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Assessment of Heavy Metals in Groundwater and Their Association with Kidney Disease in Flood-Affected Areas of Maiduguri, North-Eastern Nigeria

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ABSTRACT

Heavy metal poisoning of groundwater especially that of cadmium (Cd) and lead (Pb), has been made worse by flooding in Maiduguri, North-Eastern Nigeria, raising worries about the health dangers involved. Using atomic absorption spectroscopy, this study determined the levels of Cd, Cr, and Pb in groundwater from 29 flood-prone locations spread over five Local Government Areas: Konduga, Maiduguri, Mafa, Jere, and Magumeri. Cd and Pb were consistently above World Health Organization (WHO) guideline values, whereas Cr was below detection limits in every sample. Pb levels at London Ciki (Jere) above the 0.01 mg/L limit by reaching up to 0.071 mg/L, while Cd levels varied from 0.006 to 0.017 mg/L (WHO limit: 0.003 mg/L). Other hotspots were located at Ngomari, Gwange, and Mafa. Significant risks were identified by non-carcinogenic risk assessment utilizing hazard quotient (Q_i): Pb (up to 20.29) and Cd (6.00–17.00), both of which were significantly over the USEPA threshold of 1.0 and suggested the possibility of renal, skeletal, neurological, and developmental injury. Critical hotspots, including WT14, WT25, WT22, and WT17, were identified using the cumulative hazard index (Q_Σ), which varied from 6.00 to 36.43. The carcinogenic risk assessment for Cd (Cr undetectable; Pb removed due to model limits) produced lifetime risk values that were within the allowed range of the USEPA but nonetheless suggestive of worry, ranging from 0.8×10^{-5} to 2.2×10^{-5}. WT14 had the highest risk of cancer. These results highlight the necessity of proactive public health initiatives, focused repair, and ongoing groundwater monitoring in Maiduguri's flood-affected metropolitan districts.

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INTRODUCTION

Safe drinking water access is still a significant public health concern, especially in areas where floods make groundwater contamination worse. Heavy metals like cadmium (*Cd*), chromium (*Cr*), and lead (*Pb*) were probably mobilized into aquifers from industrial zones, polluted soils, and dumpsites by the recent floods in September 2024 in Maiduguri, North-Eastern Nigeria (Abrahim et al., 2008). Groundwater is the main source of drinking water in this semi-arid area. However, its susceptibility to contamination has increased due to growing urbanization, inadequate flood control infrastructure, and poor waste management (Uwah & John, 2014). Even at low quantities, heavy metals pose serious health hazards because they are poisonous, persistent, and bioaccumulative (Wu et al., 2016). Exposure to lead (*Pb*) is known to affect neurodevelopment, especially in children; *Cd* builds up in the kidneys and causes bone demineralization and renal dysfunction (Järup, 2003); and hexavalent chromium (Cr^{6+}) is known to cause cancer and affect the respiratory and hepatic systems (EPA, 2023). These pollutants are easily carried into drinking and irrigation groundwater systems during flooding, increasing the long-term ecological and health effects (WHO, 2022).

Due to inadequate urban design and their close proximity to unregulated industrial activity, Maiduguri's flood-prone regions are disproportionately affected. Even while earlier research has shown that soils and surface water have higher quantities of heavy metals, there is still a significant information gap about groundwater contamination, even though it is the primary source of water. For low-income communities that depend on untreated wells, where contamination may linger for decades, this is especially worrisome (Arora *et al.,* 2018).

In order to evaluate carcinogenic and non-carcinogenic health risks via ingesting exposure pathways, stratified by age groups, this study uses standardized risk models, such as the hazard quotient (Q_i), hazard index ($\underline{Q_\Sigma}$), and carcinogenic risk (r_{tc}) (USEPA IRIS, 2023; Štrbac et al., 2017). Evidence-based policymaking relies heavily on these integrative methods. The results are intended to inform sustainable water resource management and public health measures in accordance with WHO guidelines by assessing the hazards of heavy metal exposure in flood-impacted areas. In order to reduce environmental health inequities in urban Nigeria, the study concludes that better waste management, increased flood resilience, and ongoing groundwater monitoring are necessary (Mapanda et al., 2005; WHO, 2022).

METHODOLOGY

Study Area

Five (5) Local Government Areas (LGA) in Borno State (Table 1), which is in northeastern Nigeria, were the sites of this study. Positioned geographically between latitudes 11.80°N and 11.90°N and longitudes 13.00°E and 13.20°E, Maiduguri has an average elevation of around 354 *m* above sea level. The city is in the Sudano-Sahelian climate zone, which is hot and semi-arid with seasonally heavy rainfall from June to September and then extended dry spells. Based on historical flood data and reliance on groundwater for residential consumption, the five (5) flood-prone LGAs were chosen as sampling locations. Konduga, Maiduguri, Mafa, Jere, and Magumeri are some of these places. High population densities and a mix of light industrial, commercial, and residential activity define each site. To facilitate spatial analysis, a GPS device was used to capture the sampling spots' coordinates. The main sources of water for the people living in these areas are hand-dug wells, shallow boreholes, and other groundwater sources. Flood occurrences make these sources especially susceptible to pollution because weakened well casings let surface runoff seep in and add heavy metals including *Cd*, *Cr*, and *Pb*. Due to the dearth of thorough baseline data on groundwater quality in its flood-prone areas, Maiduguri was chosen.

