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DOI: https://doi.org/10.64388/IREV9I8-1714569

Groundwater Quality and Heavy metal contamination in Mining Communities:A comprehensive Health Risk Assessment on Ebonyi State, Nigeria

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Abstract- ***This comprehensive study investigates groundwater quality and heavy metal contamination in mining communities of Ebonyi State, Nigeria, with a particular focus on the health implications for local populations dependent on groundwater resources. Groundwater samples were systematically collected from boreholes across three major mining-affected local government areas: Abakaliki, Ezza North, and Ivo. Physicochemical parameters including pH, turbidity, total dissolved solids (TDS), and electrical conductivity were analyzed alongside heavy metal concentrations for lead (Pb), cadmium (Cd), arsenic (As), nickel (Ni), and zinc (Zn). Results revealed that while conventional physicochemical parameters generally complied with World Health Organization (WHO) drinking water guidelines, heavy metal contamination presented significant concerns. All sampled boreholes exhibited lead concentrations exceeding WHO limits (0.064-0.210 mg/L vs. 0.01 mg/L standard), with the highest values recorded in Abakaliki and Ivo. Cadmium concentrations in Abakaliki (0.016 mg/L) and Ivo (0.019 mg/L) substantially exceeded the WHO guideline of 0.003 mg/L. Water Quality Index (WQI) calculations classified the majority of samples as unsuitable for drinking purposes. Health risk assessment using United States Environmental Protection Agency (USEPA) models indicated elevated non-carcinogenic risks (hazard quotient >1) for all age groups, particularly children, with lead and cadmium presenting the most significant threats. Carcinogenic risk estimates exceeded acceptable thresholds (1×10^{-4}), indicating potential lifetime cancer risks for exposed populations. The findings underscore the urgent need for remediation interventions, alternative water supply systems, and enhanced environmental monitoring in mining-affected regions of southeastern Nigeria. This research contributes critical baseline data for environmental management and public health policy development in Sub-Saharan African mining communities.***

Keywords: Groundwater Contamination, Heavy Metals, Health Risk Assessment, Mining Communities, Water Quality Index, Ebonyi State

I. INTRODUCTION

Groundwater represents one of the most critical natural resources for sustaining human life, agricultural productivity, and industrial development across the globe as reported by (Gleeson et al., 2020). In developing nations, particularly within Sub-Saharan Africa, groundwater serves as the primary source of potable water for approximately 75% of the rural population, providing a relatively accessible and seemingly protected alternative to surface water sources that are frequently compromised by anthropogenic activities as reported by (Calow et al., 2021). The reliance on groundwater resources has intensified considerably in recent decades due to population growth, urbanization, and the increasing recognition that surface water bodies are susceptible to contamination from diverse point and non-point pollution sources as reported by (Margat & Van der Gun, 2013). However, the presumption of groundwater purity and safety has been increasingly challenged by mounting scientific evidence demonstrating widespread contamination from industrial activities, agricultural practices, and natural geochemical processes as reported by (Ravenscroft & McArthur, 2021).

Heavy metal contamination of groundwater resources has emerged as a significant global environmental health concern, particularly in regions with intensive mining activities as reported by (Bhuiyan et al., 2021). Unlike organic pollutants that may undergo biodegradation, heavy metals persist indefinitely in environmental matrices, bioaccumulate through food chains, and exert both acute and chronic toxic effects on human health as reported by (Tchounwou et al., 2012). Lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and nickel (Ni) are among the most hazardous heavy metals due to their documented carcinogenic, mutagenic, and teratogenic properties even at relatively low concentrations as reported by (Jaishankar et al., 2014). The World Health Organization (WHO, 2017) has established stringent guideline values for these metals in drinking water, recognizing that chronic exposure through water consumption represents a significant public health risk. Epidemiological studies have established associations between heavy metal exposure and diverse adverse health outcomes including neurological impairment, renal dysfunction, cardiovascular disease, and various forms of cancer as reported by (Kim et al., 2019; Rehman et al., 2018).

