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Heavy Metal Contamination and Health Risks Assessment of Groundwater Samples in Abakaliki, Southeastern Nigeria

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Abstract

Groundwater is a major source of domestic, agricultural, and industrial water supply, particularly in developing countries. pH and heavy metal contents of groundwater from six randomly selected locations in the Abakaliki metropolis was assessed with the view of estimating human health exposure risks. Atomic Absorption Spectrophotometer (AAS, Agilent 240FS) was used to determine the heavy metals. Health risks assessment of the metals was achieved via daily intake, absorption dose, hazard quotient (HQ), hazard index (HI), and probable cancer risk (PCR) for both adults and children through oral and dermal exposure pathways. The range of metal concentrations were Cu (0.007 - 0.015 mg/L), Zn (0.062 - 0.001mg/l), Fe (0.0093 mg/L), Mn (0.015 - 0.278 mg/L) and Mg (1.205 - 8.747 mg/L), Pb (0.009 - 0.115 mg/l) and Cd (0.001 - 0.011 mg/L). All metals were within permissible limits except Pb (0.009 - 0.115 mg/l) and Cd (0.001 - 0.011 mg/L) which exceeded recommended WHO standards. The HI values for certain heavy metals exceeded the safety threshold (>1), indicating potential non-carcinogenic risks, especially for children, with Pb contributing most significantly (HI=1.096- 2.937) Probable cancer risk values also exceeded acceptable safety limits (1×10^{-6} to 1×10^{-4}), with children showing higher susceptibility than adults. Pb was the major contributor to cancer risk as well, followed by Cd. Both values for non-carcinogenic and carcinogenic risks are higher than the permissible levels recommended by the USEPA in some sites. This study provides baseline data to support groundwater quality monitoring and health risk mitigation in mining regions of Nigeria.

Keywords: AAS, Abakaliki, groundwater, heavy metals, human risk assessment.

Introduction

Groundwater is a vital water resource extensively utilized for drinking, irrigation, industrial, and domestic purposes. It is stored in aquifers and other geological formations beneath the Earth's surface. Globally, over 1.5 billion people rely on groundwater as their primary source of drinking water, highlighting its critical role in sustaining

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human populations [1,2]. This resource is essential for life and plays an integral role in the hydrological cycle [3].

Groundwater contamination has emerged as a pressing global concern. Increasing demand for freshwater due to population growth and climate change, coupled with the expansion of agriculture and industrial activities, has introduced a wide range of pollutants, including heavy metals, pesticides, and personal care products, into water sources [4]. Active mining, improper disposal of mine waste, and poorly sited dumpsites are additional contributors to groundwater pollution. These contaminants pose significant threats to human health and ecosystems, as toxicity depends on both concentration and exposure pathways.

In Abakaliki metropolis, residents rely primarily on wells and boreholes for daily water supply [6]. Rapid urbanization, expansion of residential and commercial areas, and inadequate waste management systems further increase the risk of groundwater contamination [7,8]. While some heavy metals such as copper, zinc, and iron are essential for human metabolism, excess concentrations of metals like chromium, cobalt, arsenic, lead, and cadmium are highly toxic, even at low levels. Elevated concentrations of these metals in potable water can lead to serious health issues, including kidney and liver damage, gastric cancer, and other chronic conditions [6,9]. Oral exposure to contaminated water can cause gastrointestinal diseases, while dermal exposure during activities such as bathing or washing can lead to skin irritation and other health effects [10]. Previous studies in Abakaliki have documented varying levels of heavy metal contamination in groundwater, highlighting the need for continuous monitoring; [18, 19]. However, there remains a gap in assessing human health risks through both oral and dermal pathways in the metropolis.

Therefore, this study aims to quantify trace metal concentrations in groundwater and evaluate the associated non-carcinogenic and carcinogenic risks to residents of Abakaliki. The findings provide baseline data to support groundwater quality monitoring, inform public health policies, and guide effective water management strategies in regions facing similar environmental challenges.

Materials and Method

Description of study area

The study was conducted in Abakaliki metropolis, the administrative and economic center of Ebonyi State, Nigeria. The city serves as a hub of socio-economic and political activities. It lies within a tropical climate zone and experiences two main seasons: a wet season, generally from April to October, and a dry season, from November to March.

