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ASSESSMENT OF HEAVY METALS CONTAMINATION IN GROUNDWATER AND SUBSURFACE RESISTIVITY DISTRIBUTION IN ARTISANAL MINING COMMUNITIES: A COMPARATIVE STUDY OF ARUFU AND AKWANA, WUKARI LOCAL GOVERNMENT AREA, TARABA STATE, NIGERIA

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ABSTRACT

This study assesses heavy metal contamination in groundwater within the Arufu and Akwana mining communities of Taraba State, Nigeria. Thirty water samples from wells (6 streams and 24 boreholes) were analyzed for heavy metals using Atomic Absorption Spectrometry. Concentrations of Pb, Fe, Cu, Cd, Ni, Zn, Sb, and Mn exceeded World Health Organization (WHO) permissible limits for drinking water, with only Cr within safe levels. Mean concentrations (mg/L) were notably high for Fe (45.08–46.37), Pb (26.46–27.01), and Ni (16.18–16.82). Pollution indices—Heavy Metal Evaluation Index (HEI), Heavy Metal Pollution Index (HPI), and Degree of Contamination —were calculated, revealing severe pollution. Mean HEI was 786.4, HPI reached 5514.3 (far exceeding the critical value of 100), and mean of degree of contamination was 8553.3, all indicating high contamination levels. Vertical Electrical Sounding (VES) further mapped subsurface pollution, corroborating the influence of mining activities. The results demonstrate that groundwater in both communities is highly contaminated and poses significant health risks, including potential carcinogenic effects, due to artisanal and small-scale mining operations. This study underscores the urgent need for remediation and stricter regulatory measures to protect water resources and public health.

Keywords: Heavy Metals, Groundwater Contamination, Artisanal Mining, Pollution Indices

INTRODUCTION

Heavy metals are found everywhere in the environment; however, their concentration differs according to geologic formations. Natural processes and human anthropogenic activities further escalate the release of these toxic metals in hazardous proportions into the environment; accumulating in air, soils and food crops, and into the aquatic habitat (Sani et al., 2023). Heavy metal pollution in Nigeria environment is a concern due to their toxicological effect on human and plants. Heavy metals are natural constituents of earth crust and through natural processes such as erosion and volcanic eruption; they are transported and deposited in the environment. Significant amount of wastewater, generated from anthropogenic activities such as mining and smelting, fertilizer production, battery manufacturing, electroplating, wood preservation and agricultural activities pose a high risk to the environment, ecosystem and human health (Stephen & Mbamalu, 2020). According to Foulds *et al*., (2014) there is an evidence of mining activities being responsible for heavy metal contamination of both land and water (either surface or groundwater). Also, as captured by Kyowe *et al*., (2024), heavy metals are naturally occurring substances known for their toxicity even at low concentrations, are introduced into various environmental compartments through anthropogenic activities such as mining, agriculture, and manufacturing industries

Artisanal mining (also called *small scale mining*) has been on the rise as an imperative means of basic livelihood activity for some poor populations in Nigeria, residing in areas with natural resources. The sector now functions as an important social safety net and in some cases, the sector provides the only source of income in employment constrained economies, helping many poor families survive during increasingly uncertain times. While these artisanal or small scale mining activities provide jobs, they are also linked to the release of heavy metals into the mainstream environment causing environmental pollution (Awuchi et al., 2024). In artisanal mining, the interaction between money and work in the agricultural has enabled the development of residential buildings, the growth of farming operations, the enhancement of living conditions, and the establishment of entrepreneurial endeavors. Nevertheless, it is crucial to acknowledge that the close proximity of mining operations to agricultural lands has sparked apprehension regarding the adverse impact on soil fertility and water resources, thereby presenting potential risks to food security (Fagariba et al., 2024).

Indeed, heavy metals present in rocks, soils, sediments, water bodies, plants, and vegetables can, under specific environmental conditions, reach hazardous levels. Heavy metal pollution stemming from artisanal mining and the resulting mill wastes infiltrates the natural environment (Akpanowo et al., 2025). According to Mitra *et al*., (2022), Cadmium is released into the atmosphere as a result of natural or manmade activities and animals and humans can be exposed to it differently. Mercury is an extremely hazardous heavy metal that may be found in biosphere. Due to human activities, it has also become a widespread contaminant and is increasing in the atmosphere. Mercury converts to the highly toxic methylmercury when in contact with aquatic sediments. Lead is a non-biodegradable metal that is available in nature and found in relatively low amounts. Atmospheric lead levels are increasing continuously because of the human activities including manufacturing, mining, and fossil fuel burning. Lead is toxic to the human body when exposed to amounts greater than the optimum. Manganese, the most plentiful of the toxic heavy metals, is found in various oxidation states in nature. Cobalt is found in abundance across the environment, such as vegetation, soils, rocks, and water and is utilized to make alloys. Although its rate of discharge is low, it is highly dangerous to humans. These effects follow other heavy metals such Nickel, Copper, Zinc etc.

In Arufu and Akwana mining communities, Pb-Zn mining has led to contamination of water sources, posing risks such as neurotoxicity and renal dysfunction (WHO, 2021). While studies like Aloh *et al*., (2017), Senouci, (2020) and Tella & Danjibo, (2024) have examined mining impacts in Nigeria on human and environment, integrated assessments combining water quality, HEI and resistivity are very scarce. This study quantifies heavy metals in groundwater sources and evaluates health risk using HEI, maps subsurface contamination through VES with Schlumberger array and compares contamination patterns between Arufu high mining activity and Akwana moderate ming activity.

