

Heavy metal contamination assessment of the Taloka and Wurno aquifers, Sokoto Basin, northwestern Nigeria

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Abstract

A comprehensive heavy metal pollution assessment of the Taloka and Wurno aquifers within the Sokoto Basin, northwestern Nigeria, was carried out. Field mapping, borehole logging and water quality analysis were integrated to describe the distribution of heavy metals in groundwater. Heavy metal evaluation points to variations between the Taloka and Wurno aquifers. A plausible hypothesis is that the dissolution of iron-rich lithologies in the Taloka aquifer contributes to the elevated iron (Fe) concentrations observed in the Taloka Formation. In contrast, redox reactions involving organic-rich shales and limestones of the overlying Dange Formation may contribute to the relatively higher concentrations of potentially toxic metals, particularly lead (Pb) and arsenic (As), observed in the Wurno Formation. The Wurno aquifer is also more vulnerable to surface contamination due to its shallower stratigraphic position. The concentrations of As and Pb in a substantial number of groundwater samples from both aquifers exceed the World Health Organization (WHO) safe limits for heavy metals in drinking water. The findings indicate a possible combined geogenic and anthropogenic influence on groundwater quality in both aquifers and highlight the need for continuous groundwater monitoring, targeted water treatment interventions and sustainable aquifer management strategies.

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1. Introduction

The Iullemeden Basin is an intracratonic sedimentary basin extending across West and North Africa, specifically covering parts of Nigeria, Niger, Mali and Algeria [1, 2]. The southeastern part of the basin (the Nigerian sector) is locally referred to as the Sokoto Basin. Typical of intracratonic basins, the Iullemeden Basin formed within stable continental interiors and was characterised by subsidence accompanied by the accumulation of thick sedimentary successions over geologic

time [1]. The Nigerian sector of the basin, known as the Sokoto Basin, covers Sokoto State and parts of Zamfara, Kebbi and Katsina States. The basin constitutes the hydrogeological system supporting groundwater resources in semi-arid northwestern Nigeria [3].

The Maastrichtian Rima Group within the Sokoto Basin is of particular hydrogeological significance and consists of the Taloka, Dukamaje and Wurno Formations. The Taloka and Wurno Formations are prolific aquifer units because of their relatively high porosity and permeability. In terms of lithology, the aquifers consist of siltstones and very fine sandstones. The Dukamaje Formation, on the other hand, is predominantly composed of gypsiferous shales [4, 5].

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Heavy metal pollution in groundwater is a major environmental and public health concern in Nigeria and globally [6]. Arsenic (As), cadmium (Cd), chromium (Cr) and lead (Pb) constitute some of the most concerning heavy metal pollutants because of their persistence, bioaccumulation potential and toxicity [7, 8]. Iron (Fe) is also of concern because, although it is an essential micronutrient, its excessive concentration in domestic water sources can lead to problems such as discolouration of storage facilities and toilet fittings, metallic taste and scaling. Although the World Health Organization (WHO) permissible limit for iron in drinking water is 0.3 mg/L, significantly higher concentrations have been reported in groundwater samples within the Sokoto Basin [9–11].

Even at very low concentrations, heavy metals such as As, Cd, Cr and Pb are very toxic and are associated with a wide range of health effects, such as neurotoxicity, developmental disorders, renal failure and cancer [12–16]. In rural communities that rely on untreated groundwater for domestic purposes, the population faces chronic exposure to these metals, posing a significant health risk [17–19]. Both adults and children are at risk, as was the case in some rural villages in Zamfara in 2010 [20].

Groundwater hydrogeochemistry within the Sokoto Basin needs to be understood at a deeper and aquifer-specific level. This will be essential for effective contamination remediation and overall groundwater resource management. It is expected that this research will contribute to policy formulation and community-level water treatment initiatives while also inspiring further research in the field of hydrogeochemistry and water resource management.

2. Methodology

An integrated approach was adopted for the study methodology. Field investigations and laboratory experiments were combined to evaluate the baseline heavy metal pollution status of groundwater in the study area. The study area is restricted to Sokoto Metropolis, which is covered by sedimentary formations of the Sokoto Basin and was selected because of reported elevated heavy metal levels in shallow and deep wells. Land use and land cover in the study area are dominated by human infrastructure and fertile agricultural land. A notable section of the study area is the Fadama (floodplain) area (Figure 1), which occupies low-lying portions towards the north of the study area. The Fadama is intensively utilised for irrigation farming involving the heavy application of agrochemicals. Detailed geological mapping was conducted at a scale of 1:12,500 using systematic traverse methods. Rock exposures along river channels and road cuts were also examined. The geology of Sokoto Metropolis is already well established, so the mapping was carried out for revalidation purposes.

Borehole logging was conducted during drilling and involved systematically collecting and recording geological and drilling information as the borehole advanced. As drilling progressed, samples were collected at 1-m intervals. The samples were immediately described in terms of lithology, colour, grain size, texture and moisture content. At the same time, drilling

parameters such as penetration rate, torque and mud properties were recorded, as they are indicators of changes in the formation. Water strikes were noted, including their approximate depths and flow characteristics. The samples collected were labelled and stored properly, with the depth and borehole identification clearly written on each sample. The observations were finally compiled into a borehole litholog showing depth, lithology and hydrogeological attributes.

Fourteen (14) groundwater samples from the Taloka aquifer and eleven (11) groundwater samples from the Wurno aquifer, making a total of twenty-five (25) groundwater samples, were collected across Sokoto Metropolis according to the standard procedures of the American Public Health Association (APHA) [21]. The samples were collected at wellheads during the dry season. Sampling wells were pumped until pH had stabilised before the samples were collected in 250 mL high-density polyethylene (HDPE) bottles and acidified to a pH value below 2 with concentrated nitric acid (HNO₃). In the laboratory, total recoverable metals were targeted, so the samples were not filtered prior to digestion. The samples were digested by transferring 100 mL into a digestion flask and adding concentrated nitric acid. The mixture was heated until a clear solution was obtained, ensuring complete dissolution of metals. The mixture was allowed to cool and was diluted back to 100 mL with deionised water.