The relative humidity is 45% and 65% in dry and wet season respectively [11]. The elevation of the area is from 45 to 65m for highlands and 39m for lowlands.

Sample Collection

A total of eighteen groundwater samples, comprising hand-dug wells and boreholes, were collected from six distinct locations in triplicates at each study location. Sampling was conducted in July 2025 during wet season to capture representative water quality conditions.

Samples were collected using clean 2 L screw-capped polyethylene containers, pre-washed and rinsed with 10% HNO_3 to remove potential contaminants. The containers were then rinsed three times with the groundwater at each site prior to sample collection. To prevent adsorption of metals onto container walls, 5 mL of concentrated HNO_3 was added to each sample immediately after collection, and samples were stored in a refrigerator until analysis.

Heavy metals were analyzed following acid digestion. All samples were labeled as shown in Table **1** and transported to the Rivers State University Laboratory for analysis of Cr, Pb, Ni, Cu, Zn, Mn, Mg, Fe, and Co using Atomic Absorption Spectrophotometry (AAS, Agilent Technologies 200 Series, 240FS AA model).

Table 1: sample codes, location and G.P.S of water sample

Sample ID	*Sampling Location*	*Latitude*	*Longitude*
W1	Nkwagu	6°15'23.971″N	8°6'25.283″E
W2	Nkaliki	6°18'17.961″N	8°5'47.735″E
B1	Onuebonyi	6°18'35.092″N	8°8'35.908″E
B2	Amike aba	6°20'48.144″N	8°6'24.767″E
B3	Ishieke	6°22'55.695″N	8°2'3.051″E
B4	Mgbobor	6°19'29.208″N	8°4'33.129″E

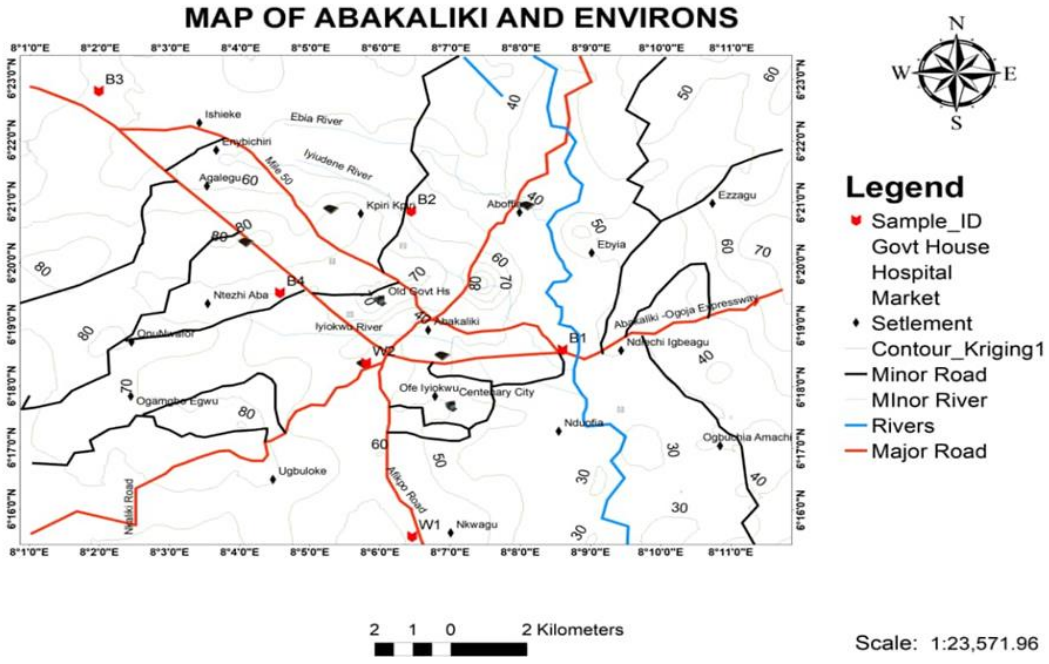


Fig. 1: Map of the Study Area

Sample Analysis

The pH of each groundwater sample was measured in situ at the sampling sites using a calibrated pHep Pocket-sized pH Meter (IHANNA Instruments). The instrument was standardized with pH 4.0 and 7.0 buffer solutions before measurements, and the electrode was rinsed with distilled water between readings. This procedure follows the APHA Standard Methods for the Examination of Water [12].