MATERIALS AND METHODS

Study Area

The geology and geological history of Taraba State is rather complex. Taraba State is underlain by Basement Complex and sedimentary rocks, each occupying a very distinctive part of the state. The Basement Complex rocks occupy the greatest part of the state (above 80%), while the sedimentary rocks are found along the valleys of River Benue and its major tributaries such as Rivers Donga and Taraba. The Basement Complex rocks are Pre-Cambrian while the Sedimentary rocks date back from Albian to recent. The undifferentiated Basement Complex rocks comprising of gneisses, migmatites, phyllites, schists and pegmatites cover a greater part of the Basement Complex area. The undifferentiated Basement Complex rocks, particularly the migmatites, generally vary from coarsely mixed gneisses to diffused textured rocks of variable grain size and are frequently porphyroblast. This rock unit constitutes principally the undifferentiated igneous and metamorphic rocks of Precambrian age (Oruonye & Ahmed, 2018).

The study areas, Arufu and Akwana (figure 1) are district in Wukari Local Government area of Taraba state, north eastern Nigeria (Yebpella et al., 2020). According to Bute *et al*., (2024) Arufu and Akwana Pb-Zn-F mineralized veins in the central Benue Trough is hosted by carbonate sequence and the Azara barites hosted in the arkosic sandstone, which are all part of the Asu River Group. The Asu River Group is Albian in age and rest unconformably on the Precambrian basement. Akwana situated between longitudes 09^{o}13'30'E and 09^{o}17'00'E and latitudes 07^{o}55'00'N and 07^{o} 57'30'N covering about 37.2 Km^{2}. It is 14 km south of Awe and about 10 km northwest of Arufu bordering Benue and Taraba States and River Benue striking the southern portion. It is also accessible through Awe Road Nasarawa State.

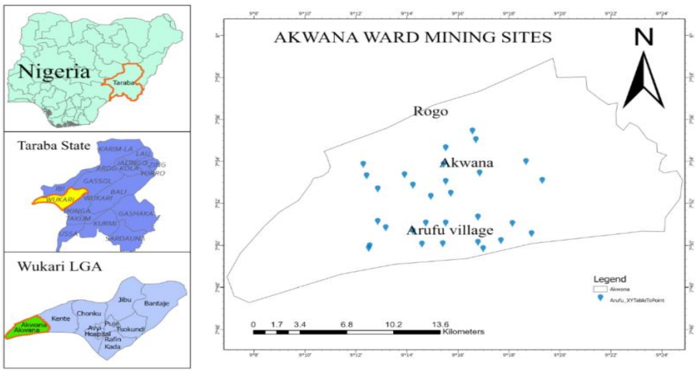

Figure 1: The Study Area of Akwana and Arufu, Wukari LGA

The climates of Arufu and Akwana are characterized by two distinct seasons (Rainy/wet and dry seasons) with a relatively brief period of harmattan compared to other parts of the state. The seasons are influenced by two local air masses; the northeast trade wind otherwise called the tropical continental air mass and southwest trade wind otherwise known as the tropical maritime air masses. The northeast trade wind is usually dry and desiccated, originating from the northeastern part of the country bringing along dusts from the Sahara Desert resulting to harmattan dust. The advent of the northeast trade wind signifies the end of rainy season and the beginning of dry season. Rainy season in the study area begins from late March and last till early November which accelerates dominant leaching (Asa et al., 2024).

Water Sampling and Analysis

Sampling

30 water samples (15 per community) from wells, streams and boreholes were taken from locations inhabited by people or as their source of water for domestic and drinking purposes. The sampling points for each water source were identified using their geographical references that were taken with a global positioning system (Garmin GPS 12 Model, UK). Sampling and preservation of samples were carried out as prescribed by APHA methods. The samples were taken in pre-cleaned 1 litre polyethene plastic kegs with dilute HN0$_{3}$ added. Each sample was labeled accurately and kept at room temperature to avoid reaction from sun rays and transported to the laboratory where they were further preserved in a refrigerator before analyses.

Sample Analysis

In the analysis of the concentration of heavy metal in each water sample, each sample was passed through a process called digestion, where the metal concentration form is separated from as many sources of interference as possible. Water sample of 100cm^{3} of the representative water sample was transferred into a beaker and 5cm^{3} of concentrated HNO$_{3}$ were added. The beaker containing the content was placed on a hot plate. The samples were boiled slowly and then evaporated on the hot plate to the lowest volume of 20cm^{3}. In the beaker were added 5cm^{3} of concentrated HNO^{3} after the beakers were allowed to cool. The beakers were covered with watch glass and returned to the hot plate then heating continued with the addition of HNO^{3} in the required quantity of 5 cm^{3} until the solution appeared light coloured and cleared (i.e. digestion process was completed). The beaker and watch glass walls were washed with distilled water and filtered to remove insoluble materials that could clog the atomizer. The filtrates were transferred to 100cm^{3} volumetric flasks and diluted to the mark with distilled water (the whole content is 100 cm^{3}). These solutions were then used for the analysis (i.e. obtaining the concentration of each metal)(Nasiru et al., 2021). The total detected metal concentration was determined using Atomic Absorption Spectrometer (AAS).

