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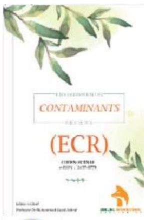

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RESEARCH ARTICLE

WATER QUALITY POTABILITY AND HEALTH RISK ASSESSMENT OF HEAVY METALS IN WATER RESOURCES WITHIN ADUDU-ABUNI METALLOGENIC PROVINCE, NORTHCENTRAL NIGERIA

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ABSTRACT

The inhabitants of Adudu and Abuni communities depend on streams, hand-dug wells, and ponds for drinking and domestic activities. To evaluate the safety of these sources, a water quality assessment was conducted focusing on heavy metal contamination and associated health risks. Physicochemical analyses followed American Public Health Association (APHA) protocols, while heavy metal concentrations were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Results indicated that both surface and groundwater are unsuitable for drinking, as several parameters exceeded recommended limits for safe consumption. Geographic Information System (GIS) tools were applied for geologic and sampling location mapping. Pollution indices, including the Heavy Metal Pollution Index (HMPI), Heavy Metal Contamination Index (HMCI), and Heavy Metal Evaluation Index (HMEI), confirmed significant heavy metal contamination. Health risk assessments further revealed that residents face both carcinogenic and non-carcinogenic risks, mainly through ingestion. Multivariate statistical analysis suggested that contamination arises from both natural processes and anthropogenic inputs, particularly Pb-Zn mining and agriculture. The study concludes that current water sources pose serious health risks, underscoring the need for alternative potable water supplies or appropriate treatment strategies to safeguard community health.

KEYWORDS

Anthropogenic, Carcinogenic, Heavy metals, Health risks, Water quality.

1. INTRODUCTION

Water is a vital resource for sustaining life, with its quality and availability essential for the growth and development of plants, animals, and humans (He and Li, 2020; Wang et al., 2022; Wei et al., 2022). Beyond its biological importance, water plays a critical role in agriculture, industry, and manufacturing, and is central to ecosystem sustainability (Ezugwu et al., 2019). However, its quality is increasingly threatened by both natural and anthropogenic factors, including solid mineral mining, agricultural use of agrochemicals, domestic and industrial effluents, and underlying geological conditions (Annapoorna and Janardhana, 2015; Adimalla et al., 2018; Egbueri et al., 2019; Keesari et al., 2019; Ezugwu et al., 2019; Kalaivana et al., 2018).

Mining activities has continued to cause environmental pollution that has adversely affected the health and economic development of many countries (He and Li, 2020). The emission of toxic metals such as leads (Pb), mercury (Hg), zinc (Zn), arsenic (As), cadmium (Cd), copper (Cu) into the environmental media such as water, soil, air, and plants are among other things, the main environmental problems associated with mining (Cobbina et al., 2015; Ezeigbo and Ezeanyim, 1993). These deleterious substances eventually find their ways into the soil, air and water bodies, and are consumed or inhaled by humans thereby posing significant health risks to humans when exposed through airborne particles, drinking or contact with contaminated water ((Kumar et al., 2020; Ganiyu 2021; Omeka et al., 2022; USEPA 2004). Based on the work of exposure of heavy metals in humans over a long period of time, may lead to muscular, physical and neurological degenerating process that mimics Alzheimer's disease, muscular dystrophy and multiple sclerosis (Otleş and Çagindi, 2010).

Several numerical models such as heavy metal pollution index (HMPI), heavy metals evaluation index (HMEI), hazard index (HI) and hazard quotient (HQ) have been developed and used for evaluation of water qualities in terms of ecological and human health potency in different parts of the globe (Singh et al., 2017; Mohammadi et al., 2019; Zakir et al., 2020; Tong et al., 2021). This approach has been efficient in quantification of ground and surface water resources into suitable and unsuitable for human consumption. In order increase the confidence in the results, heavy metals contamination index (HMCI) and Pearson correlation analyses has been in cooperated into the work.

The southern Nigeria's sedimentary basins, an industrial and densely populated region of Nigeria, the water resource from rivers, streams, ponds, boreholes and watershed has received significant research attention in terms of its physical, chemical and biological components as well as the health risks analyses of water qualities, its corresponding northern basements complex, specifically the Adudu and Abuni mining province, characterized by robust mineralization has been reported to be

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contaminated, however, no study have successfully examined the human health risks associated with heavy metals in the study area (Egbueri 2019a, 2020; Omenka et al., 2022; Adimalla 2020; Adamu 2015 Anyanwu et al 2020;, 2022, Johah et al., 2023;, Effiong et al., 2024; Igwe et al., 2020; Okafor et al., 2023).

Therefore, this study aimed to (i) Apply an integrated risk assessment approach, taking into account both non-carcinogenic and carcinogenic risks (ii) Consider dual exposure pathways (ingestion and dermal contact) which are often ignored in similar regional studies (iii) Provides the first spatial distribution analyses of toxic metals in the region's water resources (iv) Bridge a critical knowledge gap in public hydrogeochemistry within this understudied but heavily mineralized zone of Nigeria. The findings are expected to serve as baseline for future hydrogeochemical surveillance and shall provide a scientific basis for developing strategies to mitigate pollution and promote sustainable and effective management of drinking water resources.

1.1 Description, Geology and Hydrogeological characteristics of the study Area

Adudu and Abuni is an intensive, uncontrolled, artisanal mining and farming communities situated between latitude 08° 10′ 50″ and 08° 18′ 12″ N and Longitude 08° 58′ 38″ to 09° 01′ 18″. It covers an estimated area 01-30km which extends from Adudu in Obi LGA to Abuni in Awe Local Government Area of Nassarawa state, north-central Nigeria. The area is predominantly characterized by gently undulating lowlands (Igwe et al., 2017; Okafor et al., 2023). However, the natural topography has been modified by the presence of mine heaps and tailings, which are densely scattered across farmlands and stream channels within the mining zone. These features have altered the landscape into a more rugged, hill-like terrain. Elevation ranges from 116 to 268 meters above sea level. The region falls within the tropical rainy zone, marked by distinct wet and dry seasons. The wet season typically lasts for seven months, from April to September, with an annual rainfall between 1,200- and 2,000-mm. Average temperatures range from 25°C to 27.5°C. The dry season begins in October and ends in March (Okafor et al., 2023). The geological and sample location map of the study area is shown in Figure 1. The local lithology comprises a 2-meter-thick layer of light grey, fissile, and highly weathered shale with horizontal laminations. This is overlain by a distinct 4-meter-thick dark grey, fissile, carbonaceous shale layer, also highly weathered and laminated. These shales are further covered by an overburden of approximately 0.8 meters consisting of weathered silt and sandstone containing plant rootlets.

