontinuities rather than by primary porosity. Increasing artisanal mining, agricultural activity, and settlement expansion in the area have raised concerns over both the geochemical and bacteriological safety of these sources. Elevated concentrations of heavy metals such as lead, cadmium, arsenic, and iron have been reported in comparable Basement Complex settings in North Central Nigeria, typically linked to weathering of mineralized rock and mining-related disturbance (Mahammad *et al.*, 2022; Okimiji *et al.*, 2024); similar artisanal-mining-linked heavy-metal signatures in groundwater and drinking water have been reported from other North Central Nigerian mining districts, including Barkin Ladi, Plateau State (Ramadan and Haruna, 2019), Igade-Mashegu, Niger State (Sani *et al.*, 2023), and Arufu-Akwana, Taraba State (Yebpella *et al.*, 2020), with human-health consequences of artisanal mining exposure documented as far as Niger State (Bello *et al.*, 2022) and reviewed at the continental scale (The World Bank, 2024), while poor sanitary completion of wells and boreholes is a well-documented driver of bacteriological contamination in similar rural Nigerian aquifers. In a geologically comparable Basement Complex aquifer some 15 km away at Keffi, Nasarawa State, groundwater was found to be broadly acceptable on physicochemical and trace-metal grounds, with a predominantly Ca–HCO₃ hydrochemical signature and a computed non-carcinogenic health-risk index below unity for both adults and children (Obrike *et al.*, 2023); that study, however, did not include a bacteriological component, leaving the microbial safety of groundwater in this immediate geological setting an open question that the present study addresses directly for the neighbouring Uke area. Widespread faecal-indicator contamination of hand-dug wells and boreholes, often exceeding zero-coliform guidelines regardless of source type, has been reported repeatedly across Nigerian towns and cities, including Ibadan (Oloruntoba and Sridhar, 2007; Alabi *et al.*, 2024) and Lagos (Egwari and Aboaba, 2002), reinforcing the expectation that microbial safety cannot be inferred from chemical or geological setting alone.

Chemical and microbial contamination arise from largely

independent processes; one geogenic and slow-acting, the other sanitary and often acute. Groundwater quality assessment is most informative when both dimensions are evaluated jointly and interpreted against the same hydrogeological framework. This is particularly important when sampling is conducted during the dry season, when reduced recharge concentrates dissolved chemical species through evaporative and residence-time effects, while simultaneously minimising surface-runoff-driven microbial ingress conditions that, if microbial contamination is nonetheless detected, point more strongly toward structural or sanitary failure at the water point itself rather than seasonal infiltration.

This study presents an integrated hydrogeochemical and microbial assessment of groundwater quality in Uke, based on samples collected during the December dry season. The specific objectives are to: (i) characterize the geological and hydrogeological setting of the study area; (ii) evaluate the physicochemical and heavy-metal characteristics of borehole and hand-dug well water relative to WHO and NSDWQ guidelines; (iii) determine the hydrochemical facies and water-type evolution using Piper, Durov, and Schoeller diagrams; (iv) quantify heavy-metal pollution using standard indices (CF, HEI, HPI) and overall physicochemical suitability using the Water Quality Index (WQI); and (v) assess bacteriological safety using Total Coliform and *Escherichia coli* as indicator organisms, to provide an integrated basis for groundwater protection and management in this Basement Complex terrain.

MATERIALS AND METHODS

Study area

The study area covers Uke and adjoining settlements (Angwan Tofa, Sabon Gora) within the Uke Development Area of Nasarawa State, North Central Nigeria, situated between latitudes 8°52'N and 8°55'N and longitudes 7°41'E and 7°44'30"E (Figure 1). The area is accessible via the Abuja–Keffi Expressway, which transects the terrain in a broadly NW–SE direction, supplemented by minor roads linking outlying settlements. Elevation ranges from approximately 280 m to over 440 m above sea level, with topography rising from low-lying phyllite and granite terrain in the northwest toward higher-relief gneissic uplands in the southeast.

Geologically, the area forms part of the Nigerian Basement Complex the Precambrian crystalline terrain that underlies roughly half of the country and comprises migmatite-gneisses, schists, and younger granites emplaced during the Pan-African orogeny (Ajibade *et al.*, 1987; Obaje, 2009) and comprises three principal lithological units delineated along a NW–SE geological cross-section (A–B): a phyllite unit occupying the northern part of the area (around Uki), a granite unit forming a broadly lens-shaped intrusive body in the central-western

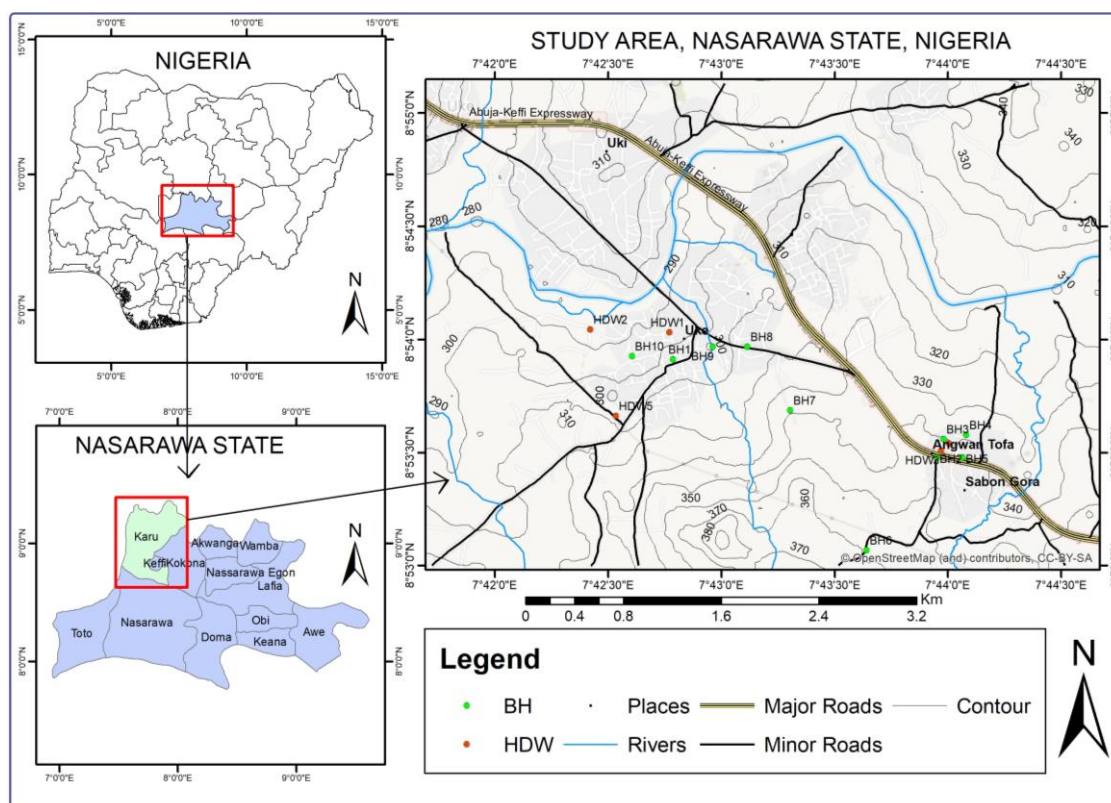


Figure 1. Location map of the study area showing borehole (BH) and hand-dug well (HDW) sampling points, Nasarawa State, North Central Nigeria.

sector (around Uke), and a gneiss unit that dominates the central-southern and eastern parts of the area, hosting the majority of the sampled boreholes and hand-dug wells around Uke, Angwan Tofa, and Sabon Gora (Figure 2). The cross-section shows the phyllite and granite units occupying comparatively subdued, lower-elevation terrain (~280–320 m), while the gneiss unit underlies the higher-relief eastern portion of the area, with elevations locally exceeding 440 m. Groundwater occurs within the weathered overburden and fractured bedrock of these units; boreholes generally exploit deeper fracture systems within the gneiss and granite, while hand-dug wells tap shallower, less protected weathered zones, rendering them comparatively more vulnerable to surface-derived contamination.

Field investigation and sample collection

Fifteen groundwater samples were collected during the dry season (December), comprising ten boreholes (BH1–BH10) and five hand-dug wells (HDW1–HDW5), distributed across mining-influenced, agricultural, and settlement zones within the study area (Figure 1; Table 1). December sampling was deliberately chosen to characterise groundwater quality under low-recharge

conditions, when dilution from rainfall infiltration is minimal, and any chemical or microbial signal is more likely to reflect intrinsic aquifer and well-construction conditions rather than transient seasonal runoff.

