


ORIGINAL RESEARCH ARTICLE

Comparative Evaluation of Heavy Metal Pollution, Pollution Index, and Physicochemical Quality of Urban Groundwater in Kaduna Metropolis, Nigeria

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ABSTRACT

An investigation was conducted to assess the heavy metal contamination, physicochemical quality, and associated non-carcinogenic health risks in well water and borehole water sources across the Kaduna Metropolis. Water samples were analyzed for six physicochemical parameters and five heavy metals (Zn, Cd, Pb, Cu, Cr) in triplicate, achieving high precision with method detection limits (LOD) typically below 0.001 mg/L. Statistical analysis showed a highly significant difference ($p < 0.01$) in Electrical Conductivity (EC), with the well water mean (1.59 mS/cm) exceeding the WHO limit. The study found widespread contamination with toxic metals in both sources. Key exceedances included Cadmium (Cd), which exceeded the WHO limit by approximately $2.3 \times$ (up to 0.008 mg/L), and Lead (Pb), which exceeded the WHO limit by over $5 \times$ (up to 0.054 mg/L) in well water. The health risk assessment confirmed a Significant Non-Carcinogenic Risk for well water (Hazard Index, HI=2.472) and a Potential Risk for borehole water (HI=1.317), with Chromium (Cr) as the primary driver (Well Cr up to 0.484 mg/L, a $9.7 \times$ exceedance). This study provides new spatial evidence of Cr and Cd migration into deep aquifers of Kaduna Metropolis, demonstrating that toxic metal pollution is not confined to shallow water sources and necessitates urgent advanced treatment interventions.

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INTRODUCTION

The reliance on groundwater for potable water supply in Nigerian households remains unacceptably high and a serious concern, especially in rapidly growing urban areas, where reliance on traditional water systems mirrors that of rural or less-developed municipal schemes. Private abstraction through boreholes and hand-dug wells is therefore common to meet domestic and commercial water demand. But the combined effect of rapid urbanization, poor waste disposal, and the indiscriminate discharge of domestic and industrial effluents was seriously threatening the safety and sustainability of these life-supporting groundwater resources in Nigerian cities, an emerging searchlight being turned on by researchers (Ojo *et al.*, 2024).

Heavy metal contamination, including lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and nickel (Ni), is recognized as one of the most critical and pervasive threats to groundwater quality. These metals pose an acute risk due to their non-biodegradability, persistence in the environment, and marked capacity for bioaccumulation within aquatic ecosystems and human tissues, even at low concentrations. Chronic exposure via contaminated drinking water is clearly associated with a spectrum of

adverse human health effects, including neurological impairments (Pb), renal dysfunction and bone demineralization (Cd), and hepatic or gastrointestinal disorders (Cu) and (Ni). While Zn is an essential micronutrient, its excessive ingestion can still provoke acute symptoms like nausea and vomiting, alongside potential long-term metabolic disruptions. These health hazards necessitate rigorous monitoring (Jomova *et al.*, 2025).

The severity of this threat necessitates not only measuring heavy metal concentrations but also quantifying overall contamination risk. Therefore, researchers often employ various pollution indices, such as the Pollution Load Index (PLI) and the Contamination Factor (CF). These indices translate complex, multi-element analytical results into a single, standardized numerical value, providing a more holistic, readily interpretable assessment of groundwater quality for risk evaluation and regulatory decision-making. By integrating physicochemical parameters (like pH and turbidity) with these pollution indices, a clearer picture emerges of both the *source* (e.g., surface infiltration) and the *extent* of pollution, which is crucial for developing effective management strategies.

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The Kaduna Metropolis (including Malali, Igabi, Millennium City, and Tudun Wada) is highly vulnerable to groundwater contamination. This susceptibility stems from rapid urban growth, unregulated waste disposal, and poor sanitation infrastructure. Recent research confirms that groundwater quality varies across regions due to urban runoff and human activities. These investigations frequently show that heavy metal concentrations (including lead, manganese, and zinc) exceed established safe limits, which consequently presents significant health risks (Ezugwu *et al.*, 2021). Groundwater quality degradation in the Kaduna Metropolis is primarily attributed to surface pollution, as the shallow water table's directly connected to the surface environment. Research indicates that pollutants from unregulated waste disposal sites and domestic wastewater (specifically unlined septic systems) are the major sources of high contaminant levels and increased turbidity. These findings strongly emphasize the need for immediate, decisive interventions, including stringent regulatory oversight, science-driven urban planning that accounts for hydrogeological risks, and integrated sewage disposal systems to protect the vital aquifer resources in the urban zone (Olayiwola *et al.*, 2024).

In response to these environmental and health concerns, the present study investigates the concentrations of selected heavy metals (Pb, Cd, Cu, Zn, and Ni), their pollution indices, as well as key physicochemical properties of borehole and well water across Malali, Igabi, Millennium City, and Tudun Wada within Kaduna Metropolis. By integrating heavy-metal analysis with pollution-index assessments and physicochemical evaluation, the study provides a comprehensive understanding of the degree of groundwater contamination. By comparing the measured parameters with World Health Organisation (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) guidelines, the study identifies compliance levels, highlights contamination hotspots, and offers evidence-based recommendations for effective groundwater-quality management and policy interventions across Kaduna Metropolis.