Fe was determined by flame atomic absorption spectroscopy (AAS), while trace concentrations of As, Pb, Cd, Cr and nickel (Ni) were determined by graphite furnace AAS; cold vapour AAS was used for mercury (Hg). Analytical quality assurance and quality control (QA/QC) were implemented throughout the AAS analysis to ensure the accuracy, precision and reliability of the analytical results. Calibration of the AAS was performed using appropriate certified calibration standards covering the expected concentration ranges of the analysed elements, and calibration curves were generated for each analyte. The linearity of the calibration curves was verified using the corresponding coefficients of determination, R². Certified reference materials (CRMs) were also analysed to evaluate analytical accuracy, and recoveries ranged from 92% to 95.8% (see Table 1). The method detection limits (LODs) were determined as reported in Table 2; all readings below the detection limit (BDL) were treated as zero during data analysis. The calibration, blank and CRM results met the laboratory's established acceptance criteria.

The modified degree of contamination (mCD) was employed to examine the degree of heavy metal contamination in both aquifers. Unlike the conventional contamination degree (CD), which is calculated by summing contamination factors [22], the mCD allows for an average measure of contamination across all investigated elements, thereby ensuring that the overall contamination status is not overly influenced by the number of contaminants evaluated in the study. The formula is given by [23] as

$$\text{mCD} = \frac{\sum_{i=1}^n C_f^i}{n}, \quad (1)$$

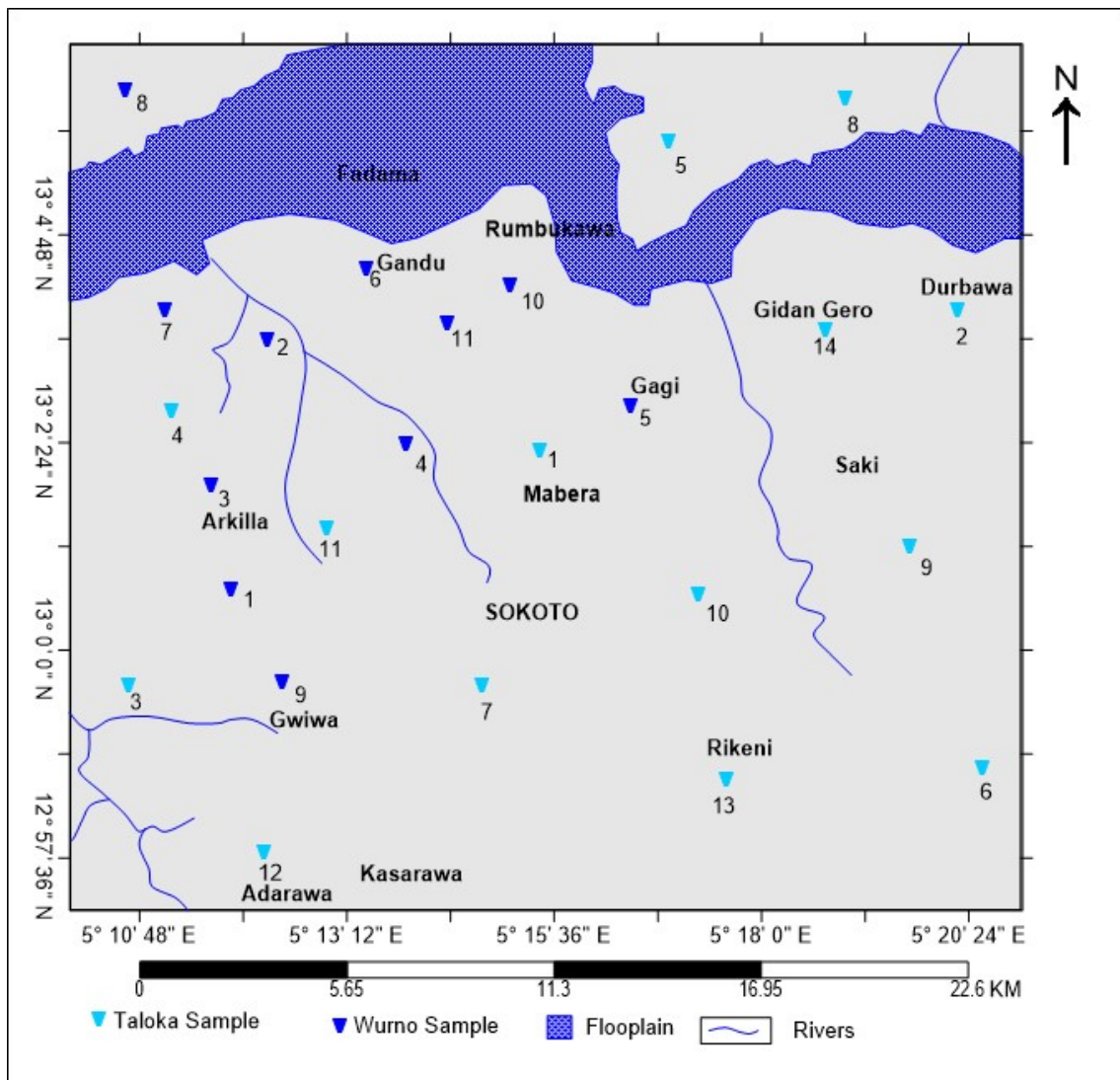


Figure 1: Study area map.

Table 1: Certified reference material (CRM) results.