Heavy metal evaluation index (HEI)

The HEI presents the overall quality of water based on the heavy metals' concentration (Hamidu et al., 2021), and is expressed as Eq. (1):

$$HEI = \sum_{i=1}^{n} \frac{H_c}{H_{mac}} \quad (1)$$

Where Hc and H_{mac} are the observed amount and MAC of the *i*th parameter, respectively

Heavy Metal Pollution Index (HPI)

HPI gives the aggregate influence of an individual heavy metal on the overall quality of sampled water, the index was developed by Akan (2007), and this index is a mathematic model that is based on weighted arithmetic quality mean method (Hamidu et al., 2021). HPI is defined as a rating reflecting the composite influence of different dissolved heavy metals. Two steps are involved, the first is the development of a rating scale for the parameters and then allocation of weight (W_i); the second step is the selection of a pollution parameter which the calculated index will be based on (Dey et al., 2021). HPI model is expressed as Eq. 2

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (2)$$

Where Q_i is the sub-index of the *i*th parameter, W_i is the unit weightage of the *i*th parameter, and n is the number of parameters considered. The sub-index (Qi) of the parameter is computed by Eq. 3

$$Q_i = \sum_{i=1}^{n} \frac{\{M_i(-)I_i\}}{(S_i - I_i)} \times 100 \quad (3)$$

Where M_i is the observed number of heavy metals of the *i*th parameter, I_i is the perfection amount (the maximum favorable amount for drinking water) of the *i*th parameter, and S_i is the modulus value (the greatest allowed amount for drinking water) of the *i*th parameter. The sign (-) demonstrates the numerical difference of the two values, relinquishing the algebraic mark. The critical pollution index of HPI value for drinking water suggested by Prasad and Bose is 100 (Prasad & Bose, 2001).

Degree of Contamination (C_d)

The overall impact of heavy metals on the quality of water can also be determined based on the degree of contamination. This index method is very useful to summarize the cumulative effect of metals on the quality of water (Abadi et al., 2024). The mathematical formula used to determine the degree of contamination (C_d) is given by Eq. 4

$$C_d = \sum_{i=1}^{n} Cf_i \quad (4)$$

$$Cf_i \frac{CA_I}{CN_I} - 1 \quad (5)$$

Where:

Cf_i represents factor of contamination factor for the *i*th parameter

CA_I is the observed concentration value of the *i*th parameter

CN_I indicates the maximum allowed concentration of the *i*th parameter

Resistivity Survey

Thirty (30) vertical electrical sounding (VES) (fifteen (15) for each community) profiles were carried out in the study area using electrical survey meter (DDR-3 resistivity equipment). Terrameter being the major equipment sent direct current into the sub-surface through a pair of electrodes i.e. current electrodes (A and B) and the resulting potential difference generated is measured by another pair of electrodes called the potential electrodes (M and N). The generalized measured apparent resistivity is given by Eq. 6

$$\rho = GR \quad (6)$$

Where G is the geometric factor which depends upon the particular electrode array system used, R is the measured resistance, ohm's law, $R = \frac{v}{l}$.

For the Schlumberger Array employed in this study, AB > 5MN and the measured apparent resistivity is given by Eq. 7

$$\rho_{sa} \approx \frac{\pi R \left(\frac{AB}{2}\right)^2}{MN} \quad (7)$$

Where, $\frac{\pi R \left(\frac{AB}{2}\right)^2}{MN}$ is the geometric factor?

The apparent resistivity computed using equation 7 was plotted against the half current electrode spacing (AB/2) using the log-log graph and the curves were smoothened to expel the effects of lateral heterogeneities and noisy signature where necessary. The current electrode spacing (AB/2) was 1-150m and the potential electrode spacing (MN/2) was 0.5-15m. these geoelectric parameters were used as initial model parameters for a 2-D computer aided forward interpretation involving RES2DINV inversion software (RMS error <5%).

RESULTS AND DISCUSSION

Heavy Metal Concentrations

The heavy metal concentration and the minimum, maximum and mean concentrations in the groundwater samples obtained from the study area i.e. from the public well, boreholes and streams of both Arufu and Akwana mining sites/communities were determined.

Table 1 contains the result of the ten (10) heavy metals assessed from fifteen (15) points at Akwana mining site. The table contains the concentration of each heavy at each point of the fifteen (15) points, it contains the minimum of 9.9 mg/L, the maximum of 68.24 mg/L and the mean of 27.01 mg/L for Pb. The table contains also contains the minimum, maximum and mean value concentrations of Co, Fe, Cr, Mn, Ni, Cu, Cd, Zn And Sb respectively.

Table 1: Heavy Metal Concentration (Mg/L) For Water Samples in Akwana Mining Site/Community

Sample ID	Pb	Co	Fe	Cr	Mn	Ni	Cu	Cd	Zn	Sb
Ak1	68.24	0.91	23.15	0.05	2.01	18.32	6.62	0.42	13.75	1.21
Ak2	35.12	0.62	20.13	0.04	1.32	9.2	13.1	0.19	18.12	1.62
Ak3	10.2	0.2	50.02	0.035	1.42	11.21	3.45	0.71	4.1	1.95
Ak4	29.64	0.72	58.52	0.07	1.95	11.09	7.02	0.57	4.9	2.21
Ak5	17.34	1.32	60.83	0.03	2.84	15.92	8.94	0.48	5.72	2.42
Ak6	21.63	0.59	83.32	0.02	3.05	16.93	5.76	0.61	3.88	2.58
Ak7	13.74	2.01	37.42	0.03	1.32	13.91	13.98	0.39	1.79	1.88
Ak8	17.73	1.31	11.13	0.04	1.71	18.81	4.04	0.68	1.85	5.42
Ak9	13.62	0.95	43.12	0.05	1.95	17.93	3.93	0.37	2.01	2.81
Ak10	14.73	0.65	40.22	0.04	3.52	26.82	8.56	1.68	3.59	5.01