Table 1: Geographic Coordinates of Groundwater Sampling Points in Maiduguri

Sample ID	Name of the Location	Coordinates	
		Latitude	Longitude
WT01	Goniri Njimtilo	11.899444	13.027778
WT02	Kalari Njimtilo	11.863889	13.026667
WT03	Jewu/ Lamboa Njimtilo	11.863889	12.995278
WT04	Usmanti	11.854167	13.218889
WT05	Mala Kaleri	11.855556	13.219167
WT06	Moramti	11.879444	13.089722
WT07	77 Housing Estate	11.863889	12.118889
WT08	Ngomari Bus stop	11.866111	13.147500
WT09	Gwange Layin Jumaâ€™a	11.833611	13.163611
WT10	Gwange Layin Gida Kifi	11.833056	13.172222
WT11	Gwange Layin Mai Dara	11.829722	13.165000
WT12	Gwange Barrack	11.825278	13.162222
WT13	Gwange IV	11.826944	13.166944
WT14	Gwange Layin Gidan Zana	11.809167	13.186111
WT15	Gwange Kasuwan Dare	11.833056	13.172222
WT16	Gwange Layin Makaranta	11.835000	13.174722
WT17	Gwange Mukaddam Usman street	11.829167	13.175833
WT18	Gwange Layin City Robber	11.829167	13.177222
WT19	Mala Kyariri	11.853333	13.218611
WT20	Mala Kyariri I	11.852778	13.210556
WT21	Kaleri Layin Church	11.830833	13.194167
WT22	Goni Kachallari	11.856389	13.212778
WT23	UMTH I	11.827500	13.182222
WT24	UMTH II	11.827222	13.176667
WT25	London Ciki	11.844444	13.178056
WT26	Kajari	12.113611	12.828056
WT27	Tashan Mata	12.113611	12.832778
WT28	Opp. Vocational Center	12.110833	12.828333
WT29	G.D.S.S Magumeri	12.114722	12.824444

Sampling Strategy

To guarantee thorough representation throughout the five communities that were identified as being at risk of flooding, a stratified random sample technique was used. According to Mohammed et al. (2021) and Edward et al., (2021), stratification was based on past flood susceptibility, proximity to possible contamination sources (open drains, scrap metal yards), and the extent of reliance on groundwater for residential use. From operational boreholes in the designated locations, a total of 29 groundwater samples were obtained. The sampling points' GPS coordinates are listed in Table 1. To reduce the effects of standing water, samples were taken in 1-liter polyethylene bottles that had been previously cleaned and flushed for five to ten minutes before collection. Before being sent to the lab, the samples were kept in coolers at 4°C and preserved

with strong nitric acid to lower the pH below 2. Duplicate sample collection, field blanks, and sample handling protocol adherence were all part of the quality assurance procedures. According to WHO (2022) and EPA (2023) criteria, the ideal conditions for trace metal analysis are exceeded by the 5–10 *minute* flushing and the 48-hour holding period before analysis. In accordance with institutional ethical norms, the study was carried out. At every sampling location, verbal informed consent was acquired from all property owners or custodians. All chemical wastes produced during sample preparation and analysis were appropriately disposed of in accordance with laboratory safety procedures and environmental protection rules were adhered to, to minimize disruption during sampling.

Laboratory Analysis

As directed by APHA (2017), Atomic Absorption Spectrophotometry (AAS) was used to measure the concentrations of *Cd*, *Cr*, and *Pb* after acid digestion. Concentrated nitric acid (HNO_3) was used to digest each sample, followed by heating it until it became clear and filtering it through Whatman No. 42 filter paper (pore size of 2.5 μm). The U.S. EPA advises using a 0.45 μm filter for precise detection of dissolved metals, even though this method works well for total metal analysis (EPA, 2023). Particulate-bound fractions may be underestimated if HNO_3 digestion is the only method used. For each metal, verified standard solutions were used for calibration. Excellent linearity ($R^2 > 0.995$) was demonstrated by the calibration curves, and adequate analytical accuracy was indicated by the 90%–105% range of spike recovery rates. In accordance with regulatory standards, detection levels of 0.001 *mg/L* for *Cd*, 0.002 *mg/L* for *Cr*, and 0.001 *mg/L* for *Pb* were attained (Ogundele et al., 2021; Massoud et al., 2023; Njuguna et al., 2022). Every sampling coordinate was loaded into a GIS platform after being georeferenced.

Risk Assessment

According to USEPA guidelines, health risk assessments for heavy metals include assessing both carcinogenic and non-carcinogenic pathways (USUSEPA IRIS, 2023, 2001, 2011). The United States Environmental Protection Agency (USEPA) methodology was used to evaluate the risks to human health posed by exposure to heavy metals (*Cd*, *Cr*, and *Pb*).