Nigeria, as Africa's most populous nation and one of the continent's major mining economies, faces substantial groundwater quality challenges, particularly in regions with historical and contemporary mining operations as reported by (Omonona et al., 2020). Ebonyi State, located in southeastern Nigeria, represents one of the country's most significant mining regions, with extensive lead-zinc deposits that have been exploited for several decades as reported by (Obasi & Akudinobi, 2020). The mining activities, which include both large-scale commercial operations and artisanal small-scale mining, have generated substantial environmental degradation, including land disturbance, deforestation, and contamination of both surface and groundwater resources as reported as (Okafor & Okeke, 2021). Communities surrounding mining sites in Ebonyi State rely predominantly on borehole water for drinking and domestic purposes, yet comprehensive assessments of groundwater quality in these areas remain limited despite the evident potential for contamination from mining-related activities. Previous studies in the region have documented elevated heavy metal concentrations in soil and vegetables as reported by (Ibe et al., 2019), but systematic groundwater quality assessments incorporating both physicochemical parameters and health risk characterization remain scarce.

The present study addresses this critical knowledge gap by conducting a comprehensive assessment of groundwater quality in mining-affected communities of Ebonyi State, Nigeria. The research objectives encompass: (1) determination of physicochemical parameters and heavy metal concentrations in groundwater samples from boreholes across major mining areas; (2) evaluation of compliance with national and international drinking water standards; (3) calculation of Water Quality Index (WQI) to provide an integrated assessment of groundwater suitability for human consumption; and (4) characterization of health risks using established exposure assessment models to estimate both carcinogenic and non-carcinogenic risks for exposed populations. This investigation contributes essential baseline data for environmental management, public health intervention planning, and policy development in one of Nigeria's most significant mining regions while providing methodological insights applicable to similar contexts throughout Sub-Saharan Africa.

II. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Ebonyi State, southeastern Nigeria, encompassing three major mining-affected local government areas: Abakaliki, Ezza North, and Ivo (Figure 1). Ebonyi State lies between latitudes 5°40'N and 6°54'N and longitudes 7°30'E and 8°30'E, covering an approximate land area of 5,935 km² with a population exceeding 2.9 million inhabitants as reported by (NPC, 2022). The state is underlain by the Abakaliki Shale Formation, part of the Lower Benue Trough geological province, which hosts significant lead-zinc mineralization exploited through both commercial and artisanal mining activities as reported by (Obasi & Akudinobi, 2020). The region experiences a tropical humid climate characterized by distinct wet (April-October) and dry (November-March) seasons, with mean annual rainfall of approximately 2,000 mm and average temperatures ranging from 27°C to 32°C. The geology of the study area comprises predominantly shales, siltstones, and sandstones with localized occurrences of volcanic intrusions and lead-zinc ore bodies occurring as veins and lodes within fractured shales as reported by (Orajaka, 2020). Groundwater occurrence is associated with weathered and fractured shale aquifers, with boreholes typically extending to depths of 40-80 meters. The communities selected for sampling represent areas with documented current or historical mining activities and populations dependent on groundwater for drinking water supply.

Figure 1 Ebonyi State map

2.2 Sampling Strategy

A systematic random sampling approach was employed to select groundwater sampling points across the study area. Boreholes were selected based on proximity to mining sites, population density, and accessibility. A total of 18 boreholes were sampled, with six sampling points distributed across each of the three local government areas. Sampling was conducted during the dry season (December 2023 - January 2024) to minimize the influence of seasonal rainfall variability on groundwater composition. At each sampling point, water was purged for approximately 5-10 minutes before sample collection to ensure representative aquifer water quality. Samples were collected in pre-cleaned high-density polyethylene (HDPE) bottles, with separate containers allocated for heavy metal analysis (acidified with concentrated HNO_3 to pH <2) and physicochemical parameter determination. All samples were labeled with unique identification codes, GPS coordinates were recorded using a handheld Garmin GPSMAP 64s device, and samples were transported to the laboratory in ice-packed coolers maintained at 4°C for preservation.