Element	Certified value	Measured value	Recovery (%)	Acceptance	Status
Iron (Fe)	93.44 ± 0.78	88.21	94.4	80–120%	PASS
Lead (Pb)	18.488 ± 0.084	17.25	93.3	80–120%	PASS
Chromium (Cr)	18.50 ± 0.13	17.02	92.0	80–120%	PASS
Cadmium (Cd)	5.89 ± 0.13	5.64	95.8	80–120%	PASS
Arsenic (As)	57.42 ± 0.38	54.16	94.3	80–120%	PASS
Nickel (Ni)	44.1 ± 0.33	41.45	94.0	80–120%	PASS
Mercury (Hg)	1.44 ± 0.07	1.35	93.8	80–120%	PASS

where C_f is the contamination factor of the i th heavy metal and n is the total number of heavy metals calculated. The contamination factor is given by

$$C_f = \frac{C_i}{C_{ref}^i}, \quad (2)$$

where C_i is the concentration of metal i in the sample and the reference concentration is the reference or background concentration for metal i . For this study, the WHO (2011) permissible limit was adopted as the reference concentration. The mCD was interpreted using a rating scale, as shown in Table 3. It should be noted that the rating scale was initially developed for

Table 2: Detection limits.

Element	Blank SD	LOD ($\mu\text{g/L}$)
Iron (Fe)	0.319	0.956
Lead (Pb)	0.175	0.525
Chromium (Cr)	0.477	1.43
Cadmium (Cd)	0.000433	0.013
Arsenic (As)	0.109	0.327
Nickel (Ni)	0.328	0.985
Mercury (Hg)	0.068	0.203

Table 3: Classification and description of the modified degree of contamination (mCD), after Ref. [23].

mCD	Interpretation
< 1.5	Nil to very low degree of contamination
1.5–<2	Low degree
2–<4	Moderate degree
4–<8	High degree
8–<16	Very high degree
16–<32	Extremely high degree
≥ 32	Ultra-high degree

classifying sediment pollution.

The Mann–Whitney U test was employed to determine whether significant differences existed in the modified contamination degree between groundwater samples from the Taloka and Wurno aquifers. The test was two-tailed and evaluated at a significance level of $p = 0.05$.

This study has some limitations. All BDL readings were treated as zero, which could potentially underestimate metal concentrations. The application of the sediment-based modified degree of contamination to groundwater may limit its validity. Sampling bias may have been introduced because the study location was selected based on previously reported high metal concentrations. Sampling at wellheads also presents a potential risk of metal contamination from corrosion of metallic well components, although this is considered unlikely because wells were sampled not long after completion. Finally, certified reference material recoveries of 92–96%, while generally acceptable, suggest possible underestimation of metal concentrations.

3. Results

3.1. Geology

Extensive field mapping reaffirmed the established geology of the study area. Lithological features that fundamentally influence groundwater chemistry and heavy metal distribution were identified. The major lithologies encountered include oolitic ironstones, which are prominent in the Dundaye area, and limestone units of the Kalambaina Formation in the Dandima area. They are, however, not restricted to these locations where they outcrop; rather, they form part of a laterally

continuous sedimentary sequence comprising ironstone, limestone, shale and siltstone. The observations indicate a depositional history characterised by alternating chemical and clastic sedimentation.

3.2. Borehole logs

Borehole logs from a well tapping into the Taloka Formation at Ofa Road (Figure 2) show a sequence of fine- to coarse-grained sandstone with intermittent claystone and ironstone horizons. The aquifer occurs between 100–104 m below ground level (bgl), with an average saturated thickness of 4 m. The Taloka aquifer is stratigraphically confined below the Dukamaje Formation and carbonaceous shales from the Taloka Formation.

The Wurno Formation well at Lodge Road (Figure 3) consists of a siltstone/silty sandstone sequence, with the aquifer zone located at 67–74 m below ground level (bgl) and a saturated thickness of 7 m. The Wurno aquifer is confined by the Dange Formation. This siltstone is a marine-influenced deposit (marginal marine depositional environment) containing pyrite, glauconite and clay minerals.

3.3. Heavy metal concentration

The results of the heavy metal analysis are presented in Table 4.

3.3.1. Iron (Fe)

Iron (Fe) concentrations in the Taloka aquifer ranged from 0.124 mg/L to 14.36 mg/L, with a mean value of 2.026 mg/L (Table 5). Water samples from 71% of the sampling points in the Taloka aquifer exceeded the WHO permissible limit of 0.3 mg/L. For the Wurno aquifer, Fe concentrations ranged from 0.122 mg/L to 2.41 mg/L, with a mean value of 0.82 mg/L. Water samples from 64% of the sampling points in the Wurno aquifer exceeded the WHO permissible limit. The relatively higher concentration of Fe in the Taloka Formation is consistent with the presence of more iron-rich beds within the Taloka Formation.

3.3.2. Lead (Pb)

In the Taloka aquifer, Pb ranged from BDL to 0.408 mg/L (mean: 0.058 mg/L), with 43% of samples exceeding the World Health Organization (WHO) guideline (Table 6). In the Wurno aquifer, Pb ranged from BDL to 0.403 mg/L (mean: 0.110 mg/L), with 5 of 11 samples (46%) exceeding the limit. The higher Pb concentration in Wurno could be attributed to anthropogenic sources due to its shallower stratigraphic position.

3.3.3. Arsenic (As)

In the Taloka aquifer, As ranged from 0.004 to 0.014 mg/L (mean: 0.011 mg/L), with 71% of samples exceeding the World Health Organization (WHO) guideline (Table 7). In the Wurno aquifer, As ranged from 0.009 to 0.014 mg/L (mean: 0.012 mg/L), with 8 of 11 samples (73%) exceeding the limit.