Non-Carcinogenic Risk

The Target Hazard Quotient, Q_i quantifies the potential risk of daily exposure of heavy metal though water consumption. The Hazard Quotient, Q_i, and the Total Hazard Quotient, Q_Σ, are the two main indices used to evaluate the non-carcinogenic risk (Echeweozo et al., 2025). Hazard Quotient for each heavy metal and exposure pathway was computed as (Yahya a al., 2022; Godwin et al., 2025),

$$Q_i = \frac{\tilde{d}_i}{C_i^r} \quad (1)$$

where $\tilde{d}_i$ is the average Daily Intake of the heavy metal ($mg \cdot kg^{-1} \cdot day^{-1}$), C_i^r is the Reference Dose for the metal ($C_{Cd}^r = 0.001\ mg \cdot kg^{-1} \cdot day^{-1}$; $C_{Cr}^r = 0.003\ mg \cdot kg^{-1} \cdot day^{-1}$; $C_{Pb}^r = 0.0035\ mg \cdot kg^{-1} \cdot day^{-1}$), which is obtained from USEPA screening levels (USEPA, 2012; Kalagbor et al., 2025). The Total Hazard Quotient, Q_Σ is the sum of the individual Q_i values for each metal under consideration (Mustatea et al., 2021),

$$Q_\Sigma = \sum_{i=1}^{3} Q_i = Q_{Cd} + Q_{Cr} + Q_{Pb} \quad (2)$$

where Q_{Cd}, Q_{Cr}, and Q_{Pb} represent the Hazard Quotients for *Cd*, *Cr* and *Pb*, respectively. The Q_Σ provides an overall measure of the non-carcinogenic health risk from exposure to multiple heavy metals (Muhammad et al., 2021; Echeweozo et al., 2025).

Carcinogenic Rick

Carcinogenic risk from heavy metal exposure is assessed using the Carcinogenic Risk Index, r_{ic} for individual metals and the Total Carcinogenic Risk Index, r_{tc} for multiple metals. These indices are calculated following USEPA guidelines (USUSEPA IRIS, 2023, 2001, 2012). The Chronic Daily Intake of the metal, $\tilde{d}_i$ for each exposure pathway can be calculated using standard exposure equations (Dayananda & Liyanage, 2021),

$$\tilde{d}_i = C_i \cdot \frac{\dot{g} \cdot \upsilon \cdot \tau}{w_t \cdot \tilde{t}} \quad (3)$$

where $\dot{g}$ is the Ingestion rate (0.001 $mg \cdot kg^{-1} \cdot day^{-1}$) (Echeweozo e al., 2025), υ is the Exposure frequency (350 *days/year*), τ is the Exposure duration (30 *years*), w_t is the Average body weight of the individual (70 *kg*) and $\tilde{t}$ is the Averaging time (*days*), typically $\tilde{t} = 70 \cdot 365\ days$ (for a 70-year lifetime) and ς_i is the Cancer Slope Factor for the heavy metal $(mg \cdot kg^{-1} \cdot day^{-1})^{-1}$, a value that indicates the potential for a substance to cause cancer ($\varsigma_{Cd} = 6.1$; $\varsigma_{Cr} = 0.50$; $\varsigma_{Pb} = 0.0085$ o carcinogenic risk (USEPA, 2012; Miletic at al., 2023; Pokorska-Niewiada et al., 2022). The Carcinogenic Risk Index, r_{ic} for each heavy metal is determined using the formula,

$$r_{ic} = d_c \cdot \varsigma_i \quad (4)$$

where d_c is the Chronic Daily Intake of the heavy metal ($mg \cdot kg^{-1} \cdot day^{-1}$). The Total Carcinogenic Risk Index, r_{tc} is the sum of the r_{ic} values for all the heavy metals under consideration (USUSEPA IRIS, 2023; Wojciechoka et al., 2019):

$$r_{tc} = \sum_{i=1}^{n} r_{ic} \quad (5)$$

This index estimates the lifetime probability of developing cancer due to long-term ingestion of contaminated water (Wojciechoka et al., 2019; USUSEPA IRIS, 2023, 2012).

RESULTS

The levels of *Cd*, *Cr*, and *Pb* in water samples taken from the Konduga, Maiduguri, Mafa, Jere, and Magumeri LGAs are covered in this section. Table 2 displays the mean concentrations ± standard deviations (SD). The following are the findings from Table 2:

Cd Levels: The levels of Cd in the groundwater samples varied from 0.017 *mg/L* in Gwange Layin Gidan Zana (WT14, Maiduguri) to 0.006 *mg/L* at Goniri Njimtilo (WT01, Konduga). These readings show possible health hazards, particularly with prolonged exposure, as they greatly surpass the World Health Organization's (WHO) drinking water recommendation of 0.003 *mg/L*. Urban locations like Maiduguri (WT07, WT14) and Mafa (WT20) had the greatest values, which may indicate localized contamination from industrial processes, inappropriate waste disposal, or vehicle emissions. A combination of sources, such as industrial discharges, corroding metal pipes, phosphate-based fertilizers, and agricultural runoff, may be responsible for the pervasive low-level pollution shown by the consistent finding of *Cd* across all sampling locations.

Rural locations like Konduga may reflect agricultural inputs, while urban environments may contribute through anthropogenic emissions and inadequate waste management. Long-term exposure to cadmium is known to have negative health effects, such as renal failure, bone demineralization, and other chronic illnesses. In order to reduce the dangers of long-term exposure, the increased levels found in this study emphasize the urgent need for routine groundwater monitoring, pollution source reduction, and public health initiatives.