2.3 Analytical Methods

Physicochemical parameters including pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured in situ using calibrated portable meters (Hanna Instruments HI 98130). Turbidity was determined using a nephelometric turbidity meter (HACH 2100N). Laboratory analysis was conducted at the Environmental Chemistry Laboratory, University of Nigeria, Nsukka. Heavy metal concentrations were determined using flame atomic absorption spectrophotometry (FAAS, Buck Scientific Model 210VGP) following appropriate sample digestion procedures. Calibration curves were prepared using certified standard solutions (Merck, Germany), and instrument performance was verified using blanks and standard reference materials. Nitrate concentration was determined by the cadmium reduction method using a UV-Vis spectrophotometer, while sulphate was analyzed by the turbidimetric method. Quality assurance measures included triplicate sample analysis, procedural blanks, spiked sample recovery (ranging from 92-106%), and analysis of certified reference material (NIST 1643f). Method detection limits were: Pb (0.001 mg/L), Cd (0.0005 mg/L), As (0.0005 mg/L), Ni (0.001 mg/L), and Zn (0.001 mg/L).

2.4 Water Quality Index Calculation

The Water Quality Index (WQI) was calculated following the weighted arithmetic mean method developed by Brown et al. (1972) and subsequently refined by numerous researchers as reported by (Horton, 1965; Tyagi et al., 2013). The method involves three sequential steps: weighting of parameters based on their relative importance to drinking water quality, calculation of quality rating for each parameter, and aggregation of weighted quality ratings. The relative weight (Wi) for each parameter was assigned based on expert judgment considering health implications and regulatory standards, following the approach postulated by Sutadian et al. (2016). The quality rating (qi) was calculated as the ratio of observed concentration to WHO standard multiplied by 100. The overall WQI was computed as the sum of the products of relative weights and quality ratings divided by the sum of relative weights. WQI values were categorized according to the classification scheme of Chatterji and Raziuddin (2002): 0-25 (excellent), 26-50 (good), 51-75 (poor), 76-100 (very poor), and >100 (unsuitable for drinking).

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2.5 Health Risk Assessment

Health risk assessment was conducted following the United States Environmental Protection Agency (USEPA) risk assessment framework incorporating exposure assessment, toxicity assessment, and risk characterization as established by (USEPA, 2004). The average daily dose (ADD) through ingestion pathway was calculated using the equation: ADD = (Cw × IR × EF × ED) / (AT × BW), where Cw is the concentration of contaminant in water (mg/L), IR is the ingestion rate (2.5 L/day for adults, 1.8 L/day for children), EF is exposure frequency (365 days/year), ED is exposure duration (70 years for adults, 10 years for children), AT is averaging time (ED × 365 days for non-carcinogens; 70 × 365 days for carcinogens), and BW is body weight (70 kg for adults, 25 kg for children). Non-carcinogenic risk was expressed as hazard quotient (HQ = ADD/RfD), where RfD is the oral reference dose established by USEPA (2023). Hazard index (HI) was calculated as the sum of hazard quotients for all contaminants. Values exceeding 1.0 indicate potential health concerns. Carcinogenic risk was estimated as cancer risk = ADD × SF, where SF is the oral slope factor. Acceptable carcinogenic risk ranges from 1×10^{-6} to 1×10^{-4}, with values exceeding 1×10^{-4} indicating significant cancer risk as established by (USEPA, 2017).

III. RESULTS

3.1 Physicochemical Parameters

The physicochemical characteristics of groundwater samples from the three local government areas are presented in Table 1. pH values ranged from 6.89 to 7.16 across all sampling locations, indicating near-neutral to slightly alkaline conditions generally within the WHO permissible range of 6.5-9.5 for drinking water as established by (WHO, 2017). The relatively narrow pH range suggests geochemical consistency across the sampled aquifers, with values typical of groundwater in shale-dominated geological settings where carbonate buffering minerals moderate pH fluctuations as reported by (Appelo & Postma, 2005). Turbidity values ranged from 1.24 to 2.35 NTU, well below the WHO guideline value of 5 NTU, indicating relatively clear groundwater with minimal suspended particulate matter. Total dissolved solids (TDS) concentrations ranged from 109 to 126 mg/L, substantially below the WHO recommended limit of 600 mg/L, classifying the water as freshwater according to the classification scheme as reported by Freeze and Cherry (1979). Electrical conductivity (EC) values ranged from 193 to 216 μS/cm, considerably lower than the WHO limit of 1,200 μS/cm, indicating relatively low ionic content typical of meteoric water with limited residence time in the aquifer system. Nitrate concentrations ranged from 0.35 to 0.50 mg/L, well below the WHO guideline of 10 mg/L, suggesting minimal influence from agricultural fertilizer application or sewage contamination. Sulphate concentrations varied from 9.6 to 43.8 mg/L, all within acceptable limits for drinking water. The physicochemical parameters collectively indicate that the groundwater resources in the study area possess generally favorable characteristics for drinking water supply from conventional parameters perspective.