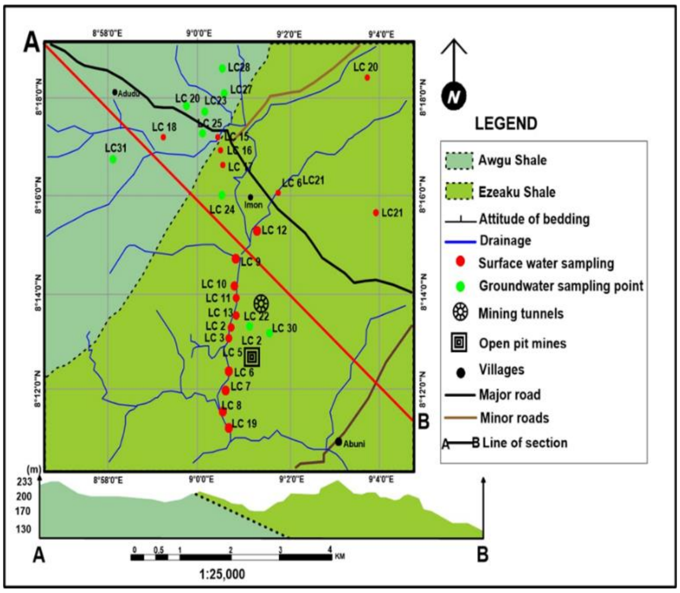

Figure 1: Geologic map of the study area showing sample location points

The study area exhibits diverse hydrogeological characteristics. The Asu River Group comprises folded shales and siltstones that are highly fractured, enabling the storage of appreciable quantities of water (Okafor et al 2023). The sandstone unit of the Awgu Formation serves as a confined, water-bearing member that yields artesian (pressurized) water (Patrick et al., 2013; Okafor et al., 2023). The coal-bearing measures consist of highly fractured coal shales, which facilitate continuous groundwater flow. Although the Awe Formation is also water-bearing, its groundwater is saline, rendering it a poor-quality aquifer due to low permeability of the siltstones and ferruginous sandstones (Offodile, 1992). Infiltration and precipitation are the primary source of groundwater recharge. The network of rivers, including the Imon and Bakau streams also discharges water through faults, fractures and joints into the groundwater recharge in the study area while the groundwater circulation patterns are controlled by lithologies, undulating topography structural features like faults, folds and joints that characterized the middle Benue trough of the Nigerian sedimentary basins (Offodile, 1992; Obaje, 2004).

2. MATERIALS AND METHODS

2.1 Sampling and Laboratory analyses

A total of thirty-one water samples including streams, ponds, boreholes and hand-dug well waters were collected in a 45cl neatly washed and sterilized containers. At each sampling location, three separate water samples were collected for anion, cation, and heavy metal analyses. Immediately after collection, concentrated nitric acid (HNO_3) was added to the samples to prevent precipitation, elemental biodegradation, and sorption (Okafor et al., 2023). The samples were securely sealed, clearly labeled, and stored in an ice-cooled container. Within 48 hours, they were transported to the National Water Resources Institute (NWRI) Laboratory in Kaduna for analysis. The temperature and pH were measured using mercury thermometer and pH meters respectively, other physical parameters and anions were measured in the laboratory following the American Public Health Association procedures as described in (Okafor et al., 2023)

2.2 Heavy Metal Pollution Index (HMPI)

The HMPI is computed on the basis of weighted arithmetic procedure. To do this, a model described and used by a group researcher was adopted following the steps outlined below (Zakir et al., 2020; Tygai et al., 2013): All the analyzed heavy metals Cd, Fe, Cr, Pb, As, Cu, and Zn were considered in this calculation. Firstly, the quality rating scale (Qi) for each parameter is calculated using the expression in Eqn.1

$$\mathrm{Qi} = \frac{\mathrm{V_{actual}} - \mathrm{V_{ideal}}}{\mathrm{V_{standard}} - \mathrm{V_{ideal}}} \times 100 \tag{1}$$

Where, Vstandard is the standard value of ith parameter for the drinking water, Videal is the ideal value of this parameter in pure water (for all parameters, the ideal value is assigned a value of zero (0) and Vactual is the calculated value of ith parameter in the analyzed water sample.

The unit weight (Wi) for each water quality parameter was calculated using the mathematical expression:

$$Wi = \frac{K}{V_{standard}}$$

Where, K is the constant of proportionality expressed by the equation below:

$$K = \frac{1}{\sum(1/V_{standard})} \tag{2}$$

HMPI is, therefore, calculated using Eqn. 3 below:

$$HMPI = \frac{\sum(Qi \times Wi)}{\sum Wi} \tag{3}$$

To better understand the degree of heavy metal contamination, the HMPI values were grouped into three classes (Edet et. al., 2002) Thus: If HMPI <15, it is classified as low, between 15-30 as medium whereas those greater than thirty (>30) are considered to be high.

2.2.1 *Heavy metal evaluation index (HMEI)*

The HMEI is an invaluable tool in evaluating the overall water quality in relation to heavy metals contamination/pollution. Both HMPI, HMEI and Contamination index serves a complementary purpose to one another. The following expression (Eqn.4) was used in calculating the HMEI

$$HMEI = \sum_{i=1}^{n} \frac{HM_{conc}}{HM_{MPC}} \tag{4}$$

Where, HMMPC = the maximum permissible concentration of the same heavy metal and HM Conc. = the monitored concentration of a particular heavy metal. To evaluate heavy metal contamination level in ground and surface water, a threshold value of 1.0 was set, which implies that HMEI

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value > 1.0 is “unfit” and a value < 1.0 is rated as “fit” for domestic purposes (Singh et al., 2017; Zakir et al., 2020).

