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ORIGINAL RESEARCH ARTICLE

Integrated Assessment of Cumulative Health Risk Index and Lifetime Cancer Risk of Groundwater Heavy Metals in Bokkos Town, Plateau State, Nigeria

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ABSTRACT

Groundwater is the main source of drinking water in Bokkos Town, Plateau State, Nigeria. This study assessed water quality and human health risks using hydrochemical analysis, statistical evaluation, and the USEPA risk framework. Twenty sources (17 wells, 3 boreholes) were sampled for manganese (Mn), chromium (Cr), and arsenic (As) using Atomic Absorption Spectrophotometry. Risks were quantified using Hazard Quotient (HQ), Hazard Index (HI), Total Carcinogenic Risk (TCR), and child-to-adult TCR ratios. Results showed mean concentrations of Mn (0.074 **mg/L**), Cr (0.055 mg/L), and As (0.014 mg/L), with several samples exceeding WHO limits, particularly Mn and As. Non-carcinogenic risk analysis indicated elevated HI at multiple sites, with children showing greater vulnerability. Carcinogenic risk assessment revealed most sources exceeded the USEPA acceptable threshold (1.0×10^{-3}), with BIO having the highest TCR (adult: 2.48×10^{-3}; child: 5.02 x 10-3). Pearson correlation indicated strong positive associations, especially between Cr and As ($r = 0.82$, $P < 0.01$). One-sample t-tests confirmed significant exceedances for Mn ($t = 2.45$, $P = 0.024$) and As ($t = 3.98$, $P = 0.001$). Arsenic and manganese are major contaminants, with children disproportionately affected. Recommendations include regular groundwater monitoring, provision of safe water sources, public awareness campaigns, and enforcement of water quality regulations to reduce exposure and protect vulnerable populations.

Introduction

Groundwater is a major source of drinking water globally, particularly in rural and low-income regions where treated surface water infrastructure is limited (Wu et al., 2020; Li et al., 2021; UNESCO, 2022). However, groundwater is increasingly threatened by contamination from heavy metals such as lead

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(Pb), cadmium (Cd), chromium (Cr), arsenic (As), and nickel (Ni), arising from both natural geogenic processes and anthropogenic activities (Wu et al., 2020; Zhang et al., 2022; Li et al., 2021). Chronic exposure to heavy-metal-contaminated groundwater has been associated with kidney and liver dysfunction, neurological disorders, endocrine disruption, and various cancers (Tchounwou et al, 2012; Wu et al., 2020; Li et al., 2021), Consequently, integrated human health risk assessment frameworks incorporating non-carcinogenic risk (Hazard Index, HI) and carcinogenic risk (Total Carcinogenic Risk, TCR) are widely applied to evaluate potential health impacts (United States Environmental Protection Agency, 2011; Li et al., 2021; Zhang et al.,,2022),

In Sub-Saharan Africa, groundwater serves as the principal drinking water source for many rural and peri-urban communities due to rapid population growth and limited water treatment infrastructure (Lapworth et al., 2017; Tyopine et al., 2024), Studies across the region have reported elevated concentrations of toxic metals in groundwater associated with mining, agriculture, waste disposal, and industrial activities, posing significant health risks (Tyopine et al., 2024; Gwira et al., 2024), Recent research also shows that children often experience higher carcinogenic and noncarcinogenic risk levels than adults because of lower body weight and higher water intake relative to body mass (Guron et al., 2025; Kumar & Maurya, 2025), Despite these findings, few studies explicitly evaluate demographic disparities using indicators such as the child-to-adult TCR ratio,

Groundwater is widely utilized for drinking and domestic purposes across Nigeria, particularly in rural communities where municipal water supply systems are often inadequate or unreliable. (Tyopine et al., 2024; Oyebode et al., 2025), Several studies have reported heavy metal concentrations exceeding guideline limits established by the World Health Organization, with associated carcinogenic and non-carcinogenic health risks (Gwira et al., 2024; Ehsan et al., 2025), For instance, investigations in southeastern Nigeria identified elevated Pb and Cd levels in groundwater with higher cancer risk estimates for children than adults (Gwira et al., 2024, 2024; Ehsan et al., 2025), Additionally, anthropogenic activities such as waste disposal and mining have been identified as major drivers of heavy metal mobilization into aquifers (Farzana et al., 2025; Kumar & Maurya, 2025),

Plateau State, including Bokkos Town, is characterized by complex geology, agricultural land use, mining activities, and informal waste disposal practices that may influence groundwater quality, However, comprehensive studies integrating heavy metal contamination with cumulative noncarcinogenic and carcinogenic health risk assessments including age-stratified comparisons such as the child-to-adult TCR ratio remain limited, This study therefore evaluates heavy metal contamination in groundwater and assesses the associated health risks to residents,

To statistically examine groundwater contamination patterns, the study tested the following null hypotheses: (H_o) there is no significant correlation between heavy metals (Mn, Cr, As) and water quality parameters (TDS and EC); (H_o) the mean concentrations of heavy metals do not differ significantly from the permissible limits recommended by the World Health Organization;

Materials and Methods

The study area

Bokkos Town, situated in Bokkos Local Government Area (LGA) of Plateau State, North-Central Nigeria, encompasses and is a

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semi-urban. The town lies between 9.25° N and 9.30° N latitude and 8.88° E to 9.00° E longitude, defining the spatial extent where groundwater samples were collected and analyzed. Bokkos covers an area of roughly 12.6 km2 and has an estimated population of 18,966 (National Population Commission, Jos Office, 2024).