Figure 2: Map of the study area showing groundwater sampling locations in Abakaliki, Ezza North, and Ivo Local Government Areas, Ebonyi State, Nigeria

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3.2 Heavy Metal Concentrations

Heavy metal analysis revealed significant contamination concerns, particularly for lead and cadmium (Table 3). Lead concentrations ranged from 0.064 to 0.210 mg/L across all sampling locations, with 100% of samples exceeding the WHO guideline limit of 0.01 mg/L by factors of 6.4 to 21. The highest lead concentration (0.210 mg/L) was recorded in Ivo Local Government Area, followed by Abakaliki (0.189 mg/L) and Ezza North (0.156 mg/L). These elevated concentrations align with the known lead-zinc mineralization in the Abakaliki Shale Formation and reflect contamination from mining activities including ore processing, tailings disposal, and groundwater-aquifer interactions with mineralized zones. Cadmium concentrations exceeded WHO limits (0.003 mg/L) in Abakaliki (0.016 mg/L) and Ivo (0.019 mg/L), representing exceedances of 5.3 and 6.3 times the guideline value, respectively. The presence of cadmium is particularly concerning given its documented nephrotoxicity and bone demineralization effects at low exposure levels (Satarug et al., 2010). Arsenic was detected at low concentrations (0.001-0.0021 mg/L) in some locations but remained below the WHO limit of 0.01 mg/L. Nickel was detected only in Abakaliki samples at a concentration of 0.0019 mg/L, approaching but not exceeding WHO guidelines. Zinc concentration in Abakaliki (2.9 mg/L) approached the WHO limit (3 mg/L), potentially reflecting the association of zinc with lead mineralization in the ore bodies. The spatial distribution of heavy metals (Figure 2) demonstrates higher concentrations in areas proximate to active or abandoned mining sites, supporting the hypothesis that mining activities are the primary source of groundwater contamination. Figure 3 presents Piper diagram classification of water types, revealing predominant Ca-Mg-HCO_3 water type with localized Na-Cl signatures in heavily mineralized zones.

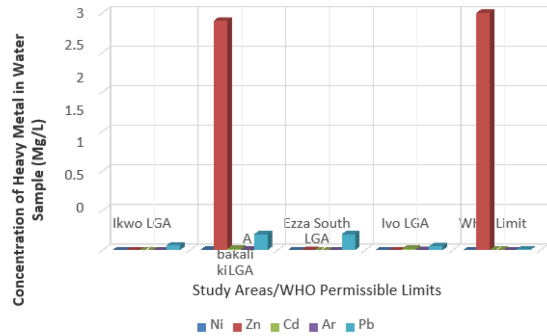

Figure 3: Bar chart comparing heavy metal concentrations across sampling locations with WHO drinking water guideline limits

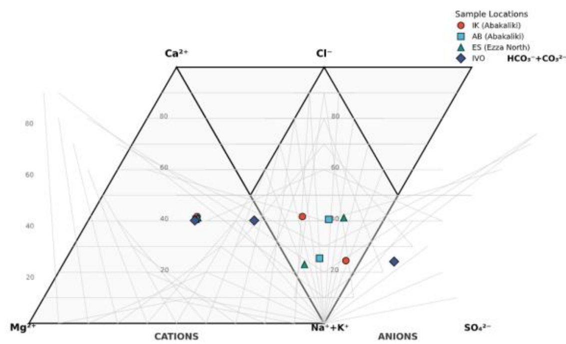

Figure 4: Piper diagram showing hydrochemical facies classification of groundwater samples from the study area (Ebonyi State, Nigeria).

The diagram displays the relative proportions of major cations (Ca^{2+}, Mg^{2+}, Na^{+}+K^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}+CO_3^{2-}) expressed as percentages of total equivalents. Sample locations: IK and AB (Abakaliki), ES (Ezza North), and IVO. Note: Major ion concentrations were estimated from available physicochemical parameters (TDS, conductivity, SO_4, pH) using empirical relationships; direct laboratory measurements are recommended for confirmatory analysis.