MATERIALS AND METHODS

Locations of the Study Area, Groundwater Depth Ranges and Aquifer Characteristics

Locations	Quality Factor	Well Water Table Depth	Borehole Total Depth
Malali (10.5581° N, 7.4665° E)	Surface water proximity (Kaduna River) may create a shallower water table and heighten contamination risk.	0.2 m to 11.6 m (for hand-dug wells in the general Kaduna area). This range is likely to be shallower closer to the river.	40 m to over 70 m. Boreholes are often drilled deep to ensure year-round supply and avoid surface contamination.
Millennium City (10.53569° N, 7.47739° E)	Rapid, modern urbanization. Boreholes are generally newer and may be drilled to access the more stable, deeper aquifer.	6 m to 10 m (based on geotechnical studies for the weathered/fractured zone thickness in nearby areas).	45 m to 60 m is a common estimate for the depth required to hit the significant, water-yielding fracture zone.
Igabi Local Government Area (10.79874° N, 7.52472° E)	Large, agricultural area; contamination risk from agrochemicals. Groundwater potential is often tied to the overburden thickness and fracture zones.	7.1 m to 10.9 m (Unconfined shallow aquifer zone depth in Mando/Igabi LGA).	~10 m (for successful shallow boreholes tapping the weathered overburden) to over 60 m for deeper, more sustainable yields tapping the fractured basement.
Tudun Wada (10.5186° N, 7.4111° E)	High Anthropogenic Risk: Densely populated with older infrastructure. Risks include nitrate/coliform contamination from proximity to pit latrines and soakaways. Recent studies show high turbidity and iron levels in shallow sources.	1.5 m to 9.2 m: The water table is generally shallow, especially in areas near the Kaduna River or during the rainy season. Some locations report levels within 2–5 meters of the surface.	35 m to 55 m: Productive aquifers are found in the weathered and fractured basement. Deeper drilling (beyond 40 m) is recommended to bypass shallow contaminated zones.

Sample Collection

A total of twenty-four (24) groundwater samples were collected from Kaduna Metropolis, comprising three (3) borehole and three (3) well samples each from Malali, Millennium City, Igabi, and Tudun Wada. Samples were collected in pre-cleaned 750 mL high-density polyethylene (HDPE) bottles, previously soaked in 20% nitric acid (HNO₃) and rinsed with deionized water (APHA, 2017).

During sampling, the sources were flushed to obtain representative water, and bottles were rinsed with the sample water before collection. Samples were filtered through 0.45 µm membrane filters to remove particulates, acidified to pH < 2.0 using concentrated HNO₃ (65%) to prevent metal adsorption or precipitation (APHA, 2017), and stored at approximately 4°C in an icebox prior to transport to the Kaduna Polytechnic laboratory.

Sample Preparation

In the laboratory, samples were digested with aqua regia (HCl:HNO₃, 3:1 v/v) according to the method described by USEPA (2020). A 100 mL aliquot of each sample was heated gently on a hot plate under a fume hood until near

dryness. The digest was cooled, diluted to a known volume with deionized water, and filtered through a Whatman No. 42 filter paper into acid-washed polyethylene bottles. Method blanks and reagent blanks were processed alongside the samples to ensure quality control (USEPA, 2020).

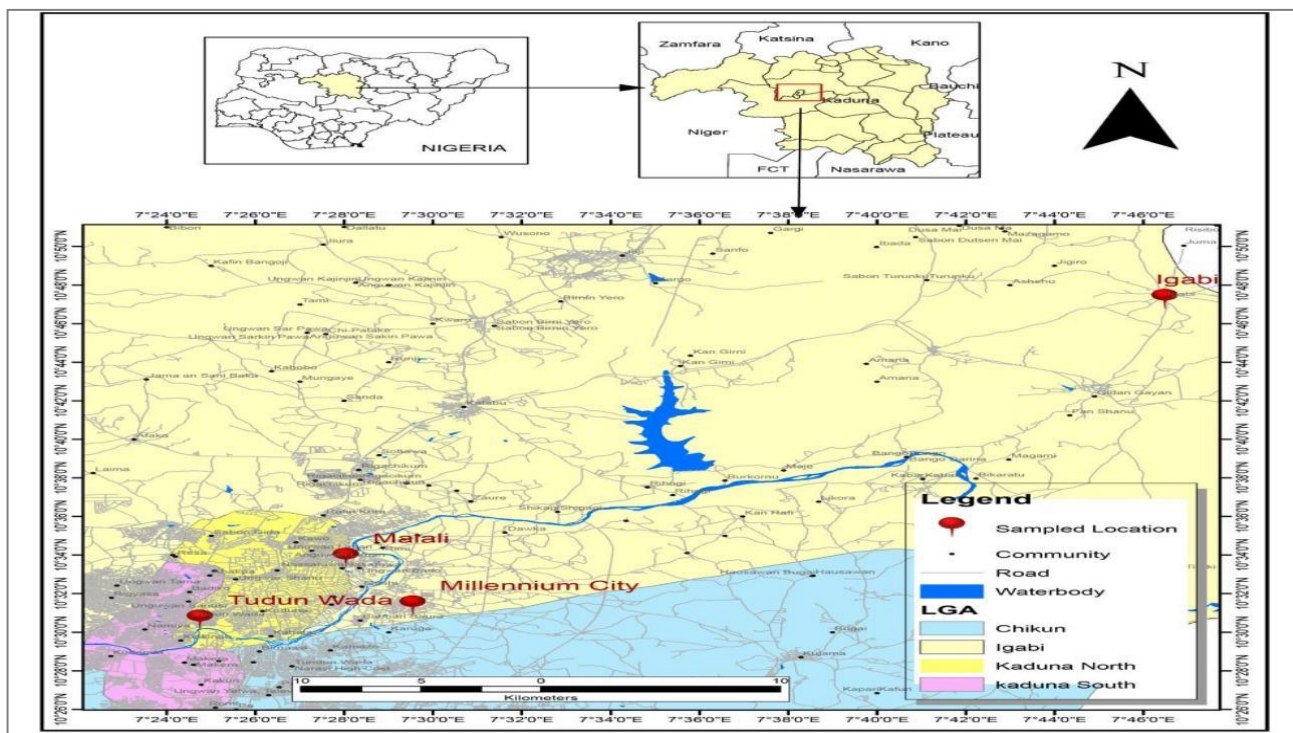


Figure 1: Map of the Study Areas with Sampling Sites

Analytical Methodologies for Heavy Metal Quantification

The concentrations of Zn, Cd, Pb, Cu, and Cr were determined using a Buck Scientific Model 210 Atomic Absorption Spectrophotometer (AAS), operated according to manufacturer specifications and APHA (2017) procedures. Calibration was achieved using multi-element standard solutions, and quality control was maintained through the use of certified reference materials (CRMs), matrix spikes, duplicates, and blank determinations (USEPA, 2020; WHO, 2022). Results were expressed as mean ± standard deviation (mg/L), and compared with WHO (2022) and Nigerian Standard for Drinking Water Quality (NSDWQ, 2015) limits.