Sample ID	Pb	Co	Fe	Cr	Mn	Ni	Cu	Cd	Zn	Sb
Ak11	9.9	0.43	59.42	0.05	1.72	17.73	1.94	0.41	5.92	1.03
Ak12	19.42	0.38	62.14	0.03	3.21	24.9	7.23	0.25	3.21	3.53
Ak13	38.21	0.35	68.89	0.04	2.2	9.11	3.43	0.31	3.98	2.71
Ak14	47.52	1.11	43.12	0.045	3.11	21.83	6.98	0.71	25.8	1.99
Ak15	30.12	0.54	34.23	0.06	1.24	18.62	4.31	0.2	6.31	1.86
Min	9.9	0.2	11.13	0.02	1.24	9.11	1.94	0.19	1.79	1.03
Max	68.24	2.01	83.32	0.07	3.52	26.82	13.98	1.68	25.8	5.42
Mean	27.01	0.806	46.37	0.042	2.17	16.82	6.619	0.53	6.995	2.548

In addition, table 2 depicts also the result of the groundwater contaminants of heavy metals from Arufu mining site which was analyzed from fifteen (15) points of groundwater source. The heavy metals are Pb with minimum value of 5.22, maximum value of 73.44 and mean value of 26.46. Others are Co and Fe with minimum values of 0.18 and 10.91, maximum values of 1.97 and 81.29 and mean values of 0.767 and 45.08 respectively. Table 2 also contains such result for Cr, Mn, Ni, Cu, Cd, Zn and Sb respectively.

Table 2: Heavy Metal Concentration (Mg/L) For Water Samples in Arufu Mining Site/Community

Sample ID	Pb	Co	Fe	Cr	Mn	Ni	Cu	Cd	Zn	Sb
Ar1	73.44	0.81	24.11	0.05	1.77	17.69	6.43	0.39	13.67	1.13
Ar2	45.17	0.58	20.32	0.03	1.21	6.5	12.2	0.16	17.07	1.55
Ar3	5.22	0.18	44.92	0.03	1.44	10.17	3.39	0.65	3.39	1.86
Ar4	31.26	0.65	59.85	0.06	1.93	11.05	6.45	0.53	4.6	2.21
Ar5	15.75	1.27	58.21	0.03	2.79	15.95	8.77	0.46	5.58	2.31
Ar6	16.97	0.63	81.29	0.01	3.02	17.01	5.67	0.5	3.78	2.46
Ar7	13.44	1.97	38.33	0.02	1.22	13.94	13.94	0.31	1.74	1.74
Ar8	16.54	1.25	10.91	0.02	1.69	18.85	3.97	0.64	1.98	5.36
Ar9	12.93	0.97	41.91	0.04	1.91	18.1	3.81	0.31	1.91	2.76
Ar10	15.48	0.65	35.84	0.03	3.23	25.99	8.07	2.05	3.58	4.84
Ar11	6.3	0.36	59.37	0.04	1.67	17.63	1.86	0.39	5.57	0.93
Ar12	18.3	0.3	56.32	0.02	3.16	24.7	6.92	0.2	2.96	3.46
Ar13	45.84	0.35	68.72	0.02	2.05	7.11	3.16	0.25	3.95	2.69
Ar14	52.26	1.03	42.83	0.03	3.01	20.92	6.97	0.68	24.9	1.89
Ar15	28.01	0.51	33.39	0.06	1.2	17.12	4.28	0.19	6.01	1.8
Min	5.22	0.18	10.91	0.01	1.2	6.5	1.86	0.16	1.74	0.93
Max	73.44	1.97	81.29	0.06	3.23	25.99	13.94	2.05	24.9	5.36
Mean	26.46	0.767	45.08	0.032	2.08	16.18	6.39	0.51	6.71	2.46

The mean concentrations of Pb, Cu, Cd, Co, Cr, Mn, Zn, Sb, Fe and Ni of Arufu mining sites/community was 26.46, 6.39, 0.51, 0.767, 0.032, 2.08, 6.71, 2.46, 45.08 and 16.18 while for Akwana mining site/community was 27.01, 6.619, 0.53, 0.806, 0.042, 2.17, 6.995, 2.548, 46.37, 16.82 as shown in Table 3 respectively, which contain 30 groundwater sampling points. According to the WHO guideline for drinking water, the highest permissible concentrations for Pb, Cu, Cd, Cr, Mn, Zn, Sb, and Ni are 0.01, 2.0, 0.03, 0.05, 0.04, 3.0, 0.02 and 0.07 mg/L, respectively. For Co and Fe, a permissible limit has not been established and there is no health concern at levels found in drinking water for them.

Table 3: The Comparative Computation Of The Heavy Metal Concentration Of Both Akwana And Arufu Mining Sites/Communities In Relation To The WHO Recommended Concentration For Drinking Water (Mg/L)

Metal	Arufu (mg/L)	Akwana (mg/L)	WHO (mg/L)
Pb	26.46	27.01	0.01
Cu	6.39	6.619	2.0
Cd	0.51	0.53	0.03
Co	0.767	0.806	No guideline
Cr	0.032	0.042	0.05
Mn	2.08	2.17	0.04
Zn	6.71	6.995	3.0
Sb	2.46	2.548	0.02
Fe	45.08	46.37	No guideline
Ni	16.18	16.82	0.07

The concentrations of all studied heavy metals except Cr, in the groundwater exceed he permissible levels for drinking water, therefore, all the sampled water is not suitable for drinking (WHO, 2021).

