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Geological Controls on the Distribution of Pharmaceutical Residues, Heavy Metals, and Hydrochemical Characteristics of Groundwater in Semi-Arid Communities of North-Central Nigeria

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Abstract

This study assessed geological controls on the distribution of pharmaceutical residues and associated contaminants in groundwater from semi-arid communities in North-Central Nigeria. Groundwater samples were collected from five locations representing contrasting lithological settings and analysed for pharmaceutical residues, physicochemical parameters, heavy metals, trace metals, and health-risk indices. Pharmaceutical residues were detected in all samples, with the highest concentrations recorded in fractured and weathered aquifer zones. Ciprofloxacin ranged from 1.74 ± 0.18 µg/L at G3 to 6.31 ± 0.62 µg/L at G4, while paracetamol reached 6.12 ± 0.56 µg/L and ibuprofen 5.74 ± 0.53 µg/L at G4. Physicochemical deterioration was also pronounced at G4, where EC, TDS, nitrate, chloride, phosphate, and BOD recorded 1564 ± 138 µS/cm, 984 ± 85 mg/L, 61.2 ± 5.8 mg/L, 301 ± 28 mg/L, 4.1 ± 0.4 mg/L, and 8.1 ± 0.8 mg/L, respectively. Heavy metals and trace metals, including Pb, Cd, Cr, Ni, Mn, As, and Hg, exceeded permissible limits at G2 and G4. Hazard index values were highest at G4 (3.42) and G2 (3.18), indicating potential non-carcinogenic health risks. The study concludes that fractured migmatite-gneiss and weathered granite gneiss formations enhance contaminant migration, whereas clayey sandstone provides greater natural protection. Routine groundwater monitoring and geology-guided borehole sitting are recommended.

Keywords: Pharmaceutical residues, groundwater contamination, geological controls, trace metals, health risk, North-Central Nigeria.

1.0 Introduction

Groundwater remains one of the most important freshwater resources for domestic, agricultural, and industrial activities, particularly in semi-arid regions where surface water availability is highly seasonal and unreliable. In many communities across North-Central Nigeria, boreholes and shallow wells constitute the principal sources of potable water. However, increasing anthropogenic activities such as indiscriminate disposal of pharmaceutical products, wastewater discharge, agricultural runoff, open dumping, and urbanisation have significantly threatened groundwater quality and sustainability (Akpor & Muchie, 2011; AL Falahi et al., 2022). The infiltration of contaminants into aquifer systems is especially severe in regions characterised by shallow water tables, weathered basement formations, and fractured lithological units that facilitate rapid contaminant migration.

Pharmaceutical residues are increasingly recognised as emerging contaminants of major environmental and public health concern due to their persistence, bioactivity, and continuous introduction into aquatic environments. These contaminants include antibiotics, analgesics, anti-inflammatory drugs, hormones, and personal care products that enter water systems through domestic sewage, hospital effluents, agricultural wastes, pharmaceutical industries, and improper disposal of unused drugs (Patel et al., 2019; Obinna et al., 2023). Conventional wastewater treatment systems are often ineffective in completely removing these compounds, thereby allowing them to persist in surface water and groundwater systems (Kashif et al., 2021; Li et al., 2024).

Recent studies have reported the widespread occurrence of pharmaceutical residues in aquatic environments globally. Deryal et al. (2025) detected fluoxetine and serotonin hormone in the Istanbul Strait and demonstrated associated ecological risks, while dos Santos et al. (2025) observed significant seasonal variation in pharmaceutical contamination within Brazilian urban rivers. Similarly, Nibamureke and Barnhoorn (2025) identified pharmaceutical contaminants in South African surface waters, indicating the global nature of emerging contaminant pollution. Lee et al. (2025) further reported the occurrence of persistent pharmaceutical compounds in coastal stream systems in Southeast Asia, highlighting the transboundary and persistent nature of pharmaceutical pollution in aquatic ecosystems.

The presence of pharmaceutical residues in groundwater systems is particularly concerning because groundwater is often consumed without extensive treatment in many developing regions. Long-term exposure to pharmaceutical contaminants may result in chronic health effects, antimicrobial resistance, endocrine disruption, reproductive impairment, and ecological toxicity (Patel et al., 2019; Li et al., 2024). Antibiotics such as ciprofloxacin, sulfamethoxazole, and tetracycline may contribute to the development of antimicrobial-resistant microorganisms, while endocrine-active compounds may interfere with hormonal and reproductive systems in aquatic organisms and humans (Gonsioroski et al., 2020; Kar et al., 2021).

Endocrine-disrupting compounds have received significant attention because of their ability to alter reproductive and physiological functions in aquatic fauna. Adeogun et al. (2016) reported endocrine-disruptor molecular responses, gonado-histopathological alterations, and intersex occurrence in tilapia species exposed to contaminated aquatic systems in Nigeria. Arcand-Hoy and Benson (1998) similarly identified fish reproductive abnormalities as important ecological indicators of endocrine disruption. Okuthe et al. (2025) further demonstrated that pharmaceuticals and endocrine-disrupting chemicals adversely affect the reproductive biology of aquatic fauna, thereby threatening ecological sustainability.

In addition to pharmaceutical residues, groundwater contamination is frequently associated with elevated concentrations of heavy metals and trace metals. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), mercury (Hg), arsenic (As), manganese (Mn), and iron (Fe) are persistent environmental pollutants capable of bioaccumulation and biomagnification. Jaishankar et al. (2014) noted that these metals can induce neurological, renal, cardiovascular, hepatic, and carcinogenic effects in humans following prolonged exposure. Castro-González and Méndez-Armenta (2008) also reported that heavy metal contamination in aquatic systems constitutes a major public health concern due to dietary and drinking water exposure pathways.

Several studies have demonstrated the accumulation of toxic metals in aquatic organisms and environmental media. Al-Busaidi et al. (2011) reported elevated concentrations of toxic metals in marine fish species, while Alturiqi and Albedair (2012) detected significant heavy metal contamination in fish and meat products. Farkas et al. (2003), Yilmaz et al. (2007), and Zhao et al. (2012) further demonstrated that heavy metals accumulate differentially in fish tissues depending on environmental conditions and contamination levels. Similarly, Gabriel et al. (2020) identified bisphenol A and related contaminants in fish tissues associated with microplastic contamination, suggesting multiple pathways of contaminant exposure in aquatic ecosystems.