The region experiences relatively mild temperatures due to its high altitude, with average maximum and minimum values of about 20°C and 18 °C, respectively. The climate is distinctly bimodal, characterized by a wet season from April to October and a dry season from November to March, which coincides with the harmattan period featuring dry, dust-laden north-easterly winds. The coolest periods generally occur between July and August and from November to February. The geology of Bokkos Local Government Area (LGA), situated on the southwestern escarpment of the Jos Plateau in Plateau State, is primarily and generally composed of Precambrian Basement Complex rocks, notably granite gneiss, biotite granite, syenite, and hornblende granite (Gwanshak & Danbauchi, 2021). Residents of Bokkos Town primarily rely on hand-dug wells and boreholes for drinking water for domestic use. The major ethnic groups are the Ron and Kulere, with agriculture and trading as the predominant occupations. Commonly cultivated crops include Irish and sweet potatoes, maize, beans, and other local produce.

Figure 1 illustrates the spatial distribution of the 20 groundwater sampling sites across Bokkos Town, with boreholes indicated by blue circles and hand-dug wells by red hexagons.

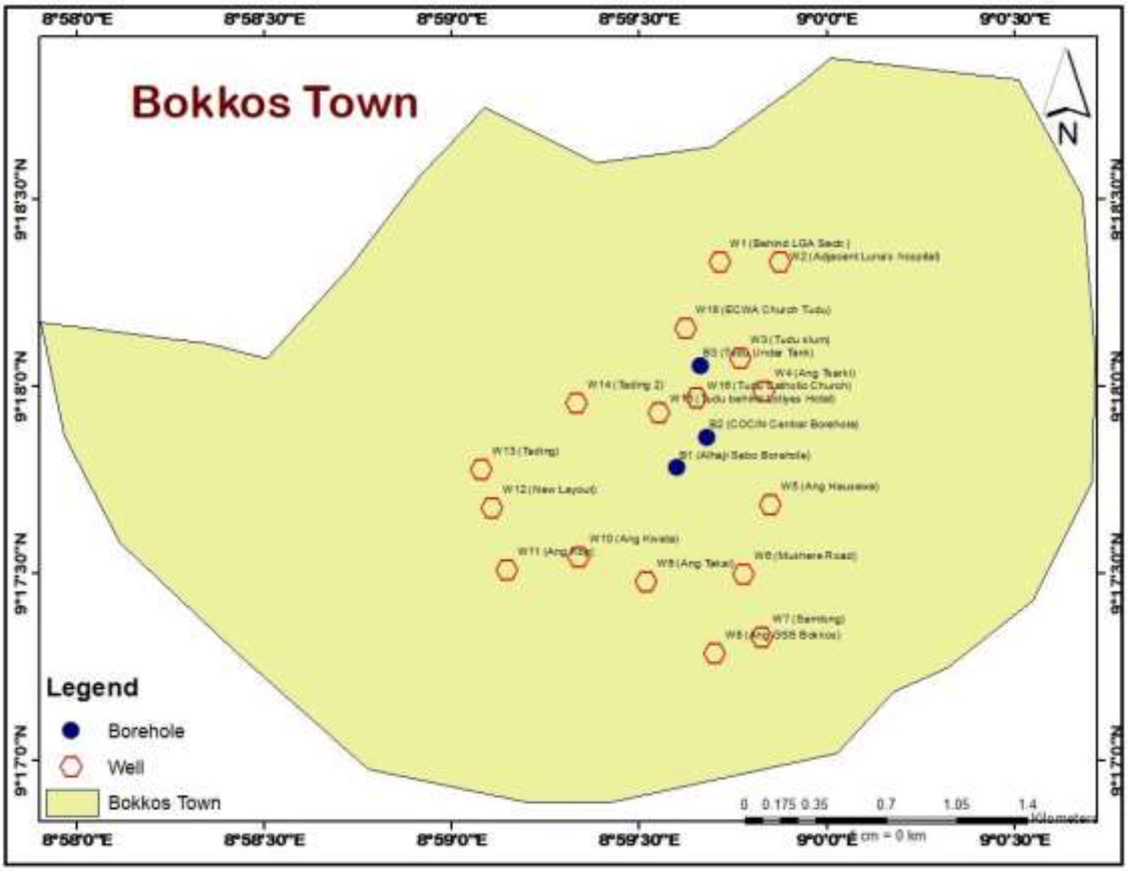

Figure 1: Map of Bokkos showing sample collection locations.

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Study Design and Analytical Framework

A cross-sectional analytical design was adopted to assess groundwater quality in Bokkos Town, Plateau State, Nigeria. Justification: Provides a snapshot of groundwater quality across multiple sources, identifying contamination hotspots and regulatory compliance.

Sampling and Field Measurement

- **Sampling:** Twenty groundwater sources (17 wells, 3 boreholes) were randomly selected. Geographic coordinates were recorded using GPS for representative spatial coverage.
- **Trace Metals:** Mn and Cr determined using air-acetylene flame AAS; As determined using hydride generation AAS for higher sensitivity (WHO, 2017).
- **Sample Preservation:** Samples stored in pre-cleaned polyethylene bottles; trace metals acidified to pH < 2 and transported in insulated coolers to prevent alteration.

Laboratory Analysis

Health Risk Assessment Framework

Human health risk assessment followed USEPA guidelines (USEPA, 1989; 2004), covering hazard identification, exposure, dose-response, and risk characterization. Both non-carcinogenic (HQ, HI) and carcinogenic (TCR) risks were calculated for adults and children (Table 1).