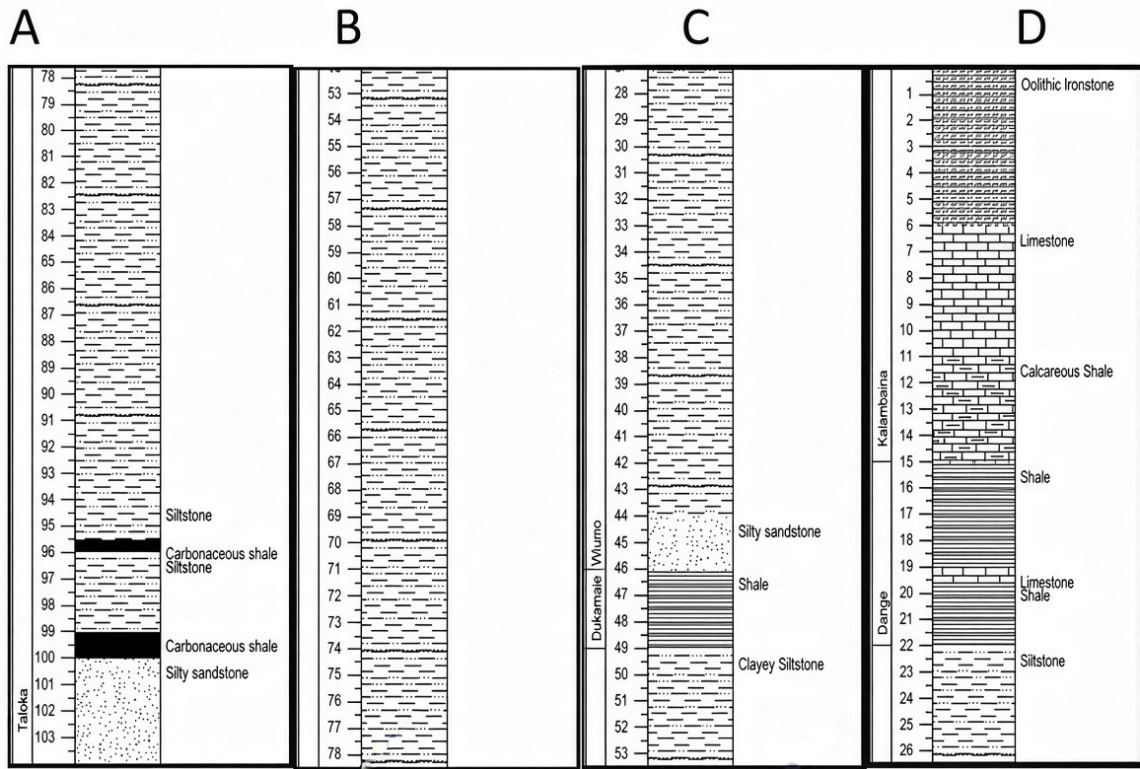


Figure 2: Borehole log of a well tapping the Taloka Formation at Ofa Road, Sokoto Metropolis.

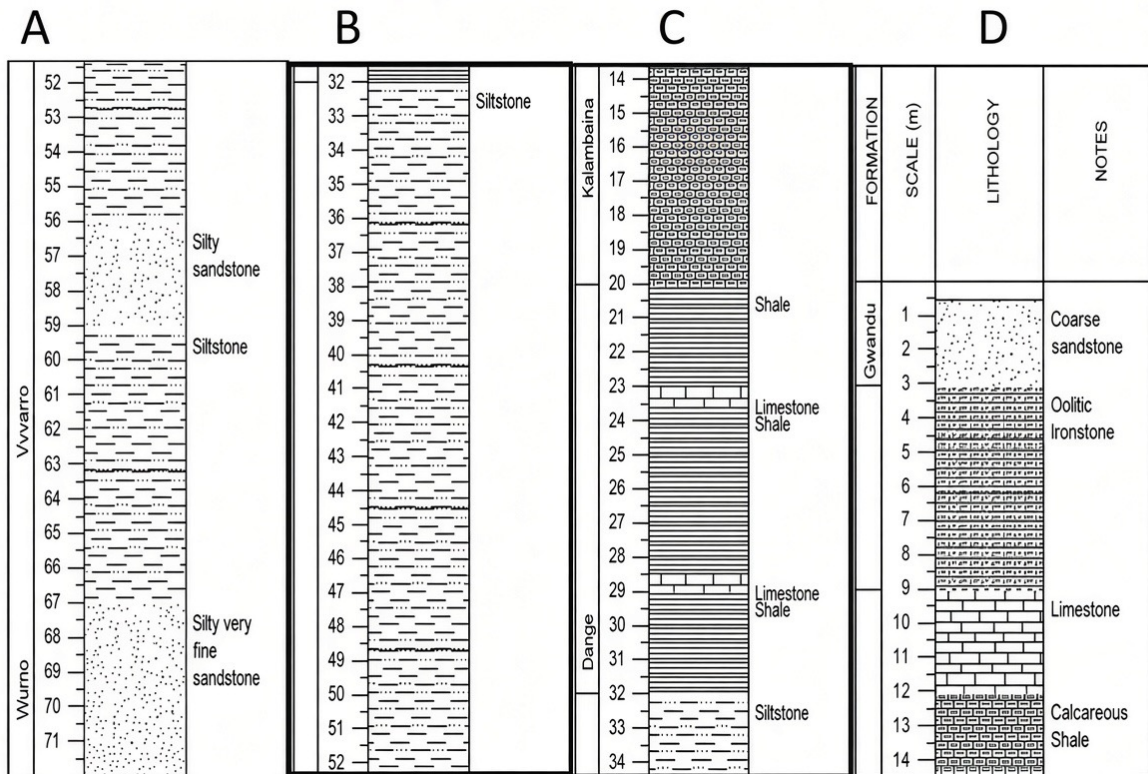


Figure 3: Borehole logs of a well tapping the Wurno Formation at Lodge Road, Sokoto Metropolis.

Table 4: Heavy metal concentrations in groundwater from the Taloka and Wurno aquifers.