In Nigeria, several environmental studies have shown increasing contamination of water resources by heavy metals, hydrocarbons, and industrial pollutants. Aghanwa et al. (2025) reported atmospheric deposition of soot and heavy metals into surface waters around gas-flaring environments, while Etesin et al. (2025) documented polychlorinated biphenyl contamination in industrial effluents and soils. Okpoji et al. (2025a) observed toxicity and bioaccumulation of heavy metals and polycyclic aromatic hydrocarbons in estuarine fish species, whereas Okpoji et al. (2025b) reported the transport of volatile organic compounds from gas-flaring sites into aquatic environments. Related studies have also demonstrated significant hydrocarbon, surfactant, and heavy metal contamination in urban rivers, sediments, and biota within the Niger Delta region (Ogbaji et al., 2025; Ohaturuonye et al., 2025; Okpoji et al., 2025c).

The ecological implications of contaminant exposure extend beyond chemical toxicity to include physiological, biochemical, and parasitological responses in aquatic organisms. Varanka et al. (2001) demonstrated that exposure to copper sulphate and tannic acid induced biochemical and morphological changes in fish liver tissues, while Sures and Reimann (2003) reported trace metal accumulation within host–parasite systems. Sures (2005) and Vidal-Martínez et al. (2006) further highlighted the use of parasites and aquatic organisms as bioindicators of environmental pollution due to their sensitivity to contaminant stress.

Groundwater contamination in semi-arid regions is strongly controlled by geological and hydrogeological conditions. Lithology, aquifer type, fracture density, overburden thickness, permeability, porosity, hydraulic conductivity, and depth to water table significantly influence contaminant migration, transport, retention, and attenuation within aquifer systems. Fractured basement complexes and weathered geological formations often provide preferential pathways for rapid infiltration of contaminants into groundwater, whereas clay-rich or semi-confined formations may offer greater natural protection against pollutant migration.

Hydrochemical deterioration of groundwater systems has been widely documented in Nigeria. Ekesiobi et al. (2025) reported hydrochemical contamination and associated health risks in drinking water sources, while Ekesiobi et al. (2026) demonstrated integrated water quality deterioration and health-risk concerns in urban groundwater systems. Ebikienmo et al. (2026) similarly identified groundwater quality impairment and non-carcinogenic health risks around contaminated aquatic environments. Izuchukwu et al. (2026a) also reported heavy metal contamination and toxicological risks in agricultural soils, while Izuchukwu et al. (2026b) observed physicochemical and microbiological deterioration in borehole water systems.

Nutrient enrichment and eutrophication processes associated with anthropogenic contamination may further compromise groundwater and surface water quality. Umueni et al. (2025) demonstrated that agricultural runoff significantly contributes to nutrient enrichment and eutrophication potential in aquatic systems. Such nutrient loading may enhance microbial proliferation, oxygen depletion, and overall water quality deterioration.

Despite increasing evidence of pharmaceutical and heavy metal contamination in aquatic environments, there remains limited information on the geological controls governing the occurrence and distribution of pharmaceutical residues in groundwater systems within semi-arid regions of North-Central Nigeria. Most existing studies focus primarily on surface water contamination, industrial pollution, or ecological toxicity without integrating lithological influences, hydrogeological characteristics, pharmaceutical residues, trace metals, physicochemical parameters, and associated human health risks within groundwater systems. Therefore, this study was designed to investigate the geological controls on the distribution of pharmaceutical residues in groundwater from semi-arid communities in North-Central Nigeria.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in selected semi-arid communities within North-Central Nigeria characterised by increasing dependence on groundwater for domestic, agricultural, and small-scale industrial activities. The region experiences distinct wet and dry seasons, with annual rainfall ranging between approximately 1000 and 1500 mm and average temperatures between 27°C and 34°C. The prolonged dry season and high evapotranspiration rates significantly increase groundwater dependence within the study area.

Geologically, the area is underlain predominantly by Precambrian Basement Complex rocks comprising migmatite-gneiss, weathered granite gneiss, ferruginised sandstone, clayey sandstone, and weathered overburden materials. Groundwater occurrence is mainly associated with weathered and fractured aquifer systems characterised by variable hydraulic conductivity, secondary porosity, and shallow water table conditions. These geological formations strongly influence groundwater recharge, storage, contaminant transport, and aquifer vulnerability.

The investigated communities were selected based on increasing anthropogenic pressure associated with urbanisation, indiscriminate disposal of domestic and pharmaceutical wastes, agricultural runoff, poor sewage management practices, and groundwater dependence. The hydrogeological vulnerability of the shallow aquifer systems makes the area susceptible to contaminant infiltration and groundwater quality deterioration.