For heavy metal analysis, water samples were digested using the acid digestion method. 100 mL of each sample was transferred into a conical flask, and 1 mL of concentrated nitric acid (HNO_3) was added. The mixture was digested on a hot plate in a fume cupboard until the volume was reduced to approximately 20 mL. After cooling for 30 minutes, the digested sample was filtered through Whatman No. 1 filter paper into a 100 mL standard flask and made up to the mark with deionized water. The final solution was transferred to a 120 mL screw-capped polyethylene container and preserved for subsequent analysis.

Heavy metal concentrations (Cr, Pb, Ni, Cu, Zn, Mn, Mg, Fe, and Co) were determined using Atomic Absorption Spectrophotometry (AAS, Agilent Technologies 200 Series, 240FS AA model). Quality assurance and quality control (QA/QC) measures included the use of blanks, standards, and it was done through duplicate analysis of the elements in spiked and unspiked water samples to ensure data accuracy and reliability. Detection limits (LOD) and quantification limits (LOQ) were determined according to standard methods. Data analysis, including calculation of hazard quotients, hazard indices, and probable cancer risks, was performed using Microsoft Excel 2019 and OriginPro 2023 software.

Health risk assessment

Human health risk assessment is a way to determine and predict the probability of negative impact from environmental contaminants on public health [13], [14]. The two important forms of heavy metal exposure to people were considered and calculated, they are oral intake and dermal absorption.

Drinking water pathway: The absorption of toxic heavy metal entering the body by drinking water pathway can be expressed as Average Daily Dose (ADD). The formula for calculating intake is as according to [15].

$$ADD_{oral} = \frac{CW \times IR \times EF \times ED}{BW \times AT} \qquad (1)$$

Where ADD_{oral} is the average daily dose (ug/kg/day),

BW is the average body weight,

AT is the average exposure time (for non-carcinogens),

CW is the heavy metal concentration in groundwater (ug/l),

IR is rate of ingestion,

EF is the exposure frequency,

ED is the exposure duration.

Dermal Absorbed Dose (DAD) calculations were used to estimate the uptake of heavy metals by the human body via the dermal contact pathway.

The formula used for calculating DAD was adopted from [15].

$$DAD_{dermal} = \frac{CW \times SA \times Kp \times ET \times EF \times ED \times CF}{BW \times AT} \quad (2)$$

DAD_{dermal} is the average daily dose through dermal absorption (ug/kg/day),

SA is the exposed skin area,

ET is the exposed time,

CF is the conversion factor (10^{-3}),

Kp is dermal permeability coefficient.

Non-carcinogenic risk determination using Hazards quotient (HQ)

$$HQ_{oral} = \frac{ADD}{RfD} \quad (3)$$

$$HQ_{dermal} = \frac{DED}{RfD} \quad (4)$$

RfD is the daily estimated dose of metal considered safe either ingestion or absorbed.

Hazard index (HI) was calculated by summing HQ values.

$$HI = \sum HQ_{oral} \quad (5)$$

$$HI = \sum HQ_{dermal} \quad (6)$$

HI values show potential non-carcinogenic health risk of metals associated with water contamination. A HI ≥ 1 is a potential for non-carcinogenic health risk [16].

Table 2: Input parameters for exposure assessment of metals via oral and dermal pathway (USEPA 2004).

Parameter	Unit	Adults	Children	References
Concentration of heavy metals (CW)	mg/L	---	---	----
Body Weight (BW)	Kg	70	15	USEPA/2004
Exposure Duration (ED)	Years	30	6	USEPA/2004
Exposure Frequency (EF)	days/year	365	365	USEPA/2004
Ingestion Rate (IR)	L/days	2.2	1	USEPA/2004
Average Time (AT)	Days	10,950	2190	USEPA/2004
Skin Area (SA)	cm^2	18,000	6,600	USEPA/2004
Exposed Time (ET)	h/day	0.58	1	USEPA/2004
Conversion factor (CF)	L/cm^3	0.001	0.001	USEPA/2004