Cr Concentrations: No water sample had any *Cr*, as all values were below the detection limit (BDL). This could indicate a real lack or levels that are too low for the testing techniques available today.

Pb Concentrations: London Ciki (WT25, Jere) had the highest *Pb* concentrations, which ranged from below detection limits (BDL, as shown by negative instrument readings) to 0.071 *mg/L*. Other samples surpassed the World Health Organization's (WHO) allowable limit of 0.01 *mg/L* for drinking water, suggesting serious contamination concerns, while a few samples were BDL, meaning *Pb* levels below the instrument's detection capacity. Samples from London Ciki (WT25: 0.071 *mg/L*), Ngomari Bus Stop (WT08: 0.048 *mg/L*), Gwange Layin Gidan Zana (WT14: 0.021 *mg/L*), and Mafa (WT19: 0.070 *mg/L*) had notably elevated *Pb* values. These hotspots point to possible sources of pollution, including improper trash disposal, industrial discharges, battery recycling operations, and deteriorated lead-based piping. There are major public health issues when lead is present in certain regions. There is no known safe exposure threshold for lead, a strong neurotoxic. While chronic exposure in adults is linked to hypertension, renal failure, and reproductive damage, even low-level intake can harm children's cognitive development and behavioral function. The levels found in this study are higher than risk limits, necessitating immediate mitigation measures.

Konduga LGA exhibited moderate *Cd* levels, *Cr* concentrations mostly below the WHO permissible limit (0.05 *mg/L*), and *Pb* values largely below detection limits (BDL). These trends suggest relatively lower anthropogenic impact, with contamination possibly arising from diffuse agricultural sources or natural geochemical background. Maiduguri LGA displayed a mix of compliant and non-compliant values. Elevated Cd (WT14: 0.017 *mg/L*) and *Cr* (WT08: 0.087 *mg/L*) levels point to localized urban-industrial sources such as vehicle emissions, industrial effluents, or corroded infrastructure. *Pb* concentrations also exceeded safe limits in several sites. Mafa LGA presented moderate levels of *Cd* and *Cr*, with *Pb* concentrations in some samples surpassing the WHO guideline (0.01 *mg/L*), particularly WT19.

Pb values were mainly below detection limits (BDL), *Cr* concentrations were mainly below the WHO acceptable limit (0.05 *mg/L*), and *Cd* levels were moderate in Konduga LGA. These patterns point to a comparatively lesser anthropogenic impact, with contamination potentially coming from natural geochemical backgrounds or dispersed agricultural sources. A combination of complying and non-compliant figures, were shown by Maiduguri LGA. Increased levels of *Cr* (WT08: 0.087 *mg/L*) and *Cd* (WT14: 0.017 *mg/L*) indicate localized urban-industrial sources such corroded infrastructure, industrial effluents, and car emissions. In a number of locations, *Pb* concentrations also surpassed acceptable levels. Mafa LGA had moderate amounts of *Cd* and *Cr*, while certain samples, especially WT19, had *Pb* concentrations over the WHO recommendation of 0.01 *mg/L*.

These results raise the possibility of contamination from agricultural inputs or inappropriate waste management. Consistently high *Cr* concentrations (e.g., WT22: 0.084 *mg/L*) and *Pb* levels beyond allowable limits (WT25: 0.071 *mg/L*) were found in Jere LGA, suggesting substantial pollution most likely caused by industrial processes, battery disposal, or legacy infrastructure. The *Cd* and *Cr* contents in Magumeri LGA were comparatively mild. However, Tashan Mata's *Cr* levels (WT27: 0.086 *mg/L*) were higher above WHO guidelines, suggesting site-specific pollution that may have been brought on by local geology or industrial discharge. The impact of land use, industrialization, and infrastructure quality on groundwater contamination is highlighted by this regional heterogeneity. Significant health risks, such as nephrotoxicity (*Cd*), carcinogenicity (*Cr*), and neurotoxicity (*Pb*), are raised by the exceedances of WHO limits for *Cd*, *Cr*, and *Pb*. This is particularly true for vulnerable people who depend on untreated groundwater.

Table 2: The mean concentration of *Cd*, *Cr* and *Pb* (mean ± SD) in water samples from six LGA and Permissible Limits in Drinking Water

