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Assessment of heavy metals (As, Ba, Co and Ni), pollution in rural drinking water sources, using correlation and principal component analysis in Western Sokoto Basin, Nigeria

Abstract

The study utilizes correlation and principal component analysis to examine heavy metal pollution (As, Ba, Co, and Ni) in 63 rural drinking water sources within the Western Sokoto Basin. The study employed both field and laboratory analyses. Results showed that physical parameters such as pH (ranging from 4.4 to 9.4) and temperature (32.8 to 39.8°C) indicate acidic conditions, with a mean pH of 4.98, which falls below WHO/NSDWQ limits and may enhance the solubility of heavy metals. Though electrical conductivity (EC) and total dissolved solids (TDS) are generally within acceptable ranges, some maximum values exceed permissible limits. Dissolved oxygen levels (0.01 to 26.8 mg/L) and Turbidity (0 to 96.3 NTU) suggest localized pollution, with turbidity levels exceeding the 5 NTU standard. Among the heavy metals analyzed, barium (54.10 mg/L) and copper (35.74 mg/L) surpass WHO guidelines, presenting health risks such as cardiovascular problems and gastrointestinal issues. Although arsenic and nickel levels are below the limits, the presence of arsenic, even in small amounts, raises concern due to its toxicity and association with agricultural pesticide use. Spatial analysis points to contamination sources, including agricultural runoff, waste disposal, and industrial emissions. The results underscore the importance of ongoing groundwater monitoring, especially in agricultural areas. Future studies should broaden sampling networks, perform longitudinal and cross-seasonal analyses, identify sources of contamination, and evaluate health risks. Policy suggestions include establishing water quality standards, encouraging sustainable agricultural practices, incorporating smart monitoring technologies like IoT and sensors for real-time data collection, and enhancing awareness programs.

Keywords: correlation analysis, principal component analysis, heavy metals, Sokoto Basin

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Introduction

Access to safe and clean drinking water is essential for human health and sustainable development. Although there has been global progress towards achieving universal access to clean water as outlined in Sustainable Development Goal 6, many rural areas, especially developing countries, still struggle with water quality issues.[1,2] The Western Sokoto Basin in Nigeria is a prime example of these challenges, where rural communities primarily depend on shallow groundwater sources for their drinking and domestic needs. Unfortunately, these water sources are susceptible to contamination from natural geological processes and human activities, such as agriculture, mining, and improper waste disposal. Heavy metals like arsenic (As), barium (Ba), cobalt (Co), and nickel (Ni) are significant contaminants in rural water sources.[3,4] Unlike many other pollutants, heavy metals do not break down and can accumulate in the environment and living organisms, creating serious risks for human and ecological health.

In the Western Sokoto Basin, the presence of these metals in groundwater can be linked to the area's specific hydrogeological and geochemical features. The bedrock in this semi-arid region contains minerals that can naturally release heavy metals into groundwater through weathering and leaching.[5–7] Furthermore, increased agricultural activities, including using fertilizers and pesticides, may lead to higher levels of metals such as arsenic and cobalt in the water supply. The risk of exposure to these heavy metals through drinking water is concerning from a health standpoint. Arsenic, recognized as a carcinogen, has been associated with various cancers, skin lesions, and developmental issues.[8] Barium, while not often highlighted, can lead to cardiovascular and gastrointestinal problems when consumed in large amounts.[9]

Similarly, exposure to cobalt is linked to thyroid dysfunction, blood-related issues, and potential cancer risks, while nickel is known to cause allergic reactions and has been associated with kidney and respiratory diseases.[10,11] Long-term consumption of water contaminated with these metals could severely impact rural communities in the Western Sokoto Basin, where access to healthcare is limited and awareness of water quality issues is often low. The environmental consequences of heavy metal contamination in the region are significant. Heavy metals can change groundwater quality, disrupting aquatic ecosystems and harming biodiversity.[12,13] In areas like the Sokoto Basin, where water is a limited and vital resource, the decline in water quality presents an additional hurdle for sustainable development.

Additionally, contaminated groundwater seeps into agricultural soils, creating a cycle threatening food security and exposing local communities to toxic metals through the food chain.[14,15] This study aims to evaluate heavy metal pollution in rural drinking water sources in the Western Sokoto Basin by employing correlation and

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principal component analysis (PCA). Correlation analysis sheds light on the relationships among various water quality parameters, aiding in identifying potential contamination sources.[16,17] PCA, a powerful multivariate statistical method, simplifies complex datasets, identifying primary pollution sources and categorizing water quality variables that exhibit similar patterns.[18,19] These approaches are crucial for understanding the complex interactions between hydrogeochemical processes and human activities that lead to heavy metal contamination. The rationale for this study is its potential to fill important knowledge gaps and guide sustainable water management practices in the region.

Although previous research has looked into water quality in some regions of the Sokoto Basin,[20–22] there have been few comprehensive assessments of heavy metal contamination focusing specifically on arsenic, barium, cobalt, and nickel. Moreover, the application of advanced statistical methods like PCA has not been widely explored in rural water quality studies in Nigeria, which limits the understanding of the geochemical factors that affect groundwater quality. The results of this study will have important implications for public health, environmental protection, and policy development. As a result of pinpointing the sources and distribution of heavy metals in rural drinking water, the research can inform strategies to reduce health risks. For instance, regions with elevated arsenic levels might need to adopt arsenic removal technologies or create alternative water sources.

Additionally, understanding how agricultural practices affect groundwater quality can aid in crafting land-use policies that reduce heavy metal contamination in aquifers.[15,23] This research adds to the global conversation about water quality in developing areas, providing a case study highlighting the need to combine scientific knowledge with community-driven water management. Focusing on rural water sources addresses the urgent need to reduce the gap between urban and rural access to safe drinking water, as rural populations often face a greater risk of waterborne diseases. Evaluating arsenic, barium, cobalt, and nickel contamination in rural drinking water sources within the Western Sokoto Basin is timely and crucial. The area's reliance on shallow groundwater, its distinct geological characteristics, and rising human activities present a complicated situation regarding potential pollution. Through correlation and PCA methods, this research seeks to identify the sources and relationships of heavy metals in groundwater, providing practical insights to improve water quality management in the region. The findings will help to protect human and environmental health in the Sokoto Basin and support broader initiatives to achieve sustainable water resource management in semi-arid areas globally.