Table 3: RfD and Kp values for each analysed metal

Heavy metal	RfD_{oral} (mg/kg/day)	RfD_{dermal} (mg/kg/day)	Kp (cm/h)
Cr	0.003	0.00006	0.002
Ni	0.02	0.0054	0.004
Cu	0.04	0.012	0.001
Cd	0.001	0.0000025	0.001
Pd	0.0036	0.000525	0.001
Zn	0.3	0.06	0.0006
Fe	0.7	0.14	0.001
Mn	0.14	0.0042	0.001
Mg	NA	NA	ND
Co	0.0003	0.00006	0.003

NA not available, ND not defined

Carcinogenic health risk assessment

The cancer risks relating to the ingestion of water resources are evaluated as the incremental threat of a person developing cancer over a lifetime due to exposure to potential carcinogen. The proability of cancer risk (PCR) was estimated by multiplying the ADDoral and DADdermal (mg/kg/day) with the slope factior (SF) (mg/kg/day) as given in equation 7 and 8. SF value for Cd is 0.38and Pb is 0.0085 [18]

$$PCR_{oral} = ADD_{oral} \times SF_{oral} \quad (7)$$

$$PCR_{dermal} = DAD_{dermal} \times SF_{dermal} \quad (8)$$

The total probability for cancer risk is the sum of all PCR having more than one route of exposure to human population. The total probability of cancer risk (∑PCR) was the summation of PCR for both oral and dermal routes for children and adults.

$$\sum PCR = PCR_{oral} + PCR_{dermal} \quad (9)$$

According to [5], there is considerable carcinogenic risks when ∑PCR is greater than 10^{-4} and low or no risk at all when values are less than 10^{-6} (1 out of 100,000 persons).

Results and Discussion

The heavy metal concentrations of groundwater samples from six locations in Abakaliki metropolis are summarized in Table 4 and Figure 2

Table 4: Heavy Metal Parameters of Groundwater Samples

Sample code	Cr	Ni	Cu	Cd	Pb	Zn	Fe	Mn	Mg	Co
W1	N/D	N/D	0.007	N/D	0.009	N/D	N/D	0.015	1.205	N/D
W2	N/D	N/D	0.011	0.010	0.061	0.062	N/D	0.095	1.928	N/D
B1	N/D	N/D	0.013	N/D	0.065	N/D	N/D	0.278	1.929	N/D
B2	N/D	N/D	0.015	0.011	0.115	N/D	N/D	0.102	1.871	N/D
B3	N/D	N/D	0.013	0.001	0.066	N/D	N/D	0.126	8.747	N/D
B4	N/D	N/D	0.010	0.001	0.057	N/D	0.093	0.031	1.939	N/D
MAX	7.30	---	---	0.015	0.011	0.115	0.062	0.093	0.278	8.747
MIN	5.90	---	---	0.007	0.000	0.009	0.000	0.000	0.015	1.205
AVE	6.92	---	---	0.011	0.004	0.062	0.010	0.016	0.108	2.937
STD	0.55	---	---	0.003	0.005	0.034	0.026	0.038	0.094	2.861
WHO	0.005	0.05	0.02	2	0.003	0.01	3	0.3	0.550	0.006

N/D: "NOT DETECTED". Indicates concentrations below detection limits

pH of Groundwater

The pH values ranged from 5.90 to 7.30, indicating slightly acidic to neutral conditions. Most samples fell within the WHO recommended range (6.5–8.5), except for W1 (5.90), which is slightly below the guideline. These values are consistent with previous studies conducted in Abakaliki [18]. The slightly acidic nature of W1 may be attributed to anthropogenic activities such as sewage disposal, fertilizer application, and other consequences of rapid urbanization. Low pH can increase water **corrosiveness**, reduce disinfection efficiency, and indirectly affect human health through pipeline corrosion and metal leaching.

Heavy Metal Distribution

A total of ten heavy metals were analyzed in the groundwater samples (Table 4).