2.2.2 Heavy Metals Contamination index (HMCI)

The enrichment of potentially toxic elements (PTE) with regards to maximum admissible limit (MAL) standard prescribed by World Health Organization (2012) has been identified through the evaluation of heavy metals contamination index (HMCI). The contamination indexes for the PTEs in the water samples are computed using Eqn. 5.

$$HMCI = \frac{\left[\frac{Fe_{ij}}{0.3} + \frac{Zn_{ij}}{5} + \frac{Pb_{ij}}{0.01} + \frac{Cu_{ij}}{0.05} + \frac{Cd_{ij}}{0.05} + \frac{Cr_{ij}}{0.05} + \frac{As_{ij}}{0.01}\right]}{7} \tag{5}$$

Where, the numerator is the determined concentration of Feij, Znij, Pbij, Cuij, Cdij, Crij, and Asij at each of sampled location while the denominator equals to the WHO maximum admissible limit for each of the analyzed heavy metals accordingly. The HMCI is classified as contaminated, slightly contaminated or not contaminated if its values are greater than five (> 5), between 1-5 or less than one (<1) respectively, slightly contaminated if HMCI is between 1 to 5 and not contaminated if HMCI < 1 (Adamu et al., 2015).

2.3 Health Risks Assessment

Risk assessment involves the identification of hazards, the assessment of level of exposure, toxicity and the characterization of risk (Lee et al., 2005). Although a number of heavy metals are important for health and human nutrition, excessive body intake of these metals and other toxic substances can cause a variety of adverse health outcomes such as neurological disorder, reproductive complications, renal disease, gastrointestinal bleeding, hypertension, cancer and lung disease, (WHO 2012; Zakir et al., 2020; Ganiyu et al., 2021).

2.3.1 Non-carcinogenic health risk

Two pathways of body intake of water were considered in this study viz; dermal absorption and oral ingestion (Ogundele et al., 2019; Kumar et al., 2020). To assess the potential health risk through these media, hazard quotient (HQ) and hazard index (HI) were computed. Firstly, the method established by the US Environmental Protection Agency as given in Eqns 6 and 7, was used in calculating the Chronic Daily Intake (CDI) of heavy metal through dermal adsorption and ingestion of waters by the inhabitants (USEPA, 2004; Zakir et al., 2020).

$$CDI_{oral}(mgkg^{-1}day^{-1}) = \frac{Chm \times DI \times ABS \times EF \times ED}{BW \times AT} \tag{6}$$

$$CDI_{dermal}(mgkg^{-1}day^{-1}) = \frac{Chm \times SA \times Kp \times ABS \times ET \times EF \times ED \times CF}{BW \times AT} \tag{7}$$

Where, Chm=Heavy metal concentration; DI= Daily average intake; SA= Skin surface area; BW= Average body weight; CF= Conversion Factor; ED= exposure duration; EF=exposure frequency; ET= Exposure Time; AT= Average time and ABS= Absorption factor. The authoritative values of the above CDI input parameters are presented in Table 1.

Table 1: Input Parameters used to calculate non-carcinogenic human health risk due to metal exposure through ingestion and dermal adsorption of waters

Parameters	Unit	values		References
		Ingestion	Dermal absorption	
Heavy metal concentration (C_{hm})	Mg/L	-	-	Table 4
Daily average intake (DI)	L/Day	2.2	-	Mohammed et al., 2019
Skin surface area (SA)	Cm^2	-	18000	USEPA, 2004
Exposure Time (ET)	Hour/event	-	0.58	USEPA, 2004
Exposure frequency (EF)	Days/Year	365	350	USEPA, 2004
Exposure duration (ED)	Year	71.8	30	Zakir et al., 2020
Conversion Factor (CF)	L/cm	-	0.001	USEPA, 2004
Average body weight (BW)	Kg	60	60	BBS, 2015
Absorption Factor (ABS)	-	0.001	0.001	USEPA, 2004
Average Time (AT)	Day	26207	10500	Zakir et al., 2020

HQ is the ratio of computed mean chronic daily intakes (CDI) of a selected trace elements to the oral reference dose (RfD) for the same heavy metal (Sharmin et al., 2020), The RfD for each heavy metal used in this evaluation are presented in Table 2. The HQ of heavy metal through ingestion and dermal absorption of waters was determined using Eqn. 8 and 9 respectively.

$$HQ_{oral} = \frac{CDI_{oral}}{RfD_{oral}} \tag{8}$$

$$HQ_{dermal} = \frac{CDI_{Dermal}}{RfD_{Dermal}} \tag{9}$$

The HI is the sum of potential non-carcer health risks induced by the heavy metals present in ground and surface water. This parameter was determined using the method outlined by USEPA (2004) for dermal adsorption and ingestion of water as shown in Eqns 10 and 11 respectively.

$$HI_{ORAL} = \sum_{i=1}^{n} HQ_{oral} = HQ_{Fe} + HQ_{Zn} + HQ_{Pb} + HQ_{Cu} + HQ_{Cd} + HQ_{Cr} + HQ_{As} \tag{10}$$

$$HI_{DERMAL} = \sum_{i=I}^{n} HQ_{Dermal} = HQ_{Fe} + HQ_{Zn} + HQ_{Pb} + HQ_{Cu} + HQ_{Cd} + HQ_{Cr} + HQ_{As} \tag{11}$$

Therefore, to assess HI in the waters, a threshold value of 1.0 was set. This implies that if the HI value is < 1.0, it is unlikely that the exposed populations will experience adverse health effects, whereas if it is > 1.0, it will be indicative of high possibilities of non-carcinogenic adverse health impact on the exposed population (Mohammadi et al., 2019; Ukah et al., 2019; Wu et al., 2015: Onyemesili et al., 2020; Egbueri and Mgbenu 2020).