Material and methods

Study area

Western Sokoto Basin is situated in the Northwestern part of Nigeria, bordered by Niger Republic to the North, Sokoto State to the East, Niger State to the South, and Benin Republic to the West.[24,25] It is geographically positioned between latitudes 10° and 14° N and longitudes 3° and 6° E. This location places the study area within the Sudan and Sahel savannah zones, known for their unique climatic and environmental characteristics. The climate is semi-arid, shaped by the interaction of tropical continental (dry) and tropical maritime (wet) air masses.[25] The study area experiences two primary seasons: the dry season, which lasts from October to April, and the wet season, which runs from May to September. Rainfall in the area varies spatially and temporally, with annual totals ranging from about 400 mm in the northern regions to over 1,000 mm in the southern parts. The rainy season typically peaks in August.

The study area (Figure 1) experiences high temperatures year-round, with average daily temperatures ranging from 26°C to 40°C.[26] The peak heat occurs from March to May when temperatures frequently surpass 40°C. In contrast, the most incredible months are December and January, when the Harmattan winds bring some relief. Night-time temperatures can drop to around 15°C during this period, although the days remain warm.[27,28] This climate and geographical context significantly impact the study area's water resources, agriculture, and socio-economic activities. The fluctuations in rainfall and temperature create challenges for water availability, which is vital for the largely agrarian community.[29,30] Grasping these climatic features is crucial for formulating sustainable resource management and climate resilience strategies in the Western Sokoto Basin.

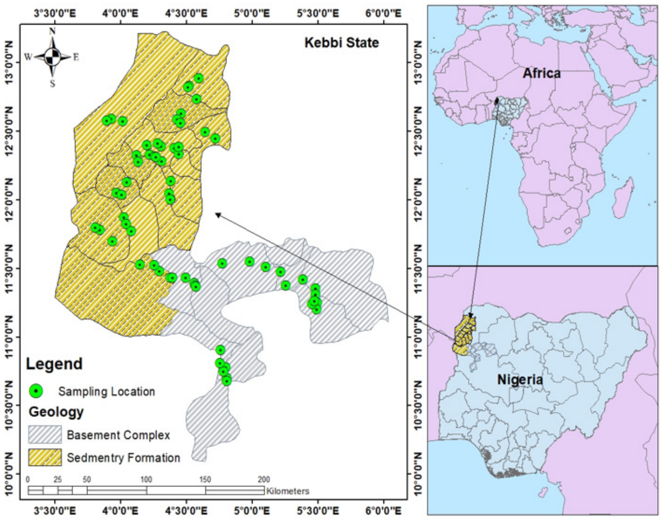

Figure 1 Map of Nigeria Showing Kebbi State.

Geological and hydrogeological settings

The Western Sokoto Basin in Northwestern Nigeria features a variety of geological formations that play a crucial role in shaping groundwater hydrochemistry.[31] This basin includes sedimentary deposits from the Iullemmeden Basin, with notable formations such as the Gundumi, Rima, and Sokoto Groups.[32] These formations are mainly made up of sandstones, clays, shales, and limestone, each exhibiting distinct geochemical properties and hydrogeological traits. The Gundumi Formation, which consists mainly of coarse-grained sandstones and clays, acts as an important aquifer, facilitating the storage and movement of groundwater.[33,34] However, the presence of clay layers can lead to geochemical interactions that increase the levels of dissolved ions. The Rima Group made up of shales and interbedded sandstones, often enhances the concentration of iron, manganese, and other metals through reductive dissolution processes.[35]

Meanwhile, the Sokoto Group, known for its fossiliferous limestone and marl, affects groundwater quality through carbonate dissolution, frequently resulting in higher levels of hardness and bicarbonate.[33,34] These geological formations can also release heavy metals like arsenic, barium, cobalt, and nickel into the groundwater, influenced by natural weathering and human activities such as agricultural runoff.[36,37] As a result, the hydrochemistry of groundwater in the Western Sokoto Basin is shaped by a complex interaction of lithology, geochemical processes, and human impacts, highlighting the importance of regular monitoring to maintain water quality and manage resources sustainably.

Figure 2 illustrates a cross-section of the Sokoto Basin, highlighting its geological features. This basin is marked by a layered structure, with different sedimentary formations resting atop the LGA.[38,39] These formations, which include the Rima Group, Continental Intercalary, and the Sokoto Group above, comprise sandstones, shales, and conglomerates. From a hydrogeological standpoint, the sedimentary layers in the Sokoto Basin are vital for groundwater presence and movement.[33,35] The sandstones in these layers, especially those with favorable porosity and permeability, serve as potential aquifers. Groundwater in the basin is mainly contained within these sandstone aquifers, flowing through interconnected pore spaces.

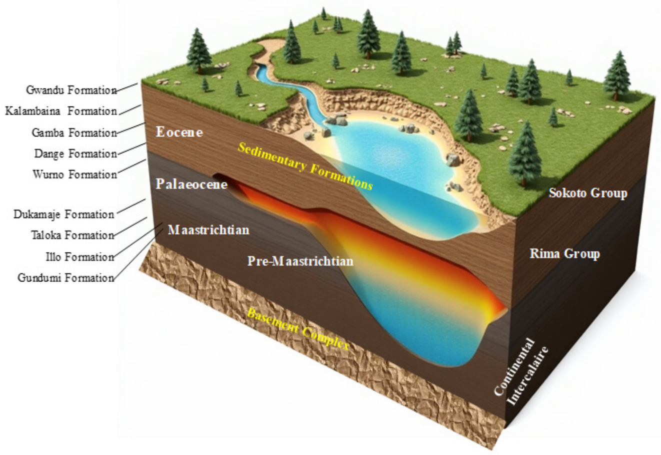

Figure 2 Hydrogeological cross-section of the Sokoto Basin.

Beneath the sedimentary layers lies the Basement Complex, consisting of crystalline rocks that create a relatively impermeable barrier. This results in a semi-confined or confined aquifer system, where groundwater is held between the impermeable layers above and the Basement Complex below.[40,41] Factors like rainfall patterns, recharge zones, and discharge locations also shape the hydrogeology of the Sokoto Basin. Rainfall seeps into the ground, replenishing the aquifers.[42] Groundwater movement is affected by the formations' landscape, hydraulic gradients, faults, and fractures.[43] Understanding the hydrogeology of the Sokoto Basin is essential for effective groundwater management. It offers valuable insights into groundwater availability, flow dynamics, and potential extraction sites. This knowledge is crucial for water resource planning, irrigation initiatives, and ensuring the long-term sustainability of water resources in the area. Note: The image provided depicts the basin's geology. The actual hydrogeology of the Sokoto Basin is more intricate and influenced by various factors, including regional differences in lithology and structural characteristics.