Zinc (Zn) was detected only in W2 at 0.062 mg/L, which is well below the WHO limit of 3.0 mg/L. Low Zn concentrations indicate no immediate health risk. Similar studies in Abakaliki and southeastern Nigeria reported Zn within permissible limits [19]. Lead (Pb) **c**oncentrations ranged from 0.009 mg/L in W1 to 0.115 mg/L in B2, with most values exceeding the WHO guideline of 0.003 mg/L (Table 4, Figure 2) Elevated Pb levels in groundwater have also been reported in other southeastern Nigerian towns, including Nnewi and Akwa districts, primarily due to mining, ore leaching, industrial discharge,

and vehicle emissions [21, 22]. Chronic ingestion of Pb can cause neurotoxicity, kidney damage, bioaccumulation in bones, and increased carcinogenic risk. Cadmium (Cd) concentrations ranged from 0.001 mg/L to 0.011 mg/L.

Samples W2 (0.010 mg/L) and B2 (0.011 mg/L) (Table 4, Figure 2) exceeded the WHO limit of 0.003 mg/L, consistent with previous reports [21]. Cd contamination may result from both natural sources and anthropogenic activities, including mining and industrial effluents. Chronic exposure poses significant health risks, including kidney and liver damage. Copper (Cu) concentrations ranged from 0.007 mg/L to 0.015 mg/L, well below the WHO limit of 2.0 mg/L. These low values indicate minimal health risk from Cu in the groundwater. Iron (Fe) detected concentrations were within WHO permissible limits, suggesting negligible health concerns. Overall, the data indicate that Pb and Cd are the primary contaminants of concern in Abakaliki groundwater, likely linked to mining, industrial, and urban activities. Other metals such as Cu, Zn, and Fe (Table 4, Figure 2) were within safe limits, posing minimal health risks.

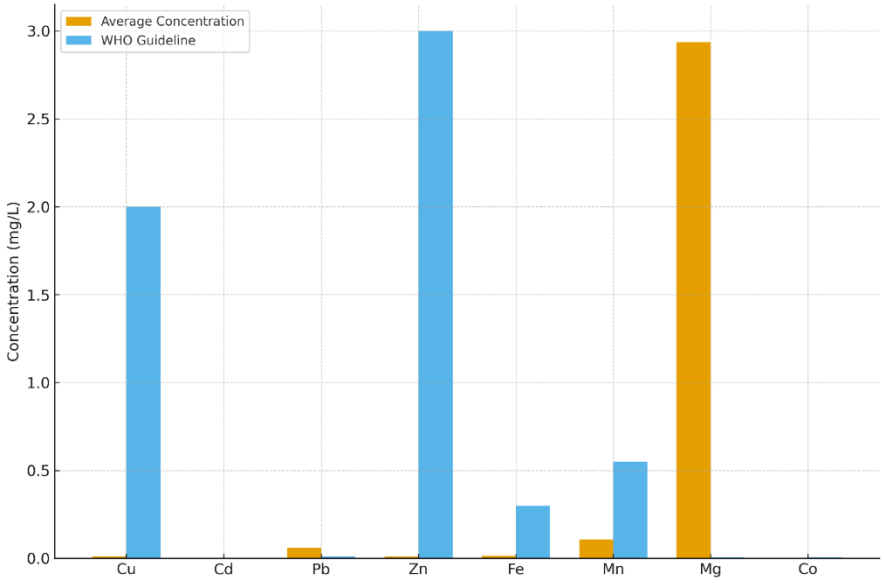


Fig. 2: Comparison of metal concentrations to WHO limits

Descriptive Statistical Analysis

The concentration data for all metals were analyzed to calculate mean, minimum, maximum, and standard deviation (Table 4). For example, Pb concentrations ranged from 0.009 mg/L to 0.115 mg/L, with an average of 0.062 mg/L and standard deviation of 0.034 mg/L. Cd concentrations ranged from 0.001 mg/L to 0.011 mg/L, with a mean of 0.004 mg/L (SD = 0.003 mg/L). Other metals such as Cu, Zn, Fe, Mn, and

Mg showed low variability between sites, indicating relatively uniform distribution.