At each location, in-situ pH, electrical conductivity (EC), total dissolved solids (TDS), temperature, and turbidity were measured using a portable multiparameter meter. Samples for heavy-metal analysis were acidified with concentrated HNO_3 immediately after collection, while samples for microbial analysis were collected in sterile containers under aseptic conditions. All samples were stored in ice-packed coolers at $\sim 4^\circ\text{C}$ and transported to the laboratory within 24 hours.

Laboratory analysis

Physicochemical parameters and major ions were determined following APHA *et al.* (2017) standard methods, with method and instrumentation specific to each parameter as follows. pH was measured electrometrically (APHA 4500-H*B) using a calibrated pH meter, following two-point buffer calibration (pH 7.0 paired with 4.0, or with 10.0/9.2) bracketing the expected sample range. Turbidity was determined nephelometrically (APHA 2130 B) using a Hach DR/890 colourimeter calibrated against formazin

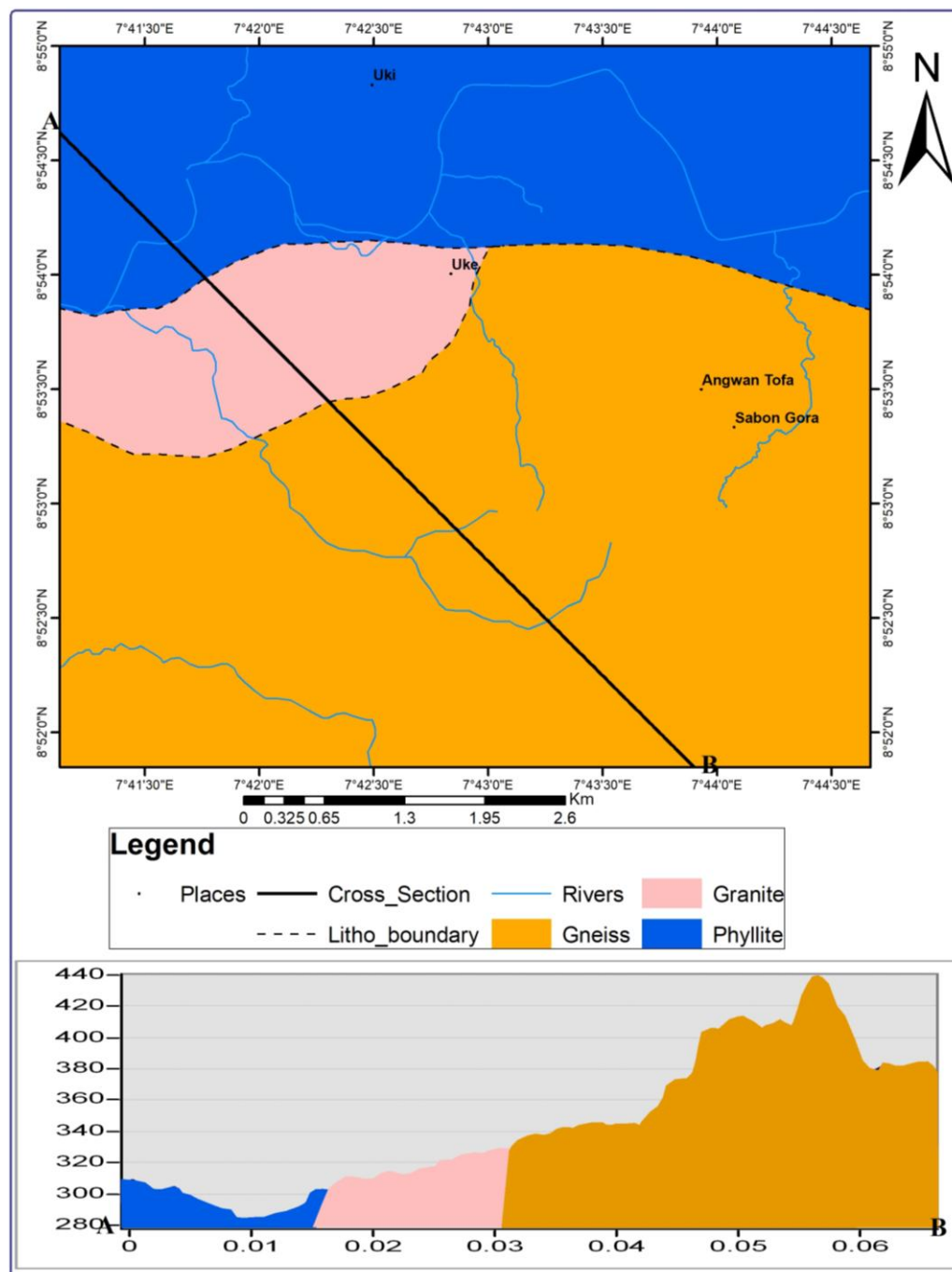


Figure 2. Geological map and NW–SE cross-section (A–B) of the study area, showing the distribution of phyllite, granite, and gneiss lithological units.

suspension standards. Total hardness was determined by the EDTA titrimetric method (APHA 2340 C). Calcium was determined by the EDTA titrimetric method (APHA 3500-Ca B) using Calver II or murexide indicator, with magnesium derived by calculation as total hardness minus calcium hardness (APHA 3500-Mg B) rather than measured directly. Total alkalinity was determined by acid titration to phenolphthalein and methyl-orange/

bromocresol-green endpoints (APHA 2320 B) and reported directly as bicarbonate (HCO_3^-), as noted above; carbonate alkalinity was below detection at all fifteen sites. Sodium and potassium were determined following standard APHA (2017) procedures for the analytical instrumentation available. Iron was determined by the 1,10-phenanthroline colorimetric method (absorbance measured at 510 nm), Chromium was determined

Table 1. Groundwater sampling locations, coordinates, and elevations.

Sample ID	Source Type	Location	Latitude (N)	Longitude (E)	Elevation (m)
HDW1	Hand-dug well	Angwan Chiroma	8°54'01.85"	7°42'46.26"	285.6
HDW2	Hand-dug well	Angwan Kwayi	8°54'02.61"	7°42'25.33"	295
HDW3	Hand-dug well	Angwan Tofa	8°53'30.46"	7°43'58.22"	340
HDW4	Hand-dug well	Angwan Tofa	8°53'32.39"	7°44'00.22"	344
HDW5	Hand-dug well	Angwan Ciroma II	8°53'39.66"	7°42'32.06"	283
BH1	Borehole	Market, Angwan Ciroma	8°53'54.65"	7°42'47.23"	306
BH2	Borehole	Angwan Tofa	8°53'28.71"	7°43'57.01"	256
BH3	Borehole	Angwan Tofa	8°53'33.53"	7°43'58.90"	352
BH4	Borehole	Angwan Tofa	8°53'34.59"	7°44'04.84"	338
BH5	Borehole	Angwan Tofa	8°53'28.68"	7°44'03.89"	346
BH6	Borehole	Angwan Tofa	8°53'04.07"	7°43'38.5"	344
BH7	Borehole	Lower Uke	8°53'41.19"	7°43'18.26"	312
BH8	Borehole	Pilot Primary School, Uke	8°53'58.06"	7°43'06.87"	278
BH9	Borehole	Angwan Baba Mallam	8°53'58.06"	7°42'57.74"	302
BH10	Borehole	ERCC, Uke	8°53'55.52"	7°42'36.39"	308

specifically as hexavalent chromium (Cr^{6+}) by the diphenylcarbazide colorimetric method (APHA 3500-Cr B, absorbance at 540 nm on a UV-Vis spectrophotometer), calibrated with a standard curve requiring a correlation coefficient of at least 0.990 and renewed at least every three months; this measures the hexavalent oxidation state specifically and does not capture other chromium species. Bacteriological quality was assessed by the membrane filtration technique (APHA 9222B): samples were filtered through sterile membrane filters, incubated on selective broth (Membrane lauryl sulphate broth) at 35–37°C for 18–24 hours for Total Coliform, and on M-FC broth at 44±0.5°C for 24 hours for faecal coliform, which is used here as an operational proxy for *E. coli* rather than a species-specific confirmatory test, a widely used indicator organism for recent faecal contamination in drinking water (Edberg *et al.*, 2000); duplicate analysis was performed on one sample in every four, or once per batch, whichever was fewer. All results were compared against WHO (2021) and NSDWQ (2015) guideline limits, which specify zero coliform organisms per 100 mL as the acceptable limit for potable water.