Non-Carcinogenic Risk

HQ = CDI / RfD; HI = ΣHQ_i. Values >1 indicate potential health effects. Evaluated for Mn, Cr, and As. 2.2.2 Carcinogenic Risk

TCR = CDI x CSF. Only arsenic assessed due to established oral CSF (Cancer Slope Factor) (1.5 mg/kg/day) and IARC Group 1 classification. Chromium speciation was not performed; manganese IS non-carcinogenic.

Table 1: Constants and Parameters

Parameter	Value (Adults / Children)	Source
IR (L/day)	2/1	USEPA (2011)
BW (kg)	70/15	NPC & ICF (2024)
EF (days/year)	365	USEPA (2011)
ED (years)	70/6	USEPA (2011)
AT (days)	ED x 365	USEPA (1989)
RID (mg/kg/day)	Mn:0.14, Cr: 0.003, As: 0.0003	USEPA IRIS (2024)
CSF **µg/kg/day**	Cr (VI):0.5, As:1.5	USEPA IRIS (n.d)
WHO Guideline (mg/L)	Mn:0.05, Cr:0.05, As: 0.01	WHO (2017)
Parameter	Value (Adults / Children)	Source

Regulatory Risk Thresholds - 10^{-6}: Negligible risk - 10-6-10^{-4}: Acceptable risk - > 10^{-4}: Unacceptable cancer risk

Age-Specific Carcinogenic Risk and Child-to-Adult TCR

TCR calculated for adults and children; child-to-adult ratio = TCR _child / TCR _adult, identifying age-dependent vulnerability and contamination hotspots.

Statistical Hypotheses

1. **Pearson Correlation:** H_0: No correlation between heavy metals and TDS/EC.
2. **One-Sample t-Test:** H_0: Mean metal concentrations equal WHO limits.
3. ANOV A: H_0: No difference across sampling locations.

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Results

Groundwater from 20 sources in Bokkos Town, Plateau State, Nigeria, was analyzed for manganese (Mn), chromium (Cr), and arsenic (As). Laboratory results showed spatial variability in metal concentrations, with several samples exceeding WHO guidelines. Non-carcinogenic and carcinogenic risks, including child-to-adult TCR ratios, were assessed. Descriptive and inferential statistical analyses were conducted to examine relationships among metals and water quality parameters and spatial differences across sites.

Laboratory Results of Groundwater Samples Collected from the Study Area

As shown in Table 2, the concentrations of Mn, Cr, As, and pH varied across the 20 groundwater sources in Bokkos Town. Manganese concentrations ranged from 0.007 to 0.357 mg/L (mean: 0.074 mg/L). Several samples exceeded the WHO limit of 0.05 mg/L, with the highest value recorded at B20, followed by B18 and B19.

Chromium ranged between 0.017 and 0.315 mg/L (mean: 0.055 mg/L). A notably high concentration was observed at B14 (0.315 mg/L), and some other samples also exceeded the WHO guideline of 0.05 mg/L.

Arsenic concentrations varied from 0.006 to 0.033 mg/L (mean: 0.014 mg/L), with several samples surpassing the WHO limit of 0.01 mg/L, particularly B1 0, B 12, B 16, and B20.
The pH values ranged from 5.50 to 8.40. Although most samples were within or close to the WHO recommended range of 6.5-8.5, a few locations exhibited slightly acidic conditions.

Table 2: Laboratory Results of Groundwater Samples Collected from the Study Area

Sample Code	Manganese (Mn) (mg/l)	Chromium (Cr) (mg/l)	(As) (mg/l)
B1	0.007	0.017	0.006
B2	0.017	0.024	0.017
B3	0.034	0.029	0.012
B4	0.046	0.035	0.006
B5	0.070	0.045	0.010
B6	0.054	0.048	0.013
B7	0.059	0.058	0.011
B8	0.063	0.058	0.007
B9	0.065	0.063	0.011
B10	0.081	0.066	0.033
B11	0.023	0.023	0.006
B12	0.030	0.023	0.020
B13	0.055	0.030	0.011
B14	0.068	0.315	0.012
B15	0.073	0.036	0.016
B16	0.067	0.037	0.020
B17	0.067	0.042	0.016
B18	0.098	0.043	0.015
B19	0.088	0.048	0.017
B20	0.357	0.053	0.020
AVERAGE	0.07425	0.05475	0.01395
WHO STANDARD	0.05	0.05	0.01

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Human Health Risk Assessment (HHRA)

Non-Carcinogenic Risk: HQ and HI

The non-carcinogenic risk from groundwater consumption was evaluated using Hazard Quotient (HQ) for manganese (Mn), chromium (Cr), and arsenic (As), along with the cumulative Hazard Index (HI), separately for adults and children (Table 4).

For adults, Mn posed minimal risk across all samples, with HQ values well below the safety threshold. Chromium showed generally low HQ values, though a few samples exhibited moderate to high levels, indicating potential concern. Arsenic contributed most significantly to risk, with several samples exceeding safe limits, resulting in cumulative HI values above the acceptable level in specific locations. These findings suggest that adults consuming water from these high-risk sources may be susceptible to non-carcinogenic health effects, particularly due to arsenic and chromium exposure.

Children exhibited higher HQ and HI values compared to adults across all contaminants, reflecting their greater physiological susceptibility. Arsenic and chromium were the main contributors to elevated cumulative risk, with HI values far exceeding the acceptable threshold in several locations. This indicates that children are significantly more vulnerable to non-carcinogenic effects from contaminated groundwater, highlighting urgent public health concerns.