Health risk assessment

Table 5: Calculated Hazard quotient (HQ oral) for both children and adults

Element	age group	W1	W2	B1	B2	B3	B4
Cu	children	0.012	0.018	0.022	0.025	0.022	0.0167
	Adult	0.0055	0.0086	0.0102	0.0118	0.0102	0.0079
Cd	children	NE	0.6667	NE	0.7334	0.0667	NE
	Adult		0.3143		0.3457	0.0314	
Pb	children	0.167	1.1297	1.2028	2.1297	1.2222	1.0556
	Adult	0.0786	0.5325	0.5675	1.0042	0.5761	0.4978
Zn	children	NE	0.0138	NE	NE	NE	NE
	Adult		0.0065				
Fe	children	NE	NE	NE	NE	NE	0.0089
	Adult						0.0042
Mn	children	0.0071	0.045	0.136	0.0486	0.060	0.0148
	Adult	0.0034	0.0213	0.0624	0.0229	0.0283	0.0066

NE-Not estimated due to non-detection of the metal in the sample

Table 6: Calculated Hazard quotient (HQ dermal) for adult and children

Element	age group	W1	W2	B1	B2	B3	B4
Cu	children	2.57E-04	4.03E-04	4.77E-04	5.05E-04	4.77E-04	3.67E-04
	Adult	8.70E-05	1.37E-04	1.62E-O4	1.86E-04	1.62E-04	1.20E-04
Cd	children	NE	1.76E-01	NE	1.94E-01	1.76E-02	NE
	Adult		5.96E-02		6.56E-02	5.96E-03	
Pb	children	7.54E-03	5.10E-02	5.45E-02	9.60E-02	5.53E-02	4.78E-02
	Adult	2.56E-03	1.73E-02	1.85E-02	3.27E-02	1.88E-02	1.62E-02
Zn	children	NE	2.73E-04	NE	NE	NE	NE
	Adult		9.25E-05				
Fe	children	NE	NE	NE	NE	NE	2.92.E-04
	Adult						9.91E-05
Mn	children	1.57E-03	9.95E-03	2.91E-02	1.07E-02	1.32E-02	3.25E-03
	Adult	5.33E-04	3.37E-03	9.87E-03	3.62E-03	4.47E-03	1.10E-03

NE-Not estimated due to non-detection of the metal in the sample

Table 7: Calculated Hazard index (HI) and total hazard index (∑HI)

Sample code	Children			Adult		
	HI oral	HI dermal	∑HI	HI oral	HI dermal	∑HI
W1	0.186	0.009	0.195	0.088	0.003	0.091
W2	2.041	0.238	2.279	0.883	0.081	0.964
B1	1.361	0.841	2.202	0.640	0.029	0.669
B2	2.937	0.301	3.238	1.385	0.104	1.489
B3	1.371	0.087	1.458	0.646	0.029	0.675
B4	1.096	0.052	1.148	0.517	0.018	0.585