Sample ID	Fe (mg/L)	Pb (mg/L)	As (mg/L)	Cr (mg/L)	Cd (mg/L)	Hg (mg/L)	Ni (mg/L)
TLK 01	0.641	0.024	0.012	0.007	BDL	BDL	0.005
TLK 02	1.94	0.008	0.012	0.005	BDL	BDL	0.006
TLK 03	0.44	0.091	0.011	0.003	BDL	BDL	0.003
TLK 04	3.815	BDL	0.013	0.002	BDL	BDL	0.005
TLK 05	0.446	0.408	0.005	0.011	BDL	BDL	BDL
TLK 06	0.528	BDL	0.011	0.034	BDL	BDL	BDL
TLK 07	14.36	BDL	0.012	0.009	BDL	BDL	BDL
TLK 08	4.401	0.124	0.008	0.007	BDL	BDL	BDL
TLK 09	0.165	0.071	0.013	0.007	BDL	BDL	BDL
TLK 10	0.62	0.085	0.014	0.017	BDL	BDL	BDL
TLK 11	0.501	BDL	0.004	0.076	0.081	BDL	BDL
TLK 12	0.168	BDL	0.009	0.006	0.001	BDL	BDL
TLK 13	0.124	BDL	0.013	0.067	0.002	BDL	BDL
TLK 14	0.213	BDL	0.014	0.041	0.008	BDL	BDL
WUR 01	0.149	BDL	0.013	0.007	BDL	BDL	BDL
WUR 02	0.158	BDL	0.013	0.019	BDL	BDL	BDL
WUR 03	0.238	0.2	0.012	0.007	BDL	BDL	BDL
WUR 04	1.449	BDL	0.009	0.031	BDL	BDL	BDL
WUR 05	2.41	0.009	0.012	0.02	BDL	BDL	BDL
WUR 06	0.563	0.402	0.014	0.045	BDL	BDL	BDL
WUR 07	1.038	0.403	0.01	0.017	BDL	BDL	0.005
WUR 08	0.122	0.052	0.014	0.026	BDL	BDL	BDL
WUR 09	0.458	0.144	0.013	0.016	BDL	BDL	BDL
WUR 10	1.026	BDL	0.013	0.017	0.01	BDL	BDL
WUR 11	1.413	0.001	0.01	0.053	0.006	BDL	BDL
WHO (2011)	0.3	0.01	0.01	0.05	0.003	0.006	0.07

BDL: Below detection limit (treated as zero for all statistical and mCD calculations).

Table 5: Summary of iron concentrations in the Taloka and Wurno Formation aquifers.

Parameter	Taloka	Wurno
% Samples exceeding 0.3 mg/L [24]	71%	64%
Mean	2.02 mg/L	0.82 mg/L
Maximum	14.36 mg/L	2.41 mg/L
Standard Deviation	3.667	0.693

Table 6: Summary of lead concentrations in the Taloka and Wurno Formation aquifers.

Parameter	Taloka	Wurno
% Samples exceeding 0.01 mg/L [24]	43%	46%
Mean	0.058 mg/L	0.11 mg/L
Maximum	0.408 mg/L	0.403 mg/L
Standard Deviation	0.106	0.152

3.3.4. Chromium (Cr)

In the Taloka aquifer, Cr ranged from 0.002 to 0.076 mg/L (mean: 0.021 mg/L), with 14% of samples exceeding the World Health Organization (WHO) guideline (Table 8). In the Wurno aquifer, Cr ranged from 0.007 to 0.053 mg/L (mean: 0.023 mg/L), with 9% exceeding the limit.

3.3.5. Cadmium (Cd)

In the Taloka aquifer, Cd ranged from BDL to 0.081 mg/L (mean: 0.007 mg/L), with 14% of samples exceeding the World

Health Organization (WHO) guideline (Table 9). In the Wurno aquifer, Cd ranged from BDL to 0.01 mg/L (mean: 0.001 mg/L), with 18% exceeding the limit.

3.3.6. Nickel (Ni)

In the Taloka aquifer, Ni ranged from 0 to 0.006 mg/L (mean: 0.001 mg/L); all samples were within the World Health Organization (WHO) guideline limit (Table 10). In the Wurno aquifer, Ni ranged from 0 to 0.005 mg/L (mean: 0.0005 mg/L), and all samples were also within the limit. The higher con-

Table 7: Summary of arsenic concentrations in the Taloka and Wurno Formation aquifers.

Parameter	Taloka	Wurno
% Samples exceeding 0.01 mg/L [24]	71%	73%
Mean	0.011 mg/L	0.012 mg/L
Maximum	0.014 mg/L	0.014 mg/L
Standard Deviation	0.003	0.002

Table 8: Summary of chromium concentrations in the Taloka and Wurno Formation aquifers.

Parameter	Taloka	Wurno
% Samples exceeding 0.05 mg/L [24]	14%	9%
Mean	0.021 mg/L	0.023 mg/L
Maximum	0.076mg/L	0.053 mg/L
Standard Deviation	0.023	0.014

Table 9: Summary of cadmium concentrations in the Taloka and Wurno Formation aquifers.

Parameter	Taloka	Wurno
% Samples exceeding 0.003 mg/L [24]	14%	18%
Mean	0.007 mg/L	0.001 mg/L
Maximum	0.081 mg/L	0.010 mg/L
Standard Deviation	0.021	0.003

Table 10: Summary of nickel concentrations in the Taloka and Wurno Formation aquifers.

Parameter	Taloka	Wurno
% Samples exceeding 0.07 mg/L [24]	0%	0%
Mean	0.001 mg/L	0.0005 mg/L
Maximum	0.006 mg/L	0.005 mg/L
Standard Deviation	0.002	0.001

centration of Ni in the Taloka aquifer may be attributed to the chemical affinity between Fe and Ni, since Fe was also observed to be more concentrated in the Taloka Formation.