Total Carcinogenic Risk (TCR) for Adults and Children

The Total Carcinogenic Risk (TCR) for adults and children across the 20 groundwater samples (B1-B20) is summarized in Table 5 and illustrated in Figure 2 (Adults) and Figure 3 (Children with USEPA acceptable risk line). For adults, most samples show TCR values below the USEPA acceptable limit of 1.0 x 10^{-3}, indicating generally low lifetime cancer risk (Table 5). However, several samples exceed this threshold, particularly B10 (2.48 x 10-3), B12, B14, B15, B16, B17, B18, B19, and B20, highlighting specific groundwater sources that may pose significant carcinogenic risks (Figure 2).

Children exhibit higher TCR values across all samples (Table 5), with the highest risks observed in B 10 (5.02 x 10^{-3}), B 12 (3.79 x 10^{-3}), B 16 (2.48 x 10^{-3}), and B20 (3.6 x 10^{-3}), consistently exceeding the USEPA threshold. This pattern indicates greater susceptibility of children to carcinogenic contaminants in groundwater.

The inclusion of the USEPA acceptable risk line in Figure 2 allows a clear visual comparison, showing which samples exceed safe limits and highlighting spatial variability in risk across the study area. Overall, while most adult groundwater sources remain within safe limits, the widespread exceedances among children, as reflected in Table 5 and the graphs, underscore the need for targeted monitoring, remediation, and protective interventions to minimize long-term health impacts

The results indicate that B10 recorded the highest carcinogenic risk for both adults (2.48 x 10^{-3}) and children (5.02 x 10^{-3}) (Figure 2 and Figure 3, making it the most critical hotspot in the study area. All samples exceed the USEPA acceptable risk level, suggesting widespread arsenic-related health risk.

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Table 4: Hazard Quotient (HQ) and Cumulative Hazard Index) for Groundwater Samples

Sample	HQ Mn (Adult)	HQ Cr (Adult)	HQ As (Adult)	HI (Adult)	HQ Mn (Child)	HQ Cr (Child)	HQ As (Child)	HI (Child)
B1	0.002 □	0.162 □	0.571 □	0.735 □	0.033 □	0.378 □	1.333 □	1.744 □
B2	0.003 □	0.229 □	1.911 □	2.143 □	0.008 □	0.533 □	4.222 □	4.763 □
B3	0.007 □	0.279 □	1.333 □	1.619 □	0.016 □	0.667 □	2.667 □	3.350 □
B4	0.009 □	0.333 □	0.571 □	0.913 □	0.022 □	0.800 □	1.333 □	2.155 □
B5	0.014 □	0.429 □	0.952 □	1.395 □	0.047 □	1.000 □	2.222 □	3.269 □
B6	0.011 □	0.457 □	1.429 □	1.897 □	0.026 □	1.067 □	3.111 □	4.204 □
B7	0.012 □	0.553 □	1.286 □	1.851 □	0.028 □	1.289 □	2.444 □	3.761 □
B8	0.013 □	0.553 □	0.714 □	1.280 □	0.030 □	1.289 □	1.333 □	2.652 □
B9	0.013 □	0.588 □	1.286 □	1.887 □	0.031 □	1.378 □	2.444 □	3.853 □
B10	0.016 □	0.629 □	7.333 □	7.978 □	0.046 □	1.467 □	14.667	16.180
B11	0.007 □	0.219 □	0.571 □	0.797 □	0.010 □	0.489 □	1.333 □	1.832 □
B12	0.009 □	0.219 □	3.333 □	3.561 □	0.020 □	0.489 □	7.111 □	7.620 □
B13	0.016 □	0.286 □	1.286 □	1.588 □	0.037 □	0.644 □	2.444 □	3.125 □
B14	0.014 □	7.500 □	1.429 □	8.943 □	0.045 □	16.667	2.857 □	19.569
B15	0.015 □	0.857 □	1.524 □	2.396 □	0.049 □	1.905 □	3.222 □	5.176 □
B16	0.014 □	0.871 □	3.333 □	4.218 □	0.045 □	1.952 □	7.111 □	9.108 □
B17	0.014 □	1.000 □	1.524 □	2.538 □	0.045 □	2.250 □	3.222 □	5.517 □
B18	0.020 □	1.029 □	1.429 □	3.478 □	0.057 □	2.314 □	3.111 □	5.482 □
B19	0.018 □	1.143 □	1.524 □	3.685 □	0.053 □	2.571 □	3.333 □	5.957 □
B20	0.073 □	1.271 □	3.333 □	4.677 □	0.238 □	2.967 □	7.111 □	10.316

Note: The data used for this calculation were obtained: from Table 2.
Colour Coding: Green: HQIHI ≤ 1 (Safe), Yellow: HQIHI 1-5 (Moderate Risk), Red: HQIHI > 5 (High Risk)

Table 5: Total Carcinogenic Risk (TCR)

Sample	TCR Adult (x10^{-3})	TCR Child (x10^{-3})
B11	0.45 x10^{-3}	0.37 x10-3
B12	1.5 x 10^{-3}	3.79 x10-3
B13	0.83 x 10^{-3}	1.68 xl0-3
B14	1.21 x 10^{-3}	2.23 x 10^{-3}
B15	1.2 x 10^{-3}	1.25 x 10^{-3}
B16	1.5 x 10^{-3}	2.48 x10^{-3}
B17	1.25 x10^{-3}	1.64 x10^{-3}
B18	1.13 x 10^{-3}	1.52 x 10^{-3}
B19	1.26 x 10^{-3}	1.87 x10^{-3}
B20	1.5 x 10^{-3}	3.6 x 10^{-3}