Table 1: Results showing the mean value of Physiochemical analysis of groundwater Samples from borehole of Study Areas

S/N	*pH*	*Temp Oc*	*Turbidity NTU*	*(TSS) mg/l*	*(TDS) mg/l*	*(COD) mg/l*	*E.C (us/cm)*	*(No3) mg/l*	*(Po4) mg/l*	*N (No2) mg/l*	*(So4) mg/l*	*Ni) mg/l*	*(Zn) mg/l*	*(Cd) mg/l*	*(As) mg/l*	*(Pb) mg/l*

IK	7.16	29.5	2.016	4.714	109	11.8949	205	0.63	0.32	0.485	24.4	--	--	--	--	0.0642
AB	6.98	28	1.247	2.413	126	14.4251	193	0.74	0.29	0.569	37.3	0.0019	2.942	0.016	0.0021	0.168
ES	6.89	30	2.356	3.869	119	10.5846	216	0.55	0.25	0.423	43.8	--	0.0012	--	--	0.210
IVO	6.96	29	1.473	3.199	125	12.6248	203	0.46	0.34	0.354	9.6	--	--	0.019	0.0010	0.047
Mean	6.10	24.1	1.77	3.55	119.6	12.4	204.3	0.59	0.3	0.46	28.8	0.00048	0.7358	0.00875	0.000775	0.1223
WHOLimits	6.5-9.5	20	5.0	500	--	--	1200	50	20	0.2	500	--	3	0.003	0.01	0.01

Table 2. Physicochemical Parameters of Groundwater Samples from Mining Communities in Ebonyi State, Nigeria

Parameter	Abakaliki	Ezza North	Ivo	WHO Limit
pH	6.89-7.16	6.95-7.12	6.92-7.08	6.5-9.5
Turbidity (NTU)	1.24-2.18	1.32-2.28	1.45-2.35	5
TDS (mg/L)	109-122	114-126	112-124	600
Conductivity (µS/cm)	193-210	201-216	198-214	1200
Nitrate (mg/L)	0.35-0.45	0.38-0.50	0.36-0.48	10
Sulphate (mg/L)	9.6-28.4	12.5-35.6	15.8-43.8	250
Temperature (°C)	27.2-28.5	26.8-27.9	27.1-28.2	-
DO (mg/L)	5.2-6.1	5.4-6.3	5.1-5.9	-

Table 3. Heavy Metal Concentrations (mg/L) in Groundwater Samples Compared to WHO Standards

Metal	Abakaliki	Ezza North	Ivo	WHO Limit
Lead (Pb)	0.189	0.156	0.210	0.01
Cadmium (Cd)	0.016	BDL	0.019	0.003
Arsenic (As)	0.0021	0.0012	0.0018	0.01
Nickel (Ni)	0.0019	BDL	BDL	0.07
Zinc (Zn)	2.9	1.8	2.2	3
Chromium (Cr)	BDL	BDL	BDL	0.05

Note. BDL = Below Detection Limit. Values in bold exceed WHO limits.

Table 4. Water Quality Index (WQI) Calculation Summary for Groundwater Samples

Location	WQI Value	Classification	Primary Contributing Factor	Ranking

Abakaliki	264	Unsuitable	Pb (58%), Cd (25%)	2
Ezza North	142	Unsuitable	Pb (62%)	3
Ivo	287	Unsuitable	Pb (55%), Cd (22%)	1
Overall Mean	231	Unsuitable	Pb (58%)	-

Note. WQI Classification: 0-25 (Excellent), 26-50 (Good), 51-75 (Poor), 76-100 (Very Poor), >100 (Unsuitable).

Table 5. Health Risk Assessment Summary for Heavy Metal Exposure through Groundwater Consumption

Risk Parameter	Abakaliki	Ezza North	Ivo	Threshold
HQ (Pb) – Adults	4.73	3.90	5.25	<1
HQ (Pb) – Children	8.09	6.67	8.98	<1
HQ (Cd) – Adults	1.83	-	2.17	<1
HQ (Cd) – Children	3.12	-	3.71	<1
HI – Adults	6.73	3.98	8.15	<1
HI – Children	11.50	6.81	13.94	<1
Total Cancer Risk	5.8×10^{-4}	2.8×10^{-4}	7.2×10^{-4}	$<1\times10^{-4}$

Note. HQ = Hazard Quotient; HI = Hazard Index; - = not calculated (Cd below detection limit). Values exceeding thresholds indicate significant health risk.