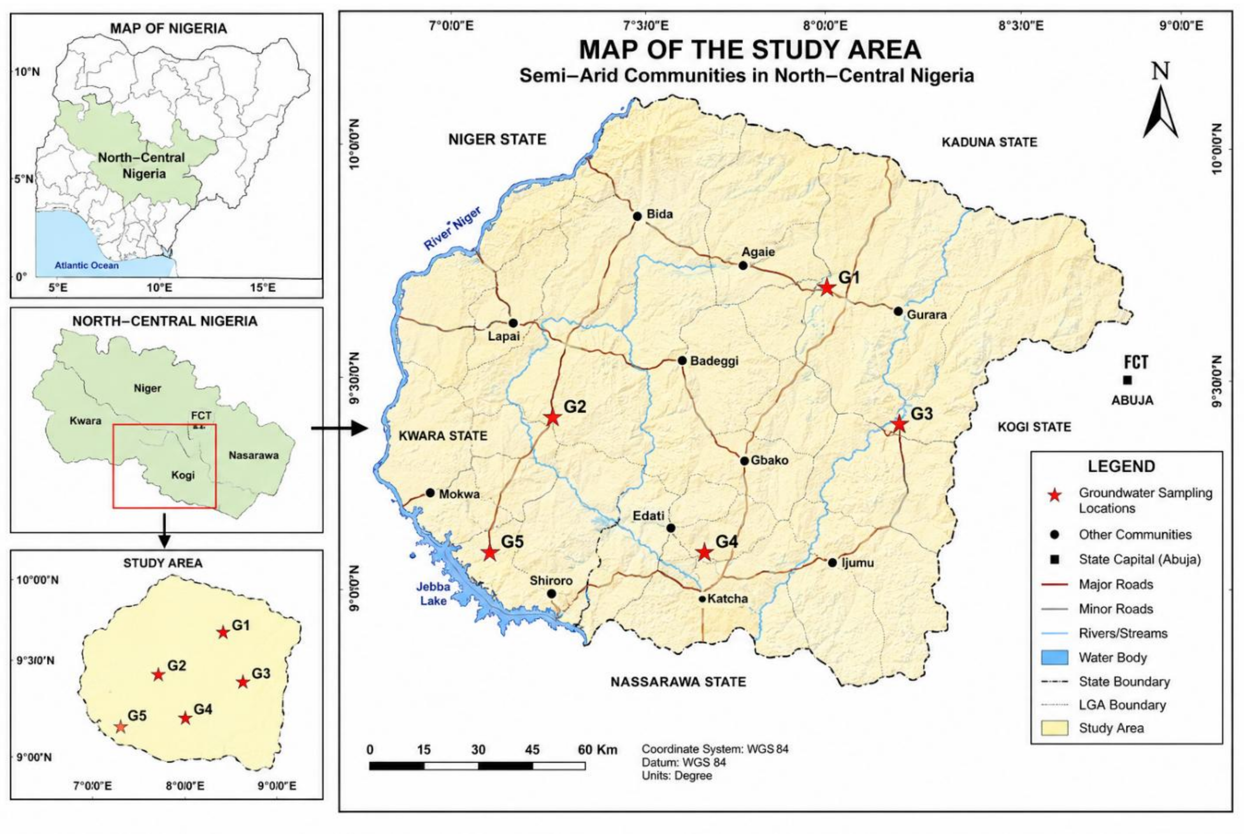

Figure 1: Map of the Study Area Showing Groundwater Sampling Locations in Semi-Arid Communities of North-Central Nigeria

2.2 Research Design

A cross-sectional environmental assessment design integrating hydrogeological, geophysical, hydrochemical, toxicological, and environmental risk assessment approaches was adopted for this study. The study involved geological field investigation, groundwater sampling, laboratory analysis, geo-electrical surveys, pollution assessment, and human health risk evaluation to determine the geological controls on pharmaceutical residue distribution within groundwater systems.

2.3 Sampling Design and Sample Size

Five representative groundwater sampling locations designated as G1, G2, G3, G4, and G5 were purposively selected based on lithological variability, aquifer characteristics, groundwater accessibility, proximity to anthropogenic contamination sources, and environmental vulnerability. The selected locations represented different geological settings including sandy clay with lateritic cover, fractured migmatite-gneiss, clayey sandstone, weathered granite gneiss, and ferruginised sandstone formations.

At each location, groundwater samples were collected from functional boreholes and shallow wells frequently utilised for domestic water supply. Triplicate groundwater samples were collected from each location to ensure analytical precision and statistical reliability, resulting in a total of fifteen groundwater samples. Sampling locations were geo-referenced using a handheld Global Positioning System (GPS) device.

2.4 Geological and Hydrogeological Investigation

Detailed geological field mapping and hydrogeological assessment were conducted to determine lithological characteristics, aquifer properties, fracture distribution, weathering intensity, overburden thickness, groundwater occurrence, and contaminant migration potential within the study area. Geological observations included rock type identification, structural discontinuities, fracture density, soil texture, and degree of weathering.

Hydrogeological parameters including depth to water table, aquifer thickness, groundwater flow characteristics, and hydraulic conductivity were determined through borehole measurements, field observations, and interpretation of geophysical data. These parameters were used to evaluate groundwater vulnerability and contaminant transport pathways.

2.5 Geophysical Investigation

Electrical resistivity surveys were conducted using the Vertical Electrical Sounding (VES) technique with Schlumberger electrode configuration to delineate subsurface lithological units and contaminant migration pathways. Data acquisition was carried out using an ABEM Terrameter SAS 1000 resistivity meter. Electrode spacing progressively increased to obtain resistivity information at varying depths.

The acquired resistivity data were interpreted using computer-assisted inversion software to generate geoelectrical models of the subsurface formations. The interpreted geoelectrical sections were used to delineate topsoil layers, weathered zones, fractured basement formations, conductive contaminant plumes, and competent basement rocks. Low-resistivity anomalies were interpreted as zones of increased contaminant infiltration and leachate accumulation.

2.6 Groundwater Sample Collection

Groundwater samples were collected using pre-cleaned high-density polyethylene bottles following standard APHA procedures for water quality assessment. Prior to sample collection, boreholes and wells were purged for approximately 5–10 minutes to obtain representative groundwater samples and minimise stagnant water influence.

Samples designated for heavy metal analysis were immediately acidified using concentrated nitric acid to maintain pH below 2 and prevent metal precipitation. Samples intended for physicochemical and pharmaceutical analyses were preserved in ice-packed insulated containers at approximately 4°C and transported to the laboratory for analysis within 24 hours.

2.7 Determination of Physicochemical Parameters

Physicochemical parameters including pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), turbidity, nitrate, sulphate, chloride, phosphate, biochemical oxygen demand (BOD), and total hardness were determined using standard analytical methods recommended by the American Public Health Association (APHA).

pH, EC, TDS, and temperature were measured in situ using a calibrated Hanna multiparameter water quality meter, while dissolved oxygen was measured using a portable dissolved oxygen meter. Turbidity was determined using a Hach turbidity meter. Nitrate, sulphate, phosphate, and chloride concentrations were analysed spectrophotometrically. Biochemical oxygen demand was determined after five-day incubation, while total hardness was analysed using the EDTA titrimetric method.

2.8 Determination of Pharmaceutical Residues

Groundwater samples were analysed for selected pharmaceutical residues including ciprofloxacin, amoxicillin, sulfamethoxazole, diclofenac, ibuprofen, metronidazole, paracetamol, and tetracycline.