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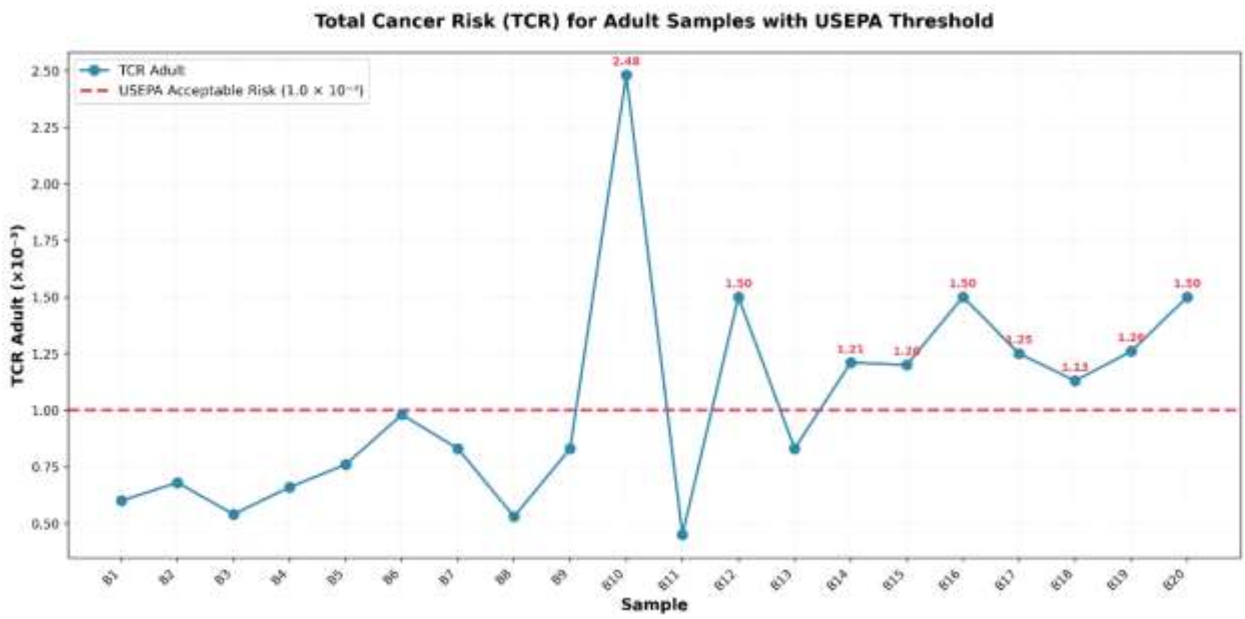

Figure 2: Total Cancer Risk (TCR) for Adults Across Groundwater Samples (B I-B20) with USEPA Acceptable Risk Threshold (1.0 x 10^{-3})

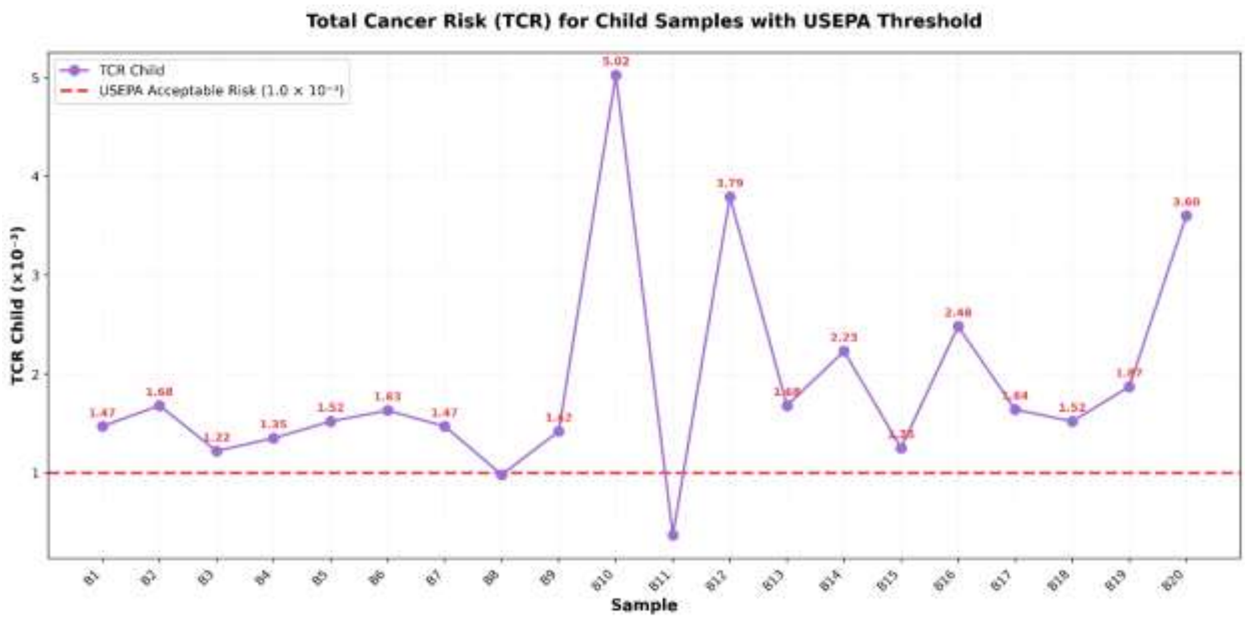

Figure 3: Total Cancer Risk (TCR) for Children Across Groundwater Samples (B1-B20) with USEPA Acceptable Risk Threshold (1.0 x 10-3).