Non-Carcinogenic Hazard Assessment (HQ & HI)

Hazard Quotient (HQ) is a unitless ratio used to estimate the non-carcinogenic risk from exposure to individual contaminants. It compares the estimated exposure dose to a tolerable reference dose. The HQ compares the exposure dose to the tolerable reference dose:

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

Where:

ADD is the Average Daily Dose (mg/kg/day) calculated above.

RfD is the Oral Reference Dose (mg/kg/day) for the specific contaminant (a standard non-carcinogenic value).

Hazard Index (HI) is the sum of the HQ values for all non-carcinogenic contaminants. It assesses the cumulative non-carcinogenic risk from exposure to multiple substances. The HI sums the risks from multiple contaminants to assess the cumulative non-carcinogenic risk:

$$HI = \sum_{i=1}^n HQ_i = HQ_{Pb} + HQ_{Cd} + HQ_{Cr}$$

Contamination Factor (CF) and Pollution Load Index (PLI) for Heavy Metals

Contamination Factor (CF): A fundamental index used in environmental assessment to quantify the contamination level of a single heavy metal or pollutant in a sampled medium (e.g., water, sediment, or soil) relative to a reference level. The Contamination Factor is calculated as the ratio of the pollutant's concentration in the sample (C_{sample}) to its reference or background concentration (C_b)

$$CF = \frac{C_{sample}}{C_b}$$

Where:

C_{sample} is the measured concentration of the heavy metal in the water (or other medium).

C_b is the background or reference value. In water quality assessments, C_b is typically the maximum permissible limit set by regulatory bodies (like WHO or NSDWQ).

Pollution Load Index (PLI): This is a multi-factor index used in environmental studies to provide a

comprehensive, standardized assessment of the overall level of heavy-metal contamination at a specific site. The PLI is calculated as the n-th root of the product of the individual Contamination Factors (CF) for all assessed pollutants at a given location:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times \dots \times CF_n}$$

Where:

CF_i is the Contamination Factor for the i -th metal (calculated as $\frac{C_{sample}}{C_b}$).

n is the total number of heavy metals analyzed.

Water Quality Parameters for Wells and Boreholes Water

The physicochemical analysis of borehole and well water samples was conducted according to the procedures outlined by the American Public Health Association (APHA, 2017). Parameters analyzed included pH, temperature, electrical conductivity (EC), turbidity, total dissolved solids (TDS), total hardness, total alkalinity, chloride, nitrate, and nitrite concentrations.

All analyses were carried out in triplicate to ensure accuracy and reproducibility. The results were compared with the World Health Organization (WHO, 2022) and Nigerian Standard for Drinking Water Quality (NSDWQ, 2015) guidelines for drinking water.

Determination of electrical conductivity (EC)

Electrical conductivity (EC), an indicator of ionic strength and salinity, was measured using a Hach HQ40d digital conductivity meter at 25°C. The instrument was calibrated with standard KCl solutions prior to measurement to ensure precision (WHO, 2022).

Determination of pH

The pH of each water sample was measured in situ using a calibrated Hanna HI 98129 portable multiparameter meter immediately after sample collection to prevent alteration due to exposure or chemical changes. The instrument was standardized with buffer solutions of pH 4.0, 7.0, and 10.0 before each use, following the procedures outlined by APHA (2017).

Determination of dissolved oxygen (DO)

The dissolved oxygen (DO) concentration in each water sample was determined in situ using a Hach HQ40d portable DO meter equipped with a luminescent dissolved oxygen (LDO) probe. The probe was calibrated prior to measurement using the air-saturation method, ensuring accurate readings as recommended by APHA (2017). Samples were analyzed immediately after collection to prevent oxygen exchange with the atmosphere or biological alteration. The DO values were recorded in milligrams per litre (mg/L) and reflect the amount of oxygen available to aquatic life and microbial activity.

Determination of temperature

The temperature of each water sample was determined on-site using the Hanna HI 98129 portable meter's temperature probe. Measurements were taken immediately after collection to avoid variations due to ambient conditions or heat exchange. The readings were recorded in degrees Celsius (°C) in accordance with APHA (2017).

Determination of turbidity

Turbidity was determined using a Hach 2100P Turbidimeter and expressed in nephelometric turbidity units (NTU). The equipment was calibrated with Formazin standards before sample analysis, following APHA (2017) guidelines.

Determination of total dissolved solids (TDS)

Total Dissolved Solids (TDS) were determined by conductivity, with TDS concentration directly measured using the Hach HQ40d meter, which automatically converts conductivity values to TDS in mg/L APHA (2017).

Statistical analysis

The results of triplicate are presented as mean ± standard deviation (SD). The analysis of variance (ANOVA) (SPSS version 20.0) was used to compare the means of the groups. *Post-hoc* tests were performed using Duncan's multiple range test; a probability level of less than 5% ($P < 0.05$) was considered significant.

RESULTS

Table 1: Concentrations (mg/L) of Heavy Metals in Well Water

Locations	Zn (mg/L)	Cd (mg/L)	Pb (mg/L)	Cu (mg/L)	Cr (mg/L)
Malali	0.099±0.011 ^a	0.008±0.001 ^a	0.054±0.006 ^a	0.038±0.004 ^a	0.111±0.020 ^a
Tudun Wada	0.087±0.014 ^a	0.007±0.002 ^a	0.049±0.005 ^a	0.386±0.090 ^b	0.075±0.008 ^b
Mellenium City	0.221±0.022 ^b	0.006±0.001 ^{ba}	0.032±0.003 ^b	0.022±0.002 ^a	0.484±0.049 ^c
Igabi LGA	0.069±0.017 ^c	0.006±0.001 ^b	0.053±0.005 ^a	0.016±0.001 ^c	0.126±0.013 ^a
WHO (2017)	3.000 ^d	0.003 ^d	0.010 ^d	2.000 ^d	0.050 ^d
NSDWQ (2015)	3.000 ^d	0.003 ^d	0.010 ^d	1.000 ^d	0.050 ^d

Keys: Zn, Zinc; Cd, Cadmium; Pb, Lead; Cu, Copper; Cr, Chromium; WHO, World Health Organization; NSDWQ, Nigerian Standard for Drinking Water Quality.