Hydrogeochemical and pollution indices

The Water Quality Index (WQI) was computed using the weighted arithmetic index method (Horton, 1965; Brown *et al.*, 1970), following the general form $\text{WQI} = \Sigma(\text{W}_i\text{Q}_i)/\Sigma\text{W}_i$, where Q_i is the quality rating for the i -th parameter ($\text{Q}_i = (\text{V}_i/\text{S}_i) \times 100$, with V_i the measured concentration and S_i the WHO/NSDWQ standard value for that parameter) and W_i is a unit weight inversely proportional to S_i . Six parameters were included, namely pH, TDS, turbidity, nitrate, sulphate, and chloride with relative weights assigned according to WHO guideline values, and results were classified as excellent (<50), good (50–100), poor

(100–200), very poor (200–300), or unsuitable (>300). Heavy-metal pollution was evaluated using the Contamination Factor ($\text{CF} = \text{C}_{\text{sample}}/\text{C}_{\text{reference}}$, where $\text{C}_{\text{reference}}$ is the WHO/NSDWQ guideline concentration for each metal rather than a natural geochemical background level; Håkanson, 1980, adapted here with a guideline-based reference value), the Heavy Metal Evaluation Index ($\text{HEI} = \Sigma \text{Hc}/\text{Hmac}$; Edet and Offiong, 2002; <10 low, 10–20 moderate, >20 high pollution; the general rationale for such guideline- or background-referenced contamination indices is reviewed in Barbieri, 2016), and the Heavy Metal Pollution Index (HPI, weighted sub-index method; Prasad and Bose, 2001; <100 safe, =100 critical, >100 unsafe).

Hydrochemical facies and statistical analysis

Hydrochemical facies were interpreted using Piper (1944), Durov (1948), and Schoeller (1977) diagrams generated in AquaChem software, with facies boundaries additionally cross-checked against the ion-exchange classification of Chadha (1999). Descriptive statistics and Pearson (1895) correlation coefficients were computed in Microsoft Excel to evaluate inter-parameter relationships separately within the borehole and hand-dug well datasets, with Spearman's (1904) rank correlation applied as a distribution-free robustness check given the small hand-dug well sample size (see *Statistical Correlation Analysis* section).

RESULTS

Physicochemical characteristics

Groundwater pH ranged from 6.0 (BH2) to 8.2 (HDW1), with a mean of 6.94; pH fell below the 6.5 guideline at three sites (BH2, BH6, HDW3). The low pH values at BH2 and

Table 2. Basis of guideline values used for exceedance screening (WHO 2021; NSDWQ 2015).

Parameter	Guideline Value	Basis
pH	6.5–8.5	Operational/aesthetic (not a strict health-based limit)
EC	1000 $\mu\text{S}/\text{cm}$	Operational (proxy for total dissolved solids)
TDS	500 mg/L	Aesthetic/acceptability
Turbidity	5 NTU	Aesthetic/operational; also relevant to disinfection efficacy
Potassium (K)	10 mg/L (NSDWQ)	Aesthetic/acceptability; not set by WHO as a health-based limit
Magnesium (Mg)	20 mg/L (NSDWQ) / 30 mg/L (WHO taste threshold)	Aesthetic (taste)
Nitrate (NO_3)	50 mg/L	Health-based
Sulphate (SO_4)	100 mg/L	Aesthetic/acceptability
Chloride (Cl)	250 mg/L	Aesthetic (taste)
Iron (Fe)	0.3 mg/L	Aesthetic/operational (staining); WHO does not set it as health-based
Lead (Pb)	0.01 mg/L	Health-based
Chromium (Cr)	0.05 mg/L	Health-based
Mercury (Hg)	0.006 mg/L (WHO) / 0.001 mg/L (NSDWQ)	Health-based; WHO and NSDWQ values differ, WHO value used here
Arsenic (As)	0.01 mg/L	Health-based
Total Coliform / <i>E. coli</i>	0 CFU/100 mL	Health-based

Table 3. Statistical summary of physicochemical parameters in groundwater (n=15).

Parameter	Min	Max	Mean	WHO/NSDWQ Limit
pH	6.0	8.2	6.94	6.5–8.5
Temperature ($^{\circ}\text{C}$)	25.2	26.9	26.15	Ambient
EC ($\mu\text{S}/\text{cm}$)	96	1886	704.6	1000
TDS (mg/L)	58	1132	435.4	500
Turbidity (NTU)	0	34	7.47	5

BH6 may be attributed to oxidation of sulphide minerals (pyrite, arsenopyrite) associated with artisanal gold mining and exposure of mineralised quartz veins in Angwan Tofa. Electrical conductivity ranged widely from 96 $\mu\text{S}/\text{cm}$ (BH6) to 1886 $\mu\text{S}/\text{cm}$ (BH1), with four samples (BH1, BH4, BH9, HDW2) exceeding the 1000 $\mu\text{S}/\text{cm}$ guideline. TDS mirrored this pattern, ranging from 58–1132 mg/L, with six samples (BH1, BH2, BH4, BH8, BH9, HDW2) exceeding the 500 mg/L guideline. Turbidity exceeded the 5 NTU guideline at four sites (HDW1, BH3, BH8, BH9; 12–34 NTU), the elevated EC, TDS, and turbidity values recorded at these specific sites may reflect a combination of water–rock interaction and reduced seasonal dilution, superimposed on localised anthropogenic input. The elevated EC at BH1 in particular associated with proximity to a market area. These values contrast with a nearby crystalline basement aquifer in Keffi, roughly 15 km to the northeast, where a wet-to-early-dry-season survey recorded EC values of only 50–360 $\mu\text{S}/\text{cm}$ and pH of 5.7–7.3, attributed to short groundwater residence time and active recharge (Obrike *et al.*, 2023); the comparatively higher EC and TDS observed here during the December low-recharge period are consistent with reduced dilution

and prolonged water–rock contact rather than a difference in underlying lithology. Summary statistics are presented in Table 3; guideline values used are summarised in Table 2, with an indication of whether each is health-based or aesthetic/operational in nature, following WHO (2021) and NSDWQ (2015), which are themselves broadly aligned with Nigeria's statutory surface- and groundwater-quality control regulations (NESREA, 2011).

Major ion chemistry

Expressed on an equivalent (meq/L) basis, the mean cation order in groundwater was $\text{Mg}^{2+} > \text{Ca}^{2+} > \text{Na}^+ > \text{K}^+$ (33.2%, 28.5%, 25.6%, 12.6% of total cation charge respectively), and the mean anion order was $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$ (67.1%, 17.3%, 15.5% of total anion charge respectively; see Figure 5, Schoeller plot, for the full ionic sequence in meq/L). On a mass-concentration (mg/L) basis, bicarbonate was the dominant anion (15–309 mg/L, mean 154 mg/L), followed by chloride (7.0–79.9 mg/L) and sulphate (2–67 mg/L), while calcium (3.2–80.1 mg/L) and magnesium (1.5–48.3 mg/L) dominated the cation budget

Table 4. Statistical summary of major ion concentrations (mg/L) in groundwater (n=15).

Ion	Min	Max	Mean	WHO/NSDWQ Limit
K ⁺	6	71	25.54	10
Na ⁺	2	67	30.53	200
Ca ²⁺	3.2	80.1	29.61	200
Mg ²⁺	1.46	48.31	20.92	20 (WHO 30)
Cl ⁻	6.99	79.92	23.04	250
NO ₃ ⁻	0.003	0.20	0.10	50
SO ₄ ²⁻	2	67	28.0	100
HCO ₃ ⁻	15	309	153.67	250

Table 5. Mean equivalent concentrations (meq/L) and percentage contribution to total cation/anion charge, groundwater (n=15).