Sample extraction and purification were conducted using solid-phase extraction (SPE) techniques prior to instrumental analysis. Quantification of pharmaceutical residues was carried out using High-Performance Liquid Chromatography (HPLC) equipped with ultraviolet-visible (UV-Vis) detection. Separation was achieved using a reverse-phase C18 analytical column with appropriate mobile phase gradients under controlled analytical conditions.

Calibration standards, reagent blanks, duplicate samples, and quality-control samples were included during analysis to ensure analytical accuracy, precision, and reproducibility. Pharmaceutical residue concentrations were expressed in micrograms per litre (μg/L).

2.9 Heavy Metal and Trace Metal Analysis

Heavy metals and trace elements including Pb, Cd, Fe, Zn, Cu, Cr, Ni, Mn, As, and Hg were determined using Atomic Absorption Spectrophotometry (AAS). Prior to analysis, groundwater samples were digested using nitric acid-perchloric acid digestion methods following standard laboratory procedures.

The digested samples were filtered and analysed using a Buck Scientific Atomic Absorption Spectrophotometer. Calibration standards and analytical blanks were prepared using certified standard solutions. Metal concentrations were expressed in milligrams per litre (mg/L) and compared with World Health Organization permissible limits for drinking water.

2.10 Hydrochemical Facies Classification

Hydrochemical facies classification was performed using the relative abundance of major cations and anions to evaluate groundwater evolution processes, hydrochemical characteristics, and groundwater-rock interaction within the study area. Groundwater samples were classified into hydrochemical facies such as Ca–HCO_3, Na–Cl, and Ca–Mg–Cl water types based on dominant ionic composition. Hydrochemical interpretations were used to assess lithological influence, contaminant intrusion, weathering processes, and anthropogenic impacts on groundwater chemistry.

2.11 Pollution Indices and Human Health Risk Assessment

Groundwater pollution assessment was conducted using contamination factor (CF), pollution load index (PLI), and water quality index (WQI). These indices were computed to evaluate contamination severity and groundwater suitability for domestic consumption.

The contamination factor (CF) was calculated as:

$$CF = \frac{C_s}{C_b}$$

Where:
C_s= concentration of contaminant in groundwater sample
C_b= background concentration of contaminant

The pollution load index (PLI) was calculated as:

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \ldots \times CF_n)^{1/n}$$

Human health risk assessment was conducted using chronic daily intake (CDI), hazard quotient (HQ), and hazard index (HI) models to estimate non-carcinogenic risks associated with groundwater consumption.

The chronic daily intake was calculated using:

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

Where:
C= contaminant concentration
IR= ingestion rate
EF= exposure frequency
ED= exposure duration
BW= body weight
AT= averaging time

Hazard quotient was determined as:

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

Where:
RfD= reference dose

Hazard index (HI) was calculated as the summation of all individual hazard quotient values.

2.12 Statistical Analysis

Descriptive statistics including mean, standard deviation, minimum values, and maximum values were computed using Statistical Package for Social Sciences (SPSS) version 25. Pearson correlation analysis was performed to evaluate relationships among geoelectrical parameters, physicochemical characteristics, pharmaceutical residues, and heavy metal concentrations.

One-way Analysis of Variance (ANOVA) was further applied to determine significant spatial variations among sampling locations, while statistical significance was considered at $p < 0.05$. Results were presented using tables, pollution indices, and hydrochemical classifications.

3.0 Results

3.1 Geological and Hydrogeological Characteristics of the Study Area

The geological and hydrogeological characteristics of the investigated semi-arid communities are presented in Table 3.1. The study area is predominantly underlain by weathered basement complexes comprising fractured migmatite-gneiss, weathered granite gneiss, ferruginised sandstone, sandy clay with lateritic cover, and clayey sandstone formations. Groundwater occurrence within the area was mainly associated with weathered and fractured aquifer systems characterised by varying hydraulic conductivity, overburden thickness, and groundwater recharge conditions.

Depth to water table varied across the investigated locations, ranging from 9.7 ± 0.9 m at G4 to 14.1 ± 1.5 m at G3. The relatively shallow groundwater levels observed at G2 and G4 indicate greater aquifer susceptibility to contaminant infiltration and rapid contaminant migration. Overburden thicknesses were lowest at G4 (5.8 ± 0.5 m) and G2 (6.2 ± 0.6 m), suggesting limited natural protection against contaminant percolation into groundwater systems.

Hydraulic conductivity values were highest at G4 (7.4×10^{-5} m/s) and G2 (6.8×10^{-5} m/s), indicating highly permeable subsurface conditions capable of facilitating contaminant transport through fractured and weathered geological units. Conversely, G3 recorded the lowest hydraulic conductivity (2.4×10^{-5} m/s) and the greatest overburden thickness (11.3 ± 1.1 m), indicating relatively protected groundwater conditions. These findings demonstrate that lithological variability and aquifer properties strongly controlled contaminant occurrence and groundwater vulnerability within the study area.

Table 3.1: Geological and Hydrogeological Characteristics of the Study Area

Sampling Location	Dominant Lithology	Aquifer Type	Depth to Water Table (m)	Overburden Thickness (m)	Hydraulic Conductivity (m/s)	Geological Interpretation
G1	Sandy clay with lateritic cover	Weathered basement aquifer	12.4 ± 1.2	8.6 ± 0.8	3.2×10^{-5}	Moderate groundwater potential
G2	Fractured migmatite-gneiss	Fractured basement aquifer	10.8 ± 1.0	6.2 ± 0.6	6.8×10^{-5}	High contaminant migration potential
G3	Clayey sandstone	Semi-confined aquifer	14.1 ± 1.5	11.3 ± 1.1	2.4×10^{-5}	Relatively protected aquifer
G4	Weathered granite gneiss	Weathered/fractured aquifer	9.7 ± 0.9	5.8 ± 0.5	7.4×10^{-5}	Highly vulnerable groundwater zone
G5	Ferruginised sandstone	Unconfined aquifer	13.2 ± 1.3	9.4 ± 0.7	3.9×10^{-5}	Moderate vulnerability

3.2 Geoelectrical Characteristics of Subsurface Layers

The geoelectrical investigation identified three major subsurface layers across the study locations, namely the topsoil layer, weathered/fractured conductive layer, and fresh basement rock (Table 3.2). Variations in resistivity values reflected differences in lithology, moisture saturation, fracture density, and contaminant accumulation within the subsurface formations.