DISCUSSION

Concentrations of Heavy Metals in Well Water

Zinc (Zn) concentrations in well water were low (0.069–0.221 mg/L), remaining well below the 3.0 mg/L limit

(WHO, NSDWQ) and indicating negligible contamination. This finding is consistent with literature on Northern Nigerian urban well water (Dickson *et al.*, 2025; Nneka, 2024). The maximum Zn level recorded in Millennium City (0.221 mg/L) may be due to corrosion of

galvanized materials or runoff from urban surfaces (Nicholas *et al.*, 2024).

Cadmium concentrations in well water ranged from 0.006 to 0.008 mg/L, exceeding the permissible limits set by both the WHO and NSDWQ (0.003 mg/L). This elevation points to anthropogenic pollution, likely

stemming from discarded batteries, pigments, and electronic waste prevalent in residential areas and dumpsites (Iqbal & Bonasi, 2024; Olalekan *et al.*, 2022). The particularly high concentrations observed in Malali and Tudun Wada further suggest the infiltration of surface waste leachate, along with contributions from vehicular emissions (Alao, 2025).

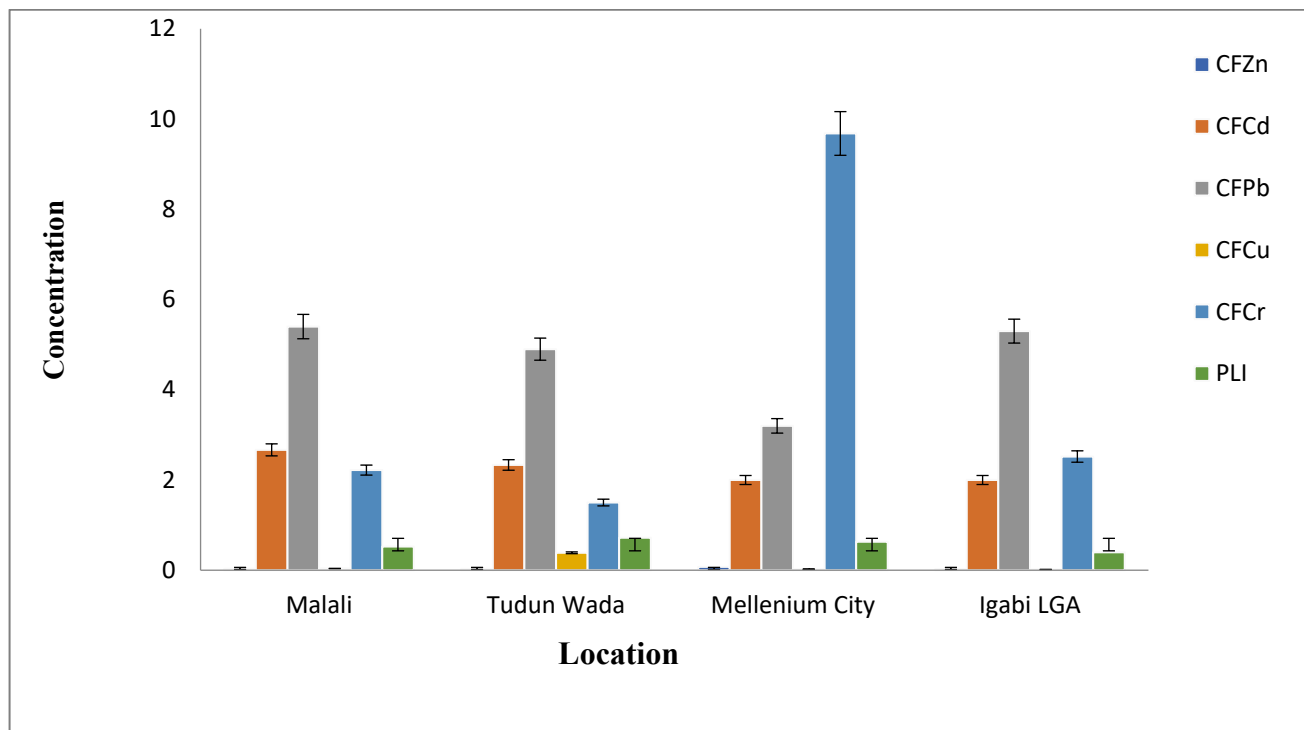


Figure 2: The Well-Water Contamination Factor (CF) and Pollution Load Index (PLI)

Data are presented as mean ± SD of triplicates of analysis. Different letters above the bars for a given concentration in each extract are significantly different from each other (p < 0.05; Duncan post-hoc test; IBM SPSS, version 20).

Interpretations: CF < 1 (Low), 1 ≤ CF < 3 (Moderate), 3 ≤ CF < 6 (Considerable), CF ≥ 6 (Vey high), PLI < 1 (Unpolluted/Baseline), PLI = 1 Baseline/Starting Point, PLI > 1 (Polluted)

Table 2: Concentrations (mg/L) of Heavy Metals in Borehole Water

Locations	Zn (mg/L)	Cd (mg/L)	Pb (mg/L)	Cu (mg/L)	Cr (mg/L)
Malali	0.059±0.006 ^a	0.008±0.080 ^a	0.033±0.003 ^a	0.045±0.005 ^a	0.201±0.110 ^a
Tudun Wada	0.020±0.002 ^b	0.006±0.010 ^{ba}	0.019±0.001 ^b	0.386±0.039 ^b	0.076±0.080 ^b
Mellenium City	0.737±0.074 ^c	0.007±0.000 ^a	0.017±0.001 ^b	0.045±0.005 ^a	0.105±0.010 ^c
Igabi LGA	0.057±0.006 ^a	0.007±0.001 ^a	0.021±0.002 ^c	0.014±0.001 ^c	0.010±0.009 ^d
WHO (2017)	3.000 ^d	0.003 ^c	0.010 ^b	2.000 ^d	0.050 ^e
NSDWQ (2015)	3.000 ^d	0.003 ^c	0.010 ^b	1.000 ^e	0.050 ^e

Results are presented as mean ± SD. Values with different letters down the column are significantly different from each other at P < 0.05.