Ion	Mean (meq/L)	% of Cation or Anion Total
Ca ²⁺	1.48	28.5
Mg ²⁺	1.72	33.2
Na ⁺	1.33	25.6
K ⁺	0.65	12.6
Cl ⁻	0.65	17.3
SO ₄ ²⁻	0.58	15.5
HCO ₃ ⁻	2.52	67.1

Charge-balance errors, computed as $100 \times (\Sigma \text{Cations} - \Sigma \text{Anions}) / (\Sigma \text{Cations} + \Sigma \text{Anions})$ in meq/L, ranged from -32.9% to +66.1% across the fifteen samples. These values are above the conventional $\pm 5\%$ analytical quality-control criterion typically applied in hydrogeochemical studies (Table 6).

in mass terms; this mg/L-based ranking is reported for comparability with guideline values and should not be read as an equivalent-concentration dominance order. The mg/L-based pattern is broadly consistent with weathering of plagioclase feldspar and ferromagnesian minerals within the gneiss and granite host rocks, a process whose stoichiometric and ionic-ratio signatures in river and groundwater systems have been characterised in detail elsewhere (Gaillardet *et al.*, 1999; Cerling *et al.*, 1989). This interpretation should be read alongside the charge-balance caveat discussed in the *Hydrochemical Facies Section*, which reflects a confirmed feature of the verified dataset rather than a data-entry error. This ordering differs from the Na⁺>Mg²⁺>Ca²⁺>K⁺ cation sequence reported for the geologically comparable Keffi basement aquifer (Obrike *et al.*, 2023), suggesting a relatively greater contribution of alkaline-earth weathering (plagioclase and ferromagnesian minerals) relative to alkali-feldspar dissolution at Uke; the shared HCO₃⁻>Cl⁻>SO₄²⁻ anion order at both sites, however, points to a broadly similar bicarbonate-dominated weathering regime across this part of the Basement Complex. Applying the freshwater TDS classification of Todd (1980), used for the same purpose by Obrike *et al.* (2023) to confirm freshwater status across all fifteen Keffi samples (TDS < 1000 mg/L), fourteen of the fifteen Uke samples likewise fall within the freshwater category, with BH1 (TDS = 1132 mg/L) as the sole exception. Potassium exceeded the 10 mg/L guideline at

twelve of fifteen sites (notably BH8, 71 mg/L, and BH9, 40 mg/L), a pattern that may reflect an anthropogenic possibly agricultural. Sodium, calcium, chloride, and sulphate remained within permissible limits at all sites, and nitrate was uniformly low (≤ 0.20 mg/L against a 50 mg/L limit) well below levels reported at agriculturally intensive North Central Nigerian sites such as Gboko (mean 26.5 mg/L; Omonona and Okogbue, 2021) and below the concentration range at which nitrate poses a recognized methaemoglobinaemia risk (Fewtrell, 2004), consistent with the largely non-agricultural land use immediately around most of the Uke sampling points, in contrast to farming-impacted basement sites elsewhere in Nigeria where fertilizer application has been linked to elevated groundwater nitrate and potassium (Hassan *et al.*, 2016; Fadipe *et al.*, 2019). Statistical summaries are given in Table 4; equivalent (meq/L) concentrations and percentage ionic contributions are provided in Table 5. The sample-by-sample charge-balance errors for all fifteen samples are presented in Table 6 and are discussed further in the Hydrochemical Facies section.

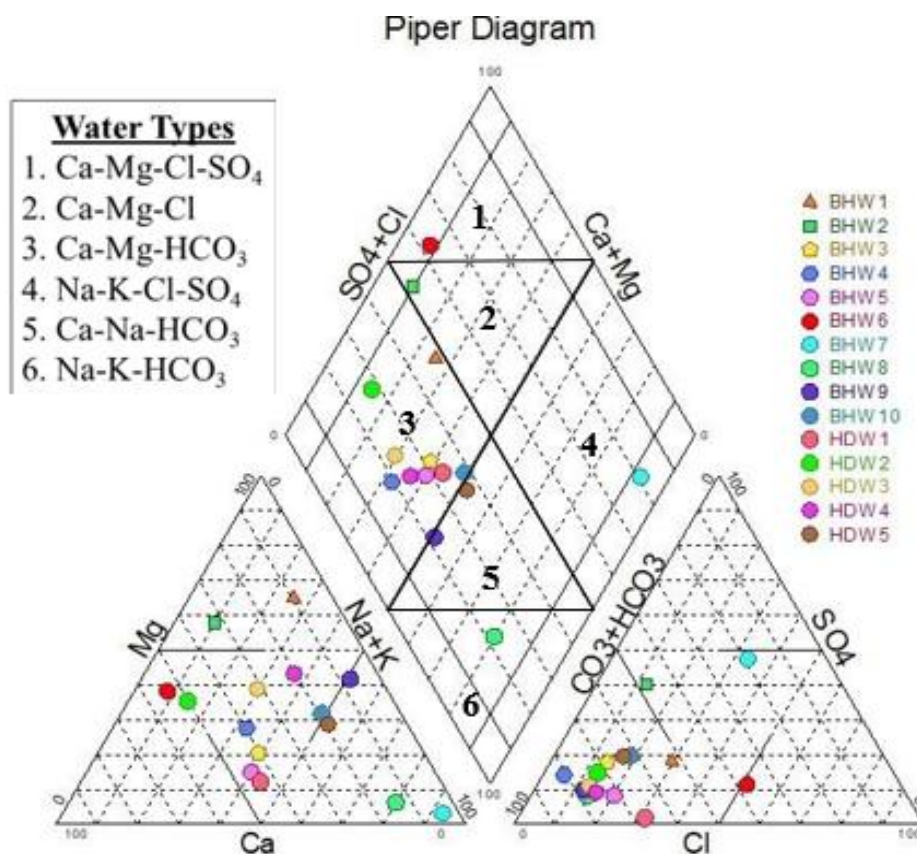
Hydrochemical facies

The Piper trilinear diagram (Figure 3; samples labelled BH1–BH10 and HDW1–HDW5) shows groundwater cations plotting predominantly within the Ca–Mg field and

Table 6. Sample-by-sample charge-balance error (CBE), computed as $100 \times (\Sigma \text{Cations} - \Sigma \text{Anions}) / (\Sigma \text{Cations} + \Sigma \text{Anions})$ in meq/L.

Sample	Σ Cations (meq/L)	Σ Anions (meq/L)	CBE (%)	QC Band
BH1	4.18	7.66	-29.5	> $\pm 20\%$
BH2	6.89	3.38	+34.2	> $\pm 20\%$
BH3	2.97	5.87	-32.9	> $\pm 20\%$
BH4	6.72	3.84	+27.4	> $\pm 20\%$
BH5	1.60	1.52	+2.8	within $\pm 5\%$
BH6	4.84	1.10	+63.0	> $\pm 20\%$
BH7	3.86	1.27	+50.4	> $\pm 20\%$
BH8	5.93	4.09	+18.3	± 10 – 20%
BH9	5.51	6.48	-8.1	± 5 – 10%
BH10	5.19	1.06	+66.1	> $\pm 20\%$
HDW1	3.63	2.18	+25.0	> $\pm 20\%$
HDW2	7.97	6.58	+9.6	± 5 – 10%
HDW3	5.71	3.87	+19.1	± 10 – 20%
HDW4	7.51	4.56	+24.4	> $\pm 20\%$
HDW5	5.20	2.81	+29.9	> $\pm 20\%$

Of the fifteen samples, only one (BH5) falls within the conventional $\pm 5\%$ acceptance band; two fall within ± 5 – 10% (BH9, HDW2); two fall within ± 10 – 20% (BH8, HDW3); and the remaining ten (two-thirds of the dataset) exceed $\pm 20\%$, several by a wide margin (BH10 at +66.1%, BH6 at +63.0%, BH7 at +50.4%). This distribution shows that the imbalance is not confined to one or two outlier samples but is pervasive across the dataset, and is consistently positive (cation-excess) in twelve of the fifteen samples, which may itself be a diagnostic clue

**Figure 3.** Piper trilinear diagram of groundwater samples (BH1–10, HDW1–5; original AquaChem series legend uses "BHW" for boreholes), showing predominant Ca–Mg–HCO₃ facies.

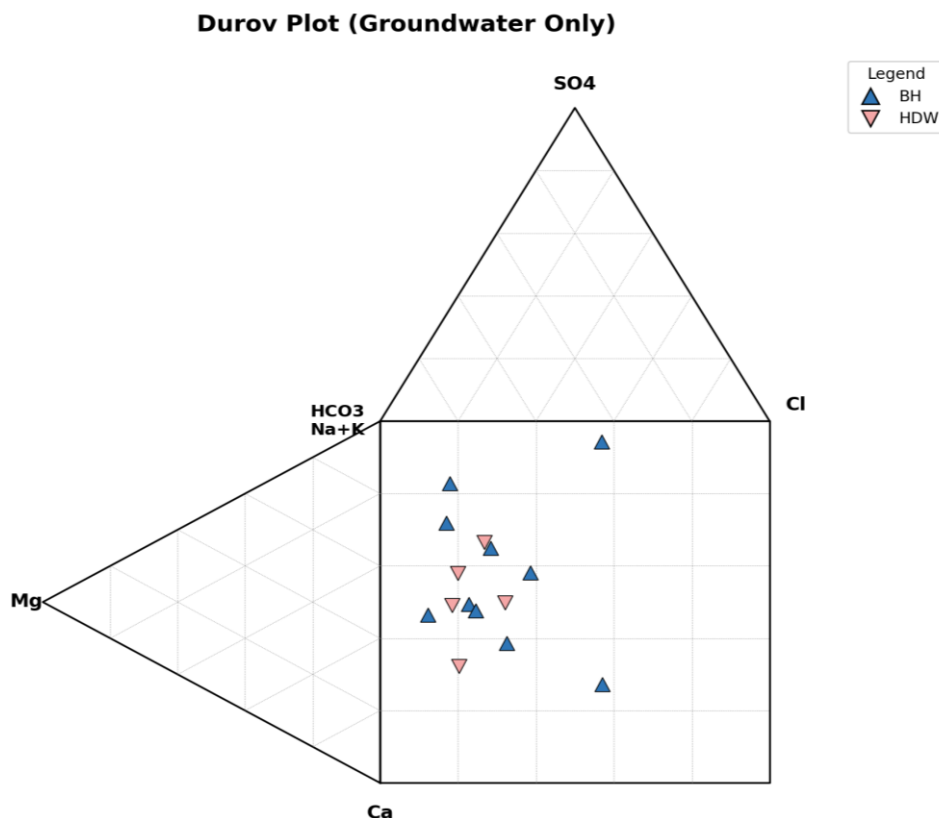


Figure 4. Durov diagram of groundwater samples (BH, HDW), regenerated from ionic data.