The topsoil layer exhibited moderate resistivity values ranging from 96.5 ± 7.6 Ωm at G4 to 136.2 ± 11.5 Ωm at G3. The second subsurface layer, interpreted as the weathered and fractured aquifer zone, recorded significantly lower resistivity values at G2 (38.9 ± 4.3 Ωm) and G4 (35.7 ± 3.8 Ωm). These low-resistivity anomalies indicate highly conductive zones associated with contaminant infiltration, leachate accumulation, and increased groundwater vulnerability.

In contrast, G3 recorded comparatively higher resistivity values (67.4 ± 6.2 Ωm) within the weathered layer, suggesting lower contaminant influence and relatively protected hydrogeological conditions due to the clayey sandstone lithology and thicker overburden materials. Fresh basement formations recorded the highest resistivity values across all locations, indicating competent and less weathered subsurface conditions.

The geoelectrical findings therefore demonstrate that fractured and weathered basement formations significantly enhanced contaminant migration pathways and groundwater contamination within the study area.

Table 3.2: Electrical Resistivity Characteristics of Subsurface Layers

Location	Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Interpretation
G1	1	118.6 ± 10.2	1.5	1.5	Sandy topsoil
	2	54.3 ± 5.1	6.8	8.3	Weathered conductive layer
	3	295.4 ± 18.4			Fresh basement
G2	1	102.8 ± 8.7	1.2	1.2	Topsoil
	2	38.9 ± 4.3	5.9	7.1	Highly conductive contaminated zone
	3	270.6 ± 16.7			Fractured basement
G3	1	136.2 ± 11.5	1.8	1.8	Dry sandy layer
	2	67.4 ± 6.2	7.4	9.2	Moderately weathered layer
	3	340.1 ± 20.3			Competent basement
G4	1	96.5 ± 7.6	1.0	1.0	Sandy clay
	2	35.7 ± 3.8	5.4	6.4	Leachate-influenced conductive zone
	3	255.8 ± 15.2			Fresh basement
G5	1	124.3 ± 9.8	1.6	1.6	Topsoil
	2	58.2 ± 5.4	6.5	8.1	Weathered aquifer

	3	312.5 ± 19.1			Competent basement

3.3 Distribution of Pharmaceutical Residues in Groundwater

The concentrations of pharmaceutical residues detected in groundwater samples are presented in Table 3.3. All investigated pharmaceutical compounds including ciprofloxacin, amoxicillin, sulfamethoxazole, diclofenac, ibuprofen, metronidazole, paracetamol, and tetracycline were detected across all sampling locations, indicating widespread pharmaceutical contamination of groundwater systems within the study area.

The highest concentrations were consistently observed at G2 and G4, which are characterised by fractured and weathered aquifer systems with shallow water table conditions and high hydraulic conductivity. Ciprofloxacin concentrations ranged from 1.74 ± 0.18 µg/L at G3 to 6.31 ± 0.62 µg/L at G4. Similarly, paracetamol concentrations reached 6.12 ± 0.56 µg/L at G4, while ibuprofen concentrations increased from 1.62 ± 0.15 µg/L at G3 to 5.74 ± 0.53 µg/L at G4.

Diclofenac concentrations exceeded recommended environmental threshold values in all locations, indicating persistent contamination and continuous anthropogenic input into the groundwater systems. Sulfamethoxazole, metronidazole, and tetracycline also recorded elevated concentrations at G2 and G4 compared with the relatively protected aquifer at G3.

The comparatively lower pharmaceutical concentrations recorded at G3 suggest that clayey sandstone formations and thicker overburden materials provided greater natural attenuation and reduced contaminant migration. The spatial distribution pattern therefore confirms that lithological characteristics and aquifer vulnerability exerted significant control on pharmaceutical residue occurrence within groundwater systems.

Table 3.3: Concentrations of Pharmaceutical Residues in Groundwater Samples (µg/L)

Pharmaceutical Residue	**G1**	**G2**	**G3**	**G4**	**G5**	**Guideline Threshold**
Ciprofloxacin	2.85 ± 0.24	5.92 ± 0.51	1.74 ± 0.18	6.31 ± 0.62	2.43 ± 0.21	1.00
Amoxicillin	1.76 ± 0.15	4.18 ± 0.39	1.05 ± 0.11	4.56 ± 0.44	1.63 ± 0.14	1.00
Sulfamethoxazole	0.92 ± 0.08	2.64 ± 0.22	0.58 ± 0.05	2.88 ± 0.26	0.81 ± 0.07	0.50
Diclofenac	1.28 ± 0.11	3.41 ± 0.33	0.84 ± 0.08	3.76 ± 0.35	1.14 ± 0.10	0.10
Ibuprofen	2.15 ± 0.19	5.26 ± 0.48	1.62 ± 0.15	5.74 ± 0.53	1.98 ± 0.18	0.30
Metronidazole	1.12 ± 0.10	3.08 ± 0.27	0.74 ± 0.06	3.42 ± 0.31	1.01 ± 0.09	0.50

Paracetamol	2.41 ± 0.21	5.84 ± 0.52	1.95 ± 0.18	6.12 ± 0.56	2.18 ± 0.20	1.00
Tetracycline	0.88 ± 0.07	2.37 ± 0.21	0.51 ± 0.05	2.61 ± 0.24	0.79 ± 0.07	0.50

3.4 Physicochemical Characteristics of Groundwater Samples

The physicochemical characteristics of groundwater samples are presented in Table 3.4. Significant spatial variations were observed across the sampling locations, reflecting the influence of lithology, contaminant infiltration, groundwater-rock interaction, and anthropogenic activities.