In a similar study Nasiru et al, 2021, the concentration of Pb, Cd, Cr, Zn and Fe in well and borehole water samples of Tudun Murtala, Nasarawa state local government of Kano State was investigated. They reported that concentrations of

HMs both from the wells and boreholes were higher than the WHO recommended permissible values for drinking water (Nasiru et al., 2021). In another study carried out around Kashere and its environs, upper Benue Trough, Northeastern Nigeria by Yusuf et al, 2018, the analysis of the groundwater on HMs showed that Pb, Cu, Cr, Cd and Ni with concentrations of 1.85, 0.17, 0.08, 0.08, 0.88 are higher than the WHO recommended permissible levels, respectively (Yusuf et al., 2018).

Pollution Indices

The groundwater samples was evaluated for quality by measuring the concentration of the heavy metals (Lorestani et al., 2020). The results of pollution indices which HEI, HPI and C_d for both Arufu and Akwana are shown in figures 3-8. The calculated results of HEI, HPI and C_d for one sample demonstration is given in Tables 4-6.

The HPI values ranged between 20 and 33,333 (capped at 100) with a mean value of 5,514, which exceeds the critical index value of 100. Under any circumstances, the critical impurity index value over the overall pollution level should not be exceeded. This is not the case in this study as the HPI value was more than 100, which indicates that the sources of water in the study area which is groundwater is contaminated with metals due to the mining activities near the study area (Prasad & Bose, 2001).

Table 4: An Example of the HEI Calculation Results for One Groundwater Samples

Heavy metals	H_c (mg/L)	H_{mac} (mg/L)	H_c/H_{mac}
Pb	73.44	0.01	7344
Co	0.81	0.05	16.2
Fe	24.11	0.3	80.37
Cr	0.05	0.05	1
Mn	1.77	0.1	17.7
Ni	17.69	0.07	252.71
Cu	6.43	2.0	3.22
Cd	0.39	0.03	130
Zn	13.67	5.0	2.73
Sb	1.13	0.02	56.5
HEI			Σ =7864.43

Table 5: An Example of HPI Calculation Results for One Groundwater Samples

Heavy metals	M_i(mg/L)	S_i(mg/L)	I_i(mg/L)	W_i	Q_i	$W_i \times Q_i$ (capped)
Pb	73.44	0.01	0.001	100	100	10000
Co	0.81	0.05	0.001	20	100	2000
Fe	24.11	0.3	0.05	3.33	100	333
Cr	0.05	0.05	0.005	20	100	2000
Mn	1.77	0.1	0.01	10	100	1000
Ni	17.69	0.07	0.005	14.29	100	1429
Cu	6.43	2.0	0.01	0.5	100	50
Cd	0.39	0.03	0.0001	333.33	100	33333
Zn	13.67	5.0	0.05	0.2	100	20
Sb	1.13	0.02	0.0005	50	100	5000
				541.65		HPI=55145

Table 6 presents a quantitative analysis of heavy metal contamination in a water sample by comparing measured concentrations (Mi) against established regulatory limits (Ii). The key metric is the Contamination Factor (Ci = Mi/Ii), which calculates the degree of contamination for each metal. The results are alarming: Lead (Pb) and Cadmium (Cd) show extreme severity, with Ci values in the thousands. Most other metals, including Nickel, Cobalt, and Antimony, rank as "Very high." The cumulative Contamination Degree (Cd) of 85,533 signifies an exceptionally severe level of overall pollution, indicating a critical environmental and potential public health concern requiring immediate attention.

Table 6: An Example of the Result of Calculation for Degree of Contamination (C_d) Of Groundwater Samples

Heavy metals	M_i (mg/L)	I_i (mg/L)	$C_i = M_i/I_i$	Exceedance severity
Pb	73.44	0.001	73440	Extreme
Co	0.81	0.001	810	Very high
Fe	24.11	0.05	482	Very high
Cr	0.05	0.005	10	Low
Mn	1.77	0.01	177	High
Ni	17.69	0.005	3538	Very high
Cu	6.43	0.01	643	Very high
Cd	0.39	0.0001	3900	Extreme
Zn	13.67	0.05	273	High
Sb	1.13	0.0005	2260	Very high
			C_d = 85533	

Figure 2 plots the Heavy metal Evaluation Index (HEI) against various sample locations in Akwana community. It visualizes how the level of heavy metal contamination changes across different geographical points within the area.