anions within the HCO_3^- field, with a secondary spread toward Cl^- . Projected into the central diamond, ten of the fifteen samples (BH3, BH4, BH6, BH8, BH9, BH10, HDW1, HDW3, HDW4, and HDW5) (67%) cluster close to field 3 (Ca-Mg-HCO_3), the most frequently represented facies in this dataset. A smaller group, BH2 and BH7 (13%), plots within field 2 (Ca-Mg-Cl); BH1 (7%) plots within field 1 (Ca-Mg-Cl-SO_4) at the most Cl/SO_4 -enriched extreme of the dataset; and BH5 with HDW2 (13%) trend toward field 5 (Ca-Na-HCO_3), consistent with a degree of Na-enrichment. No samples plot within the Na-K-dominated fields 4 or 6. The diagram is consistent with silicate weathering and carbonate dissolution as important controls on groundwater chemistry in Uke, consistent with the classical rock-dominance signature of crystalline-terrain groundwater with limited direct atmospheric input (Davis and DeWiest, 1966), with a secondary cation-exchange signature (Chadha, 1999) and Cl/SO_4 -enrichment at a minority of sites that may be linked to localised anthropogenic input. The dominance of the HCO_3 -type facies (67% of samples) parallels the Piper-plot outcome for the neighbouring Keffi basement aquifer, where a Ca-HCO_3 facies likewise accounted for the majority of samples (66.7%), with subordinate Na- Ca-HCO_3 (26.7%) and Ca-Mg-Cl (6.6%) mixed-water types (Obrike *et al.*, 2023); that study interpreted its Ca-HCO_3 -dominant facies as characteristic of young, actively

recharging groundwater, while its Na-enriched mixed-water samples were attributed to progressive base-exchange softening of Ca-HCO_3 water against Na-bearing clays and silicates at depth (Clark, 2015). The comparable Ca-Na-HCO_3 trend shown here by BH5 and HDW2 is consistent with the same softening mechanism operating locally within the Uke aquifer.

The Durov diagram (Figure 4) shows that most groundwater points cluster in the lower-central part of the square field, corresponding to moderate-to-low Cl and Na+K dominance suggestive of the Ca-Mg-HCO_3 (simple dissolution) facies, with a smaller spread of borehole samples (notably BH1 and BH2) extending toward higher Na+K and Cl values, possibly indicating localised cation exchange and chloride enrichment. The Schoeller semi-logarithmic plot (Figure 5) shows a broadly consistent ionic sequence across samples, with Mg, Ca, and HCO_3 concentrations (in meq/L) generally exceeding Na, Cl, and SO_4 , consistent with Ca-Mg-HCO_3 -type groundwater, while the wide vertical spread at each parameter reflects variability in water-rock interaction across sample sites. Because these facies interpretations depend on the ionic balance of each sample, they should be read alongside the sample-by-sample charge-balance errors in Table 6, which show that only BH5 falls within the conventional $\pm 5\%$ band while ten of the fifteen samples exceed $\pm 20\%$; the facies classification is therefore

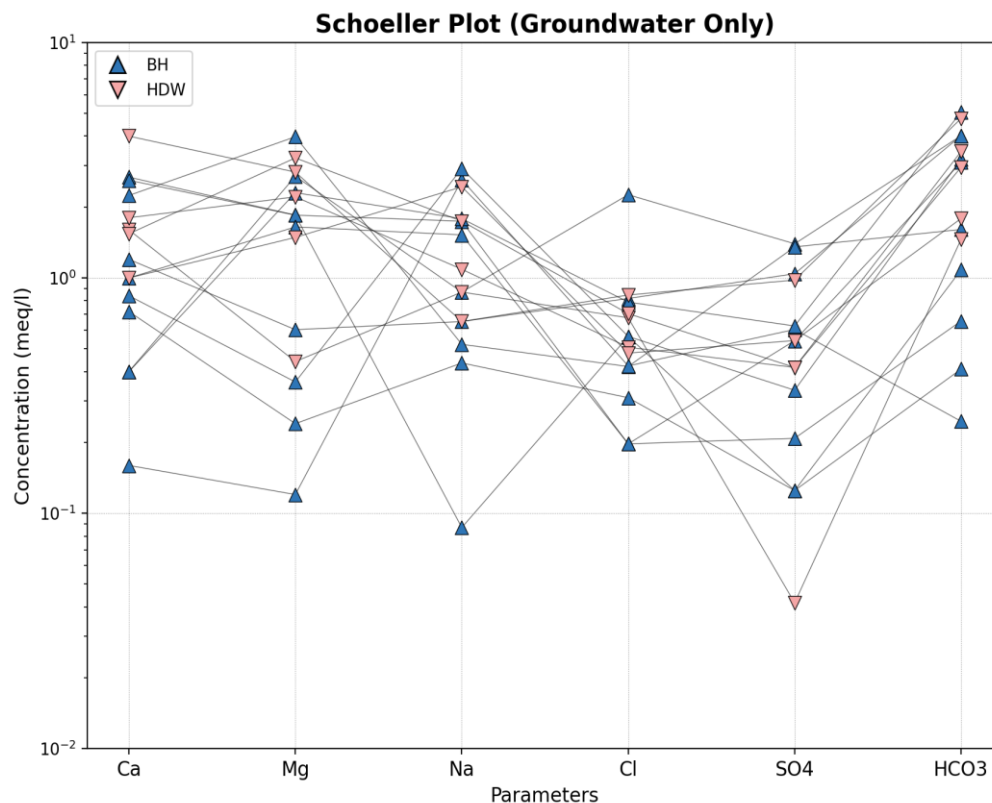


Figure 5. Schoeller semi-logarithmic diagram of groundwater samples (BH, HDW), regenerated from ionic data.

Table 7. Pearson correlation matrix for borehole water samples (n=10).

Parameter	pH	EC	TDS	TH	Ca ²⁺	Mg ²⁺	Na ⁺
pH	1.000	0.205	0.224	0.350	-0.806	-0.631	0.563
EC	0.205	1.000	0.998	0.807	-0.193	0.476	0.181
TDS	0.224	0.998	1.000	0.834	-0.214	0.461	0.205
TH	0.350	0.807	0.834	1.000	-0.274	0.259	0.178
Ca ²⁺	-0.806	-0.193	-0.214	-0.274	1.000	0.413	-0.429
Mg ²⁺	-0.631	0.476	0.461	0.259	0.413	1.000	-0.398
Na ⁺	0.563	0.181	0.205	0.178	-0.429	-0.398	1.000

indicative of the dominant water type rather than definitive.

Statistical correlation analysis

Correlation analysis (Tables 7 and 8) revealed a strong positive relationship between EC and TDS in both borehole ($r = 0.998$, $n=10$) and hand-dug well ($r = 0.997$, $n=5$) samples, consistent with dissolved ionic load being an important control on water conductivity across both source types; an almost identical EC–TDS coupling (0.98) was reported for groundwater at the nearby Keffi basement aquifer using the same total-cation/total-anion

correlation approach (Obrike *et al.*, 2023), suggesting this relationship is a general feature of dissolved-solute behaviour in this regional aquifer system rather than a site-specific artefact; correlation- and PCA-based approaches of this kind have been widely used to disentangle geogenic from anthropogenic controls on groundwater chemistry elsewhere (Belkhiri *et al.*, 2011; Liu *et al.*, 2003; Cao *et al.*, 2014; Balakrishnan *et al.*, 2011). In borehole water, Total Hardness classified according to the conventional scale of Sawyer and McCarty (1967) correlated strongly with EC ($r = 0.807$) and TDS ($r = 0.834$), while pH showed a strong negative correlation with Ca²⁺ ($r = -0.806$) and a moderate negative correlation with Mg²⁺ ($r = -0.631$), a pattern

Table 8. Pearson correlation matrix for hand-dug well water samples (n=5).