Table 2: Oral & dermal reference doses (RfD) and cancer slope factor (CSF) values used HQ and ILCR

Heavy metals	Cu	Zn	Cr	Pb	Fe	Cd	As
RfD oral (mg/kg/day)	0.040[a]	0.300[a]	0.003[b]	0.0035[c]	0.700[a]	0.001[a]	0.0003[a]
RfD dermal (mg/kg/day)	0.012[c]	0.060[c]	0.000015[c]	0.00042[c]	0.300[c]	0.000025[c]	0.00035[a]
CSF (mg/kg/day)	-	-	0.42[d]	0.0085[d]		15.0[d]	1.5[a]
a =USEPA (2010), b, c = Zakir et al. (2020), d =OEHHA (2019)							

2.3.2 Carcinogenic health risk

The likelihood of developing cancer over a lifetime from exposure to carcinogenic contaminants such as Cd, Cr, and Pb is quantified as the Incremental Lifetime Cancer Risk (ILCR). This risk is calculated as the product of the Cancer Slope Factor (CSF) and the Chronic Daily Intake (CDI) (USEPA, 2010; Zakir et al., 2020).

$$ILCR = CDI \times CSF \tag{12}$$

Cancer slope factor (CSF) values for the selected carcinogens were obtained from the California Office of Environmental Health Hazard Assessment (OEHHA., 2019) and are presented in Table 2. The chronic daily intake (CDI) from both dermal and oral exposure pathways was used to estimate the total incremental lifetime cancer risk (ΣILCR). According to USEPA (2010), the acceptable ΣILCR range for single or multiple carcinogens is 1.0×10^{-6} to 1.0×10^{-4}, representing a probability from one case of cancer per 1,000,000 individuals for a single carcinogen to one case per 10,000 individuals for multiple carcinogens (Mohammadi et al., 2019; Zakir et al., 2020).

3. RESULTS AND DISCUSSION

3.1 Descriptive summary of the physicochemical properties of water

The physicochemical and heavy metal contents in the ground and surface water of the study area were compared with the permissible limits of WHO (2012) & (NSDWQ 2007) for drinking purposes. The statistical summary of all the parameters that were analyzed is presented in Table 3. The pH ranges from 7.0 to 7.80 and 6.70 to 7.60 for ground and surface water respectively, pH values fall within the permissible limit (WHO 2012; NSDWQ 2007), they have no significant effect on human health, however, it affects the efficiency and flocculation processes (Egbueri, 2019a; Deustch, 1997).

The EC ranged from 72.20 to 1237µS/cm and 350 to 1080µS/cm in ground and surface water respectively, the TDS ranged from 80 to 542ng/l in groundwater and 35 to 690mg/l in surface water while salinity ranged from 19.40 to 233mg/l and 6.22 to 12610.30mg/l in ground and surface water respectively (Table 5), 14% of TDS concentration in the sampled groundwater exceeds the Nigeria Standard for Drinking Water Quality (2007) and World Health Organization (2012). The high concentrations of EC, TDS and salinity is indicative of the presence of dissolved ions in water which is caused by high rate of mineralization, dissolution of host rock, contamination of the water regime in the study area by mine effluents (Deustch, 1997; Arstad et al., 2017) and the occurrence of brine or connate water (Offodile 1992; Moustafa et al., 2021; Okafor et al., 2023).

The total hardness (TH) ranged from 55 to 383mg/l and 15.6 to 325mg/l for ground and surface water respectively while the average concentration of TH in ground and surface water samples is 256.40 and 141.57mg/l respectively. Water is classified as very hard, hard, moderately hard and soft if their TH values fall between >300, 150-300, 75-150 and 0-70 respectively (Todd, 1980), hence 10% of the sampled groundwater is moderate, 60% is hard and 30% is classified as very hard, also 33% of the surface water sample is fresh, 19% is moderate, 43% is hard while 5% is very hard.

The concentration of cations in order of increasing dominance Ca>Na>K>Mg and Na>K>Ca>Mg for surface and ground water respectively, the average concentration of Na, Mg, Ca and K are 25.55, 5.16, 16.62, 16.02 and 26.59, 5.96, 37.06, 13.73mg/L for ground and surface water respectively. The concentration of Na and Mg in all samples falls within the WHO (2012) and NSDWQ (2007) allowable limit for drinking, the high concentration of Ca and K in the surface and groundwater samples is attributed to the dissolution of carbonate rocks (limestone, shales, coal) that characterized the study area, as well as the application of fertilizer for enhancement of crop yield and productivity in the farmlands (Rao, 2018; Okafor et al., 2023).

The mean concentration of SO^{2+} Cl, $\mathbf{HCO_3}^-$ and NO_3^- are 5.0, 73.56, 256.40, 63.49 and 26.68, 2557.56, 141.56, 30.28mg/l for ground and surface water respectively. High concentrations of bicarbonate indicate the dominance of mineral dissolutions high concentration of nitrate is anthropogenic, sourced from farmlands because of intensive application of agrochemicals to farmlands whereas high values of chloride are thought to be from natural geochemical and geological condition (connate water), poor sanitary conditions and leaching from soil layers witnessed in the study area (Stumm and Morgan 1996, Okafor et al., 2023; Egbueri, 2019a).

Heavy metal concentrations in groundwater and surface water followed the order: Fe > Zn > Pb > Cu > Cr > Cd > As and Fe > Pb > Zn > Cu > Cr > Cd > As, respectively. The mean concentrations (mg/L) for surface water were: As (0.02), Cr (0.32), Cd (0.05), Cu (0.17), Pb (0.67), Zn (0.66), and Fe (10.46); while for groundwater they were: As (0.04), Cr (0.17), Cd (0.03), Cu (0.20), Pb (0.14), Zn (0.29), and Fe (8.40). Most values exceeded the permissible limits set by NSDWQ (2007) and WHO (2012). The elevated concentrations are largely attributed to anthropogenic influences, including direct discharge of mine effluents, mineral washing and processing in streams, and deposition of mine spoils into nearby water bodies (Jablonska-Czapala et al., 2016; Igwe et al., 2017; Egbueri et al., 2019).