Table 3: Non-carcinogenic Health Risk Assessment for Heavy Metals (Pb, Cd, and Cr)

Source	HQ (Pb)	HQ (Cd)	HQ (Cr)	HI (∑HQ)	Risk Status (HI ≥ 1)
Well Water	0.384 ^a	0.193 ^a	1.895 ^a	2.472 ^a	Significant Risk
Borehole Water	0.184 ^b	0.20 ^b	0.933 ^b	1.317 ^b	Potential Risk

Values with different letters down the column are significantly different from each other at P < 0.05.

Table 4: Physicochemical Parameters in Well Water from Kaduna Metropolis

Parameter	Tudun Wada	Malali	Igabi LGA	Millennium City	WHO, 2017
EC (mS/cm)	1.61 ^a	1.51 ^a	1.62 ^a	1.61 ^a	≤1.5
pH	6.60 ^a	6.00 ^b	7.26 ^c	6.75 ^a	6.5–8.5
DO (mg/L)	2.04 ^a	1.87 ^a	2.04 ^a	1.99 ^a	4–6
Temperature (°C)	25.0 ^a	24.50 ^a	25.0 ^a	25.00 ^a	25–30
Turbidity (NTU)	5.50 ^a	5.30 ^{ac}	3.20 ^b	5.70 ^a	≤5
TDS (mg/L)	966.00 ^a	906.003 ^a	972.00 ^a	966.00 ^a	≤1000

Keys: EC, Electrical Conductivity; TDS, Total Dissolved Oxygen; Temp., Temperature; TDS, Total Dissolved Solid

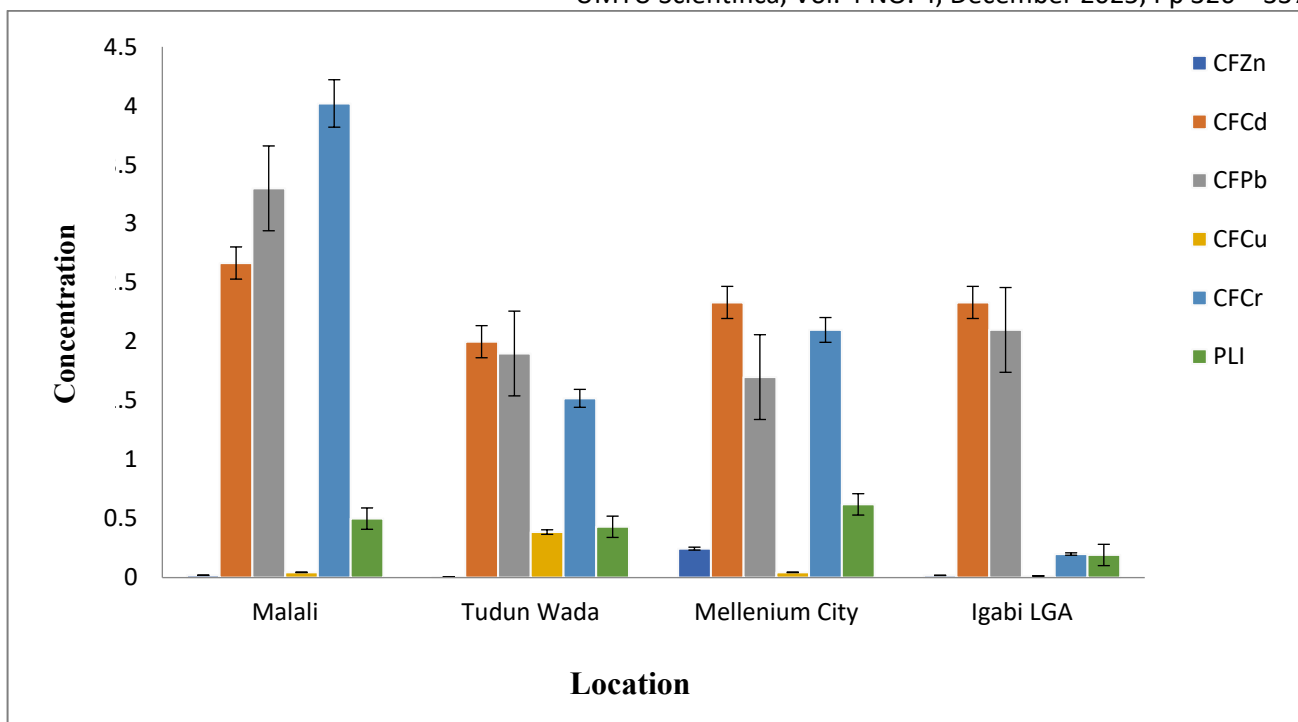


Figure 3: The Borehole Water Contamination Factor (CF) and Pollution Load Index (PLI)

Data are presented as mean ± SD of triplicates of analysis. Different letters above the bars for a given concentration in each extract are significantly different from each other ($p < 0.05$; Duncan post-hoc test; IBM SPSS, version 20).

Interpretations: $CF < 1$ (Low), $1 \leq CF < 3$ (Moderate), $3 \leq CF < 6$ (Considerable), $CF \geq 6$ (Vey high), $PLI < 1$ (Unpolluted/Baseline), $PLI = 1$ Baseline/Starting Point, $PLI > 1$ (Polluted)

Table 5: Physicochemical Parameters in Borehole Water from Kaduna Metropolis

Parameter	Tudun Wada	Malali	Igabi LGA	Millennium City	WHO (2017)
EC (mS/cm)	0.78 ^a	0.86 ^a	0.62 ^b	1.08 ^c	≤1.5
pH	6.88 ^a	5.90 ^b	6.81 ^a	6.68 ^a	6.5–8.5
DO (mg/L)	2.01 ^a	1.99 ^a	2.70 ^b	2.17 ^b	4–6
Temp. (°C)	24.5 ^a	24.00 ^a	24.25 ^a	25.00 ^a	25–30
Turbidity (NTU)	2.40 ^a	4.80 ^b	6.80 ^c	4.50 ^b	≤5
TDS (mg/L)	467.33 ^a	513.33 ^b	372.33 ^c	645.66 ^d	≤1000

Values with different letters across the column are significantly different from each other at $P < 0.05$.