Groundwater sampling and in-situ analysis

The research employed both on-site data collection and laboratory analysis. When gathering groundwater samples, physical properties will be measured directly at the source. The study began by pinpointing accessible rural communities within Kebbi State. Subsequently, 63 rural communities were randomly selected, prioritizing accessibility and safety for sample collection.[44,45] Ultimately, groundwater samples were obtained from rural drinking water sources, including public or community boreholes and hand-dug wells. The sampling was conducted in February 2023. The timing for groundwater sampling is strategic because, during this period, water bodies exhibit more stable hydrochemical properties. They are less impacted by the recharge from rainfall infiltration, which occurs during the wet season, and surface runoff. To ensure the integrity of the samples, water collected from rural areas was stored in shielded containers that maintained a controlled temperature of below 5°C.[46] Physical parameters (pH, Temperature, TDS, EC, DO, and Turbidity) were analyzed using handheld meters.

In-situ and laboratory analysis

Heavy Metals (As, Ba, Co, and Ni) were analysed using the MOP-AES machine (Model 4210). Quality assurance and control procedures adhered to the methods outlined by Cofino[47] The reagents for heavy metal analysis were prepared using high-purity chemicals of analytical grade, specifically AnalaR. Each reagent container will be washed with a detergent solution and then thoroughly rinsed to ensure cleanliness. Blank samples will be analyzed after every five sample analyses to monitor background contamination. Each sample was tested in triplicate, and the results must exhibit productivity within an error margin of ±5%. Groundwater samples were collected in 1-liter polyethene (PE) bottles for laboratory analysis. After filling the sampling bottles with water, the bottles were capped tightly, labelled, and stored in a box. Groundwater samples were filtered through WHATMAN 0.45ml membrane cellulose nitrate filter paper using a glass filtration unit.[46,48]

The samples were acidified with concentrated Analar HNO_3 to pH < 2 to prevent adsorption onto the container surface retard biological activity while avoiding hydrolysis and precipitation of cations within the matrix.[49,50] Typical detection limits for the MP AES vary from low µg/l to ng/l levels for various elements. The superb detection capabilities, joined with a wide linear dynamic, vary from 4 to 6 orders of magnitude, allowing for precise heavy metal analysis in a single measurement.[51,52] The machine offers low detection limits for heavy metals, mainly in the ppb range, ensuring sensitivity to water quality analysis. The calibration standards are prepared using certified reference materials for accuracy. Quality assurance comprises duplicates, blanks, and standard reference samples to validate analyses, ensuring reliability and precision in heavy metals analysis.[53] It was calibrated using conventional multi-element calibration and the technique for standard additions. The calibration fits for all the wavelengths used is linear. The quality control spike recovery tests were used to check the procedure's validity.

Statistical analysis

Pearson's correlation analysis

The correlation analysis was used to study the relationship between phosphate and heavy metals.[54,55] The Pearson correlation is defined in Eq. 1:

$$r = \frac{\sum (x - m_x)(y - m_y)}{\sqrt{\sum (x - m_x)^2 \sum (y - m_y)^2}} \qquad Eq.1$$

where the dual vectors are x and y of the n, $m_z and\, m_y$ size equivalents of the average value of x and y. The correlation coefficient expresses the relationship (or p-value) ion's significance level, typically a matrix table for the degrees of freedom: $df = n - 2$, where n is the sum of the reflection in the x and y variables. It can be measured by calculating the t value as follows in Equation 2:

$$t = \frac{r}{\sqrt{1 - r^2}} \sqrt{n - 2} \qquad Eq.2$$

In Eq. 2, the subsequent *p-value* is explained by the t distribution table for $df = n - 2$. The relationship between hydrochemical elements is substantial if the *p-value* is less than 0.50.[56]

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Principal component analysis

Hydrogeochemical analysis of shallow groundwater aquifers is a multivariate problem. The PCA's significance relates to reducing hydrochemical data.[57,58] Although some analogous hydrochemical data can be lost in the transformation process, the system's explanation is considerably abridged. The bilinear PCA model can be rearranged vis the matrix decomposition equation (Equation 3), thus:

$$X = TP^T + E \qquad \text{Eq. 3}$$

X represents the data matrix, abridged to T (scores of the matrices), and PT represents matrix loadings, plus the E (residual of the matrix). This study uses PCA to study the area's heavy metals concentration variability. Even though there might not be much to realise after statistical application, PCA is a transforming data method that eases hydrochemical data interpretation. After this process, the new axes, referred to as principal components (PCs), are chosen based on a linear model as defined below:

Therefore, PC1 defines the most crucial variance in the data set, followed by PC2, which describes the second most crucial variance in the data set, though it is built orthogonally to PC1 and consequently is independent from PC2. It is measured using the Equation 4 below:

$$PC_{jk} = a_{j1}x_{k2} + \ldots + a_{jn}x_{kn} \qquad Eq.4.$$

where PC_{jk} is the PC value j for variable k (the score for object j on component k), $aj1$ is the scoring of variable 1 on component j, $xk1$ is the length of the score for variable 1 on item k, and n is the sum of variables observed. This process can be repetitive until the number of PCs corresponds to the initial variables' sum. The advantage of the technique is that the variance in the hydrochemical data is restricted to the first few PCs; thus, the magnitude or size of the multivariate matrix.[59–63]

Results and discussion

Physical parameters

Table 1 presents the results of physicochemical parameters. The data in Table 2 offers a summary of important water quality parameters, including temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), and turbidity (TUR), compared against the permissible limits established by WHO (2011) and NSDWQ (2007). The analysis indicates notable deviations in some parameters, raising concerns about the water's suitability for drinking. Temperature readings range from 32.80°C to 39.80°C, with an average of 39.10°C, surpassing recommended levels. Elevated temperatures can impact water's taste and gas solubility, which may indirectly affect other quality parameters like DO. The pH values vary from 4.40 to 9.40, with an average of 4.98, showing that many samples are outside the acceptable range of 6.5–8.5. The low pH indicates acidic conditions, which may stem from natural geochemical processes or human activities, potentially increasing the leaching of metals into the water.