Station	Sample ID	Concentration (*mg/L*)		
		Cd	***Cr***	***Pb***
Konduga	WT01	0.006±0.0007	BDL	BDL
	WT02	0.009±0.0012	BDL	BDL
	WT03	0.009±0.0011	BDL	BDL
	WT04	0.008±0.0009	BDL	BDL
	WT05	0.007±0.0013	BDL	BDL
	WT06	0.009±0.0021	BDL	BDL
	WT07	0.013±0.0008	BDL	0.024±0.0515
	WT08	0.010±0.0011	BDL	BDL
	WT09	0.013±0.0017	BDL	0.013±0.0927
	WT10	0.008±0.0011	BDL	BDL
Maiduguri	WT11	0.010±0.0004	BDL	0.005±0.0226
	WT12	0.010±0.0004	BDL	0.011±0.1081
	WT13	0.009±0.0015	BDL	BDL
	WT14	0.017±0.0010	BDL	0.068±0.1166
	WT15	0.010±0.0011	BDL	0.012±0.0219
	WT16	0.008±0.0001	BDL	BDL
	WT17	0.009±0.0010	BDL	0.065±0.0599
	WT18	0.010±0.0011	BDL	0.041±0.0622
Mafa	WT19	0.009±0.0020	BDL	0.070±0.0284
	WT20	0.013±0.0007	BDL	0.023±0.0842
	WT21	0.008±0.0018	BDL	0.016±0.0471
	WT22	0.013±0.0012	BDL	0.054±0.0211
Jere	WT23	0.011±0.0016	BDL	0.018±0.0210
	WT24	0.009±0.0002	BDL	0.037±0.0067
	WT25	0.012±0.0004	BDL	0.071±0.0279
	WT26	0.009±0.0015	BDL	0.004±0.0268
Magumeri	WT27	0.008±0.0006	BDL	0.018±0.0151
	WT28	0.009±0.0015	BDL	0.014±0.0083
	WT29	0.011±0.0011	BDL	0.033±0.0363
Maximum		**0.017**	**BDL**	**0.071**
Average		**0.010**	**BDL**	**0.022**
Minimum		**0.006**	**BDL**	**0.000**
WHO (2011)		**0.050**	**0.100**	**0.050**
USEPA (2012)		**0.005**	**-**	**-**
NSDW (2003)		**0.003**	**-**	**0.010**

Q_i was used to assess the non-carcinogenic health risks associated with exposure to *Cd* and *Pb*. All samples had Q_i values for *Cd* that were much higher than the US Environmental Protection Agency's (USEPA) safety criterion of 1.0, ranging from 6.00 to 17.00. This persistent overabundance suggests a significant and pervasive non-carcinogenic risk, especially to the health of the kidneys and bones. For the 18 samples where *Pb* was found, Q_i values were computed. A number of samples had significantly higher Q_i's, such as WT14 (19.429), WT17 (18.571), and WT25 (20.286), all of which were significantly higher than the safe limit of 1.0. These values suggest a high probability of neurological and developmental harm, especially among vulnerable groups such as children and pregnant women. The Q_Σ, representing the cumulative non-carcinogenic risk from both *Cd* and *Pb*, ranged from 6.000 to 36.429. Every sample exceeded the regulatory threshold of 1.0, indicating that residents exposed to these water sources are at significant risk of adverse health effects from long-term ingestion of multiple contaminants. Critical high-Q_Σ samples—WT14, WT25, WT22, and WT17—should be prioritized for immediate remediation.

For carcinogenic risk, only *Cd* was assessed, as *Cr* was undetectable and *Pb* is not commonly evaluated for carcinogenicity via ingestion in water. The *Cd* r_{tc} values ranged from 0.008 to 0.022 × 10^{-4}, which falls within the USEPA's acceptable risk range of 1 × 10^{-6} to 1 × 10^{-4}. While all values remain within regulatory limits, they still represent a non-negligible lifetime cancer risk. The highest observed r_{ic} value in WT14 (2.2 × 10^{-6}), underscores the necessity for continued surveillance, especially in areas with sustained low-level *Cd* contamination. Since *Pb* is rarely studied for carcinogenicity by intake in water and *Cr* was undetectable, only *Cd* was investigated for carcinogenic risk. The permissible risk range set by the USEPA is 1 × 10-6 to 1 × 10^{-4}, while the *Cd* r_{tc} values fell between 0.008 and 0.022 × 10^{-4}. All numbers indicate a non-negligible lifetime cancer risk, even though they are all within regulatory bounds. WT14's highest recorded r_{ic} value (2.2 × 10^{-6}) emphasizes the need for ongoing monitoring, particularly in regions with persistently low levels of *Cd* pollution.

Table 3: Concentration, Non-Carcinogenic and Carcinogenic Risk Parameters of Heavy Metals (*Cd, Cr, Pb*) in Groundwater Samples from Flood-Affected Areas of Maiduguri, Borno State, Nigeria