Table 6: Comparative Physicochemical Mean Concentrations and Statistical Analysis (T-Test) of Well Water versus Borehole Water in Kaduna Metropolis

Parameter	Well	Borehole	T-Statistic	P-value	Significance
EC (mS/cm)	1.59±0.05 ^a	0.84±0.19 ^b	7.589	0.0029	Highly Significant ($p < 0.01$)
pH	6.65±0.52 ^a	6.57±0.45 ^a	0.247	0.8133	Not Significant (NS)
DO (mg/L)	1.99±0.08 ^a	2.22±0.33 ^b	-1.363	0.2573	Not Significant (NS)
Temp. (°C)	24.88±0.25 ^a	24.44±0.43 ^a	1.769	0.1391	Not Significant (NS)
Turbidity(NTU)	4.92±1.16 ^a	4.62±1.80 ^a	0.28	0.7904	Not Significant (NS)
TDS (mg/L)	952.50±31.13 ^a	499.66±113.67 ^b	7.685	0.0028	Highly Significant ($p < 0.01$)

Results are presented as mean ± SD. Values with different letters across the column are significantly different from each other at $P < 0.05$.

Lead concentrations in well water ranged from 0.032 to 0.054 mg/L, exceeding the WHO/NSDWQ permissible limit of 0.010 mg/L. The elevated Pb levels likely originate from corroded lead pipes, lead-based paints, and vehicular emissions. Wells, being more exposed to surface runoff, are more vulnerable to Pb contamination (Mahmud *et al.*, 2025). The higher Pb values recorded in Malali and Tudun Wada are consistent with observations from northern Nigerian mining and residential environments reported by Ifediegwu *et al.* (2022) and Akpa *et al.* (2025).

Copper concentrations in well water ranged from 0.016 to 0.386 mg/L, below the WHO (2.000 mg/L) and NSDWQ (1.000 mg/L) limits. The highest Cu value (0.386 mg/L) recorded in Tudun Wada may be due to corrosion of copper pipes or fittings. Contamination of wells can also arise from the dissolution of roofing materials during rainfall infiltration (Matimbwa, 2025).

Chromium levels in well water ranged from 0.075 to 0.484 mg/L, exceeding the WHO and NSDWQ limits of 0.050 mg/L at several sites. The high Cr concentrations suggest

pollution from industrial effluents, tanneries, and waste dumps (Harshan *et al.*, 2025). Elevated Cr in Millennium City and Malali may result from the leaching of metal plating wastes or corrosion of chromium-containing alloys. Hexavalent chromium (Cr⁶⁺) is particularly toxic, causing liver and kidney damage and posing carcinogenic risks (WHO, 2017).

Concentration of Heavy Metals in Borehole Water

Zinc (Zn) concentrations in the borehole water ranged from 0.020–0.737 mg/L, which is within acceptable drinking water limits. The highest recorded level of 0.737 mg/L at Millennium City likely resulted from the corrosion of metallic infrastructure (casings, pipes, and fittings) exposed to variable groundwater chemistry (Dawoud & Al Hassan, 2025). While Zn is vital for enzymatic and metabolic functions, excessive intake may lead to gastrointestinal discomfort and interfere with copper metabolism (Fu *et al.*, 2025).

Cadmium (Cd) concentrations in borehole water, ranging from 0.006 to 0.008 mg/L, exceeded regulatory standards. The consistent presence of Cd in both well and borehole samples indicates that the contamination has percolated into deeper aquifers, likely via poorly sealed boreholes or hydraulic connections with contaminated surface soils (Xiao *et al.*, 2025). This poses a serious public health risk, as chronic Cd exposure is linked to kidney dysfunction, skeletal deformities, and cancer (WHO, 2017). Similar high Cd levels have been documented in urban groundwater systems, including Kano and Abuja (Bolade *et al.*, 2025).

Lead (Pb) concentrations in borehole water, ranging from 0.017 to 0.033 mg/L, exceed the 0.010 mg/L safety limit set by both the WHO (2017) and the NSDWQ (2015). Although levels were lower than those in wells, indicating some natural attenuation in the aquifer, this marginal reduction is insufficient. The detected Pb is highly concerning as it is a potent neurotoxin capable of causing severe neurological, renal, and hematological disorders even at trace levels (Kumar, 2025).

Copper (Cu) concentrations in borehole samples were low, ranging from 0.014–0.386 mg/L. These levels are well below the safety limits set by the WHO (2.000 mg/L) and the NSDWQ (1.000 mg/L), consistent with other low Cu reports in Zaria groundwater (Narayanan *et al.*, 2025). The pattern (similar to, but lower than, wells) suggests the primary source is minor plumbing corrosion, not industrial or geogenic inputs. While Cu is essential, excessive levels can cause a metallic taste and gastrointestinal irritation (Botle *et al.*, 2025).

Chromium (Cr) concentrations in borehole water ranged from 0.010–0.201 mg/L. Crucially, these levels exceed the permissible safety limits (set at 0.050 mg/L by WHO and NSDWQ) in some locations. Although concentrations were generally lower than in wells, suggesting partial natural attenuation in the subsurface, the presence of Cr in deeper aquifers confirms the downward migration of contaminants. Poorly protected borehole casings likely facilitate this migration. Similar Cr contamination trends

have been observed in other urban aquifers (Ning *et al.*, 2025).