3.4. Modified contamination degree (mCD)

The results for the contamination factor and modified contamination degree are presented in Tables 11 and 12.

The average modified contamination degree for the Taloka aquifer is 2.32, which falls into the “moderate degree” category (2 to <4). This indicates multiple heavy metals (Fe, Pb, As, Cd,

Cr) are present at concentrations above background or guideline values.

The average modified contamination degree for the Wurno aquifer is 2.27, which also falls within the “moderate degree” range (2 to <4). Compared with the Taloka aquifer, the contamination degree of the Wurno aquifer is lower; however, the Mann–Whitney U test indicated no statistically significant difference in overall modified contamination degree between the Taloka and Wurno aquifers ($U = 76$, $U_{critical} = 40$, $p > 0.05$). Nevertheless, the mCD results indicate that both aquifers exhibit contamination within the moderate category.

4. Discussion

4.1. Geology

One of the most prominent lithological features uncovered by surface mapping is the oolitic ironstone and other iron-rich clastic sediments, which are significantly influential from a hydrogeochemical point of view. Given the depositional history of the Sokoto Basin, these lithologies would have been deposited in a shallow marine, oxygen-abundant environment; however, following burial and diagenesis, the mineral composition of the rocks would make them highly susceptible to chemical weathering and geochemical transformations. For example, redox-controlled reactions would be dominant under subsurface conditions; these would facilitate the transformation of insoluble ferric iron (Fe^{3+}) into more soluble ferrous iron (Fe^{2+}) [25, 26]. The end product of such reactions would lead to higher iron mobility, allowing it to be readily incorporated into circulating groundwater.

Furthermore, the stratigraphic setting, which comprises interbedded iron-rich layers and permeable siltstone units, favours intensive water–rock interaction as the residence time of groundwater within the rock units increases. The increased residence time promotes the dissolution of iron and other metals into the aquifer system. Possible evidence of this process was observed in the Gagi area (Figure 6), where pumped water changes to a reddish-brown colour after a few minutes of exposure to air. It can be hypothesised that the reddish-brown colour exhibited by some of the pumped borehole water may indicate high levels of dissolved ferrous iron (Fe^{2+}) that rapidly undergoes oxidation upon exposure to the atmosphere, resulting in its precipitation as ferric iron (Fe^{3+}). This is particularly because the water has a clear appearance upon pumping and changes to a reddish-brown colour after a few minutes of exposure.

On the other hand, the limestone units observed during surface mapping constitute a carbonate buffering system that would keep water pH levels neutral or near neutral. While buffering is beneficial from a heavy metal pollution standpoint because it reduces metal mobility, the presence of limestone units can still lead to the enrichment of certain trace metals, such as Cd, Pb, Cr and As, in groundwater during the carbonate dissolution process.

4.2. Borehole logs

The borehole logs from the Taloka Formation reveal a stacking of siltstone and silty sandstone interbedded with carbona-

Table 11: Contamination factors for individual heavy metals assessed in the Taloka and Wurno aquifers.

Sample ID	C_f (Fe)	C_f (Pb)	C_f (As)	C_f (Cr)	C_f (Cd)	C_f (Hg)	C_f (Ni)
TLK 01	2.14	2.40	1.20	0.14	0.00	0.00	0.07
TLK 02	6.47	0.80	1.20	0.10	0.00	0.00	0.09
TLK 03	1.47	9.10	1.10	0.06	0.00	0.00	0.04
TLK 04	12.72	0.00	1.30	0.04	0.00	0.00	0.07
TLK 05	1.49	40.80	0.50	0.22	0.00	0.00	0.00
TLK 06	1.76	0.00	1.10	0.68	0.00	0.00	0.00
TLK 07	47.87	0.00	1.20	0.18	0.00	0.00	0.00
TLK 08	14.67	12.40	0.80	0.14	0.00	0.00	0.00
TLK 09	0.55	7.10	1.30	0.14	0.00	0.00	0.00
TLK 10	2.07	8.50	1.40	0.34	0.00	0.00	0.00
TLK 11	1.67	0.00	0.40	1.52	27.00	0.00	0.00
TLK 12	0.56	0.00	0.90	0.12	0.33	0.00	0.00
TLK 13	0.41	0.00	1.30	1.34	0.67	0.00	0.00
TLK 14	0.71	0.00	1.40	0.82	2.67	0.00	0.00
WUR 01	0.50	0.00	1.30	0.14	0.00	0.00	0.00
WUR 02	0.53	0.00	1.30	0.38	0.00	0.00	0.00
WUR 03	0.79	20.00	1.20	0.14	0.00	0.00	0.00
WUR 04	4.83	0.00	0.90	0.62	0.00	0.00	0.00
WUR 05	8.03	0.90	1.20	0.40	0.00	0.00	0.00
WUR 06	1.88	40.20	1.40	0.90	0.00	0.00	0.00
WUR 07	3.46	40.30	1.00	0.34	0.00	0.00	0.07
WUR 08	0.41	5.20	1.40	0.52	0.00	0.00	0.00
WUR 09	1.53	14.40	1.30	0.32	0.00	0.00	0.00
WUR 10	3.42	0.00	1.30	0.34	3.33	0.00	0.00
WUR 11	4.71	0.10	1.00	1.06	2.00	0.00	0.00