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Statistical analyses

Descriptive Statistics of Trace Metals and Water Quality Indicators

Table 6: Descriptive Statistics of Key Groundwater Quality Parameters Across the Study Area

Parameter	Mean	Standard Deviation	Variance
Mn	0.074 mg/l	0.083 mg/	0.0069
Cr	0.055 mg/l	0.1245 mg/l	0.0155
As	0.014 mg/l	0.0075 mg/l	0.000056
pH	6.43	0.60	0.36

Descriptive statistical analysis of groundwater parameters was conducted to summarize the central tendency and variability of the measured values across the study area. Manganese (Mn) concentrations had a mean of 0.074 mg/l, with a standard deviation of 0.083 mg/l and a variance of 0.0069, indicating moderate variability among sampling locations (Table 6). Chromium (Cr) showed a mean concentration of 0.055 mg/l, with higher variability reflected in a standard deviation of 0.1245 mg/l and a variance of 0.0155, suggesting more spread in Cr levels across the sites. Arsenic (As) concentrations were relatively low and consistent, with a mean of 0.014 mg/l, standard deviation of O. 0075 mg/l, and variance of 0.000056, indicating minimal dispersion across samples.

These descriptive measures provide a clear understanding of the average levels and variability of key water quality parameters, allowing for straightforward comparison with WHO guideline values and highlighting locations of potential concern.

Inferential statistics

The statistical analyses were conducted to understand relationships among metals, water quality parameters, and spatial variation across sampling locations. Three key methods were applied:

Pearson correlation, one-sample t-test.

Pearson Correlation Matrix

Hypotheses:

H_0: There is no significant correlation between metals (Mn, Cr, As) and water quality parameters DS, EC).

Table 7: Pearson Correlation Matrix

	Mn	Cr	As	TDS	EC
Mn	1	0.48*	0.56*	0.64*	0.62*
Cr	0.48*	1	0.82**	0.73*	0.71*
As	0.56*	0.82**	1	0.66*	0.68*
TDS	0.64*	0.73*	0.66*	1	0.91 **
EC	0.62*	0.71*	0.68*	0.91**	1

- *p < 0.05; **p < 0.01

The Pearson correlation analysis revealed significant positive correlations between metals and water quality indicators. Manganese correlated moderately with Cr (r = 0.48, P < 0.05), As (r = 0.56, P < 0.05), TDS (r =0.64, P < 0.05), and EC (r= 0.62, P < 0.05) Table 7. Chromium strongly correlated with As (r = 0.82, P < 0.01) and moderately with TDS (r = 0.73, P < 0.05) and EC (r = 0.71, P < 0.05). TDS and EC were highly correlated (r = 0.91, P < 0.01), indicating that ionic content strongly influences conductivity. These

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findings suggest that the presence of metals is closely linked to overall water quality, and the null hypothesis is rejected.

One-Sample t-Test Against WHO Guidelines Hypotheses:

H^0: Mean concentrations of metals do not differ significantly from WHO permissible limits.

Table 8: One-Sample t-Test Against WHO Guidelines

Metal	Sample Mean	WHO Limit	t-value	p-value	Decision
Mn	0.074	0.05	2.45	0.024	Reject Ho
Cr	0.055	0.05	1.32	0.201	Accept Ho
As	0.014	0.01	3.98	0.001	Reject Ho

The one-sample t-test showed that Mn (0.074 mg/L, t = 2.45, P = 0.024) and As (0.014 mg/L, t = 3.98, P = 0.001) concentrations were significantly above WHO guideline values, indicating potential health risks for consumers. Chromium (Cr), with a mean of 0.055 mg/L, was not significantly different from the guideline (t = 1.32, P = 0.201), suggesting it is largely within safe limits Table 8. These results highlight Mn and As as the primary contributors to groundwater contamination, leading to rejection of H_0 for these metals while Ho is accepted for Cr.

Age-Specific Carcinogenic Risk and the Child-to-Adult TCR Ratio

The combined results (Figure 4) reveal pronounced age-based disparities in groundwater-related cancer risk, clearly demonstrated by the child-to-adult TCR ratio. This ratio, calculated as child TCR divided by adult TCR, serves as a direct indicator of vulnerability differential. A value greater than 1.0 signifies higher carcinogenic risk in children under identical exposure conditions.

Across the study area, the child-to-adult TCR ratio exceeded unity in 95% of samples (19 out of 20), confirming that children bear a disproportionately higher cancer burden. The ratios ranged from 0.82x to 2.53x, with a mean value of 1.83x, indicating that children experience approximately 83% higher carcinogenic risk on average. Most locations (70%) fall within the moderate differential range (1.5-2.5x), while B12 recorded the highest differential (2.53x), representing a high-risk category. B11 was the only site where the ratio was below 1.0 (0.82x), indicating slightly higher adult risk.

When absolute TCR values are compared with the acceptable cancer risk benchmark established by the United States Environmental Protection Agency (1.0 x 10-3) (Figure 4), child TCR values exceed the threshold in nearly all locations, whereas adult values approach or exceed the benchmark in several samples. Critical hotspots with the highest absolute child TCR include BI0 (S.02 x 10-3), B12 (3.79 x 10-3), B20 (3.60 x 10-3), and B 16 (2.48 x 10-3). The consistent elevation of child TCR over adult TCR across sampling points visually and statistically reinforces the significance of the child-to-adult TCR ratio as a key vulnerability indicator.