Table 2 Summary of Physical Parameters

Parameters	Tem	PH	EC	TDS	DO	TUR
Min	32.8	4.4	14	7	0.01	0
Max	39.8	9.4	2472	1162	26.8	96.3
Mean	39.1	4.98	390.94	184.22	4.28	18.01
SE	0.96	0.55	54.58	25.67	0.42	3.75
WHO (2011)	Ambient	6.5-8.5	500(uS/cm)	1000	6.5-8	5 NTU
NSDWQ(2007)	Ambient	6.5-8.5	1000	1000		5 NTU

The electrical conductivity (EC) ranges from 14.00 µS/cm to 2472.00 µS/cm, averaging 390.94 µS/cm. Although the average EC falls within the limits of WHO and NSDWQ, the maximum value significantly exceeds the standard, indicating high ion concentrations that could affect taste and potability. Similarly, total dissolved solids (TDS) range from 7.00 mg/L to 1162.00 mg/L, averaging 184.22 mg/L. Even though the average TDS is acceptable, the maximum value surpasses WHO guidelines, suggesting possible contamination from sources like agricultural runoff or geological dissolution.[64,65] Figure 3 further illustrates the variation of physical parameters.

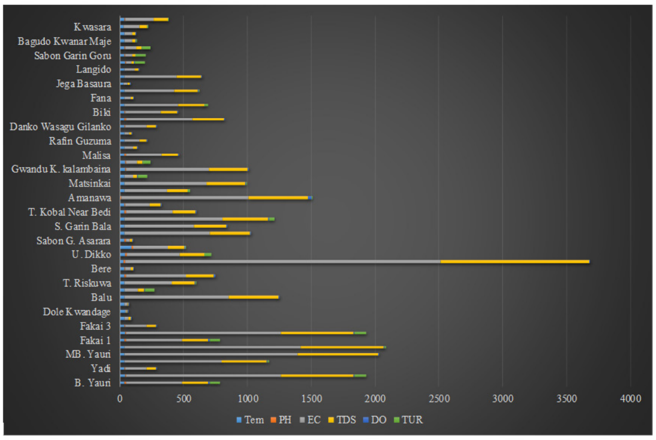

Figure 3 Physical parameters.

Dissolved oxygen (DO) levels range from 0.01 mg/L to 26.80 mg/L, with an average of 4.28 mg/L, below the WHO-recommended range of 6.5–8 mg/L for most samples. Low DO levels may indicate organic pollution or thermal stratification, posing risks to aquatic ecosystems and human health.[66,67] Turbidity values vary from 0.00 NTU to 96.30 NTU, with an average of 18.01 NTU, significantly exceeding the recommended limit of 5 NTU. High turbidity levels suggest the presence of suspended particles that could harbor pathogens and degrade water quality.[68,69] Therefore, the findings show that while some parameters meet the recommended standards, others—especially pH, Turbidity, and occasional spikes in EC and TDS—point to potential contamination and health risks, underscoring the importance of regular monitoring and mitigation efforts.

The water quality issues observed in the Sokoto Basin are closely linked to its geological and environmental features. The acidic pH, high electrical conductivity (EC), and total dissolved solids (TDS) levels indicate interactions between groundwater and the area's sedimentary formations, including shales, sandstones, and limestone, which release dissolved ions and heavy metals. Increased Turbidity may stem from erosion and runoff during the rainy season, which transports suspended particles into water sources.[70,71] Furthermore, low dissolved oxygen (DO) levels and elevated temperatures are affected by the basin's semi-arid climate,[72,73] intensifying evaporation and the breakdown of organic matter, further compromising water quality and highlighting the effects of both natural and human activities.

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Heavy metals concentration in shallow groundwater

Table 3 presents a summary of heavy metals concentrations in shallow groundwater. The results of heavy metal analysis in the shallow groundwater of the Western Sokoto Basin reveal significant spatial and temporal variability, potentially influenced by the geological framework, environmental conditions, and land use patterns. Barium (Ba), with a maximum concentration of 54.10 mg/L, far exceeds the WHO guideline of 1 mg/L, suggesting substantial geological control. Barium enrichment is commonly associated with barite deposits and the weathering of silicate minerals in the region's sedimentary formations,[74,75] particularly in areas underlain by the Gwandu and Illo Formations, which are known to contain feldspathic sandstones and associated sulfides. This highlights the natural geogenic contribution to groundwater contamination, exacerbated by the region's semi-arid climate that limits the dilution and flushing of soluble ions.

Table 3 Summary of heavy metals

Parameters	Ba	Cu	Ni	As
Min	0	0.07	1.58	24.56
Max	54.1	35.74	1.55	7.4
Mean	3.7	1.96	0	9.26
SE	0.99	0.55	0.057	1.05
WHO (2011)	1 mg/L.	2 mg/L	2 mg/L.	10 μg/L
NSDWQ(2007)	-	-	-	-

Copper (Cu) also displays elevated levels, with concentrations reaching 35.74 mg/L in some locations, exceeding the WHO guideline of 2 mg/L. The mean concentration of 1.96 mg/L indicates localized hotspots of contamination rather than pervasive regional pollution. Anthropogenic activities such as mining, improper waste disposal, and agricultural practices may contribute to copper enrichment.[76,77] The use of copper-containing agrochemicals and the disposal of industrial effluents could lead to leaching into groundwater. Additionally, weathering of copper-bearing minerals in the sedimentary sequence may add to its presence in groundwater.[78] Nickel (Ni) concentrations are generally below the WHO guideline of 2 mg/L, with a maximum of 1.55 mg/L. The absence of widespread nickel contamination suggests minimal anthropogenic influence and highlights the low geogenic availability of nickel in the basin's lithological units. However, isolated occurrences may be linked to localized inputs from agricultural activities or the weathering of ultramafic fragments within the basin's sediments.

Arsenic (As) concentrations, with a maximum value of 7.4 μg/L, are below the WHO guideline of 10 μg/L, but its mean negative value suggests possible analytical corrections or the influence of baseline conditions. Arsenic in groundwater often derives from the oxidation of arsenic-bearing sulfides or desorption under reducing conditions.[79,80] In the Western Sokoto Basin, arsenic mobilization may be influenced by fluctuations in the groundwater table and redox conditions, particularly in areas with clayey lithologies that promote reductive dissolution. The observed variability in heavy metal concentrations is also closely tied to land use and environmental factors. Intensive farming practices, particularly in irrigated areas, contribute to the leaching of metals like copper and arsenic from agrochemicals into shallow aquifers.[81,82] Similarly, urbanization and the absence of robust waste management systems result in the percolation of pollutants into groundwater. The semi-arid environment, characterized by low rainfall and high evaporation rates, further concentrates dissolved metals in groundwater, particularly in poorly flushed areas.