Electrical conductivity values ranged from 782 ± 68 µS/cm at G3 to 1564 ± 138 µS/cm at G4. Elevated EC values observed at G2 and G4 exceeded WHO permissible limits and indicate increased ionic enrichment associated with contaminant intrusion and groundwater mineralisation. Total dissolved solids also exceeded the recommended limit of 500 mg/L in most locations, with the highest values recorded at G4 (984 ± 85 mg/L) and G2 (918 ± 76 mg/L).

Turbidity values were highest at G4 (9.4 ± 0.9 NTU) and G2 (8.6 ± 0.8 NTU), indicating increased suspended materials and groundwater quality deterioration. Dissolved oxygen concentrations were lowest at G4 (2.4 ± 0.2 mg/L) and G2 (2.8 ± 0.3 mg/L), suggesting elevated microbial degradation activities and increased organic pollution.

Nitrate concentrations exceeded WHO permissible limits at G2 (56.8 ± 5.4 mg/L) and G4 (61.2 ± 5.8 mg/L), indicating contamination from domestic sewage, agricultural runoff, pharmaceutical waste, and wastewater infiltration. Similarly, phosphate and chloride concentrations were considerably elevated in the same locations, further confirming strong anthropogenic influence.

Groundwater at G3 consistently recorded comparatively lower concentrations of most physicochemical parameters, indicating relatively protected hydrochemical conditions associated with the semi-confined clayey sandstone aquifer system.

Table 3.4: Physicochemical Characteristics of Groundwater Samples

Parameter	**G1**	**G2**	**G3**	**G4**	**G5**	**WHO Standard**
pH	6.48 ± 0.22	6.21 ± 0.18	6.87 ± 0.25	6.15 ± 0.17	6.52 ± 0.21	6.5–8.5
Temperature (°C)	28.4 ± 1.1	29.7 ± 1.3	27.9 ± 1.0	30.2 ± 1.4	28.7 ± 1.2	Ambient
EC (µS/cm)	925 ± 82	1486 ± 125	782 ± 68	1564 ± 138	864 ± 73	1000
TDS (mg/L)	588 ± 48	918 ± 76	462 ± 41	984 ± 85	531 ± 45	500
Turbidity (NTU)	3.8 ± 0.4	8.6 ± 0.8	2.9 ± 0.3	9.4 ± 0.9	4.1 ± 0.4	5

Dissolved Oxygen (mg/L)	4.6 ± 0.5	2.8 ± 0.3	5.2 ± 0.5	2.4 ± 0.2	4.8 ± 0.4	>5
BOD (mg/L)	3.2 ± 0.3	7.4 ± 0.7	2.6 ± 0.2	8.1 ± 0.8	3.0 ± 0.3	5
Nitrate (mg/L)	34.5 ± 3.6	56.8 ± 5.4	27.1 ± 2.8	61.2 ± 5.8	31.7 ± 3.2	50
Sulphate (mg/L)	86 ± 7	164 ± 15	72 ± 6	181 ± 17	78 ± 7	250
Phosphate (mg/L)	1.6 ± 0.1	3.8 ± 0.3	1.2 ± 0.1	4.1 ± 0.4	1.5 ± 0.1	0.5
Chloride (mg/L)	178 ± 16	286 ± 25	142 ± 13	301 ± 28	165 ± 15	250
Total Hardness (mg/L)	124 ± 11	218 ± 19	108 ± 10	236 ± 22	116 ± 11	500

3.5 Heavy Metal and Trace Metal Concentrations in Groundwater

The concentrations of heavy metals and trace elements in groundwater samples are presented in Table 3.5. Elevated concentrations of Pb, Cd, Cr, Ni, Mn, Fe, and As were observed at G2 and G4, exceeding WHO permissible limits. Iron concentrations ranged from 0.44 ± 0.04 mg/L to 1.08 ± 0.09 mg/L, while Pb concentrations reached 0.037 ± 0.004 mg/L at G4. The results indicate significant anthropogenic contamination associated with pharmaceutical waste infiltration and geological weathering processes.

Table 3.5: Heavy Metal and Trace Metal Concentrations in Groundwater (mg/L)

Heavy Metal	**G1**	**G2**	**G3**	**G4**	**G5**	**WHO Limit**
Pb	0.016 ± 0.002	0.034 ± 0.003	0.011 ± 0.001	0.037 ± 0.004	0.014 ± 0.001	0.01
Cd	0.004 ± 0.001	0.010 ± 0.001	0.003 ± 0.001	0.011 ± 0.001	0.004 ± 0.001	0.003
Fe	0.58 ± 0.05	0.96 ± 0.08	0.44 ± 0.04	1.08 ± 0.09	0.52 ± 0.05	0.30
Zn	1.21 ± 0.11	1.96 ± 0.18	0.88 ± 0.07	2.15 ± 0.20	1.07 ± 0.09	3.00
Cu	0.28 ± 0.03	0.47 ± 0.04	0.16 ± 0.02	0.53 ± 0.05	0.22 ± 0.02	2.00
Cr	0.041 ± 0.004	0.086 ± 0.007	0.028 ± 0.003	0.091 ± 0.008	0.034 ± 0.003	0.05
Ni	0.026 ± 0.003	0.074 ± 0.006	0.019 ± 0.002	0.081 ± 0.007	0.024 ± 0.002	0.02
Mn	0.18 ± 0.02	0.42 ± 0.04	0.12 ± 0.01	0.48 ± 0.05	0.15 ± 0.02	0.10
As	0.006 ± 0.001	0.013 ± 0.001	0.004 ± 0.001	0.015 ± 0.002	0.005 ± 0.001	0.01
Hg	0.0008 ± 0.0001	0.0021 ± 0.0002	0.0005 ± 0.0001	0.0024 ± 0.0002	0.0007 ± 0.0001	0.001

3.6 Pollution Indices and Human Health Risk Assessment

The pollution indices and human health risk assessment results are presented in Table 3.6. Groundwater at G2 and G4 recorded the highest contamination factor, pollution load index, hazard quotient, and hazard index values. Water quality index values classified groundwater at G2 and G4 as "very poor," while G3 showed comparatively lower contamination levels. Hazard quotient values for Pb, Cd, and Cr exceeded the safe threshold of 1.0 at G2 and G4, indicating potential non-carcinogenic health risks from prolonged groundwater consumption.