Sample ID	$d_i(10^{-3})$			r_{ic}			r_{tc} (10^{-4})	Q_i			Q_Σ
	Cd	*Cr*	*Pb*	*Cd*	*Cr*	*Pb*		*Cd*	*Cr*	*Pb*	
WT01	2.920	0.000	0.000	17.812	0.000	0.000	17.812	6.00	0.000	0.000	6.000
WT02	4.380	0.000	0.000	26.718	0.000	0.000	26.718	9.00	0.000	0.000	9.000
WT03	4.380	0.000	0.000	26.718	0.000	0.000	26.718	9.00	0.000	0.000	9.000
WT04	3.893	0.000	0.000	23.749	0.000	0.000	23.749	8.00	0.000	0.000	8.000
WT05	3.407	0.000	0.000	20.781	0.000	0.000	20.781	7.00	0.000	0.000	7.000
WT06	4.380	0.000	0.000	26.718	0.000	0.000	26.718	9.00	0.000	0.000	9.000
WT07	6.327	0.000	11.680	38.593	0.000	0.099	38.692	13.00	0.000	6.857	19.857
WT08	4.867	0.000	0.000	29.687	0.000	0.000	29.687	10.00	0.000	0.000	10.000
WT09	6.327	0.000	6.327	38.593	0.000	0.054	38.646	13.00	0.000	3.714	16.714
WT10	3.893	0.000	0.000	23.749	0.000	0.000	23.749	8.00	0.000	0.000	8.000
WT11	4.867	0.000	2.433	29.687	0.000	0.021	29.707	10.00	0.000	1.429	11.429
WT12	4.867	0.000	5.353	29.687	0.000	0.046	29.732	10.00	0.000	3.143	13.143
WT13	4.380	0.000	0.000	26.718	0.000	0.000	26.718	9.00	0.000	0.000	9.000
WT14	8.273	0.000	33.093	50.467	0.000	0.281	50.749	17.00	0.000	19.429	36.429
WT15	4.867	0.000	0.000	29.687	0.000	0.000	29.687	10.00	0.000	0.000	10.000
WT16	3.893	0.000	0.000	23.749	0.000	0.000	23.749	8.00	0.000	0.000	8.000
WT17	4.380	0.000	31.633	26.718	0.000	0.269	26.987	9.00	0.000	18.571	27.571
WT18	4.867	0.000	19.953	29.687	0.000	0.170	29.856	10.00	0.000	11.714	21.714
WT19	4.380	0.000	34.067	26.718	0.000	0.290	27.008	9.00	0.000	20.000	29.000
WT20	6.327	0.000	11.193	38.593	0.000	0.095	38.688	13.00	0.000	6.571	19.571
WT21	3.893	0.000	7.787	23.749	0.000	0.066	23.816	8.00	0.000	4.571	12.571
WT22	6.327	0.000	26.280	38.593	0.000	0.223	38.816	13.00	0.000	15.429	28.429
WT23	5.353	0.000	8.760	32.655	0.000	0.074	32.730	11.00	0.000	5.143	16.143
WT24	4.380	0.000	18.007	26.718	0.000	0.153	26.871	9.00	0.000	10.571	19.571
WT25	5.840	0.000	34.553	35.624	0.000	0.294	35.918	12.00	0.000	20.286	32.286
WT26	4.380	0.000	1.947	26.718	0.000	0.017	26.735	9.00	0.000	1.143	10.143
WT27	3.893	0.000	8.760	23.749	0.000	0.074	23.824	8.00	0.000	5.143	13.143
WT28	4.380	0.000	6.813	26.718	0.000	0.058	26.776	9.00	0.000	4.000	13.000
WT29	5.353	0.000	16.060	32.655	0.000	0.137	32.792	11.00	0.000	9.429	20.429
Max	8.273	0.000	34.553	**50.467**	**0.000**	**0.294**	**50.749**	**17.00**	**BDL**	**20.286**	**36.429**
Ave	4.932	0.000	10.642	**30.082**	**0.000**	**0.090**	**30.173**	**10.13**	**BDL**	**6.248**	**16.352**
Min	2.920	0.000	0.000	**17.812**	**0.000**	**0.000**	**17.812**	**6.000**	**BDL**	**BDL**	**6.000**

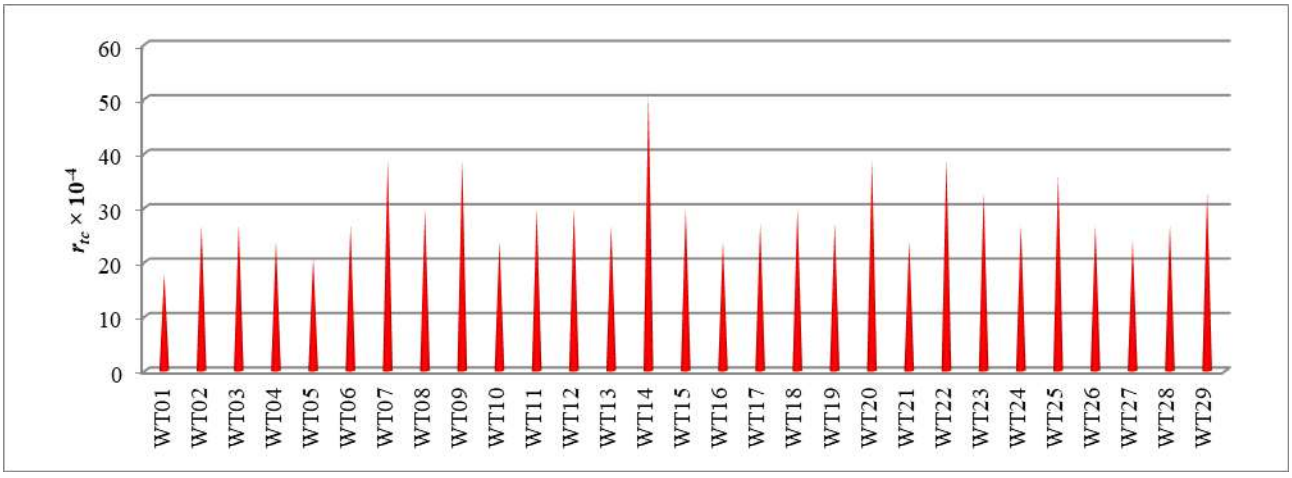

Figure 1: Total Carcinogenic Risk (r_{tc}) Estimates for Cd and Cr in Groundwater Samples from Flood-Affected Areas of Maiduguri