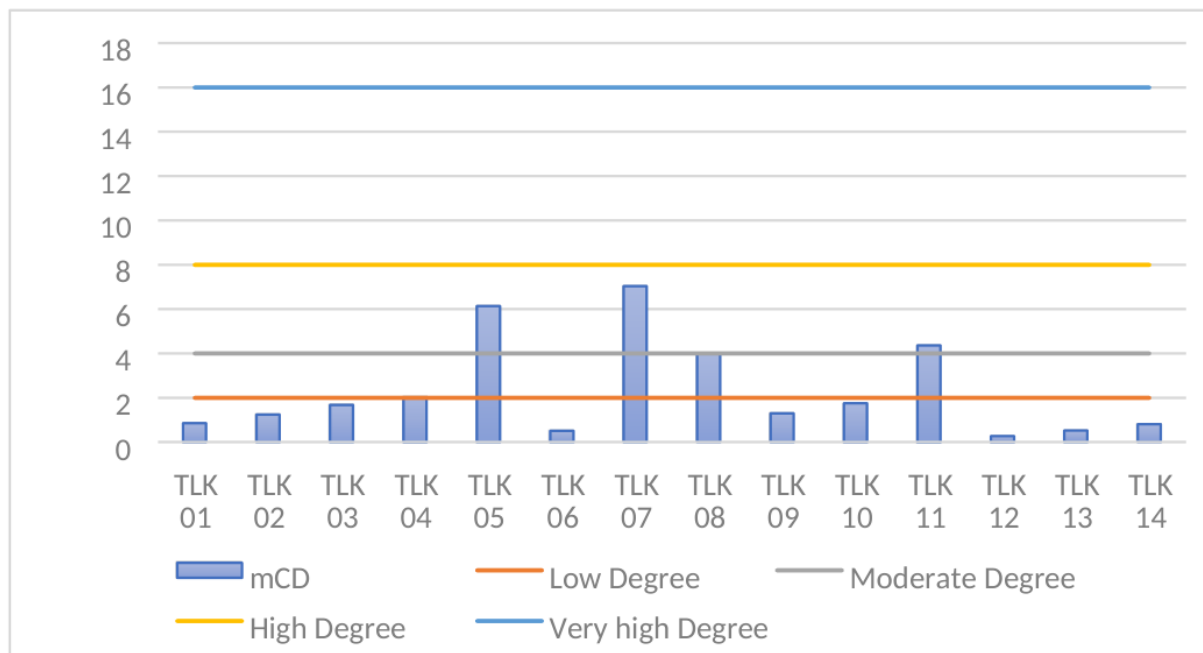


Figure 4: Contamination degree chart for the Taloka Formation.

Table 12: Modified contamination degree for the Taloka and Wurno aquifers.

Sample ID	mCD	Comment
TLK 01	0.85	Nil to very low degree of contamination
TLK 02	1.24	Nil to very low degree of contamination
TLK 03	1.68	Low degree
TLK 04	2.02	Moderate degree
TLK 05	6.14	High degree
TLK 06	0.51	Nil to very low degree of contamination
TLK 07	7.04	High degree
TLK 08	4.00	High degree
TLK 09	1.30	Nil to very low degree of contamination
TLK 10	1.76	Low degree
TLK 11	4.37	High degree
TLK 12	0.27	Nil to very low degree of contamination
TLK 13	0.53	Nil to very low degree of contamination
TLK 14	0.80	Nil to very low degree of contamination
AVERAGE TLK	2.32	Moderate degree
WUR 01	0.28	Nil to very low degree of contamination
WUR 02	0.32	Nil to very low degree of contamination
WUR 03	3.16	Moderate degree
WUR 04	0.91	Nil to very low degree of contamination
WUR 05	1.50	Low degree
WUR 06	6.34	High degree
WUR 07	6.45	High degree
WUR 08	1.08	Nil to very low degree of contamination
WUR 09	2.51	Moderate degree
WUR 10	1.20	Nil to very low degree of contamination
WUR 11	1.27	Nil to very low degree of contamination
AVERAGE WUR	2.27	Moderate degree

aceous shale and ironstone. Shales are naturally rich in sulfide minerals such as pyrite and organic matter; they can act as a source of iron, sulfate and even arsenic because of its high affinity for iron. These metals can be released into groundwater when oxidised. The permeability of the siltstones and silty sandstones provides conduits for these metals to reach the aquifer units. The overlying limestone units offer some natural attenuation by reducing metal mobility; however, this capacity is finite and can break down under changing redox conditions. The results of borehole logging in Taloka wells support the hypothesis that Fe and As contamination in the Taloka aquifer is likely from geogenic rather than anthropogenic sources, although surface contamination cannot be completely ruled out.

The relatively shallower depth and lower permeability of the Wurno Formation aquifer make it more vulnerable to surface-derived heavy metals (Pb, Cd, Cr) from agrochemicals and industrial waste. However, siltstones can also trap these metals within their pore structure, thus serving as temporary sinks.

Unlike the Taloka Formation, the Wurno siltstone/silty sandstone aquifer requires more careful geochemical management to avoid heavy metal contamination.

4.3. Heavy metal concentration

Iron (Fe) and nickel (Ni) concentrations are higher in the Taloka aquifer, while lead (Pb) and arsenic (As) concentrations are higher in the Wurno aquifer. This indicates that the hydrogeochemical controls influencing the distribution of heavy metals in the two aquifers are different. The higher concentrations of Fe and Ni in the Taloka aquifer may be connected to a geogenic source as a result of mineral dissolution of its iron-rich layers. The weak correlations between Fe and the other metals in the Taloka aquifer (Table 13) could indicate that Fe is controlled by a different geochemical process from the other metals; this is consistent with its suggested geogenic source, attributed to weathering and dissolution of the iron-rich units.

The heavy metal distribution observed in the Wurno aquifer suggests that it is influenced by mixed sources. Weak correlations among the heavy metals in the Wurno aquifer could indicate that their distribution is not controlled by a common source. This pattern is consistent with the influence of multiple hydrogeochemical processes and potentially mixed geogenic and anthropogenic inputs.