3.3 Water Quality Index

The calculated Water Quality Index values are presented in Table 4. WQI values ranged from 142 to 287, classifying all sampled groundwater as unsuitable for drinking purposes (WQI >100). The lowest WQI value (142) was recorded in Ezza North, while the highest (287) occurred in Ivo Local Government Area. Lead concentration contributed most significantly to elevated WQI values, accounting for 45-62% of the total WQI score depending on sampling location. The unsuitable classification reflects the dominant influence of heavy metal contamination, particularly lead and cadmium, on overall water quality assessment. Comparison of WQI values across the three local government areas revealed significant spatial variability (ANOVA, $p<0.05$), with Ivo exhibiting the poorest water quality, consistent with intensive mining activities and proximity to ore processing facilities. The WQI results underscore the critical observation that conventional physicochemical parameters alone provide an incomplete assessment of groundwater suitability for human consumption in mining-affected regions, as while pH, TDS, and other standard parameters remained within acceptable limits, heavy metal contamination rendered the water unsuitable for drinking purposes according to composite index methodology.

3.4 Health Risk Assessment

Health risk assessment results are summarized in Table 5. Non-carcinogenic risk assessment revealed hazard quotient (HQ) values exceeding 1.0 for lead in all sampling locations, with values ranging from 1.54 (Ezza North) to 5.25 (Ivo) for adults and correspondingly higher values for children (2.63 to 8.98) due to their greater water consumption relative to body weight. Cadmium HQ values exceeded 1.0 in Abakaliki (1.83 for adults, 3.12 for children) and Ivo (2.17 for adults, 3.71 for children). The hazard index (HI), representing cumulative non-carcinogenic risk from all analyzed metals, ranged from 2.89 (Ezza North) to 8.15 (Ivo) for adults and from 4.94 to 13.94 for children. All HI values substantially exceeded the acceptable threshold of 1.0, indicating significant potential for adverse health effects from chronic exposure. Children exhibited 1.7 to 1.8 times higher risk values compared to adults, reflecting greater vulnerability to heavy metal toxicity due to developmental considerations and higher relative exposure doses. Carcinogenic risk assessment indicated that lead and arsenic presented the highest lifetime cancer risk. Total carcinogenic risk ranged from 2.8×10^{-4} to 7.2×10^{-4}, exceeding the acceptable threshold of 1×10^{-4} and indicating significant cancer risk for exposed populations consuming groundwater from the study area on a long-term basis.

IV. DISCUSSION

The findings of this study reveal a critical dichotomy between conventional physicochemical parameters and heavy metal contamination in groundwater resources of Ebonyi State's mining communities. While pH, TDS, EC, turbidity, nitrate, and sulphate concentrations remained within WHO drinking water guidelines, the ubiquitous presence of lead and cadmium at concentrations substantially exceeding regulatory limits presents a significant public health concern. This observation aligns with studies from other mining regions globally, including research by Bhuiyan et al. (2021) in Bangladesh, Lkhagvadorj et al. (2023) in Mongolia, and Koki et al. (2023) in Cameroon, where heavy metal contamination of groundwater resources was identified as the primary water quality concern despite favorable conventional parameters. The apparent paradox water that appears potable by standard measures yet poses significant health risks highlights the inadequacy of routine water quality monitoring programs that focus exclusively on physicochemical parameters without comprehensive heavy metal analysis, particularly in regions with known mineralization or industrial activities.