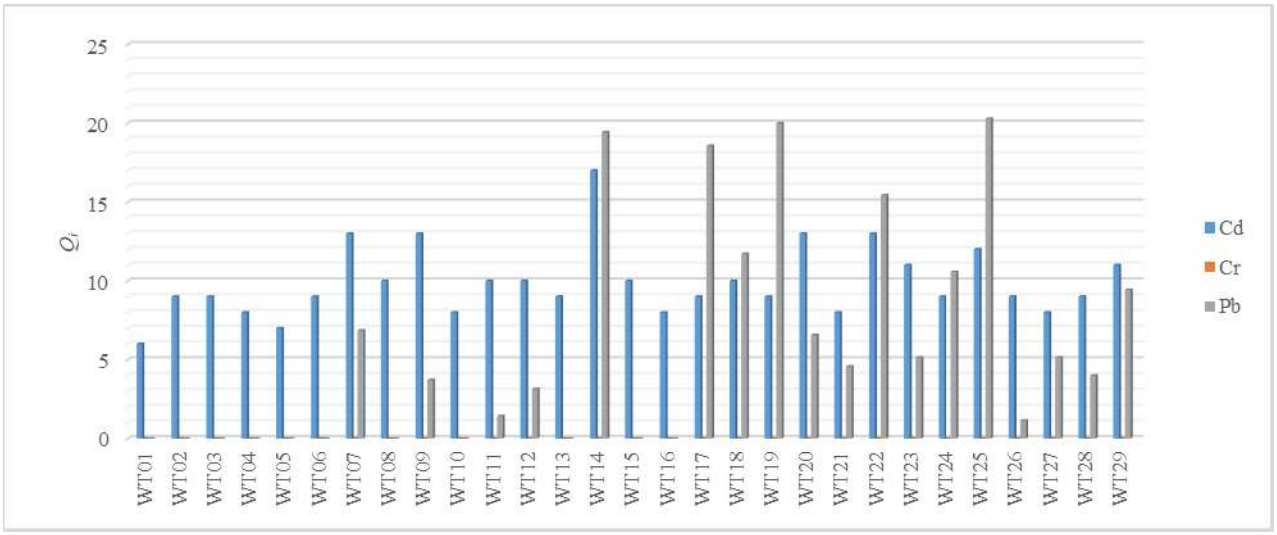

Figure 2: Hazard Quotients (Q_i) for *Cd*, *Cr*, and *Pb* in Groundwater Samples from Flood-Affected Areas of Maiduguri

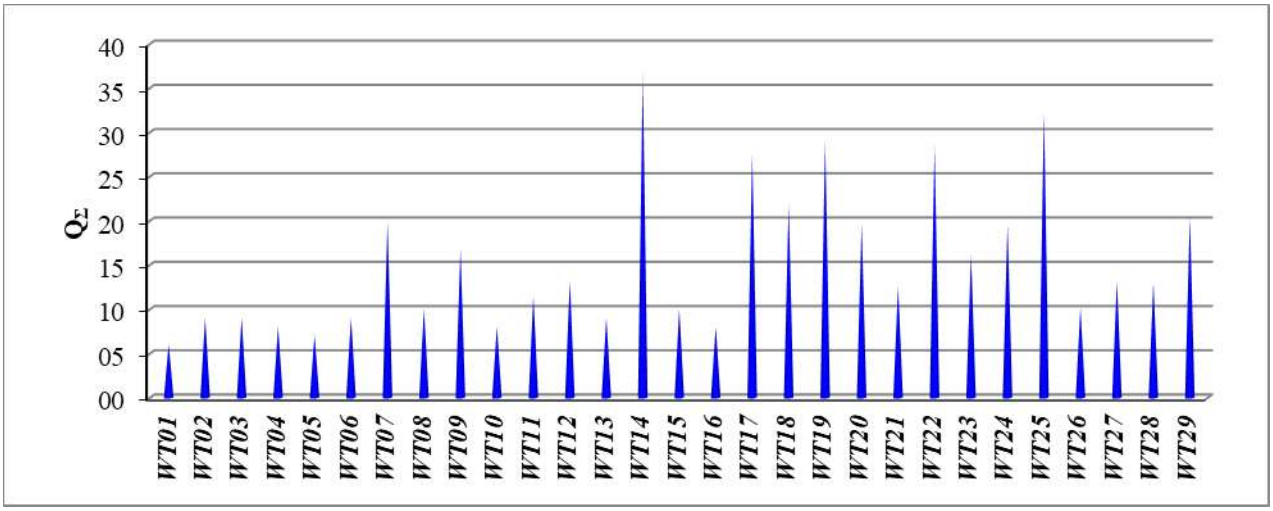

Figure 3: Hazard Indices (Q_Σ) Representing Combined Non-Carcinogenic Risk from *Cd, Cr*, and *Pb* in Groundwater Samples