Parameter	pH	EC	TDS	TH	Ca ²⁺	Mg ²⁺	Na ⁺
pH	1.000	0.197	0.267	-0.265	-0.070	-0.384	-0.171
EC	0.197	1.000	0.997	0.791	0.953	0.365	-0.797
TDS	0.267	0.997	1.000	0.765	0.929	0.345	-0.793
TH	-0.265	0.791	0.765	1.000	0.851	0.833	-0.426
Ca ²⁺	-0.070	0.953	0.929	0.851	1.000	0.419	-0.714
Mg ²⁺	-0.384	0.365	0.345	0.833	0.419	1.000	0.014
Na ⁺	-0.171	-0.797	-0.793	-0.426	-0.714	0.014	1.000

As a robustness check, Spearman rank correlations were also computed for the same parameter pairs. For boreholes, the Spearman results broadly support the Pearson results reported above: EC–TDS ($\rho = 0.988$, $p < 0.001$) and pH–Ca²⁺ ($\rho = -0.862$, $p = 0.001$) remain strong and statistically significant, while Total Hardness–EC ($\rho = 0.782$, $p = 0.008$) is also significant. For hand-dug wells, however, the Spearman results diverge from the Pearson results in an instructive way: EC–TDS remains essentially perfect ($\rho = 1.000$), but EC–Ca²⁺ and TDS–Ca²⁺ drop to $\rho = 0.700$ ($p = 0.188$, not significant) — markedly weaker than the Pearson $r = 0.953$ and $r = 0.929$ reported above — while Ca²⁺–Na⁺ emerges as the only other significant hand-dug-well relationship ($\rho = -0.900$, $p = 0.037$). This divergence is itself the clearest demonstration of the small-sample instability flagged above: with only five hand-dug well observations, the Pearson coefficients for EC/TDS–Ca²⁺ should not be treated as robust evidence of a specific geochemical mechanism, and the borehole-derived relationships are the more reliable of the two correlation sets in this dataset.

consistent with possible carbonate-buffering and ion-exchange reactions. Weak negative correlations between Ca²⁺–Na⁺ ($r = -0.429$) and Mg²⁺–Na⁺ ($r = -0.398$) are consistent with possible base-exchange processes in which sodium progressively replaces calcium and magnesium along the flow path, though correlation alone cannot establish this mechanism; chloro-alkaline index calculations (CA-I, CA-II) for the neighbouring Keffi aquifer found almost all samples plotting in the negative domain, a pattern interpreted there as reverse ion-exchange enrichment of Na⁺ at the expense of dissolved Ca²⁺ and Mg²⁺ (Obrike *et al.*, 2023), consistent in direction with the negative Na⁺–Ca²⁺/Mg²⁺ correlations reported here, though the chloro-alkaline indices themselves were not computed for the present dataset. Hand-dug well samples showed comparably strong EC–Ca²⁺ ($r = 0.953$) and TDS–Ca²⁺ ($r = 0.929$) correlations, suggesting that calcium-bearing mineral dissolution may be an important driver of shallow-groundwater mineralisation.

Heavy-metal distribution and pollution indices

Five heavy metals, namely iron, chromium, lead, mercury, and arsenic, were analysed in groundwater; cadmium was not analysed for groundwater sources in this study. Chromium and mercury were not detected (below detection limit) in any of the fifteen samples and are therefore excluded from the pollution-index calculations below. Iron exceeded the 0.3 mg/L guideline only at BH5 (0.44 mg/L). Lead exceeded the 0.01 mg/L guideline at two sites: BH5 (0.011 mg/L) and BH6 (0.012 mg/L). Arsenic remained within or equal to the guideline at all sites, reaching the 0.01 mg/L threshold exactly at HDW2 without exceeding it. Twelve of fifteen groundwater samples were fully compliant across all analysed metals; BH5 and BH6 were not. Heavy-metal concentrations were generally low

overall (Table 9): all Heavy Metal Evaluation Index (HEI) values were below 10, indicating low pollution by the interpretation scale used, and all Heavy Metal Pollution Index (HPI) values were below the critical threshold of 100, indicating that none of the sampled sources falls in the unsafe heavy-metal pollution category. BH5 recorded the highest HPI (76.17) because of its combined iron and lead concentrations, while BH6 (HPI = 59.02) reflects a localised lead exceedance alone. These isolated exceedances echo the pattern reported for the Keffi basement aquifer, where iron concentrations were attributed to dissolution of Fe-bearing minerals from the weathered vadose zone while the one recorded lead exceedance was traced to a specific point source, a nearby cottage paint factory, rather than to diffuse geogenic input (Obrike *et al.*, 2023); by analogy, the localized nature of the BH5/BH6 lead exceedance is consistent with a discrete anthropogenic source superimposed on an otherwise low background, though the actual source at Uke (candidates include mining-related disturbance, as noted in *Introduction Section*) requires field verification. BH5 and BH6 are accordingly treated here as priority sites for confirmation sampling and monitoring rather than as confirmed pollution hotspots. Comparable Fe/Pb enrichment patterns in groundwater from other Basement Complex and mining-adjacent settings in Nigeria have been reported at Kashere, Upper Benue Trough (Yusuf *et al.*, 2018), and around a municipal solid-waste site in southwestern Nigeria (Kolawole *et al.*, 2023), while the general toxicological basis for treating iron and lead as parameters of health concern is reviewed by Balali-Mood *et al.* (2021), and the specific risk posed by ingesting metal-bearing groundwater through drinking water has been quantified for other Nigerian and West/Central African settings (Vetrimurugan *et al.*, 2017; Agbasi *et al.*, 2023; Muhaya *et al.*, 2021).

Table 9. Contamination Factor (CF), Heavy Metal Evaluation Index (HEI), and Heavy Metal Pollution Index (HPI) for groundwater (Fe, Pb, As only). CF uses the WHO (2021) guideline concentration as the reference value (Fe 0.3 mg/L, Pb 0.01 mg/L, As 0.01 mg/L). Non-detects were treated as zero in all index calculations.

Sample	Fe (mg/L)	Pb (mg/L)	As (mg/L)	CF (Fe)	CF (Pb)	CF (As)	HEI	HPI
BH1	0.040	0.006	0.000	0.13	0.60	0.00	0.73	29.73
BH2	0.020	0.006	0.001	0.07	0.60	0.10	0.77	34.54
BH3	0.030	0.007	0.000	0.10	0.70	0.00	0.80	34.59
BH4	0.200	0.001	0.002	0.67	0.10	0.20	0.97	15.85
BH5	0.440	0.011	0.004	1.47	1.10	0.40	2.97	76.17
BH6	0.000	0.012	0.000	0.00	1.20	0.00	1.20	59.02
BH7	0.000	0.003	0.001	0.00	0.30	0.10	0.40	19.67
BH8	0.040	0.000	0.005	0.13	0.00	0.50	0.63	24.81
BH9	0.050	0.006	0.000	0.17	0.60	0.00	0.77	29.78
BH10	0.040	0.007	0.001	0.13	0.70	0.10	0.93	39.56
HDW1	0.012	0.000	0.000	0.04	0.00	0.00	0.04	0.07
HDW2	0.018	0.000	0.010	0.06	0.00	1.00	1.06	49.28
HDW3	0.012	0.003	0.003	0.04	0.30	0.30	0.64	29.57
HDW4	0.300	0.008	0.001	1.00	0.80	0.10	1.90	45.90
HDW5	0.190	0.009	0.001	0.63	0.90	0.10	1.63	50.22

The Pollution Load Index (PLI, geometric mean of CF values) is not reported separately: with chromium and mercury both at zero CF, including them would force PLI to zero for every sample regardless of the genuine Fe/Pb/As signal, and would obscure rather than clarify the pattern already visible in the CF and HPI columns above.

Table 10. Water Quality Index (WQI) results and classification for groundwater.