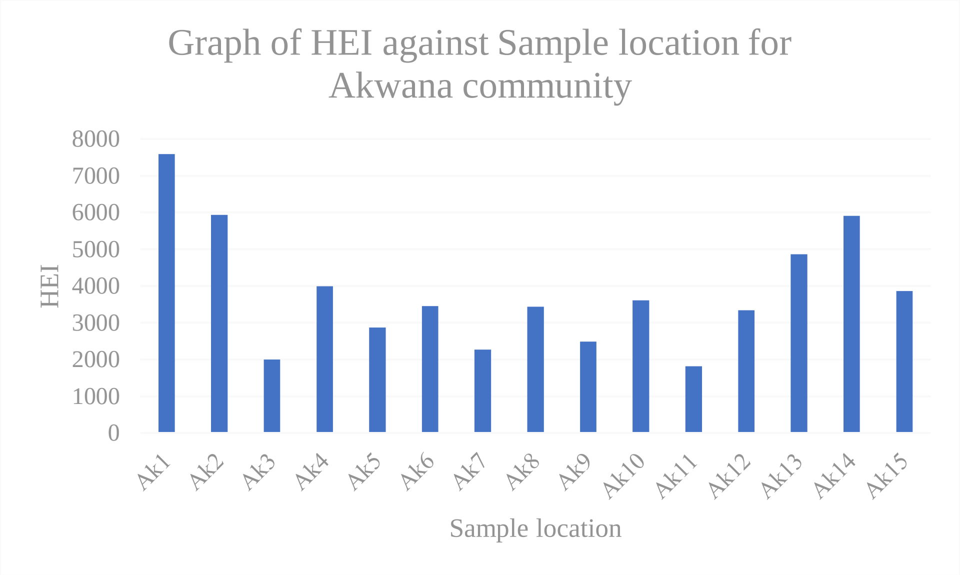

Figure 2: The HEI Values for the Studied Groundwater Samples in Akwana

Figure 3 displays the Heavy Metal Pollution Index (HPI) for different sampling locations within the Akwana community. It illustrates variations in pollution levels across the area, helping to identify specific sites with higher contamination risks for targeted action.

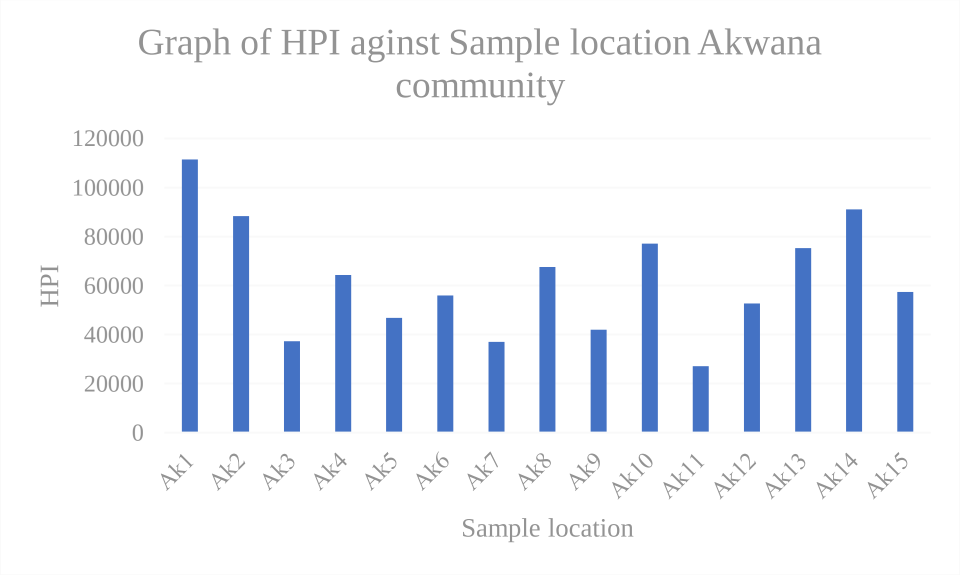

Figure 3: The HPI Values for the Studied Groundwater Samples in Akwana

Figure 4 plots the Contamination Degree (CD) across various sample locations in the Akwana community. It visually identifies pollution hotspots by showing how the cumulative level of heavy metal contamination varies from one sampling site to another within the area.

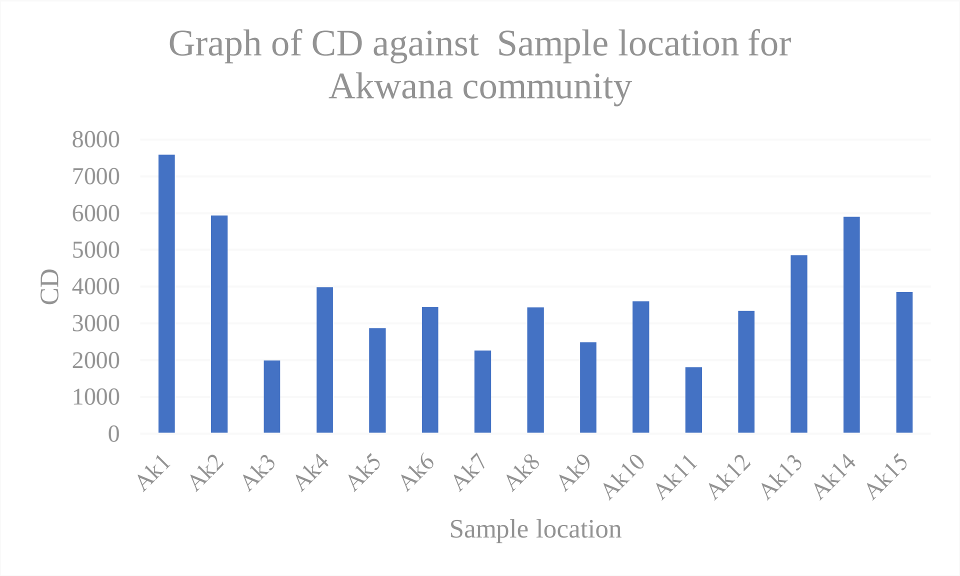

Figure 4: The C_d Values for the Studied Groundwater Samples in Akwana

Figure 5 shows the Heavy metal Evaluation Index (HEI) values at 15 different sample locations (Ar1-Ar15) in Arufu community. It tracks the spatial variation of heavy metal contamination, identifying which specific areas have the highest and lowest pollution levels.