3.2 Heavy Metals Contamination Index

Heavy metals contamination index (HMCI) is primarily used to assess the collective contribution of selected heavy metals to the water pollution (Adamu et al., 2015). The HMCI results showed that 60% of the groundwater samples is highly contaminated while 40% is slightly contaminated. 76% of the surface water in the study area is highly contaminated while 24% shows slight contamination (Table 4a), generally, water resource in the study area is highly contaminated by heavy metals as result of near proximity of the mine sites to stream, ponds and hand dug wells as well as improper disposal of mine effluents and tailings into the streams within the study area.

3.2.1 Heavy metal pollution index (HMPI) and Heavy metal evaluation index (HMEI)

HMPI gives a comprehensive assessment of the quality of water as it relates to heavy metals, The HMPI and HMEI results presented in Table 4a are used here to test the strength and integrity of HMCI results. Based on the work of HMPI can be low, medium or high if its values are <15, 15-30 and >30 respectively, the HMEI greater than 1 is described as unfit, whereas values less than one are fit for drinking and domestic purposes (Edet and Offiong, 2002; Zakir et al., 2020; Mthembu et al., 2022; Singh et al., 2017; Zakir et al., 2020). The HMPI and HMEI values for both ground and surface water showed 100% high and 100% unsuitable respectively.

A group researcher warned that heavy metals taken internally is highly toxic and its effect can be felt in the human body over time (Igwe et al., 201; 2017; Duruibe et al., 2007). Correlation mean score of 0.5 was used to evaluate the strength and relationship of each pollution index to the generated results (Table 4b), all the heavy metal pollution indexes show positive correlation with each other, implying that all the calculated parameters significantly contaminate the water resources in the study area (Onwuka and Ezugwu, 2019).

Table 3: Heavy Metals contamination index (HMCI), Heavy metal pollution Index (HMPI) and Heavy metal evaluation index (HMEI) values and descriptions

Water source	Sample ID	HMCI		HMPI		HMEI	
		Value	**Description**	**Value**	**Description**	**Value**	**Description**
Surface water	LC1	39.59	H Contaminated	902.84	High	124.09	Unsuitable
	LC2	34.69	H. Contaminated	658.74	High	105.00	Unsuitable
	LC3	14.92	H. Contaminated	407.36	High	34.74	Unsuitable
	LC4	11.81	H. Contaminated	454.32	High	32.00	Unsuitable
	LC5	14.05	H. Contaminated	304.48	High	26.68	Unsuitable
	LC6	11.07	H. Contaminated	222.18	High	20.25	Unsuitable
	LC7	9.04	H. Contaminated	267.33	High	20.25	Unsuitable
	LC8	9.96	H. Contaminated	255.95	High	20.40	Unsuitable
	LC9	11.19	H. Contaminated	318.98	High	27.13	Unsuitable

Table 3 (cont): Heavy Metals contamination index (HMCI), Heavy metal pollution Index (HMPI) and Heavy metal evaluation index (HMEI) values and descriptions

	LC10	38.44	H. Contaminated	945.73	High	127.66	Unsuitable
	LC11	15.22	H. Contaminated	381.56	High	55.34	Unsuitable
	LC12	11.02	H. Contaminated	342.55	High	55.55	Unsuitable
	LC13	29.54	H. Contaminated	578.76	High	110.71	Unsuitable
	LC14	4.18	S. contaminated	431.96	High	75.36	Unsuitable
	LC15	4.2	S. contaminated	232.39	High	31.95	Unsuitable
	LC16	22.65	H. Contaminated	759.0s4	High	117.00	Unsuitable
	LC17	4.62	S. contaminated	108.07	High	2.20	Unsuitable
	LC18	19.4	H. Contaminated	420.73	High	52.88	Unsuitable
	LC19	8.95	S. contaminated	145.43	High	15.93	Unsuitable
	LC20	14.24	H. Contaminated	443.89	High	52.12	Unsuitable
	LC21	3.1	S. contaminated	231.41	High	17.36	Unsuitable
Groundwater	LC22	3.86	S. contaminated	236.78	High	14.72	Unsuitable
	LC23	10.47	H. contaminated	381.92	High	44.91	Unsuitable
	LC24	12.3	H. contaminated	423.32	High	59.23	Unsuitable
	LC25	10.22	H. contaminated	311.10	High	35.27	Unsuitable
	LC26	9.01	H. contaminated	361.04	High	50.60	Unsuitable
	LC27	4.9	S. contaminated	264.33	High	41.73	Unsuitable
	LC28	3.2	S. contaminated	309.22	High	34.60	Unsuitable
	LC29	11.34	H. contaminated	431.02	High	45.60	Unsuitable
	LC30	4.5	S. contaminated	159.75	High	7.97	Unsuitable
	LC31	9.75	H. contaminated	270.71	High	23.60	Unsuitable
	Min	3.10		108.07		2.20	
	Max	39.59		945.73		127.66	
	Mean	13.27		385.90		47.83	
	Median	11.02		342.55		35.27	
	SD	9.97		201.12		35.00	

Table 4: Correlation analysis of all the calculated heavy metal pollution indicators

	HMCI	***HMPI***	***HMEI***
HMCI	1		
HMPI	0.91191	1	
HMEI	0.569155	0.704855	1

3.3 Assessment of health risks

The health risk assessment is the quantifies the nature, form, degree and indices of health impacts as a result of exposure to potentially harmful substances (Lee et al., 2005, Wang et al., 2022). It is given in terms of a non-carcinogenic or carcinogenic health risk (He and Wu, 2019; Adamu et al., 2015; Ukah et al., 2019; Egbueri and Mgbenu 2020; Ogundele et al., 2020). The non-carcinogenic and carcinogenic human health risks were measured by evaluating the health index (HI) and health quotient (HQ) as described in Eqn. 6-12.