The geological framework of the basin plays a pivotal role in shaping the hydrogeochemical characteristics of the groundwater. The sedimentary aquifers, composed of sandstone, clay, and limestone, provide a variable matrix for metal mobilization. The presence of clay layers, for example, may retard the movement of heavy metals, while carbonate-rich units could buffer acidic conditions and precipitate some metals.[83,84] Conversely, the dissolution of minerals in aquifer systems under varying pH and redox conditions can enhance metal mobility.[85,86] In summary, the interplay of geology, environment, and land use significantly influences the distribution of heavy metals in the shallow groundwater of the Western Sokoto Basin.

Barium and copper contamination appear to be predominantly geogenic, with localized anthropogenic inputs, while nickel and arsenic levels remain largely within acceptable limits but could be influenced by site-specific conditions. Understanding these dynamics is crucial for developing targeted interventions to protect groundwater quality in the region. Effective land use planning, improved agricultural practices, and regular groundwater monitoring are essential for mitigating risks and ensuring the sustainability of water resources in the western Sokoto Basin.

Spatial variation and human health impact of arsenic, barium, copper, nickel

The contour plot for nickel (Ni) as illustrated by Figure 4, indicates a more heterogeneous distribution, with localized areas of higher concentrations. Nickel exposure can lead to respiratory and skin problems.[87,88] While the overall levels of nickel in the basin appear to be within acceptable limits, it is essential to monitor areas with elevated concentrations to prevent potential health risks. The spatial variation in the distribution of these elements can be attributed to several factors, including geological formations, anthropogenic activities, and hydrological processes. The basin's underlying geology, comprising various sedimentary formations, can influence the natural background levels of these elements.

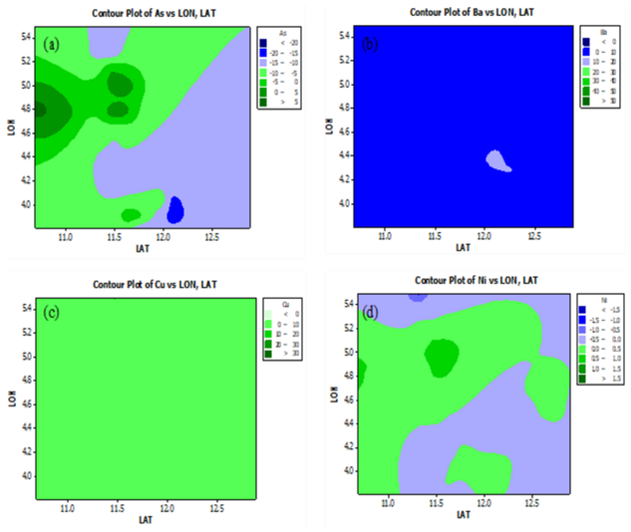

Figure 4 Spatial variation of Heavy metals in Kebbi State.

Additionally, anthropogenic activities such as mining, industrial processes, and agricultural practices can contribute to environmental metal contamination, leading to elevated groundwater levels. Hydrological factors, such as groundwater flow patterns and water table depth, also play a role in the distribution of metals.[89,90] The movement of groundwater can disperse or concentrate metals, depending on the hydrogeological conditions. It is important to note that the health risks associated with these metals depend on various factors, including exposure pathways, duration of exposure,

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and individual susceptibility. Therefore, a comprehensive risk assessment is necessary to evaluate the potential health impacts of these elements in the region. To mitigate the potential health risks associated with these metals, it is crucial to implement effective water quality monitoring programs, promote sustainable water management practices, and educate the public about the potential health risks and preventive measures.

Statistical analysis

This project used several samples: ANOVA, Pearson's Correlation Analysis, and Principal Component Analysis. Table 4 shows the ANOVA results. The study assessed temperature, pH, EC, TDS, DO, TUR, As, Ba, Co and Ni.

Table 4 Pearson Correlation (r)

Parameters	Tem	PH	EC	TDS	DO	TUR	Ba	Cu	Ni	As
Tem		0.067608	0.69342	0.69836	0.95258	0.72531	0.66387	0.92182	0.64537	0.44035
PH	0.23175		0.85993	0.86355	0.37117	0.11216	0.14542	0.36309	0.55311	0.70943
EC	-0.05065	0.022684		1.46E-127	0.000558	0.55533	0.4731	0.85164	0.051949	0.17545
TDS	-0.04979	0.022092	0.99996		0.000551	0.55841	0.4697	0.85171	0.052468	0.17707
DO	-0.00765	0.11459	0.4227	0.42306		0.73521	0.65807	0.76421	0.22875	0.50625
TUR	0.04515	0.20212	0.075717	0.075129	-0.04346		0.51031	0.71416	0.000565	0.10549
Ba	-0.05583	-0.18554	-0.09204	-0.09275	-0.05685	-0.08449		0.5794	0.33549	0.79519
Cu	-0.01262	0.11653	-0.02404	-0.02403	0.038549	-0.04706	-0.07117		0.83627	0.36823
Ni	0.059114	0.076141	0.24601	0.24549	0.15381	0.42231	-0.12335	0.026565		0.007469
As	-0.09896	0.047878	0.17287	0.17224	0.085298	0.20588	-0.03336	-0.11529	0.33399	

Pearson's correlation (r)

Table 4 shows the correlation between physicochemical parameters. The correlation analysis results provide an insightful perspective on the interactions among various water quality parameters, such as temperature (Tem), pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), turbidity (TUR), and several metals (barium [Ba], copper [Cu], nickel [Ni], and arsenic [As]). Understanding these correlations is fundamental for interpreting water chemistry in environmental studies, as it helps reveal underlying relationships and patterns that may signify specific hydrological or geochemical processes. This study examined the significance of the positive and negative correlations observed, noting any potential causal implications or environmental phenomena that may drive these relationships.