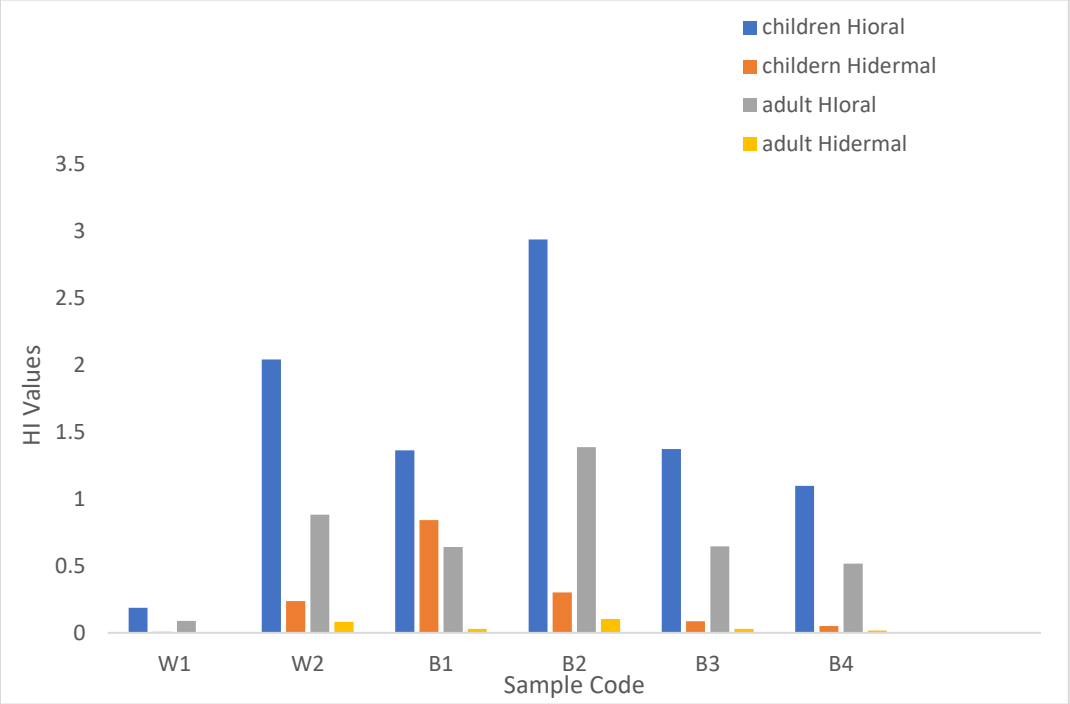


Fig. 3: Comparison of Oral and Dermal HI in Children and Adults

Non-Carcinogenic Risk (HQ and HI)

The calculated Hazard Quotients (HQ) for oral and dermal exposure are presented in Tables 6 and 7. The results show that Pb and Cd are the primary contaminants of concern.

Oral ingestion

For children HQ values for Pb exceeded 1 in most locations (range: 1.0556–2.1297), indicating potential non-carcinogenic risk, with the highest at B2. Adults showed lower HQ values, exceeding 1 only at B2 (HQ = 1.0042). Other metals like Cu, Zn, Fe, Mn showed HQ values < 1, indicating minimal risk.

Dermal exposure

HQ values were < 1 for all metals in both children and adults, suggesting negligible risk via skin contact. The Hazard Index (HI), which sums HQ values for all metals, reinforces these findings (Table 7, Figure 3). Children had HI ≥ 1 at all sites except W1, with the highest at B2 (ΣHI = 3.238), confirming greater vulnerability compared to adults. Adults showed HI ≥ 1 only at B2 (ΣHI = 1.489).

This trend reflects children's higher exposure dose per unit body weight, highlighting their increased susceptibility to non-carcinogenic effects of Pb and Cd [23].

Table 8: probable cancer risk (PCR) and total probable cancer risk (∑PCR)

	Oral PCR			Dermal PCR		
Sample code	Children	Adult	∑PCR	Children	Adult	∑PCR
W1	5.10E-06	2.40E-06	7.50E-06	3.37E-08	1.14E-08	4.51E-08
W2	2.88E-04	1.35E-04	4.23E-04	1.90E-06	6.44E-07	2.54E-06
B1	3.68E-05	1.74E-05	5.42E-05	2.43E-07	8.24E-08	3.25E-07
B2	3.44E-04	1.62E-04	5.06E-04	2.27E-06	1.79E-06	4.06E-06
B3	6.27E-05	2,96E-05	9.23E-05	4.14E-07	1.04E-07	5.54E-07
B4	3.23E-05	1.52E-05	4.75E-05	2.13E-07	2.23E-08	2.85E-07