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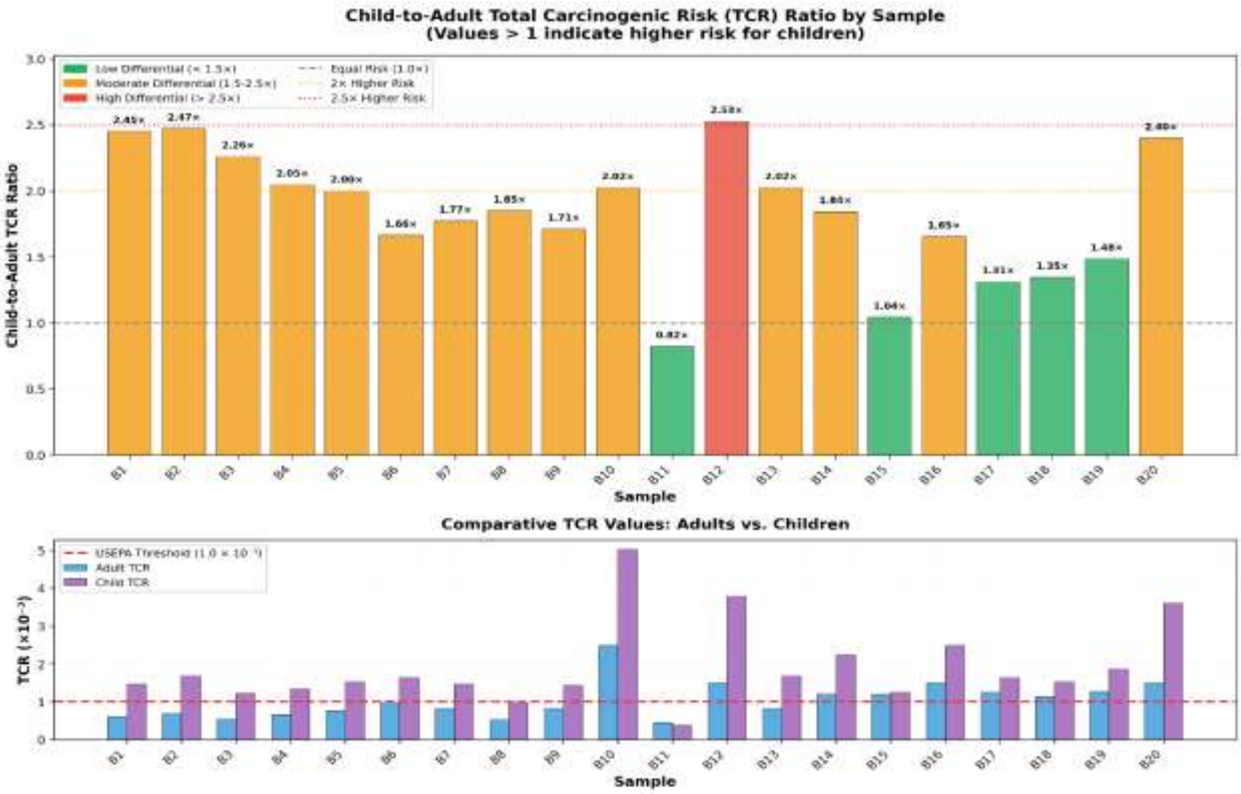

Figure 4: Child-to-Adult Total Carcinogenic Risk (TCR) Ratios and Comparative TCR Values for Arsenic in Groundwater Samples from Bokkos Town, Plateau State, Nigeria.

Discussion of Results

The concentrations of trace metals in groundwater across the 20 sampling sites in Bokkos Town exhibited substantial variability, with several locations exceeding the guideline values recommended by the World Health Organization (WHO). Manganese (Mn) had a mean concentration of 0.074 mg/L, surpassing the WHO recommended limit of 0.05 mg/L, particularly at sites B 18, B 19, and B20. Although manganese is an essential micronutrient, chronic exposure above recommended limits may lead to neurological and developmental effects in children. The elevated Mn concentrations observed in this study are consistent with findings from other rural communities in northern Nigeria where geogenic sources have been identified as primary contributors to manganese enrichment in groundwater (Abdullahi et al., 2025; Mohammed et al., 2023).

Chromium (Cr) concentrations were generally moderate but displayed a notable peak at site B14 (0.315 mg1L), exceeding the WHO threshold. Chromium, particularly in its hexavalent form, is known for its carcinogenic potential. Similar patterns of localized chromium contamination have been reported in several developing regions, including South Asia, where both natural geological conditions and anthropogenic activities contribute to elevated groundwater concentrations (Kumar & Singh, 2020; Adimalla & Li, 2019). Arsenic (As) presented the most critical public health concern, with mean concentrations of 0.014 mg/L surpassing the WHO guideline in several locations, particularly at B10, B 12, B 16, and B20. These findings are consistent with studies from South Asian aquifers and other developing regions where geogenic arsenic contamination in shallow aquifers has been extensively documented (Rahman et al., 2021; Saha & Rahman, 2020). The observed

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variability in trace metal concentrations highlights the influence of geological formations, land use patterns, and localized anthropogenic activities, reinforcing the need for spatially targeted interventions.

Descriptive statistical analysis of the trace metals further highlighted the variability and distribution of contaminants. Manganese showed a moderate spread with a standard deviation of 0.083 mg/L, while chromium exhibited higher heterogeneity with a standard deviation of 0.1245 mg/L. Arsenic was relatively consistent across the study area, reflected in a lower standard deviation of 0.0075 mg/L. These statistical measures provide a quantitative understanding of central tendency and dispersion, allowing identification of potential contamination hotspots. Comparable descriptive trends have been reported in groundwater studies globally, where mean concentration and variability indices serve as preliminary indicators of hydrochemical processes and contamination sources (Adimalla & Li, 2019; Mohammed et al., 2023).