3.3.1 Non-carcinogenic health risk

The results of the oral ingestion hazard quotient (HQ-oral) for groundwater and surface water are presented in Table 5a. The HQ-oral values follow the order As > Pb > Cd > Fe > Zn > Cr > Cu for groundwater, and Pb > Fe > As > Cd > Cr > Cu > Zn for surface water. HQ values greater than one (HQ > 1) indicate potential health risks, while values below one (HQ < 1) imply safe limits (Mohammadi et al., 2019; Zakir et al., 2020). Arsenic and lead recorded high HQ-oral values in studied area. The results of HQ-dermal, its corresponding statistics values are shown in Table 5b. The Health Index (HI), representing the sum of all HQ values, was also determined. About 30% of groundwater and 52% of surface water HI-oral values exceeded the safe limit of 1, indicating potential health risks from drinking. Similarly, 14% of the HI-dermal values for surface water were above 1, suggesting possible risks through skin contact.

The effect of dermal absorption is negligible; however, ingesting water sourced within the study area poses adverse health effects to its consumers. A group researcher has demonstrated that long-term exposures of Cd to the body through drinking water may lead to reduction of androgen receptors thereby enhancing the development of prostate cancer, neurotoxicity and nephrotoxicity (Neshlund-Dudas et al., 2018; Quing et al., 2020; Tong et al., 2021).

Excessive intake of Zinc can cause neuronal injuries and neurodegenerative diseases (Neshlund-Dudas et al., 2018, Tong et al. 2021). Other heavy metal exposures to human body could cause bone fractures, kidney damage, and lung cancer (Wei et al., 2022; Zakir et al., 2020; Ganiyu et al., 2021; Mohammed et al., 2019; Mbaka et al., 2020). Hence, measures are required to minimize exposure of Cd, Pb, As, Cr. to water resources, the mitigative measures reduces adverse health outcomes on the inhabitants and enhances quality and safe water (Akoto et al., 2019).

Table 5a: Calculated Hazard quotient (HQ) and Hazard Index (HI) due to dermal absorption of water in Adudu-Abuni Lead-Zinc mine province

Water source	**Sample ID**	**Hazard quotient (HQ-$_{\text{dermal}}$)**							**HI=∑HQ-dermal**
		Fe	**Zn**	**Pb**	**Cu**	**Cd**	**Cr**	**As**	
Surface water	LC1	0.0384	0.005	0.6355	0.0033	0.2714	0.0037	0.118	1.0754
	LC2	0.034	0.0039	0.559	0.003	0.0826	0.0034	0.1573	0.8431
	LC3	0.0057	0.002	0.2454	0.0059	0.1652	0.0191	0.0197	0.4631
	LC4	0.0053	0.0019	0.1736	0.0103	0.2431	0.0131	0.0236	0.471

Table 5a (Cont): Calculated Hazard quotient (HQ) and Hazard Index (HI) due to dermal absorption of water in Adudu-Abuni Lead-Zinc mine province

Water source	**Sample ID**	**Hazard quotient (HQ-$_{\text{dermal}}$)**							**HI=∑HQ-dermal**
		Fe	**Zn**	**Pb**	**Cu**	**Cd**	**Cr**	**As**	
	LC5	0.0025	0.0013	0.2569	0.0043	0.118	0.0173	0.0157	0.416
	LC6	0.0024	0.0009	0.1864	0.0041	0.059	0.0165	0.0983	0.3676
	LC7	0.0028	0.0017	0.1409	0.0078	0.0354	0.0144	0.0118	0.2148
	LC8	0.0021	0.0016	0.175	0.0035	0.118	0.0135	0.0039	0.3176
	LC9	0.0048	0.0015	0.1773	0.0086	0.0354	0.0084	0.1573	0.3934
	LC10	0.0384	0.0055	0.681	0.004	0.2832	0.0054	0.3933	1.4109
	LC11	0.0204	0.0024	0.1891	0.0053	0	0.0086	0.0236	0.2494
	LC12	0.0235	0.0022	0.1136	0.005	0.059	0.009	0.0708	0.2831
	LC13	0.0479	0.0072	0.2556	0.0063	0.118	0.0069	0.9833	1.4251
	LC14	0.0347	0.0014	0.0836	0.0032	0.0472	0.0076	0.0393	0.2172
	LC15	0.0124	0.001	0.0802	0.0032	0.0826	0.0096	0.0197	0.2088
	LC16	0.0518	0.0012	0.1487	0.0065	0.0472	0.0086	0.0393	0.3033
	LC17	0.0008	0.0016	0.0836	0.0055	-0.2938	0.0075	0.0787	0.1161
	LC18	0.0138	0.008	0.3247	0.0072	0.0236	0.0066	0.0787	0.4626
	LC19	0.0022	0.0012	0.1524	0.0034	0	0.0142	0.0393	0.2128
	LC20	0.0207	0.0014	0.0742	0.0097	0	0.0044	0.0157	0.1262
	LC21	0.0055	0.0015	0.2899	0.0065	0.0354	0.0059	0.0787	0.4233
Groundwater	LC22	0.0012	0.0018	0.0971	0.0086	0.0094	0.0112	0.0787	0.2081
	LC23	0.0167	0.0013	0.0954	0.0075	0.0236	0.0075	0.0472	0.1992
	LC24	0.0267	0.0011	0.0475	0.0063	0	0.0072	0.3933	0.4823
	LC25	0.015	0.0005	0.0421	0.0047	0.059	0.0074	0.7867	0.9155
	LC26	0.0226	0.0008	0.0384	0.0051	0.0106	0.0045	0.0157	0.0977
	LC27	0.0189	0.0004	0.0435	0.0026	0	0.0045	0.0275	0.0974
	LC28	0.0139	0.0008	0.0371	0.0039	0.0826	0.0054	0.0865	0.2302
	LC29	0.0164	0.0012	0.0927	0.0066	0.1062	0.0079	0.4327	0.6638
	LC30	0.0014	0.0016	0.087	0.0062	0.0118	0.0076	0.0157	0.1313
	LC31	0.0088	0.002	0.145	0.0074	0.0236	0.003	0.0157	0.2054
Min		0.0008	0.0004	0.0371	0.0026	-0.2938	0.0030	0.0039	0.0974
Max		0.0518	0.0080	0.6810	0.0103	0.2832	0.0191	0.9833	1.4251
Mean		0.0165	0.0021	0.1856	0.0057	0.0599	0.0087	0.1408	0.4268
SD		0.0146	0.0019	0.1658	0.0021	0.1016	0.0042	0.2301	0.3562