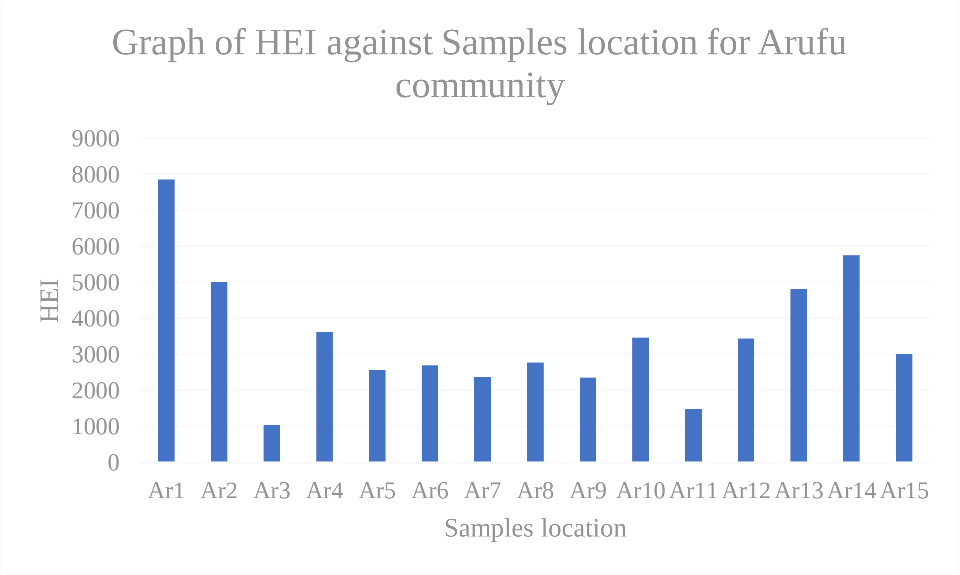

Figure 5: The HEI Values of the Studied Groundwater Samples in Arufu

Figure 6 illustrates the Heavy Metal Pollution Index (HPI) across 15 sampling points (Ar1-Ar15) in Arufu. It demonstrates the spatial variation in composite heavy metal pollution, highlighting which specific locations exceed safe thresholds and are potential contamination hotspots requiring further investigation or remediation.

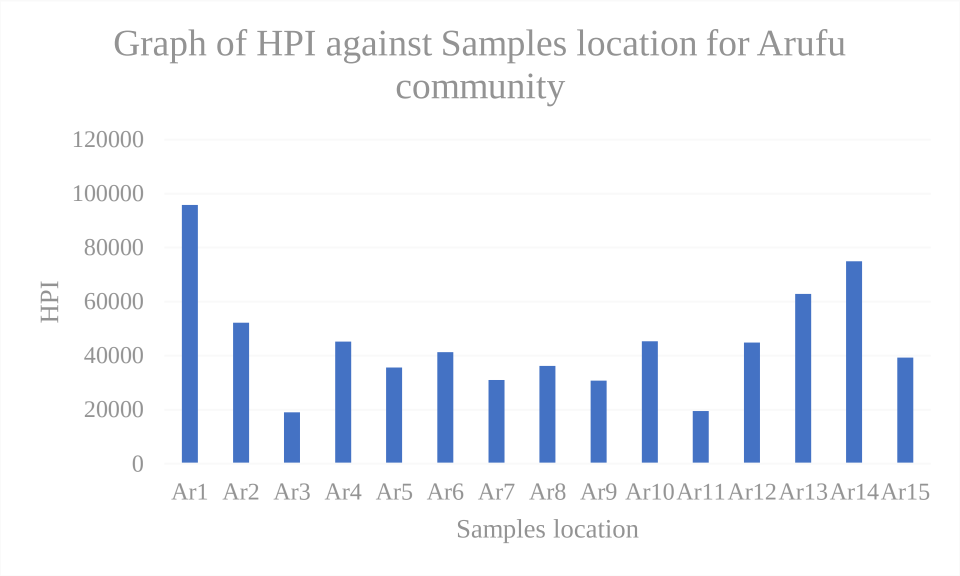

Figure 6: The HPI Values Forthe Studied Groundwater Samples in Arufu

Figure 7 presents the Contamination Degree (CD) across 15 distinct sampling locations (Ar1 to Ar15) within the Arufu community. By plotting the cumulative concentration of multiple heavy metals at each site, it effectively identifies and visualizes the specific areas with the most severe overall contamination, pinpointing critical pollution hotspots that demand prioritized environmental management and remediation efforts.