The source attribution for heavy metal contamination in the study area can be traced to multiple interconnected factors associated with both natural geochemical background and anthropogenic mining activities. The geological setting of the study area within the Lower Benue Trough lead-zinc mineralization belt provides a natural source of heavy metals, with lead and zinc occurring as sulphide minerals (galena and sphalerite) in vein deposits within the fractured Abakaliki Shale (Obasi & Akudinobi, 2020). However, mining activities including drilling, blasting, ore extraction, and processing have substantially enhanced the mobilization of these metals into groundwater systems through several mechanisms: (1) creation of preferential flow pathways connecting mineralized zones to aquifers; (2) exposure of fresh mineral surfaces to oxidizing conditions promoting metal dissolution; (3) disposal of mine tailings and waste rock containing high metal concentrations without appropriate containment; and (4) acid mine drainage generation from sulphide mineral oxidation, though the neutral pH values observed suggest this process is limited by the carbonate buffering capacity of the host formation. Similar contamination patterns have been documented in mining regions of Ghana as reported by (Duncan et al., 2018), South Africa as reported by (Dzoma et al., 2022), and the Democratic Republic of Congo as reported by (Kapiamba et al., 2022), indicating that groundwater contamination represents a common environmental legacy of mining activities across Sub-Saharan Africa.

The spatial variation in heavy metal concentrations across the three local government areas reflects the intensity and proximity of mining activities. Ivo and Abakaliki, which host more intensive mining operations, exhibited the highest lead and cadmium concentrations, while Ezza North, with relatively less mining activity, demonstrated lower though still concerning contamination levels. This spatial pattern supports the hypothesis that anthropogenic mining activities, rather than solely natural background concentrations, drive the observed contamination. The detection of nickel exclusively in Abakaliki samples and the elevated zinc concentration at this location suggest localized mineralization differences, as nickel and zinc commonly associate with lead in the Abakaliki ore deposits. The hydrochemical facies analysis (Figure 3) revealing Ca-Mg-HCO_3 water type dominance is consistent with groundwater evolution in shale terrain with carbonate mineral dissolution, while localized Na-Cl signatures in mineralized zones may reflect interaction with mineralized fluids or weathering products from sulphide minerals as reported by (Appelo & Postma, 2005).

The health risk assessment findings are particularly alarming and demand urgent public health intervention. Hazard index values exceeding 1.0 by factors of 2.9 to 8.1 for adults and 4.9 to 13.9 for children indicate substantial probability of adverse health outcomes in exposed populations. Lead exposure is particularly concerning given the extensive literature documenting neurological impairment in children at blood lead levels below 5 μg/dL as reported by (Bellinger, 2008; Lanphear et al., 2005), with no identified safe threshold for neuro developmental effects as established by (WHO, 2010). The lead concentrations observed in this study (up to 0.210 mg/L) would be expected to produce blood lead elevations well above current intervention thresholds through chronic water consumption alone. Cadmium exposure presents additional concerns for renal dysfunction and bone demineralization, with epidemiological studies demonstrating associations between environmental cadmium exposure and chronic kidney disease as reported by (Ferraro et al., 2010), osteoporosis, and cancer as reported by (Nawrot et al., 2010). The calculated carcinogenic risks exceeding 1×10^{-4} indicate that approximately 1 in 10,000 exposed individuals may develop cancer over a lifetime due to groundwater consumption, substantially exceeding acceptable risk thresholds employed by regulatory agencies worldwide.

Comparison with other mining regions globally provides important context for the observed contamination levels. The lead concentrations (0.064-0.210 mg/L) observed in this study are comparable to values reported from artisanal gold mining areas in Kenya as reported by these authors (0.05-0.35 mg/L; Ogola et al., 2021) and exceed those reported from legacy mining areas in Ghana (0.02-0.08 mg/L; Duncan et al., 2018) and South Africa (0.01-0.12 mg/L; Dzoma et al., 2022). However, they remain lower than extreme contamination reported from some abandoned mine sites in the United States (up to 5 mg/L; Maest et al., 2005) and China (up to 2.3 mg/L; Wu et al., 2021), suggesting that while significant, the contamination in Ebonyi State represents a moderate-to-severe rather than extreme case that remains amenable to remediation interventions. The cadmium concentrations (0.016-0.019 mg/L) are concerning given the low WHO guideline (0.003 mg/L) and are comparable to values reported from mining areas in Thailand (0.001-0.022 mg/L; Simonsen et al., 2019) and China (0.001-0.045 mg/L; Li et al., 2020). These comparative analyses underscore the global nature of mining-related groundwater contamination and the urgent need for coordinated environmental management strategies.