Sample	pH	TDS	NTU	NO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	WQI	Class
BH1	7.0	1132	0	0.14	67	79.92	114.82	Poor
BH2	6.0	521	0	0.12	65	14.89	94.67	Good
BH3	6.9	195	30	0.14	50	28.97	83.91	Good
BH4	6.7	684	0	0.19	26	6.99	104.56	Poor
BH5	6.9	269	0	0.15	6	10.98	59.73	Good
BH6	6.3	58	0	0.09	6	19.98	39.68	Excellent
BH7	7.3	186	0	0.13	29	14.98	44.51	Excellent
BH8	6.9	629	12	0.06	16	19.98	99.84	Good
BH9	7.1	838	34	0.20	30	27.97	119.63	Poor
BH10	6.6	169	0	0.18	10	6.99	54.38	Good
HDW1	8.2	393	26	0.003	2	23.98	69.74	Good
HDW2	7.2	651	3	0.014	47	29.97	94.92	Good
HDW3	6.4	286	3	0.015	20	17.98	59.88	Good
HDW4	7.6	364	4	0.027	20	24.98	64.91	Good
HDW5	7.0	156	0	0.05	26	16.98	44.27	Excellent

Water Quality Index

The Water Quality Index (Table 10) reported is based on pH, TDS, turbidity, nitrate, sulphate, and chloride; it does not incorporate the microbial indicators reported separately in the *Microbial Water Quality Section*, and should be read as a measure of chemical/aesthetic suitability only. Groundwater WQI values ranged from 39.7 (BH6, excellent) to 119.6 (BH9, poor). Three samples (BH6, BH7, HDW5) were classified as excellent; nine

(BH2, BH3, BH5, BH8, BH10, HDW1–HDW4) were classified as good; this includes BH8 (WQI = 99.84), which falls just below the 100-point poor-quality boundary; and three samples (BH1, BH4, BH9) were classified as poor, primarily associated with elevated TDS and turbidity. The spatial distribution of WQI (Figure 6) was generated using Inverse Distance Weighting (IDW) interpolation (Shepard, 1968) in ArcGIS Pro 3.4, with the resulting raster reclassified into five classes for visualisation. The best observed water quality is concentrated around BH5, BH6,

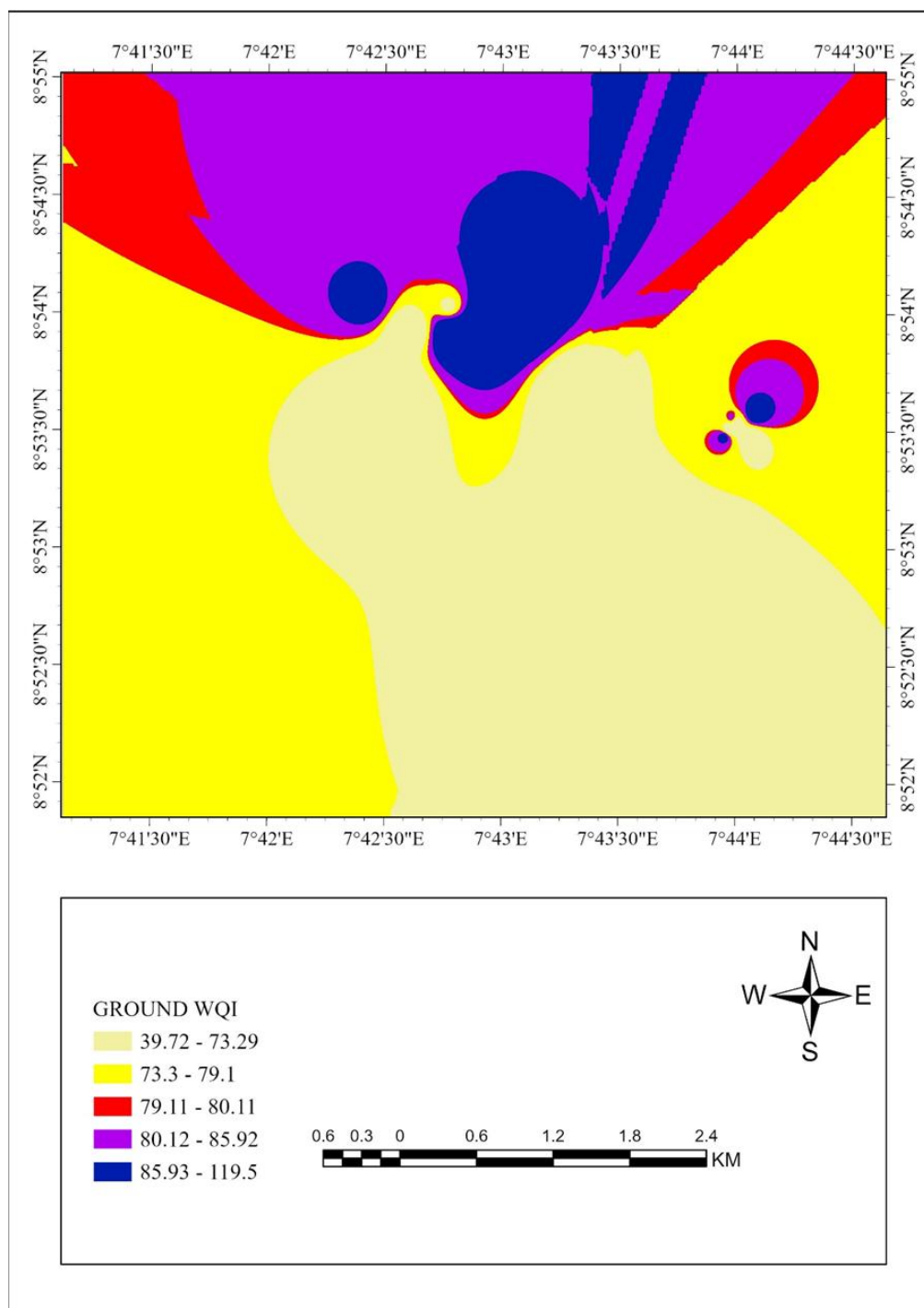


Figure 6. Spatial distribution of groundwater Water Quality Index (WQI) across the study area, generated by Inverse Distance Weighting (IDW) interpolation.

BH7, and HDW5 (Angwan Tofa/Lower Uke), while the poorest water quality clusters around BH1 (Angwan Ciroma), BH8 (Pilot Primary School, Uke), BH9 (Angwan Baba Mallam), and the BH3/BH4/HDW2 grouping; these localised zones suggest site-specific influences on groundwater chemistry.

Microbial water quality

Total Coliform was detected in all fifteen groundwater sources, and faecal coliform was enumerated at 44°C and used here, per the laboratory's stated method, as an operational proxy for *E. coli* rather than a species-

Table 11. Microbial quality of groundwater samples compared with WHO and NSDWQ guidelines (0 CFU/100 mL).

Sample	Source Type	Total Coliform (CFU/100 mL)	<i>E. coli</i> (CFU/100 mL)	Status
BH1	Borehole	239	170	Unsafe
BH2	Borehole	28	0	Unsafe (TC present, <i>E. coli</i> not detected)
BH3	Borehole	880	765	Unsafe
BH4	Borehole	198	100	Unsafe
BH5	Borehole	127	89	Unsafe
BH6	Borehole	811	578	Unsafe
BH7	Borehole	900	680	Unsafe
BH8	Borehole	119	77	Unsafe
BH9	Borehole	700	490	Unsafe
BH10	Borehole	544	456	Unsafe
HDW1	Hand-dug well	38	20	Unsafe
HDW2	Hand-dug well	17	320	Unsafe
HDW3	Hand-dug well	50	34	Unsafe
HDW4	Hand-dug well	200	180	Unsafe
HDW5	Hand-dug well	100	49	Unsafe

confirmed count was detected in fourteen of the fifteen (all except BH2, where Total Coliform was nonetheless present, so BH2 is still classified unsafe) (Table 11). No sampled groundwater source met the microbiological criterion for direct consumption. Total Coliform counts ranged from 17 CFU/100 mL (HDW2) to 900 CFU/100 mL (BH7), and the faecal-coliform/*E. coli* proxy ranged from 0 CFU/100 mL (BH2) to 765 CFU/100 mL (BH3); every sample exceeded the WHO/NSDWQ guideline of 0 CFU/100 mL (Table 11). Five sources (BH3, BH6, BH7, BH9, and BH10) recorded Total Coliform concentrations exceeding 500 CFU/100 mL. The persistence of contamination across virtually all sources suggests that it may be sustained by structural deficiencies (such as compromised sanitary seals or well casing), stored contamination within the well or storage system and hydraulic connection with shallow polluted zones.

DISCUSSION

The Piper, Durov, and Schoeller diagrams are consistent with groundwater hydrochemistry in Uke being governed substantially by water–rock interaction within the gneiss- and granite-dominated Basement Complex aquifer, with the Ca–Mg–HCO₃ facies the most frequently represented type among the fifteen samples examined. This pattern is broadly consistent with comparable Basement Complex studies elsewhere in Nigeria (Kana *et al.*, 2022; Obrike *et al.*, 2023; Edet *et al.*, 2023), where feldspar and ferromagnesian mineral weathering, combined with dissolution of soil-zone CO₂, are reported to influence the major-ion budget; however, as noted in *Major Ion Chemistry Section*, the charge-balance errors computed for this dataset (–32.9% to +66.1%; Table 6) exceed

conventional quality-control thresholds; the underlying raw laboratory values have been checked and confirmed correct, so this discrepancy is a genuine feature of the dataset rather than a transcription artefact, and the facies interpretation is accordingly treated as a working hypothesis rather than a fully confirmed result. The minority mixed Ca–Mg–Cl and Na–HCO₃ facies, together with the moderate-to-strong negative correlations between Na⁺ and Ca²⁺/Mg²⁺, are consistent with possible secondary cation-exchange processes operating along the groundwater flow path, though correlation and facies classification alone cannot establish this mechanism with certainty.