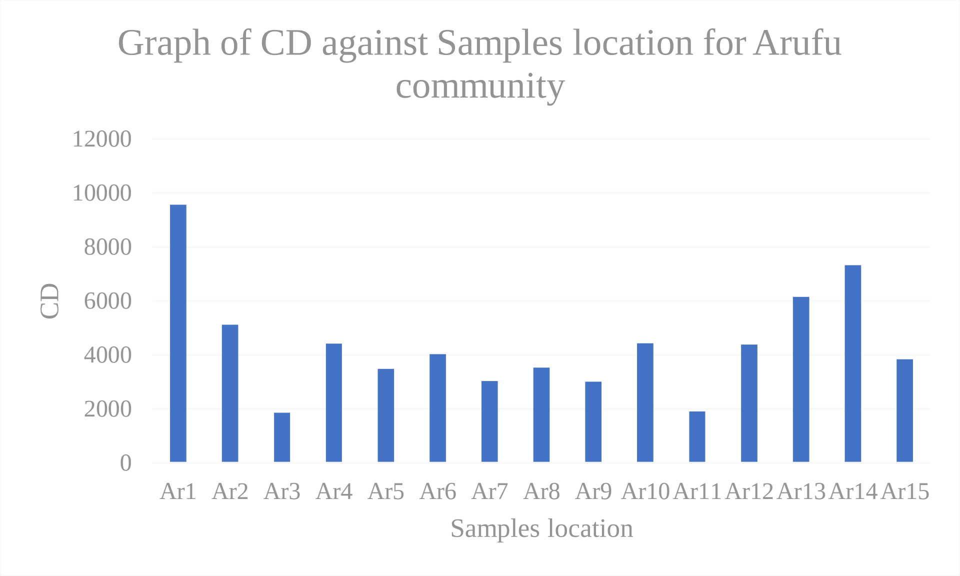

Figure 7: The C_d Values for the Studied Groundwater Samples in Arufu

The optimum pH changes according to the composition of water and the nature of the components in different water sources. WHO 2017 guidelines for drinking water stipulates that the pH ranges from 6.5 to 8.5 (WHO, 2017).

In table 3, the mean concentrations of heavy metals in the groundwater samples for both Arufu and Akwana were as follows Fe > Pb > Ni > Zn > Cu > Sb > Mn > Co > Cd > Cr and Fe > Pb > Ni > Zn > Cu > Sb > Mn > Co > Cd > Cr respectively. According to the results, the heavy metals concentrations of Pb, Ni, Zn, Cu, Sb, Mn, Cd for both communities were all above the WHO recommended permissible levels for drinking water. The concentration of Cr only was well below the WHO recommended value of drinking water. As for Fe and Co, there is no guideline by WHO for them, so there consumption has no direct on humans (WHO, 2017).

Table 7 shows reports by several researchers where the heavy metals concentration in groundwater is reported. From such studies, it can be realized that the heavy metals concentration obtained from this study are consistent.

Table 7: Heavy Metals Concentration (Mg/L) In Groundwater Samples Reported By Other Studies

Fe	Pb	Ni	Zn	Cu	Sb	Mn	Co	Cd	Cr	Reference
0.00 – 0.08	0.00-0.80		0.00-2.09			0.00-12.1	0-0.15	0.00 – 0.88		(Philip et al., 2023)
41.00	12.00	13.02	7020.84	2.95		151.59	7.51	31.99	6.49	(Zhou et al., 2024)
	0-0.379									(Siame et al., 2023)
0.15-1.49	0.09-0.44	0.07-0.90	4.05-9.56	1.06-8.17	0.01-0.07	1.22-8.46	0.01-0.09	0.01-0.05	0.02-0.19	(Adewumi & Laniyan, 2023)
1.698	0.658		3.930			0.0304		0.501		(Ganiyu et al., 2021)
0.189	16.63		9.66	6.049				0.0012		(Sanusi et al., 2017)
0.369-0.490	0.181-0.428							0.008-0.01	0.489 - 0.793	(Mshelia et al., 2025)
0.967-1.359									0.243 - 0.358	(Garba et al., 2023)
	0.05							0.04		(Olagunju et al., 2020)

The HEI values ranged from 1-7344, with the average value 786.44. The HEI in this study is to examine the potential of the impact of heavy metals on human health which led to the toa rapid assessment of the overall quality of drinking water. Increasing the concentration of heavy metals higher than the MAC leads to a decrease in water quality. The mining activities in the study area causes the higher value of HEI by washing the mine waste from the topsoil soil into the aquifer. As seen from the study, the HEI values are divided into three classes: low contamination (HEI < 400), medium contamination (HEI = 400-800) and high contamination (HEI > 800) (Roshinebegam et al., 2015). HEI for Arufu and Akwana ranged from 1-7344 with mean of 786.44, denotes a fall into high contamination zone.

The HPI for Arufu and Akwana were calculated separately for each sampling location to compare the pollution load and assess the water quality of the selected locations (Table 5). The highest value of HPI 10,000 (capped at 100) was found in downstream Arufu at location Ar1.In all the HPI could be said to have exceeded the critical metal pollution index of 100, which was suggested for drinking water by Lorestani *et al*., (2020) knowing potentially hazardous effects on the aquatic environment. The HPI values in the studied groundwater show that the samples are not suitable for drinking.

The computed values for C_d provide insight into the level of contamination by their heavy metals. According to the degree of contamination classification scheme presented in Edet & Offiong, (2002), C_d can be grouped into three categories as follows: low (<10), medium (10-20) and high (>20) (Kana, 2022). For the study area, the C_d values in the groundwater samples ranged from 10-73440 with a mean value of 855.3. Only one sample has a 10 with the remaining all have above 20. Based on the classification, all the samples from the study area were within the high classification zone. The C_d indices indicate that the samples were heavily polluted.

CONCLUSION

The study results from the study area showed that all the heavy metals analyzed in all except Cr were higher than the permissible limits for drinking water, according to the WHO drinking water guideline. Among the heavy metals verified in this study, the sequence of the mean concentration of heavy metals was recorded in this sequence Fe > Pb > Ni > Zn > Cu > Sb > Mn > Co > Cd > Cr, considering the C_d index. In this study, the HPI of the groundwater samples was 855.43, which is higher than the critical index value of 100, indicating that the groundwater in the studied areas i.e. Arufu and Akwana is contaminated with heavy metals concentration which is not good for consumption. Similarly, the mean HEI value of the groundwater was 786.4 while that of the C_d had the mean value of 5514.3. Both of these indices evaluation indicates that there is cancer risk for residents through daily and long-term consumption of the groundwater of the study area. It could be concluded that the present result clearly illustrated the contamination of groundwater with heavy metals was mainly due to the mining activities in these areas.

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