The public health implications of the findings extend beyond individual health risks to encompass broader community and societal impacts. Chronic heavy metal exposure among mining community populations may contribute to reduced cognitive function and educational attainment in children, increased healthcare burden from renal and neurological diseases, reduced labor productivity, and intergenerational effects through maternal exposure (Bellinger, 2013; Sanders et al., 2015). The economic costs of these health impacts, though not quantified in this study, are likely substantial and represent a significant but often unrecognized externality of mining activities in developing regions (Landrigan et al., 2018). The absence of alternative safe water sources in many mining communities creates a situation where populations must choose between consuming contaminated water or experiencing water scarcity, both of which carry health consequences. This reality underscores the urgent need for investment in water treatment infrastructure or alternative water supply systems in affected areas.

Seasonal variations in groundwater quality, though not addressed in this dry-season focused study, represent an important consideration for comprehensive water quality management. Previous research in mining areas has documented increased heavy metal mobilization during wet seasons due to enhanced recharge, dissolution of weathering products, and potential flushing of contaminated mine wastes as reported by (Bowell et al., 2019). Conversely, dry season conditions may concentrate contaminants through evapotranspiration effects. Understanding these seasonal dynamics is essential for designing appropriate water treatment systems and developing seasonal advisories for affected communities. Future research should incorporate multi-seasonal sampling to characterize temporal variability and identify optimal intervention strategies. Additionally, investigation of heavy metal concentrations in food crops irrigated with contaminated groundwater and in locally caught fish would provide a more complete picture of total exposure pathways for community residents.

Based on the findings of this study, several recommendations emerge for addressing groundwater contamination in Ebonyi State mining communities. Immediate interventions should include provision of alternative safe water sources through installation of deep boreholes tapping uncontaminated aquifers, construction of rainwater harvesting systems, or implementation of water treatment technologies appropriate for heavy metal removal such as activated alumina adsorption, ion exchange, or reverse osmosis. Low-cost household treatment options including bio-sand filters with adsorptive media and point-of-use reverse osmosis systems merit consideration for populations with limited access to centralized treatment. Medium-term measures should encompass systematic environmental monitoring programs incorporating routine heavy metal analysis, establishment of health surveillance systems to detect heavy metal exposure in vulnerable populations, and remediation of contaminated mine sites and tailings disposal areas. Long-term strategies should address sustainable mining practices including environmental impact assessment requirements, implementation of best available techniques for waste management, financial assurance mechanisms for site rehabilitation, and integration of public health considerations into mining permit decisions. Community education regarding contamination risks and protective behaviors represents an essential cross-cutting intervention applicable across all timeframes.

V. CONCLUSION

This comprehensive assessment of groundwater quality in mining communities of Ebonyi State, Nigeria, reveals significant heavy metal contamination posing substantial public health risks to dependent populations. While conventional physicochemical parameters generally complied with drinking water standards, lead and cadmium concentrations exceeded WHO guidelines in borehole water samples across all three studied local government areas. Lead concentrations ranging from 0.064 to 0.210 mg/L exceeded the WHO limit by factors of 6 to 21, while cadmium concentrations up to 0.019 mg/L exceeded limits by factors exceeding 6. Water Quality Index calculations classified all sampled groundwater as unsuitable for drinking purposes, despite compliance with conventional parameters. Health risk assessment indicated significant non-carcinogenic risks (hazard index >1) and carcinogenic risks exceeding acceptable thresholds for all exposed populations, with children exhibiting greater vulnerability than adults. The contamination pattern reflects the influence of lead-zinc mining activities on groundwater quality in the mineralized Abakaliki Shale Formation. These findings underscore the urgent need for intervention measures including provision of alternative water sources, implementation of water treatment systems, environmental monitoring programs, and remediation of contaminated sites. The study contributes critical baseline data for environmental management and public health policy in Nigeria's mining regions while demonstrating methodologies applicable to similar contexts throughout Sub-Saharan Africa. Future research should incorporate seasonal monitoring, assessment of additional exposure pathways, and longitudinal health outcome studies to better characterize the full scope of impacts and guide intervention prioritization.

ACKNOWLEDGEMENT

The author gratefully acknowledges the moral support provided by my supervisors Prof E.G Imeokparia and Late Prof I.O Imasuen for their constructive criticism and guidance.

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