The overlying Dange Formation may be a potential source of the geogenic contribution to high Pb and As concentrations

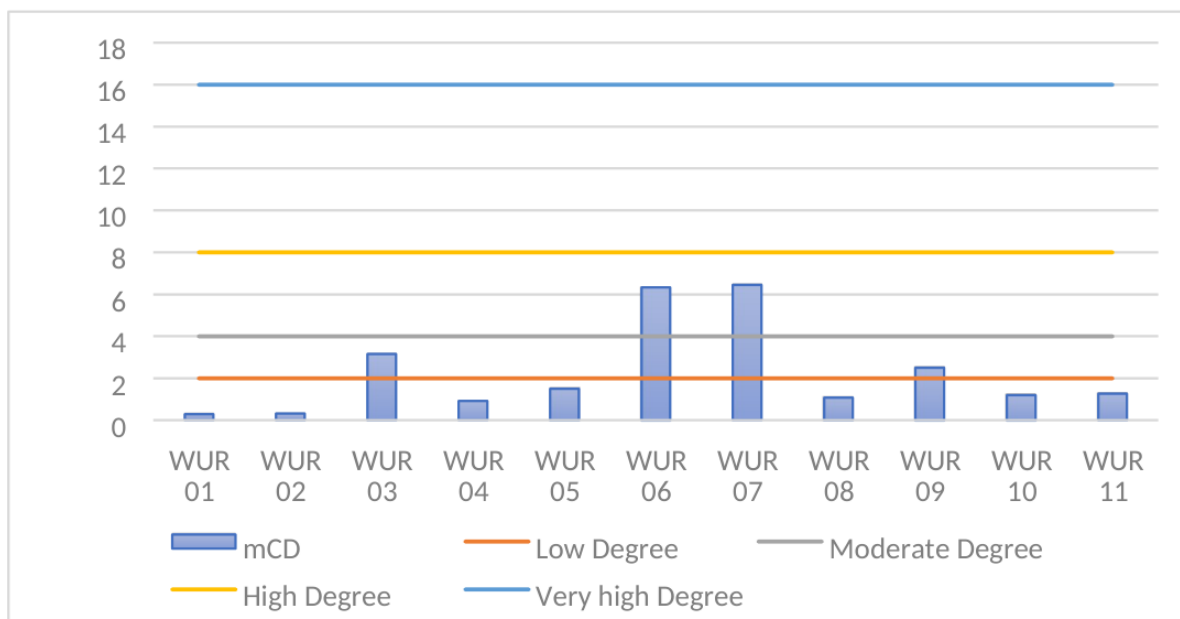


Figure 5: Contamination degree chart for the Wurno Formation.



Figure 6: Iron-rich sedimentary layers exposed in the Gagi area (left) and iron-rich groundwater pumped from a borehole in the same area (right). N13°03'45" E005°17'55".

Table 13: Heavy metal correlation analysis for the Taloka Formation aquifer ($p = 0.05$).

	Fe	Pb	As	Cr	Cd
Fe	1				
Pb	-0.14389	1			
As	0.089388	-0.4916	1		
Cr	-0.26345	-0.26316	-0.22068	1	
Cd	-0.1349	-0.1738	-0.58819	0.689709	1

Table 14: Heavy metal correlation analysis for the Wurno Formation aquifer ($p = 0.05$).

	Fe	Pb	As	Cr	Cd
Fe	1				
Pb	-0.17771	1			
As	-0.55933	0.049396	1		
Cr	0.312427	0.078815	-0.22439	1	
Cd	0.230107	-0.32793	-0.06051	0.23099	1

in the Wurno aquifer because the formation is rich in organic shales, which are potential sources of heavy metals [27, 28]. However, this remains a hypothesis. At depth, when conditions become reducing (low oxygen), these shales may release previously bound metals into the groundwater system. Metals such as Pb and As may have been released into the Wurno aquifer by such means, although through different pathways.

Aside from the geogenic source, the geochemistry of the Wurno aquifer could also be influenced by anthropogenic sources of pollution due to its relatively shallower stratigraphic position. Contaminants of anthropogenic origin, such as those from agrochemical application and waste disposal, may infiltrate the aquifer more easily than a deeper aquifer such as the Taloka aquifer. This could be responsible for the relatively higher concentrations of metals such as Pb and As in the Wurno aquifer.

From a public health perspective, the elevated concentrations of these metals are of particular concern. They are carcinogens and could be toxic even at very low concentrations over prolonged exposure [29, 30]. Their persistence in both the Wurno and Taloka aquifers emphasises the need for continuous groundwater monitoring and effective water treatment initiatives.

4.4. Modified contamination degree (mCD)

Although the mCD for the Wurno aquifer is lower than that of the Taloka aquifer, both aquifers show a similar proportion of sampling points exceeding the low-contamination-degree threshold ($mCD > 2.0$), with 36% of sampling points in each aquifer falling above this threshold.

However, the occurrence of sampling points above the low-contamination-degree threshold in both the Taloka and Wurno aquifers indicates that neither aquifer is free from heavy metal contamination concerns.

5. Conclusion

Heavy metal pollution analysis of the Taloka and Wurno aquifers of the Sokoto Basin, northwestern Nigeria, reveals significant contamination by trace metals including iron (Fe), lead (Pb), arsenic (As), chromium (Cr) and cadmium (Cd). The contamination is, however, not uniformly distributed across both aquifers. While the Taloka aquifer shows high contamination with Fe and As, the Wurno aquifer shows high Pb and As contamination. This implies that the distribution of heavy metals

in both aquifers is influenced by different lithological and external controls. The geochemistry of the Taloka aquifer seems to be controlled more by its geology, while that of the Wurno aquifer appears to be controlled by both geology and surface contamination. This suggests that the geology of the aquifers, such as their mineral composition, weathering processes and water-rock interaction, may influence the distribution of metals in both aquifers. One working hypothesis is that geological processes may be largely responsible for the elevated Fe and As concentrations, while external anthropogenic inputs may be compounding the Pb and Cd concentration levels.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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