Non-carcinogenic Risk Assessment using HQ and HI for Well and Borehole Water

Table 3 presents the results of the non-carcinogenic health risk assessment for heavy metals (Pb, Cd, and Cr) in both well water and borehole water. The assessment is based on the Hazard Quotient (HQ) for individual metals and the aggregated Hazard Index (HI). Well water showed a Significant Risk (HI=2.472), driven primarily by Chromium (HQ=1.895), which alone exceeds the safe threshold of 1.0. High Cr levels in shallow aquifers are often linked to anthropogenic inputs (Zheng *et al.*, 2025). Borehole water indicated a Potential Risk (HI=1.317). Although risk decreased due to natural attenuation (lower Pb and Cr HQs), the HI still exceeds 1.0. Cr (HQ=0.933) remains the highest contributor, suggesting ongoing contamination migration possibly through poorly sealed infrastructure (Xiao *et al.*, 2025). The overall HI > 1 in both sources confirms that cumulative exposure poses a serious threat of adverse non-carcinogenic health outcomes (e.g., kidney, neurological, and skeletal damage) to the exposed population (Kumar, 2025; Rajabi *et al.*, 2025; Gamero-Vega *et al.*, 2025).

Contamination Factor (CF) and Pollution Load Index (PLI) for Well and Borehole Water

The analysis of contamination using the Contamination Factor (CF) and Pollution Load Index (PLI) reveals a crucial difference between the overall pollution status and localized heavy metal risk across the study sites (Figure 2 and 3). The Pollution Load Index (PLI) remained consistently below 1.0 (PLI<1) for all locations in both well water (0.397 to 0.719) and borehole water (0.192 to 0.621), suggesting an unpolluted baseline based on the geometric mean (Bashir *et al.*, 2025). However, the Contamination Factor (CF) for individual metals highlights severe localized contamination. Chromium (Cr) is the most alarming contaminant, reaching a Very High contamination level (CF=9.680) in the Millennium City well and remaining at a Considerable level (CF=4.020) in the Malali borehole. Similarly, Lead (Pb) shows widespread Considerable Contamination (CF≥3) in well water, with CF values ranging from 3.200 to 5.400. Furthermore, Cadmium (Cd) contamination is consistently at a Moderate (CF≥2) level across all sites in both shallow and deep water. This disparity confirms that while the low PLI suggests the average pollution load is low (due to very low CF for Zn and Cu, the high CF values for toxic metals (Pb, Cr) necessitate urgent intervention. The presence of Considerable Pb and Cr contamination in the deeper borehole water confirms that, despite some attenuation, contamination has migrated downward, posing a serious health threat (Alao *et al.*, 2025).

Physicochemical Properties of Well Water in Kaduna Metropolis

The Electrical Conductivity (EC) of the well water samples ranged from 1.51 to 1.62 mS/cm. Although these values are characterized as low and indicative of poorly

mineralized water, they slightly exceed the typical natural groundwater maximum of 1.5 mS/cm (WHO, 2022; Shokoohi & Moyo, 2025). EC directly reflects the concentration of dissolved ions (Ca^{2+} , Mg^{2+} , Na^+ , Cl^-) (WHO, 2022). The observed EC range suggests that the water is fresh and weakly mineralized, likely originating from recent recharge or from shallow aquifers with limited rock-water interaction (Sreedevi *et al.*, 2021).

The pH of the well water ranged from 6.00 to 7.26, indicating slightly acidic to near-neutral conditions. Since the limit is 6.5-8.5 (WHO, 2022; NSDWQ, 2015), some samples fall slightly below the limit. This mild acidity (from natural or anthropogenic sources) can accelerate pipe corrosion and increase the mobility of toxic trace metals (Fe, Mn, Pb) (Wu *et al.*, 2025).

The Total Dissolved Oxygen (TDO) concentrations in the samples were low, ranging from 1.87 to 2.04 mg/L. This reflects the limited oxygen availability typical of groundwater systems due to minimal atmospheric contact and microbial consumption (Guo *et al.*, 2025). Such low TDO levels may indicate reducing conditions, which can promote the mobility of heavy metals like iron and manganese (Wang *et al.*, 2024).

The temperature values ranged from 24.5°C to 25.0°C, consistent with the ambient temperatures of tropical aquifers. Temperature influences several water quality parameters, including oxygen solubility, microbial activity, and chemical reactions (Hammoumi *et al.*, 2024). The narrow temperature range observed suggests a relatively stable groundwater environment with minimal external influence, as also reported by Goma *et al.* (2025) in similar studies across Kaduna State.

The turbidity of the well water samples ranged from 3.2 to 5.7 mg/L. While most samples comply, some slightly exceed the WHO limit of 5.0 NTU. High turbidity, due to suspended matter, is critical because it hinders disinfection and suggests either surface infiltration or poor well integrity (Riyadh & Peleato, 2024).

The total dissolved solids (TDS) values ranged from 336.66 to 617.33 mg/L, which are within the WHO limit of 1000 mg/L for potable water. These results imply moderate mineralization of the water, likely from geological formations or from the leaching of soil minerals into the aquifer (Kalevandi *et al.*, 2019).

Physicochemical Properties of Borehole Water in Kaduna Metropolis

The Electrical Conductivity (EC) of the borehole water samples ranged from 0.62 to 1.08 mS/cm. All EC values are below the WHO (2017) aesthetic guideline of 1.5 mS/cm. This indicates that the water's electrical conductivity is low, suggesting a relatively low concentration of dissolved ions (Zhang *et al.*, 2025). Low EC is characteristic of fresh water in hard-rock environments such as the Nigerian Basement Complex. It suggests that the groundwater has a moderate residence time or is being diluted by recent, less mineralized recharge (Wali *et al.*, 2025).

The Total Dissolved Solids (TDS) concentration ranged from 372.33 to 645.66 mg/L. All TDS values are well within the WHO (2017) and NSDWQ (2015) safety and aesthetic limits of 1000 mg/L (Okoro & Apiamu, 2024). The observed range reflects moderate mineralization. This mineralization primarily results from prolonged water-rock interaction, in which groundwater dissolves minerals (e.g., Ca^{2+} , Mg^{2+} , Na^+ , etc.) from the aquifer matrix (Bouselsal *et al.*, 2024). The highest concentration (645.66 mg/L in Millennium City) suggests localized geochemical enrichment or a greater impact from urban/anthropogenic sources (Garba *et al.*, 2025).