Table 5b: Calculated Hazard quotient (HQ) and Hazard Index (HI) for oral ingestion of water from the study area and their basic statistic

Water source	**Sample ID**	**Hazard quotient (HQ-oral)**							**HI=∑HQ-oral**
		Fe	**Zn**	**Pb**	**Cu**	**Cd**	**Cr**	**As**	
Surface water	LC1	0.1075	0.0141	1.7773	0.0093	0.759	0.0103	0.33	3.0075 2.3579
	LC2	0.095	0.011	1.5633	0.0083	0.231	0.0094	0.44	
	LC3	0.016	0.0057	0.6864	0.0164	0.462	0.0535	0.055	1.295
	LC4	0.0148	0.0054	0.4856	0.0289	0.6798	0.0367	0.066	1.3171
	LC5	0.0071	0.0036	0.7185	0.012	0.33	0.0483	0.044	1.1635
	LC6	0.0066	0.0026	0.5214	0.0114	0.165	0.046	0.275	1.028
	LC7	0.0078	0.0048	0.3941	0.0217	0.099	0.0403	0.033	1.6006
	LC8	0.0058	0.0044	0.4893	0.0098	0.33	0.0378	0.011	0.8882
	LC9	0.0136	0.0043	0.4959	0.0239	0.099	0.0234	0.44	1.1001
	LC10	0.1075	0.0153	1.9046	0.0113	0.792	0.015	1.1	3.9457
	LC11	0.057	0.0068	0.5289	0.0147	0	0.0241	0.066	0.6975
	LC12	0.0658	0.006	0.3177	0.0139	0.165	0.0252	0.198	0.7916
	LC13	0.1339	0.0202	0.7147	0.0175	0.33	0.0192	2.75	3.9855
	LC14	0.0971	0.004	0.2338	0.009	0.132	0.0214	0.11	0.6074
	LC15	0.0347	0.0029	0.2244	0.0091	0.231	0.0267	0.055	0.5838
	LC16	0.1448	0.0034	0.4158	0.0181	0.132	0.0242	0.11	0.8482
	LC17	0.0023	0.0046	0.2338	0.0153	-0.8217	0.021	0.22	-0.3247
	LC18	0.0387	0.0225	0.908	0.0202	0.066	0.0184	0.22	1.2937
	LC19	0.0063	0.0033	0.4262	0.0096	0	0.0398	0.11	0.5951

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Table 5b (Conts): Calculated Hazard quotient (HQ) and Hazard Index (HI) for oral ingestion of water from the study area and their basic statistic

Water source	Sample ID	Hazard quotient (HQ-oral)							HI=∑HQ-oral
		Fe	Zn	Pb	Cu	Cd	Cr	As	
	LC20	0.058	0.0039	0.2074	0.0272	0	0.0124	0.044	0.3529
	LC21	0.0153	0.0041	0.8109	0.0182	0.099	0.0165	0.22	0.1839
Groundwater	LC22	0.0034	0.0051	0.2715	0.0241	0.0264	0.0314	0.22	0.5819
	LC23	0.0468	0.0036	0.2668	0.021	0.066	0.021	0.132	0.5572
	LC24	0.0746	0.0032	0.1329	0.0177	0	0.0202	1.1	1.3487
	LC25	0.0421	0.0013	0.1179	0.0133	0.165	0.0207	2.2	2.5603
	LC26	0.0631	0.0021	0.1075	0.0142	0.0297	0.0125	0.044	0.2731
	LC27	0.0528	0.001	0.1216	0.0073	0	0.0125	0.077	0.2723
	LC28	0.0387	0.0023	0.1037	0.0108	0.231	0.0151	0.242	0.6437
	LC29	0.046	0.0034	0.2593	0.0185	0.297	0.0221	1.21	1.8563
	LC30	0.0038	0.0045	0.2433	0.0173	0.033	0.0212	0.044	0.3671
	LC31	0.0246	0.0055	0.4054	0.0206	0.066	0.0083	0.044	0.5744
Min		0.0023	0.0010	0.1037	0.0073	-0.8217	0.0083	0.0110	-0.3247
Max		0.1448	0.0225	1.9046	0.0289	0.7920	0.0535	2.7500	3.9855
Mean		0.0462	0.0060	0.5190	0.0158	0.1676	0.0243	0.3939	1.1727
SD		0.0407	0.0052	0.4637	0.0058	0.2840	0.0119	0.6436	1.0351

3.3.2 Carcinogenic health risk

The concentrations of Pb, Cr, and Cd in the water were identified as having the potential to pose cancer risks to humans upon exposure (Zakir et al., 2020). According to USEPA (2010), the acceptable ΣILCR for a single carcinogen range from 1.0×10^{-6} to 1.0×10^{-4} elements or multi-element carcinogens respectively. Based on this proposition, the chance that one may develop cancer as a result of exposure to heavy metals in contaminated water through dermal absorption and oral ingestion due to high load of carcinogens follows the order Cd > Pb > Cr for both surface water and groundwater (Table 9). The cumulative ILCR showed that 200 out of every 1×10^6 people will develop cancer as a result of consuming surface water sources within Adudu-Abuni mine province.

In terms of groundwater, apart from groundwater sources in location LC22, LC28, LC30 and LC31 that are safe for drinking, others from LC23, LC24, LC25, LC26, LC27 and LC29 predisposes one to high risk of developing cancer over a life time. Therefore, the main threat to human health is the exposure of these heavy metals (Pb, Cd, As) to water sources in the communities of Adudu-Abuni prov1ince (Lee et al., 2003; Ayadiran and Dahunsi 2016; Ogundele et al., 2019; Ganiyu et al., 2021). Long-term exposure to heavy metals through drinking water can cause both acute and chronic toxicity, potentially damaging vital organs such as the kidneys, brain, lungs, and liver. (Obasi et al 2020; Engwa et al. 2019; Lisdsky and Schneider 2003). The work of demonstrated that that long term exposure of arsenic to leas to cardiovascular disorder, organ failures, hypertension and neuropathy (Li and Zhang, 2010; Phung et al., 2017; Tong et al., 2021).