The results from Table 3 are graphically depicted in Figures 1–3, where the presence of BDL values is also visually represented to facilitate interpretation of spatial patterns and health risk levels. The total carcinogenic risk (r_{tc}) estimations for *Cr* and *Cd* are shown in Figure 1. A few samples (most notably WT14) approach or surpass 1×10^{-5}, indicating heightened long-term cancer risk, especially from Cd, even if the majority of results stay below the USEPA allowed range (1×10^{-6} to 1×10^{-4}). Because of potential analytical limitations, the lack or low detectability of *Cr* in a number of samples may understate its true contribution to carcinogenic risk. The hazard quotient (Q_i) for *Pb*, *Cr*, and *Cd* in groundwater samples from Maiduguri flood-affected areas is shown in Figure 2. The findings show that *Cd* and *Pb* continuously surpass the $Q_i = 1.0$ reference value, indicating possible non-carcinogenic health hazards, particularly for vulnerable groups like children. On the other hand, *Cr* usually stays below the threshold, however occasionally it gets close to the limit and calls for more research. The hazard index (Q_Σ), which adds up the hazard quotients of each of the three metals per sampling point, is shown in Figure 3. Significantly increased values ($Q_\Sigma > 25$) are seen in a number of places, including WT14, WT17, WT22, and WT25, indicating a compounded health risk from cumulative exposure. For public health planning in communities that depend on these water supplies, this cumulative effect is essential.

DISCUSSION

The study's conclusions highlight the major public health risks associated with lead (Pb) and cadmium (Cd) pollution of groundwater sources in Maiduguri's flood-affected districts. Cadmium was found at values between 0.001 and 0.004 mg/L in every studied area. Interestingly, samples WT07, WT14, WT20, WT22, and WT25 were higher than the 0.003 mg/L WHO recommended limit (WHO, 2022). Ajibade et al. (2020), Akpan et al. (2014)

in Akwa Ibom, Echeweozo et al. (2025) in Ebonyi, Kabir et al. (2012; 2017) in Ilorin, Yahaya et al. (2021) in Zamfara, and Osmani et al. (2015) in Lagos are among the studies on flood-prone and industrially affected areas of Nigeria that have found similar results. These investigations also linked industrial pollutants, leaching from scrap metals, and post-flood mobilization to higher Cd levels.

Nephrotoxicity and bone demineralization are linked to chronic exposure to cadmium, underscoring the significance of ongoing environmental monitoring and focused health interventions. Pb contamination was also common; measurable amounts of the metal ranged from 0.001 to 0.015 mg/L in about 62% of samples. Five samples (WT14, WT17, WT19, WT22, and WT25) had levels over the 0.010 mg/L WHO acceptable limit. These findings concur with those of Okoro (2018), who documented comparable Pb enrichment in urban wells affected by flooding in South-Western Nigeria. Children who are exposed to lead, especially through drinking water, are at serious risk for neurodevelopmental problems such as behavioral and cognitive deficits.

Anthropogenic sources, such as the leaching of lead-based compounds from adjacent scrap metal yards and runoff including legacy pollutants during flood occurrences, are probably to blame for the reported Pb concentrations. These processes are a reflection of larger environmental trends in which floodwaters serve as conduits for the reintroduction of hazardous metals into aquifers from surface deposits.

The seriousness of the pollution is further shown by the non-carcinogenic risk assessment. Every sample had hazard index (Q_Σ) values between 6.000 and 36.429 that were higher than the USEPA standard of 1.0. Similarly, all of the Cd and Pb hazard quotient (Q_i) readings were beyond permissible limits, indicating that exposure by ingestion has serious health concerns. Q_Σ values exceeding 25 were found in high-risk zones, especially WT14, WT17, WT22, and WT25, suggesting the possibility of several negative health impacts from cumulative exposure.

These results are consistent with earlier research by Kabir et al. (2012), who documented comparable hazard patterns in semi-urban areas exposed to uncontrolled industrial wastewater. Even though the estimated carcinogenic risks for Cd (r_ic) were under the USEPA's upper allowed range (i.e., less than 1×10^{-4}), the highest value found at WT14 (2.2×10^{-5}) deserves focus, especially when taking vulnerable populations and long-term exposure into account.

CONCLUSION AND RECOMMENDATION

According to this study, the main pollutants of concern in groundwater sources in Maiduguri, Borno State, areas affected by flooding include cadmium (Cd) and lead (Pb). More than half of the samples included Pb, and several of them had levels higher than the WHO standard for safe drinking water. All samples included cadmium, with quantities in some places exceeding allowable levels. Both the hazard quotient (Q_i) and hazard index (Q_Σ) for Cd and Pb continuously surpassed the USEPA safety threshold, according to non-carcinogenic risk assessments, suggesting a substantial risk of harmful health impacts for the exposed population.

The necessity for ongoing surveillance is highlighted by higher values in several hotspots, especially near WT14, WT25, WT22, and WT17, even if the estimated carcinogenic risk (r_tc) for Cd was within the legal limits. Even though Cr was not found in this investigation, it is impossible to completely rule out the possibility of underestimate brought on by analytical detection limits. These results give policymakers and health authorities vital evidence and emphasize the pressing need for proactive environmental health initiatives.

The study suggests regular water quality monitoring in flood-prone communities for early detection and management of heavy metal contamination. Prioritizing remediation and public health interventions, including community education and alternative water sources, is recommended. Sensitive analytical techniques, age-specific health risk assessments, and stronger enforcement on industrial waste management and scrap metal recycling practices are also urged. Future research should focus on chromium speciation, especially the differentiation between Cr^{3+} and the more toxic Cr^{6+}, for accurate risk assessments and regulatory compliance.

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