Temperature shows a notably strong positive correlation with DO (0.95258), implying that the dissolved oxygen level rises as temperature increases.[91,92] This correlation may seem counterintuitive since higher temperatures generally reduce oxygen solubility in water. However, this result could indicate that DO levels are influenced by factors other than temperature, such as biological activity or specific water treatment methods that influence temperature and DO. The strong positive relationship between temperature and Turbidity (0.72531) further reinforces this, as warmer temperatures can encourage algal blooms or enhance the dissolution of organic materials, leading to increased turbidity.[93,94] A substantial positive correlation also exists between temperature and EC (0.69342) and TDS (0.69836), suggesting that warmer waters might enhance the dissolution of ionic compounds, thereby increasing conductivity and dissolved solids.[95] Additionally, the strong correlation between temperature and Ni (0.92182) and significant positive relationships with other metals such as Ba (0.66387) indicate that temperature might influence the mobilization of metals in water, possibly through changes in solubility or redox reactions that affect metal release from sediments.[96,97]

The pH exhibits a high positive correlation with EC (0.85993) and TDS (0.86355), signifying that pH variations could influence the concentration of dissolved solids and ions. Alkaline or acidic conditions may facilitate the dissolution or precipitation of various ionic species, impacting conductivity and total dissolved solids.[98,99] The pH correlation with arsenic (0.70943) is particularly noteworthy, as arsenic solubility is highly sensitive to pH conditions. This association suggests that changes in pH could influence arsenic availability, likely impacting its mobility in groundwater systems. A significant relationship exists between pH and DO (0.37117), although weaker than other associations. This correlation might reflect pH's role in affecting biological and chemical reactions that influence DO concentration, such as photosynthesis or organic matter decomposition, both of which affect oxygen dynamics in aquatic systems.[100,101]

The correlation between EC and TDS is essentially perfect (1.46E-127), an expected outcome as TDS measures the concentration of dissolved solids, directly impacting water's electrical conductivity. The significant correlation of EC with DO (0.55533) and TUR (0.075717), although weaker, might suggest that higher ion concentrations and Turbidity can influence oxygen levels, possibly through their roles in nutrient availability and subsequent biological activity.[102,103] EC's relationship with Ba (0.4731) and Cu (0.85164) indicates that the presence of these metals could be linked to ion-rich conditions, which may facilitate the dissolution of metal ions or result from geochemical weathering that releases these metals alongside other ions. The significant correlation between EC and arsenic (0.17545) may reflect arsenic's common association with specific ions or minerals in the water, such as those containing sulphur or iron, which can affect conductivity.[104,105]

Similarly, TDS's correlation with most parameters parallels that of EC, given their near-identical relationship. The correlation with DO (0.55841) underscores that dissolved solids can indirectly influence oxygen levels by affecting the biological and chemical characteristics of the water. For instance, higher TDS could support more microbial or algal activity, both consuming oxygen.[104,105] The strong correlation of TDS with Cu (0.85171) again suggests a possible link between ionic concentration and metal solubility, implying that higher dissolved solids may also lead to increased metal concentrations in water.[106,107] TDS's correlation with arsenic (0.17707) might indicate that dissolved solids, often derived from minerals and salts, may include or facilitate the presence of arsenic-bearing compounds in solution.[80,108]

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DO shows significant positive correlations with several parameters, notably temperature and Turbidity. The high correlation with temperature (0.95258) could reflect the indirect effects of temperature on DO, where warm temperatures might enhance organic and biological activity, potentially elevating oxygen levels through photosynthesis during the day.[109] However, the correlation with Turbidity (0.73521) suggests suspended particles may influence oxygen dynamics, likely through biological activity or chemical processes associated with particulate matter.[110,111] The moderate correlation with Ba (0.65807) and Ni (0.76421) suggests that metals may be affected by oxygen levels in water, as oxygen can impact the redox state of metals, influencing their solubility and mobility.[112,113]

Turbidity (TUR) is positively correlated with several parameters, though generally weaker than temperature and pH. The correlation with DO (0.73521) might reflect the role of particulate matter in enhancing microbial or algal activity, which could influence oxygen concentrations.[110,114] Turbidity's weaker association with Ba (0.51031) and Cu (0.71416) may indicate that metals can be associated with suspended particles, affecting water clarity. Interestingly, Turbidity negatively correlates with Ni (0.000565), which might reflect Ni's distinct geochemical behavior, possibly existing in a dissolved form rather than being associated with particulate matter, unlike other metals.[115,116] This difference could suggest that Ni has a different source or pathway in the aquatic environment.

Barium (Ba) displays moderate correlations with several parameters, including temperature (0.66387) and DO (0.65807). These associations suggest that Ba concentrations may be influenced by both temperature and oxygen availability, which could affect its solubility or the geochemical processes releasing Ba into the water.[117,118] Its correlation with Cu (0.5794) might indicate that these two metals share similar sources or geochemical pathways, possibly originating from mineral dissolution or anthropogenic activities. The lack of a strong correlation between Ba and Turbidity (0.51031) suggests that Ba may essentially exist in dissolved forms rather than being associated with suspended particles, contrasting with metals like Cu.[119,120]

Copper (Cu) shows a strong positive correlation with EC and TDS, both around 0.85, suggesting that Cu may be closely associated with dissolved ions in the water, potentially indicating anthropogenic or mineral-derived sources.[121] Its positive relationship with Ni (0.83627) suggests a similar origin or pathway in the water system. Cu's lack of strong correlation with arsenic (0.36823) implies that the two elements may behave differently under the given water chemistry conditions,[122,123] with Cu more readily associating with dissolved ions than arsenic, which might be controlled by pH.

Nickel (Ni) shows strong positive correlations with temperature (0.92182), DO (0.76421), and Cu (0.83627), suggesting that Ni concentration is influenced by both geochemical and biological processes, which might be temperature or oxygen-sensitive.[124,125] The correlation with arsenic (0.33399) is weaker, indicating that while both elements might exist in similar environments, their geochemical behaviours diverge under specific conditions, possibly due to redox-sensitive processes. Ni's low correlation with Turbidity (0.000565) implies it is primarily dissolved, aligning with its typical behavior in aqueous systems.[126]

Arsenic (As) shows notable positive correlations with pH (0.70943) and Ni (0.33399), reflecting its sensitivity to changes in pH and association with redox processes.[127,128] Arsenic's moderate correlation with temperature (0.44035) and Turbidity (0.10549) suggests that it may respond to environmental conditions indirectly, possibly through processes that mobilize it from sediments or minerals under varying conditions. The relatively weaker correlations with other parameters like Ba and Cu indicate that arsenic follows a different geochemical pathway, potentially influenced by pH and redox conditions rather than overall ionic composition.[80,129] Therefore, this correlation analysis offers insights into how environmental parameters interact within water systems. Temperature, EC, and TDS significantly influence the solubility and mobility of metals, while DO and Turbidity affect biological and chemical oxygen dynamics.[130,131] These relationships underscore the complexity of water chemistry, where parameters are interlinked through both direct and indirect processes, highlighting the need for comprehensive monitoring to understand water quality dynamics.