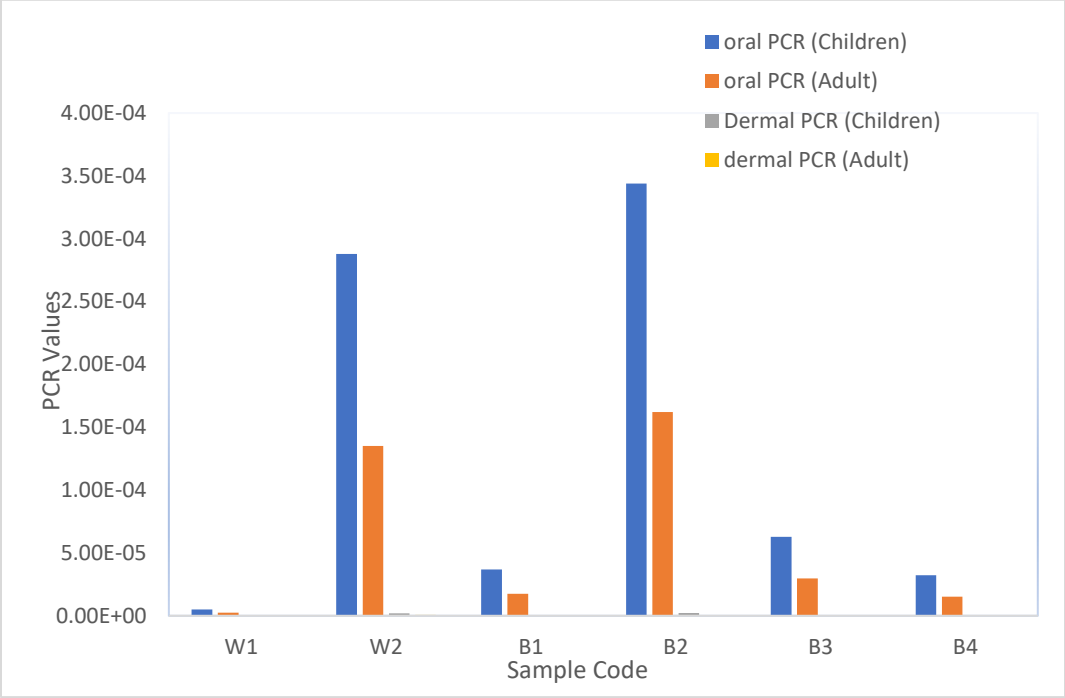


Fig 4: Comparison of Oral and Dermal PCR in children and Adults

The probable cancer risk (PCR) and total probable cancer risk (ΣPCR) were estimated for Pb and Cd (Table 9). The results showed that the oral route posed the highest cancer risk, while dermal exposure contributed far less (<1% of total risk). Samples B2 (ΣPCR = 5.06E-04) and W2 (ΣPCR = 4.23E-04) recorded the highest oral PCR values, indicating significant cancer risk through groundwater ingestion. The acceptable cancer risk range is 1×10^{-6} to 1×10^{-4}. However, B2 and W2 exceeded this permissible limit, suggesting unacceptable cancer risks, particularly through oral exposure. In contrast, sites W1, B1, B3, and B4 recorded values within or below the acceptable range.

These results align with previous studies from Ebonyi State, Nigeria, where carcinogenic risks from Pb and Cd in groundwater were also found to exceed safe limits in certain locations [23]. Children consistently showed higher PCR values

compared to adults across all sites (e.g., W2: 2.88E-04 in children vs. 1.35E-04 in adults). This reflects children's higher exposure dose per unit body weight and their increased vulnerability to long-term cancer risks. Similar patterns have been reported in groundwater studies across Nigeria, which consistently show that children are more prone to carcinogenic risks from Pb and Cd exposure. Although dermal PCR values were lower, the highest value was observed at B2 (ΣPCR = 4.06E-06), Children consistently had higher PCR values than adults (e.g., W2: 2.88×10^{-4} vs. 1.35×10^{-4}).Dermal exposure contributed <1% of total risk, with the highest at B2 (ΣPCR = 4.06×10^{-6}).These findings confirm that oral ingestion is the dominant pathway for carcinogenic risk, with Pb and Cd as the major contributors.

Uncertainty Consideration

While this study provides valuable estimates of human health risks, uncertainties exist due to:

Limited sample size (6 sites). Single-season sampling, which may not capture seasonal variations Assumptions in exposure parameters (body weight, ingestion rates, exposure duration). Future studies should include seasonal and spatially extensive sampling to improve accuracy and reduce uncertainty.

Conclusion

This study investigated the health risk of heavy metals around Abakaliki of metropolis. Concentration of metals varies at different sample points. Cd and Pb being the most critical contaminants, exceeding WHO limits in most samples. Oral ingestion posed higher risk than dermal contact, particularly for children, with HI >1 and PCR above 1×10^{-4} at B2 and W2. The measured concentration of Pb and Cd were higher than permissible limits for domestic use. Other metals (Cu, Zn, Fe, Mn, and Mg) were within safe limits. The presence of these contaminants above recommended standards implies that long-term consumption may affect residents' health in areas. Children are the most vulnerable group due to higher intake relative to body weight.

Recommendations

Continuous groundwater monitoring to track Pb and Cd levels.

Implementation of treatment technologies such as reverse osmosis or ion exchange.

Public health campaigns to raise awareness of contamination risks and promote safe water consumption. Expansion of sampling coverage and seasonal monitoring to reduce uncertainties.

Awareness of the health risks associated with drinking metal-laden water by residents is strongly recommended to minimize long-term exposure risks.

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