The pH of the borehole water ranged from 5.90 to 6.88, indicating slightly acidic to near-neutral conditions. Since the acceptable range is 6.5-8.5 (WHO, 2022; SON, 2015), samples below 6.5 are mildly acidic. This acidity, caused by natural processes (carbonic acid) or anthropogenic influences (runoff) (Asif *et al.*, 2025; Jolaosho *et al.*, 2024), can cause pipe corrosion and enhance the leaching of toxic metals (Pb, Cu, Zn) into the water (Endale *et al.*, 2024). Therefore, periodic monitoring and pH correction (limestone filtration) are necessary to mitigate the potential for corrosion and metal mobilization.

The Total Dissolved Oxygen (TDO) concentrations in the borehole water ranged from 1.99 to 2.70 mg/L. This low range, falling below the 3 mg/L threshold, indicates a reducing (anoxic) aquifer environment, likely driven by limited aeration and high microbial oxygen consumption (Li *et al.*, 2024). This reducing condition is critical because it favours the mobilization of redox-sensitive elements, such as iron (Fe^{2+}) and manganese (Mn^{2+}), into solution, thereby degrading water quality (WHO, 2022). Consequently, continuous monitoring of dissolved oxygen (DO) and associated metal concentrations is strongly recommended (Ijaz *et al.*, 2024).

The temperature of the borehole water samples ranged narrowly from 24.0 °C to 25.0 °C. This reflects stable, moderate thermal conditions typical of shallow tropical aquifers and complies with the WHO (2022) and NSDWQ (2015) limit of <30 °C. While the narrow range suggests minimal external influence, this relatively warm temperature may partly account for the observed low Total Dissolved Oxygen (TDO) concentrations (1.99-2.70 mg/L) due to reduced oxygen solubility (Sadler *et al.*, 2024).

The turbidity of the borehole water samples ranged from 2.4 to 6.8 mg/L. While some samples met the WHO/NSDWQ limit of 5.0 NTU, others exceeded the guideline, suggesting possible particulate contamination or inadequate wellhead protection (WHO, 2022). Turbidity, which reflects suspended matter like clay or organic material, can result from surface runoff infiltration or improper well construction (Matos *et al.*, 2024). Although not directly hazardous, high turbidity is an operational concern because it can shield microorganisms from disinfection (Adeniyi & Jimoh, 2024). Therefore, regular monitoring and proper wellhead sealing are necessary.

The Total Dissolved Solids (TDS) concentration ranged from 372.33 to 645.66 mg/L (Table 5), reflecting moderate mineralization from groundwater interaction with mineral-bearing formations (Stavropoulou *et al.*, 2025). While all values are within the safety limits, some slightly exceed the WHO/NSDWQ aesthetic limit of 500 mg/L (WHO, 2022; NSDWQ, 2015). Values approaching 650 mg/L suggest localized geochemical enrichment or agricultural runoff inputs (Comfort *et al.*, 2024) and necessitate periodic monitoring to ensure continued palatability and compliance.

Comparative Assessment of Physico-Chemical Water Quality in Kaduna Metropolis: Well vs. Borehole Vulnerability and Compliance

The comparative analysis of water quality in the Kaduna Metropolis in Table 6 reveals distinct differences in susceptibility between shallow well water and deeper borehole water, driven by source depth and regional aquifer characteristics. This discussion interprets the mean \pm standard deviation results and statistical p-values, contextualizing them against the World Health Organisation (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ) standards, and is supported by recent literature.

The analysis yielded a highly significant disparity ($p < 0.01$) for both Electrical Conductivity (EC) and Total Dissolved Solids (TDS), with well water exhibiting substantially higher concentrations (EC: 1.59 ± 0.05 mS/cm; TDS: 952.50 ± 31.13 mg/L) compared to borehole water (EC: 0.84 ± 0.19 mS/cm; TDS: 499.66 ± 113.6 mg/L). The mean well water EC exceeds both the WHO (1.5 mS/cm) and NSDWQ (1.0 mS/cm) limits, while its TDS value breaches the NSDWQ limit (500 mg/L). This statistical confirmation strongly indicates that shallow wells are more intrinsically vulnerable to contamination from surface sources such as sewage and urban runoff. This finding aligns with established hydrogeological principles and recent studies that correlate elevated EC values with groundwater systems possessing low protective cover, confirming the wells' exposure to high ionic loads from the shallow subsurface (Gemail *et al.*, 2023).

In contrast to the highly variable EC and TDS, the concentrations of Dissolved Oxygen (DO) showed no statistically significant difference ($p=0.2573$) between the two sources (Well: 1.99 ± 0.08 mg/L; Borehole: 2.22 ± 0.33 mg/L). The uniformity of these severely low DO levels suggests that surface interactions do not control the parameter, but rather that it is a systemic feature of the regional aquifer. This severe oxygen depletion is characteristic of reducing conditions and is primarily driven by the microbial degradation of dissolved organic carbon over extended groundwater residence times in confined settings (Rajendiran *et al.*, 2023; Wen *et al.*, 2025).

Finally, while Turbidity also showed no significant statistical difference ($p=0.7904$), both the well (4.92 ± 1.16 NTU) and borehole (4.62 ± 1.80 NTU) means approach the NSDWQ/WHO aesthetic limit of 5 NTU. This

proximity to the limit is a critical operational concern, as suspended particulate matter, particularly organic material, can significantly compromise water safety. Elevated turbidity is known to increase chlorine demand and physically shield pathogenic microorganisms from chemical disinfectants, thereby reducing overall chlorination efficacy and increasing public health risk (Parveen *et al.*, 2022).

CONCLUSION

The comprehensive assessment confirms that groundwater in the Kaduna Metropolis poses a significant public health risk due to widespread contamination with toxic heavy metals in both shallow wells and deep boreholes. While shallow wells show greater vulnerability to surface inputs (evidenced by significantly higher EC and TDS), the crucial finding is that Lead (Pb), Cadmium (Cd), and Chromium (Cr) exceed national and international safety limits in both sources. The calculated Hazard Index ($HI > 1$) in both source types confirms an unacceptable cumulative risk of adverse non-carcinogenic health effects. Notably, the detection of Cr and Cd in the deeper borehole water provides clear evidence of pollutant migration into the deep aquifer system, necessitating urgent advanced treatment to remove heavy metals.

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