Principal component analysis

This study employed PCA to analyse the data (Table 5) further. The table provided presents a principal component analysis (PCA) of various water quality parameters, with five principal components (PC 1 to PC 5) listed alongside the eigenvalues and the variance each component accounts for. The parameters included are temperature (Tem), pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), turbidity (TUR), and concentrations of metals such as barium (Ba), copper (Cu), nickel (Ni), and arsenic (As). Each parameter has a corresponding loading in each principal component, indicating the degree to which that parameter contributes to each component (Table 5).

Table 5 Principal Component Analysis

Parameters	PC 1	PC 2	PC 3	PC 4	PC 5
Tem	-0.015	0.29	0.402	0.617	0.192
PH	0.105	0.419	0.448	0.095	0.034
EC	0.561	-0.266	0.065	0.073	-0.003
TDS	0.561	-0.266	0.066	0.073	-0.003
DO	0.361	-0.187	0.233	0.023	0.127
TUR	0.19	0.535	-0.237	-0.018	0.145
Ba	-0.134	-0.249	-0.307	0.254	0.831
Cu	-0.013	0.048	0.415	-0.715	0.439
Ni	0.335	0.4	-0.233	-0.126	0.189
As	0.25	0.231	-0.444	-0.08	-0.068
Eigenvalue	2.549	1.562	1.316	1.015	0.894
% variance	25.489	15.625	13.155	10.148	8.938

Each PC is a linear combination of the original parameters, weighted by the loadings in Table 5. The loadings can be positive or negative, signifying either a direct or inverse relationship of each parameter with the corresponding principal component. The eigenvalue associated with each component represents the variance captured by that component.[132,133] For example, PC 1 has an eigenvalue of 2.549, accounting for approximately 25.5% of the total variance, while PC 5 has an eigenvalue of 0.894, accounting for 8.9%.

Principal component 1 (PC 1)

PC 1 has the highest eigenvalue (2.549) and explains 25.49% of the total variance in the dataset. This component is primarily influenced by EC, TDS, DO, and Ni, with loadings of 0.561, 0.561, 0.361, and 0.335, respectively. The strong positive loadings of EC and TDS suggest that PC 1 is closely associated with parameters related to the ionic composition and dissolved solids in water, which could indicate salinity or mineral content.[134] High EC and TDS levels can impact water quality and potentially indicate the presence of dissolved inorganic salts, which may arise from natural sources, agricultural runoff, or industrial waste.[135] The positive loading of DO implies that

PC 1 also considers oxygenation levels in the water, which are critical for supporting aquatic life. However, the relatively lower loading of DO (0.361) compared to EC and TDS indicates that while oxygen content is relevant to this component, it is not as dominant a factor. Nickel (Ni) also shows a positive loading, which could be due to the presence of nickel as a trace metal influenced by mineral dissolution or contamination from anthropogenic sources.[136]

Principal component 2 (PC 2)

PC 2 explains 15.62% of the variance and is most heavily influenced by Turbidity (TUR) and pH, with loadings of 0.535 and 0.419, respectively. The high loading of Turbidity suggests that PC 2 represents factors related to water clarity and suspended solids. High turbidity levels can affect aquatic ecosystems by reducing light penetration, which can impair photosynthesis in aquatic plants and algae.[137,138] Furthermore, Turbidity is often an indicator of erosion, runoff, or pollution. The positive loading for pH suggests that PC 2 might also reflect the acidity or alkalinity of the water, a parameter that interacts with Turbidity in affecting water quality. For example, a shift in pH can affect the solubility of minerals and metals, thereby influencing Turbidity indirectly.[99] Temperature (Tem) has a smaller positive loading (0.290) in PC 2, hinting at a mild association with this component, potentially due to its effect on physical and chemical processes in the water.

Principal component 3 (PC 3)

PC 3 accounts for 13.16% of the variance and has notable loadings for temperature (0.402), pH (0.448), and copper (Cu, 0.415). The significant loading for temperature suggests that this component is sensitive to thermal variations, which can impact several chemical and biological processes in water.[139] Water temperature affects the solubility of gases, the rate of biological reactions, and the stability of various compounds, all of which can impact water quality. The positive loading of pH in PC 3 indicates that this component also reflects the influence of water's acidity or alkalinity, which can interact with temperature in affecting the solubility and mobility of dissolved substances.[140] The substantial loading of copper (Cu) in this component might indicate its association with industrial or agricultural contaminants, which could be temperature-sensitive in their mobility or solubility in water. The association of Cu with temperature and pH may suggest that PC 3 reflects contamination that could fluctuate with environmental factors, such as seasonal temperature changes or pH variations due to biological activity.[141]

Principal component 4 (PC 4)

PC 4 has an eigenvalue of 1.015, capturing 10.15% of the variance. This component has strong loadings for temperature (0.617) and copper (-0.715), suggesting a complex interaction between these parameters. The high positive loading for temperature implies that PC 4 may relate to variations in thermal conditions, similar to PC 3. However, the strong negative loading for Cu suggests that copper concentration may decrease as temperature increases or vice versa.[142,143] This inverse relationship could indicate processes where temperature and Cu concentrations are indirectly linked, perhaps through chemical equilibria or biological uptake mechanisms that vary with thermal conditions.[144] The smaller positive loadings for Ba (0.254) and Ni (-0.126) in PC 4 indicate these metals may be involved in similar processes or environmental conditions as Cu but to a lesser extent. The inverse relationship between temperature and Cu could suggest that this component reflects environmental or seasonal dynamics that impact metal concentrations differently, perhaps due to thermal stratification or seasonal runoff.[145]

Principal component 5 (PC 5)

PC 5, with an eigenvalue of 0.894, explains 8.94% of the total variance. Ba primarily influences this component, with a high loading of 0.831. The heavy weighting of Ba in PC 5 suggests that this component may be closely related to factors affecting barium concentrations in water, which could stem from geological sources or anthropogenic activities like mining and drilling. The positive loadings of Cu (0.439) and Ni (0.189) in PC 5, though smaller than Ba, indicate that PC 5 may reflect conditions or sources associated with trace metals, albeit with a more substantial influence from barium. Ba concentrations can indicate groundwater or surface water contamination from industrial processes, and its positive association with Cu could indicate co-contamination sources or similar behaviours in response to environmental factors.[146,147] Figure 5 further illustrates the variability of the data.