Table 3.6: Pollution Indices and Human Health Risk Assessment

Location	CF	PLI	WQI	HQ (Pb)	HQ (Cd)	HQ (Cr)	Hazard Index (HI)	Risk Category
G1	1.76	1.42	118.5	0.84	0.76	0.69	1.42	Moderate
G2	3.24	2.67	184.3	1.78	1.64	1.32	3.18	High
G3	1.18	0.96	88.2	0.62	0.48	0.44	1.01	Low–Moderate
G4	3.51	2.94	196.7	1.88	1.79	1.46	3.42	High
G5	1.49	1.27	104.6	0.76	0.71	0.58	1.29	Moderate

4.0 Discussion

The findings of this study demonstrated that the occurrence, distribution, and migration of pharmaceutical residues, heavy metals, and hydrochemical contaminants within groundwater systems of semi-arid communities in North-Central Nigeria were strongly influenced by geological and hydrogeological conditions. The investigated aquifer systems showed considerable spatial variability in contaminant concentrations, groundwater quality parameters, and pollution indices due to differences in lithology, fracture density, overburden thickness, hydraulic conductivity, and groundwater vulnerability. The results therefore confirm that geological formations play a fundamental role in controlling contaminant transport, retention, and attenuation within groundwater systems (Akpor & Muchie, 2011; Patel et al., 2019).

The geological and hydrogeological assessment revealed that fractured migmatite-gneiss and weathered granite gneiss formations exhibited relatively shallow water tables, thinner overburden thicknesses, and higher hydraulic conductivity values compared with clayey sandstone formations. These geological conditions significantly enhanced contaminant infiltration and groundwater vulnerability at G2 and G4. Fractured and weathered basement rocks generally possess increased secondary porosity and permeability due to tectonic deformation and prolonged weathering processes, thereby creating preferential pathways for rapid contaminant migration into groundwater systems. In contrast, the clayey sandstone formation observed at G3 provided greater natural protection because clay-rich materials possess relatively lower permeability and higher contaminant attenuation capacity (Ekesiobi et al., 2025; Ebikienmo et al., 2026).

The geoelectrical investigation further confirmed the influence of geological structures on contaminant migration within the study area. The low resistivity anomalies observed within the weathered and fractured aquifer zones at G2 and G4 indicate highly conductive subsurface environments associated with contaminant infiltration, leachate accumulation, and increased groundwater deterioration. The conductive nature of these zones may be attributed to elevated ionic concentration, dissolved contaminants, increased moisture saturation, and anthropogenic pollution. Similar relationships between low resistivity and groundwater contamination have been widely reported in hydrogeophysical studies involving leachate migration and groundwater vulnerability assessment (Ekesiobi et al., 2026; Izuchukwu et al., 2026b).

The widespread occurrence of pharmaceutical residues in groundwater samples demonstrates increasing contamination of groundwater systems by emerging contaminants associated with domestic sewage, indiscriminate disposal of unused medications, hospital wastes, agricultural runoff, and wastewater infiltration. The detection of ciprofloxacin, amoxicillin, sulfamethoxazole, diclofenac, ibuprofen, metronidazole, paracetamol, and tetracycline across all sampling locations indicates continuous anthropogenic input into the aquifer systems. The elevated concentrations recorded at G2 and G4 suggest that fractured and weathered aquifer systems facilitated rapid contaminant transport and reduced natural attenuation processes (Patel et al., 2019; Obinna et al., 2023).

The elevated concentrations of ciprofloxacin, sulfamethoxazole, and tetracycline are environmentally significant because antibiotics in groundwater systems may contribute to the development of antimicrobial-resistant microorganisms. Persistent exposure of environmental microbes to sub-lethal concentrations of antibiotics may enhance resistance gene transfer, microbial adaptation, and public health risks. Similarly, diclofenac, ibuprofen, and paracetamol are recognised as environmentally persistent pharmaceutical compounds capable of inducing ecological stress and aquatic toxicity. Their occurrence in groundwater therefore indicates increasing deterioration of water quality and insufficient management of pharmaceutical wastes within the study area (Kashif et al., 2021; Li et al., 2024).

The comparatively lower pharmaceutical concentrations observed at G3 indicate that lithological characteristics significantly influenced contaminant migration and groundwater protection. Clayey sandstone formations possess relatively lower permeability and enhanced adsorption capacity, which may reduce contaminant mobility and facilitate natural attenuation processes. The thicker overburden observed at G3 further reduced direct contaminant infiltration into the groundwater system. This demonstrates the critical role of geological formations in regulating groundwater vulnerability and contaminant transport dynamics (Ekesiobi et al., 2025; Izuchukwu et al., 2026a).

The physicochemical characteristics of groundwater samples further revealed significant groundwater quality deterioration within vulnerable aquifer systems. Elevated electrical conductivity, total dissolved solids, turbidity, nitrate, chloride, phosphate, and biochemical oxygen demand values recorded at G2 and G4 indicate substantial anthropogenic contamination associated with wastewater infiltration, domestic sewage, agricultural runoff, and pharmaceutical waste disposal. Increased electrical conductivity and total dissolved solids generally indicate elevated ionic enrichment and groundwater mineralisation resulting from contaminant intrusion and groundwater-rock interaction (Akpor & Muchie, 2011; AL Falahi et al., 2022).

The elevated nitrate concentrations recorded at G2 and G4 are particularly concerning because nitrate contamination in groundwater may induce serious public health complications such as methaemoglobinaemia and other chronic health disorders. Elevated nitrate levels are commonly associated with sewage contamination, agricultural fertiliser application, septic tank leakage, and organic waste decomposition. Similarly, elevated phosphate concentrations indicate nutrient enrichment associated with anthropogenic activities and organic pollution within the groundwater systems (Umueni et al., 2025).

The low dissolved oxygen concentrations and elevated biochemical oxygen demand values observed at G2 and G4 indicate increased microbial degradation activities and organic contamination within the aquifer systems. Organic-rich contaminants entering groundwater systems may stimulate microbial respiration and oxygen consumption, thereby reducing dissolved oxygen concentrations and altering groundwater chemistry. Such conditions may also influence the mobility and transformation of contaminants within subsurface environments (Obunadike et al., 2025).