Sampling was conducted during the December dry season; the elevated EC and TDS values at BH1, BH4, and BH9 may partly reflect reduced seasonal dilution superimposed on longer-term water–rock contact, though a single dry-season campaign cannot itself establish whether this represents a seasonal maximum, and wet-season sampling would be needed to confirm the pattern. The low pH values at BH2 and BH6 (6.0 and 6.3) may reflect acidic mineral weathering, including possible interaction with artisanal mining activity reported in the wider Angwan Tofa area; however, confirming a specific mechanism such as acid-mine drainage from sulphide oxidation would require supporting evidence from sulphate, iron, manganese, aluminium, redox potential, alkalinity, and mineralogical data that were not comprehensively available in this study, and this explanation is offered as a hypothesis rather than a demonstrated cause.

The heavy-metal results indicate that chemical contamination in the aquifer is generally low: all HEI values are below 10, and all HPI values are below the unsafe threshold of 100. BH5 has the highest HPI because of its

combined iron and lead concentrations, while BH6 shows a localised lead exceedance; both may reflect geogenic weathering, localised mineral enrichment, or site-specific anthropogenic inputs, but source attribution cannot be established from a single sampling round and would require repeat sampling and additional geochemical evidence. This low-risk picture based on the CF/HEI/HPI indices is broadly consistent with the outcome of a chronic daily-intake and hazard-quotient assessment (USEPA, 1989) applied to the Keffi basement aquifer, where cumulative hazard-index values for both adults and children remained below the unity threshold despite localized guideline exceedances for iron, lead, and manganese (Obrike *et al.*, 2023); while that health-risk-based approach was not applied to the present dataset, the convergence of two different index families on a similarly reassuring conclusion for this regional aquifer system lends some additional confidence to the low-pollution interpretation reached here. This comparatively reassuring chemical picture stands in contrast to the bacteriological results, where every sampled source exceeded the zero-coliform guideline regardless of type, depth, or chemical quality classification. Although sampling occurred during the dry season, the persistence of contamination across virtually all sources suggests that it may be sustained by structural deficiencies, stored contamination, or hydraulic connection with shallow polluted zones, rather than being explained by seasonal surface infiltration alone; distinguishing between these possible mechanisms was beyond the scope of the data collected here and would require sanitary-survey information and repeat sampling. This decoupling of chemical and microbial quality means that a groundwater source can appear largely acceptable by conventional physicochemical and heavy-metal screening while remaining unsafe for direct consumption, underscoring the value of routine bacteriological monitoring alongside chemical analysis in groundwater-quality assessment programmes in this and similar Basement Complex terrains.

Study limitations

This study has several limitations that should be considered when interpreting the results and that define priorities for follow-up work. First, major-ion charge-balance errors for the fifteen samples ranged from -32.9% to +66.1%, well outside the $\pm 5\%$ criterion conventionally used to accept hydrochemical datasets. The raw laboratory values underlying this calculation have been checked and confirmed correct, and alkalinity was confirmed to have been measured and reported directly as bicarbonate (with carbonate below detection at all sites), so the discrepancy is not attributable to transcription error or an alkalinity/bicarbonate conversion ambiguity. It most likely reflects unmeasured minor ionic species, analytical

precision limitations at the concentrations involved, or a genuine feature of this dataset; the hydrochemical facies classification in the *Hydrochemical Facies Section* is accordingly presented as indicative of the dominant water type rather than as a fully charge-balanced, definitive classification, and this should be stated explicitly wherever the facies results are cited or reused. A Gibbs (1970) diagram, used to confirm rock-dominance versus evaporation/precipitation control in the comparator Keffi study (Obrike *et al.*, 2023), was not computed here and would be a useful confirmatory addition in any follow-up analysis of this dataset. Second, laboratory method and instrumentation detail is now available for most parameters (*Laboratory Analysis Section*: pH by APHA 4500-H⁺B; turbidity by APHA 2130 B on a Hach DR/890 colorimeter; hardness and calcium by EDTA titration; alkalinity by acid titration; iron by 1,10-phenanthroline colorimetry; hexavalent chromium by diphenylcarbazide colorimetry; Total Coliform and faecal coliform by membrane filtration, APHA 9222B, with duplicate analysis on one sample in four), but the specific methods, instrument models, and detection limits used for lead, mercury, and arsenic remain undocumented and should be added in any subsequent version; calibration ranges, blanks, and certified reference material recovery for these three metals in particular were not available. A separate, unresolved parameter-naming question is noted in *Laboratory Analysis Section*: the available laboratory procedure documentation covers nitrite but not nitrate, and the parameter reported as "nitrate" throughout this manuscript should be verified against the original laboratory report. Third, several study-area and field-methodology details that would normally be reported (exact sampling dates beyond December, borehole and hand-dug-well depths, well construction and casing details, purging procedures, sample preservation and holding times, and sanitary-inspection observations) were not fully available at the time of writing and are recommended additions once the underlying field records are compiled. Fourth, the correlation analysis is exploratory: borehole ($n=10$) and hand-dug well ($n=5$) sample sizes are small, normality was not formally tested, and correlation coefficients indicate covariation rather than proof of a specific geochemical mechanism. Fifth, while the general WQI formula and classification thresholds are reported (*Hydrogeochemical and Pollution Indices Section*), a full per-parameter worked example (standard value, unit weight, relative weight, quality rating, and contribution to the final index for one representative sample) is not included here; this should be prepared as a supplementary table from the original calculation sheet so the reported WQI values in Table 5 are independently reproducible. Sixth, the IDW-interpolated WQI surface (Figure 6) was generated in ArcGIS Pro 3.4 and reclassified into five classes, but is based on only fifteen point measurements, was not cross-validated, and its interpolation power, search radius, and neighbour count

are not documented in the available project records; it should therefore be read as indicative of a spatial tendency rather than a validated contamination boundary. Finally, this study represents a single dry-season sampling campaign; wet-season sampling is needed before any claim can be made about seasonal variation in either chemical or microbial water quality, since seasonal recharge has been shown elsewhere in Nigeria to shift groundwater chemistry and contaminant loading appreciably (Aladejana *et al.*, 2020), and groundwater contamination in Nigeria more broadly is recognized as arising from a diverse and interacting set of geogenic and anthropogenic sources that a single snapshot survey cannot fully disentangle (Adeniran *et al.*, 2023; Abanyie *et al.*, 2023).

Conclusion

This integrated hydrogeochemical and microbial assessment indicates that groundwater quality in Uke, North Central Nigeria, reflects two largely distinct dimensions of water safety. Chemically, the aquifer hosted within phyllite, granite, and gneiss units of the Basement Complex appears to be dominated by water–rock interaction, expressed as a predominantly Ca–Mg–HCO₃ hydrochemical signature, with most physicochemical parameters and heavy metals within WHO and NSDWQ guideline values; this facies interpretation is indicative rather than definitive, given a confirmed major-ion charge-balance discrepancy (–32.9% to +66.1%) that persists in the verified raw dataset and most likely reflects unmeasured minor ions or analytical precision limitations rather than data-entry error. Iron exceeded its guideline at BH5, and lead exceeded its guideline at BH5 and BH6; chromium and mercury were not detected at any site. All Heavy Metal Evaluation Index values were below 10, and all Heavy Metal Pollution Index values were below the unsafe threshold of 100, so BH5 and BH6 are best treated as priority sites for confirmation sampling and monitoring rather than as confirmed pollution hotspots. Bacteriologically, all fifteen groundwater sources contained Total Coliform, and *E. coli* was detected in fourteen of the fifteen samples, meaning none of the sampled sources is suitable for direct consumption without treatment, a finding that holds regardless of the sites' chemical classification. These results demonstrate that chemical acceptability alone is an inadequate basis for certifying groundwater as safe for domestic use in this terrain, and support prioritised actions including point-of-use disinfection or boiling as an immediate measure, sanitary wellhead protection, and re-sampling of BH5, BH6, and the five highest microbial-count sites (BH3, BH6, BH7, BH9, BH10) alongside the methodological improvements identified in the *Study Limitations Section*, before more definitive source-attribution and seasonal claims can be made.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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