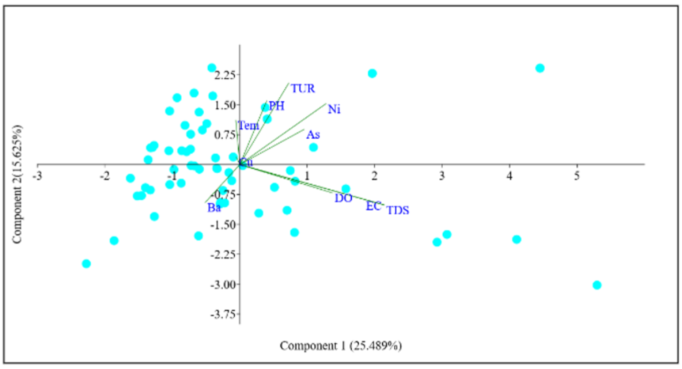

Figure 5 Biplot of components 1 and 2. (Centralize the figure).

The eigenvalues represent the variance each principal component explains in the dataset. PC 1, with an eigenvalue of 2.549, explains the highest percentage (25.49%) of the variance, highlighting it as the dominant component in this analysis. PC 2, with an eigenvalue of 1.562, explains 15.62% of the variance, followed by PC 3 (13.16%), PC 4 (10.15%), and PC 5 (8.94%). The cumulative variance explained by the first three components is 54.27%, meaning more than half of the dataset's variability can be represented alone. This suggests that while PCs 4 and 5 capture unique information, most of the dataset's structure is encapsulated by the first three components. This distribution is typical in environmental datasets, where a few dominant factors often explain most of the variability, while additional components capture smaller-scale variations or specific aspects of the data.

Implications for water quality monitoring

In water quality management, PCA results can be highly informative for prioritizing monitoring efforts. For instance, the prominence of EC, TDS, and DO in PC 1 suggests that these are primary indicators of water quality in this dataset, possibly influenced by factors like mineral content, pollution, or salinity. Monitoring these parameters might provide a reliable overall assessment of water quality and potential pollution sources. PC 2's association with Turbidity and pH underscores the importance of tracking these parameters in managing water clarity and acidity. Elevated Turbidity can signal contamination or erosion, which could warrant targeted interventions to protect aquatic life and drinking water sources. Similarly, the associations observed in PC 3 and PC 4 with temperature, pH, and trace metals like Cu and Ni could guide efforts to monitor seasonal or environmental fluctuations. Finally, PC 5's focus on barium highlights potential contamination sources related to industrial activities, which could be crucial for assessing anthropogenic impacts on water quality. This PCA analysis provides a framework for targeted, cost-effective monitoring by identifying the key components and their associated parameters, which are the most indicative of variations in water quality in this specific context.

Conclusion

This study indicates our continuous attempt to increase our understanding of heavy metals distribution in shallow groundwater by assessing heavy metals (As, Ba, Co, and Ni) pollution in rural drinking water sources, using correlation and principal component analysis in the Western Sokoto Basin. The study assessed 63 rural drinking water sources. The results of physical parameters (pH, temperature, EC, TDS, DO, and Turbidity) showed that temperature (32.8–39.8°C) and pH (4.4–9.4), with acidic conditions (mean 4.98) below WHO/NSDWQ limits (6.5–8.5). Electrical conductivity (EC) and TDS are acceptable except for maxima exceeding limits. Dissolved oxygen (0.01–26.8 mg/L) and Turbidity (0–96.3 NTU) indicate localized pollution, surpassing 5 NTU standards. There is slight acidity observed in some wells, which points to either natural geochemical processes or possible contamination from agricultural activities. An acidic pH can increase the solubility of heavy metals in groundwater, making continuous monitoring essential.

The analysis of heavy metals in shallow groundwater of the western Sokoto Basin shows Barium (Ba) with a maximum concentration of 54.10 mg/L, exceeding the WHO guideline (1 mg/L). Copper (Cu) reaches 35.74 mg/L, surpassing the 2 mg/L limit, while Nickel (Ni) and Arsenic (As) remain below their respective thresholds. Given the health implications of arsenic, any detectable level of arsenic in groundwater is concerning. The sporadic elevated levels observed could stem from geological deposits and anthropogenic factors such as pesticide use, as arsenic is often present in agrochemicals. The variability in barium levels suggests localized sources, potentially natural but possibly influenced by agricultural or industrial runoff. Barium can adversely affect cardiovascular health, emphasizing the importance of targeted monitoring. Though Copper and Nickel are less abundant, the presence of copper and nickel warrants attention due to potential accumulation in tissues. Copper, while an essential nutrient, can be toxic at high levels, leading to gastrointestinal distress and liver damage. Nickel poses risks of dermatitis and lung cancer with long-term exposure, even at low levels.

Some sampling locations near agricultural zones showed elevated levels of heavy metals, indicating that agrochemicals could be a source of contamination. This spatial correlation underscores the importance of location-specific studies to understand the interplay between agricultural practices and groundwater quality. The study's spatial analysis suggests a direct relationship between groundwater contamination and human activities, including waste disposal, agrochemical runoff, and Industrial emissions.

Recommendations for future research

This study focused on specific sites in Kebbi State. Future studies should expand the sampling network to provide a more comprehensive understanding of groundwater quality, covering more rural and peri-urban areas. High-Frequency Sampling. Longitudinal and Cross-Seasonal Analysis, Monitoring Seasonal Trends, Evaluation of Seasonal Peaks, Source Identification Studies, and Health Risk Assessment Studies. Concerning policy recommendations and interventions, there is a need for the development of water quality standards and monitoring guidelines: Awareness and education programs, sustainable agricultural practices, integration of smart monitoring tools, use of smart sensors and IoT for real-time monitoring and community-level data accessibility.

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Conflicts of interest

The author declares there is no conflict of interest.

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