Table 6: Calculated Incremental Lifetime Cancer Risks (ILCR) of PTEs for ingestion and dermal absorption of water in the study area

Water source	Sample ID	Pb		Cd		Cr		∑ILCR
		Ingestion	*Dermal*	*Ingestion*	*Dermal*	*Ingestion*	*Dermal*	
Surface water	LC1	5.29E-05	1.89E-05	1.14E-02	4.07E-03	1.73E-04	9.45E-05	1.58E-02
	LC2	4.65E-05	1.66E-05	3.47E-03	1.24E-03	1.58E-04	8.62E-05	5.01E-03
	LC3	2.04E-05	7.30E-06	6.93E-03	2.48E-03	9.00E-04	4.91E-04	1.08E-02
	LC4	1.44E-05	5.17E-06	1.02E-02	3.65E-03	6.17E-04	3.36E-04	1.48E-02
	LC5	2.14E-05	7.64E-06	4.95E-03	1.77E-03	8.11E-04	4.42E-04	8.00E-03
	LC6	1.55E-05	5.55E-06	2.48E-03	8.85E-04	7.73E-04	4.22E-04	4.58E-03
	LC7	1.17E-05	4.19E-06	1.49E-03	5.31E-04	6.76E-04	3.69E-04	3.08E-03
	LC8	1.46E-05	5.21E-06	4.95E-03	1.77E-03	6.35E-04	3.46E-04	7.72E-03
	LC9	1.48E-05	5.28E-06	1.49E-03	5.31E-04	3.94E-04	2.15E-04	2.64E-03
	LC10	5.67E-05	2.03E-05	1.19E-02	4.25E-03	2.52E-04	1.38E-04	1.66E-02
	LC11	1.57E-05	5.63E-06	0.00E+00	0.00E+00	4.05E-04	2.21E-04	6.47E-04
	LC12	9.45E-06	3.38E-06	2.48E-03	8.85E-04	4.24E-04	2.31E-04	4.03E-03
	LC13	2.13E-05	7.60E-06	4.95E-03	1.77E-03	3.23E-04	1.76E-04	7.25E-03
	LC14	6.96E-06	2.49E-06	1.98E-03	7.08E-04	3.59E-04	1.96E-04	3.25E-03
	LC15	6.68E-06	2.39E-06	3.47E-03	1.24E-03	4.49E-04	2.45E-04	5.41E-03
	LC16	1.24E-05	4.42E-06	1.98E-03	7.08E-04	4.06E-04	2.22E-04	3.33E-03
	LC17	6.96E-06	2.49E-06	1.23E-02	4.41E-03	3.53E-04	1.93E-04	1.73E-02
	LC18	2.70E-05	9.66E-06	9.90E-04	3.54E-04	3.09E-04	1.69E-04	1.86E-03
	LC19	1.27E-05	4.53E-06	0.00E+00	0.00E+00	6.68E-04	3.64E-04	1.05E-03

Table 6 (Cont): Calculated Incremental Lifetime Cancer Risks (ILCR) of PTEs for ingestion and dermal absorption of water in the study area

Water source	Sample ID	Pb		Cd		Cr		∑ILCR
		Ingestion	*Dermal*	*Ingestion*	*Dermal*	*Ingestion*	*Dermal*	
	LC20	6.17E-06	2.21E-06	0.00E+00	0.00E+00	2.08E-04	1.13E-04	3.30E-04
	LC21	2.41E-05	8.63E-06	1.49E-03	5.31E-04	2.77E-04	1.51E-04	2.48E-03
Groundwater	LC22	5.27E-04	1.88E-04	7.60E-06	2.72E-06	3.96E-04	1.42E-04	1.26E-06
	LC23	3.53E-04	1.26E-04	7.47E-06	2.67E-06	9.90E-04	3.54E-04	1.83E-03
	LC24	3.40E-04	1.21E-04	3.72E-06	1.33E-06	0.00E+00	0.00E+00	4.66E-04
	LC25	3.48E-04	1.24E-04	3.30E-06	1.18E-06	2.48E-03	8.85E-04	3.84E-03
	LC26	2.11E-04	7.53E-05	3.01E-06	1.08E-06	4.46E-04	1.59E-04	8.95E-04
	LC27	2.11E-04	7.53E-05	3.41E-06	1.22E-06	0.00E+00	0.00E+00	2.91E-04
	LC28	2.54E-04	9.07E-05	2.90E-06	1.04E-06	3.47E-03	1.24E-03	5.05E-07
	LC29	3.71E-04	1.33E-04	7.26E-06	2.60E-06	4.46E-03	1.59E-03	6.56E-03
	LC30	3.56E-04	1.27E-04	6.81E-06	2.44E-06	4.95E-04	1.77E-04	1.16E-07
	LC31	1.39E-04	4.96E-05	1.14E-05	4.06E-06	9.90E-04	3.54E-04	1.55E-06

4. CONCLUSION

The assessment of trace metals and the physicochemical properties concentration in water sources across Adudu-Abuni communities' shows that the water resources are unfit for consumption, as several parameters exceeded the Nigerian Standards for drinking water quality (NSDWQ) and world health organization (WHO) permissible standards limits.

Several contamination/pollution indexes such as HMCI, HMPI and HMEI were employed to evaluate the extent of heavy metals impact to water resources in the study area. Based on these, the quality of surface and ground water were highly contaminated by Pb, Cd, As, Zn, Cr and 100% unfit/unsuitable for drinking purpose.

The human health risk assessment, which considered both non-carcinogenic and carcinogenic risks, revealed that long-term consumption of water from these sources poses significant health hazards. The population is at elevated risk of developing both cancerous and other related ailments over a lifetime due to prolonged exposure to toxic elements such as arsenic, lead, and chromium.

This study strongly recommends that residents of the affected area immediately discontinue the use of the contaminated water sources for drinking and cooking purposes. It is also imperative that the government and local authorities urgently provide alternative sources of safe water supply to the Adudu and Abuni communities.

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