Heavy metal and trace metal contamination within the investigated groundwater systems further demonstrated the combined influence of geological weathering processes and anthropogenic contamination. Elevated concentrations of Pb, Cd, Cr, Ni, Mn, As, and Hg recorded at G2 and G4 exceeded WHO permissible limits for drinking water and indicate significant groundwater quality deterioration. The co-occurrence of pharmaceutical residues and elevated heavy metal concentrations suggests multiple contaminant sources associated with domestic waste disposal, wastewater infiltration, urban runoff, and geogenic weathering processes (Jaishankar et al., 2014; Castro-González & Méndez-Armenta, 2008).

Lead and cadmium contamination are particularly important due to their persistence, toxicity, and bioaccumulative characteristics. Lead exposure may induce neurological impairment, renal dysfunction, cardiovascular disorders, and developmental abnormalities, while cadmium exposure has been associated with renal toxicity, skeletal disorders, and carcinogenic effects. Elevated chromium and arsenic concentrations further increase public health concerns because prolonged exposure may induce mutagenic and carcinogenic effects. Mercury contamination also represents a significant environmental and toxicological concern due to its ability to bioaccumulate and induce neurological disorders (Ezemonye et al., 2019; Jaishankar et al., 2014).

Iron and manganese concentrations were also elevated in highly vulnerable groundwater systems. Although these metals may partly originate from natural geological weathering of basement rocks and ferruginised formations, their elevated concentrations in contaminated locations suggest additional anthropogenic contributions associated with wastewater infiltration and environmental pollution. The hydrochemical evolution of groundwater within the study area was therefore controlled by both natural geological processes and anthropogenic contaminant sources (Ekesiobi et al., 2026; Ebikienmo et al., 2026).

The hydrochemical facies characteristics of the groundwater systems indicate strong lithological and anthropogenic influences on groundwater chemistry. Locations characterised by fractured basement formations exhibited increased ionic enrichment and groundwater quality deterioration associated with contaminant intrusion and groundwater-rock interaction. Conversely, the semi-confined clayey sandstone aquifer exhibited relatively lower contaminant concentrations and improved hydrochemical quality due to reduced permeability and greater natural filtration capacity (Izuchukwu et al., 2026b).

The pollution indices and health risk assessment results further confirm severe groundwater contamination within vulnerable geological settings. The contamination factor, pollution load index, and water quality index values recorded at G2 and G4 indicate substantial groundwater deterioration and reduced suitability for domestic consumption. Water quality index classifications revealed that groundwater from these locations falls within poor to very poor-quality categories, requiring treatment before human consumption (Ekesiobi et al., 2025; Ebikienmo et al., 2026).

The hazard quotient and hazard index values recorded for Pb, Cd, and Cr further indicate potential non-carcinogenic health risks associated with prolonged groundwater consumption. Hazard index values exceeding unity suggest cumulative toxicological risks resulting from multiple contaminant exposure pathways. Residents relying on untreated groundwater within highly vulnerable aquifer systems may therefore face increased risks of chronic toxicity, neurological disorders, renal impairment, and other contaminant-related health complications (Jaishankar et al., 2014; Ezemonye et al., 2019).

The findings of this study have important environmental geology and groundwater management implications for semi-arid regions of Nigeria and other developing countries. The strong relationship between lithology, aquifer characteristics, contaminant migration, and groundwater vulnerability demonstrates the importance of geology-guided groundwater development and environmental monitoring. Fractured and weathered basement aquifers are particularly vulnerable to contaminant infiltration due to their high permeability and shallow groundwater conditions. Consequently, groundwater protection strategies within such environments should prioritise proper waste management, controlled sewage disposal, routine groundwater quality monitoring, and hydrogeological assessment prior to borehole development (Patel et al., 2019; Li et al., 2024).

The integration of geological mapping, geophysical investigation, hydrochemical analysis, pharmaceutical residue assessment, and human health risk evaluation in this study provides a comprehensive framework for groundwater vulnerability assessment in environmentally stressed regions. The findings therefore contribute significantly to understanding the interaction between geological conditions and emerging contaminant distribution within groundwater systems of semi-arid environments.

Conclusion

This study investigated the geological controls on the distribution of pharmaceutical residues, heavy metals, and hydrochemical characteristics of groundwater within semi-arid communities of North-Central Nigeria. The findings demonstrated that geological and hydrogeological conditions exerted significant influence on contaminant occurrence, migration, and groundwater vulnerability. Fractured migmatite-gneiss and weathered granite gneiss formations characterised by shallow water tables, thin overburden thicknesses, and high hydraulic conductivity exhibited the highest concentrations of pharmaceutical residues, heavy metals, and deteriorated physicochemical parameters. Conversely, clayey sandstone formations provided comparatively greater groundwater protection due to reduced permeability and enhanced natural attenuation capacity.

Pharmaceutical residues including ciprofloxacin, amoxicillin, sulfamethoxazole, diclofenac, ibuprofen, metronidazole, paracetamol, and tetracycline were detected across all groundwater samples, indicating widespread contamination associated with anthropogenic activities such as improper pharmaceutical disposal, wastewater infiltration, and domestic sewage contamination. Elevated concentrations of Pb, Cd, Cr, Ni, Mn, As, and Hg further revealed significant groundwater quality deterioration and potential public health risks within vulnerable aquifer systems.

The geoelectrical investigation confirmed that low resistivity anomalies corresponded with highly conductive contaminated zones associated with fractured and weathered aquifer systems. Pollution indices and health risk assessment results further demonstrate that groundwater from highly vulnerable locations may pose considerable non-carcinogenic health risks to exposed populations.

The study therefore concludes that geological formations and aquifer characteristics significantly control contaminant transport, accumulation, and groundwater quality within semi-arid environments. Effective groundwater protection within such regions requires integrated hydrogeological assessment, routine groundwater quality monitoring, controlled waste disposal practices, proper sewage management, and geology-guided borehole sitting. The study also highlights the urgent need for improved environmental regulation and sustainable groundwater management strategies to minimise contaminant infiltration and protect public health in vulnerable communities.

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