Inferential statistical analyses provided further insight into the interrelationships among metals and water quality indicators, as well as their deviation from guideline values. Pearson correlation analysis revealed significant positive associations among manganese, chromium, and arsenic, with particularly strong co-occurrence between chromium and arsenic ($r = 0.82$, $P < 0.01$). Additionally, metals were significantly correlated with total dissolved solids (TDS) and electrical conductivity (EC), reflecting the influence of groundwater ionic composition on metal mobility. These relationships indicate that contamination is not independent but rather linked through hydrogeochemical processes, consistent with findings reported in groundwater systems influenced by geogenic and hydrochemical interactions (Adimalla & Li, 2019; Kumar & Singh, 2020). Such co-occurrence underscores the potential for cumulative exposure and heightened health risks.

The one-sample t-test comparing mean metal concentrations against WHO guideline values demonstrated that manganese ($t = 2.45$, $P = 0.024$) and arsenic ($t = 3.98$, $P = 0.001$) were significantly elevated, whereas chromium ($t = 1.32$, $P = 0.201$) did not differ significantly from guideline values. These results indicate that Mn and As are the primary contributors to groundwater contamination in the study area. Similar findings have been reported in groundwater

Non-carcinogenic risk assessment showed that adults generally face low to moderate risk, with arsenic and chromium contributing the most to the cumulative hazard index. Children, however, exhibited higher Hazard Quotient (HQ) and Hazard Index (HI) values across all contaminants, reflecting their greater physiological susceptibility to toxic exposure. Several locations displayed HI values above the acceptable threshold, particularly for arsenic and chromium, highlighting potential non-carcinogenic health concerns. These results align with previous risk-assessment studies which demonstrate that children are disproportionately vulnerable to heavy metal exposure due to lower body mass and higher contaminant intake per unit body weight (Saha & Rahman, 2020; Kumar & Singh, 2020).

The Total Carcinogenic Risk (TCR) assessment further emphasized this age-specific vulnerability. Adults generally exhibited TCR values below the acceptable threshold recommended by the United States Environmental Protection Agency (USEPA), with exceptions at BlO, B12, B14, B16, B17, B18, B19, and B20, highlighting specific sites with elevated lifetime cancer risk. Children showed consistently higher TCR values, with

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multiple sites exceeding the recommended benchmark by two to five times. This pattern is consistent with global observations where children's longer life expectancy and higher exposure relative to body weight amplify carcinogenic risk from contaminated groundwater (Rahman et al., 2021; Saha & Rahman, 2020).

The Child-to-Adult TCR ratio provides a direct indicator of age-specific risk differentials. In this study, the ratio exceeded unity in 95% of the sampling sites, with a mean value of 1.83, indicating that children are, on average, 83% more susceptible to arsenic-induced carcinogenic risk than adults. The highest ratio (2.53) occurred at B 12, representing a critical hotspot requiring urgent intervention. This finding aligns with studies emphasizing the importance of age-specific risk assessment for prioritizing groundwater safety interventions in contaminated aquifers (Kumar & Singh, 2020; Rahman et al., 2021).

Integrating the statistical analyses with the Human Health Risk Assessment (HHRA) results highlights the robustness of the study. Elevated arsenic and manganese concentrations were statistically significant and spatially variable, corresponding with the highest HQ, HI, and TCR values. The positive correlations among metals suggest cumulative exposure, while age-specific metrics confirm that children are disproportionately affected. Together, these findings support the need for targeted monitoring, risk mitigation strategies, and public awareness campaigns to protect vulnerable populations, particularly children, from the long-term impacts of contaminated groundwater.

Conclusion and Recommendations

The present study provides a comprehensive assessment of trace metal contamination in groundwater sources in Bokkos Town, Plateau State, Nigeria, integrating laboratory analyses, human health risk assessment, and statistical evaluation. The results indicate that manganese (Mn) and arsenic (As) are the primary contaminants of concern, with several sampling sites exceeding WHO guideline values. Chromium (Cr) was generally within acceptable limits but exhibited localized peaks indicative of potential anthropogenic or geogenic inputs. Descriptive and inferential statistical analyses confirmed significant spatial variability in metal concentrations and revealed strong positive correlations among metals and with water quality indicators, suggesting co-occurrence and cumulative exposure potential.

Human health risk assessment highlighted differential susceptibility between adults and children. Adults generally faced low to moderate non-carcinogenic and carcinogenic risks, whereas children exhibited markedly higher Hazard Quotients (HQ), Hazard Index (HI), and Total Carcinogenic Risk (TCR) values. The child-to-adult TCR ratio further emphasized the disproportionate vulnerability of children, with children experiencing, on average, 83% higher lifetime carcinogenic risk than adults. Critical hotspots such as BI0, B12, B16, and B20 were identified as high-risk locations, necessitating urgent attention.

Overall, this study demonstrates that groundwater in Bokkos Town is subject to geogenic and possibly anthropogenic contamination, with arsenic and manganese posing the greatest public health threat. The integration of statistical analyses with human health risk assessment strengthens the evidence, highlighting the spatial heterogeneity of contamination and the critical need for age-specific risk mitigation strategies.

The study highlights the urgent need for targeted groundwater monitoring and remediation at high-risk sites, particularly for

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arsenic and manganese contamination. Vulnerable populations, especially children, require focused public health interventions and awareness programs on safe water use. Regulatory agencies should enforce water quality standards, implement early warning systems, and promote sustainable land use to reduce contamination sources. Community engagement through water safety plans and alternative safe water sources is essential to mitigate exposure. Future studies should investigate the sources, seasonal variability, and cumulative effects of trace metals to guide long-term mitigation strategies and protect public health.

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