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HEALTH RISK ASSESSMENT OF HEAVY METAL CONTAMINATION IN EKULU AND NYABA RIVERS, SOUTHEAST NIGERIA

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Abstract: *Heavy metal contamination of surface waters poses serious ecological and human health concerns, particularly in mining-impacted environments. This study evaluated the concentrations, seasonal variations, sources, and health risks of heavy metals in Ekulu and Nyaba rivers, Southeast Nigeria. Both rivers drain the abandoned Onyeama and Okpara coal mines, which continue to discharge Acid Mine Drainage (AMD) into downstream communities. A total of 34 water samples were collected during wet and dry seasons from upstream, midstream, downstream, mine discharge, and control sites. Samples were analyzed for As, Cd, Co, Fe, Hg, Mn, Ni, Pb, and Se using Atomic Absorption Spectrophotometry (AAS), following APHA protocols. The results revealed that Fe, Pb, Cd, and As concentrations consistently exceeded permissible limits set by WHO, USEPA, and FEPA/NESREA standards. Seasonal variations showed higher concentrations in Ekulu River during the dry season due to reduced dilution, while Nyaba River recorded elevated levels in the wet season as rainfall enhanced leaching from abandoned mine tunnels. Correlation analysis confirmed AMD as the dominant contamination source, with additional contributions from irrigation, laundry, effluent disposal, and sand dredging. Human health risk assessment indicated Hazard Quotient (HQ) and Hazard Index (HI) values above 1 for several metals, signifying non-carcinogenic risks, while Incremental Lifetime Cancer Risk (ILCR) values for As, Cd, Ni, and Pb exceeded the acceptable threshold of 1×10^{-4}. Children were found to be more vulnerable than adults across all exposure pathways. The study concludes that*

Ekulu and Nyaba rivers are unsafe for direct domestic and agricultural use without treatment. It recommends urgent remediation of abandoned mines, continuous water quality monitoring, provision of alternative safe water supplies, stricter regulation of anthropogenic activities, and targeted public health interventions to safeguard local communities.

1. Introduction

Surface water contamination by heavy metals is one of the most pressing environmental and public health challenges worldwide. Metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and iron (Fe) are particularly concerning due to their toxicity, environmental persistence, and tendency to bioaccumulate in aquatic and terrestrial food chains (Briffa, Sinagra, & Blundell, 2020; Tchounwou, Yedjou, Patlolla, & Sutton, 2012). Unlike organic pollutants that may degrade over time, heavy metals remain stable in ecosystems, posing long-term risks to biodiversity and human health. Exposure through contaminated water has been linked to kidney and liver damage, neurological disorders, cardiovascular diseases, developmental abnormalities, and increased cancer risks (Balali-Mood, Naseri, Tahergorabi, Khazdair, & Sadeghi, 2021; Rehman, Fatima, Waheed, & Akash, 2018)

Coal-mining regions are particularly vulnerable due to Acid Mine Drainage (AMD), a phenomenon in which sulfide minerals in exposed rocks react with oxygen and water to form sulfuric acid that mobilizes metals into adjacent rivers and streams (Gallagher, 2022; Bigham & Cravotta, 2016). Globally, abandoned and poorly managed mines continue to discharge AMD, causing ecological degradation and widespread contamination of freshwater resources (Zhao et al., 2020). In sub-Saharan Africa, weak mine closure policies and inadequate monitoring exacerbate these risks, leaving many rural and urban communities reliant on unsafe surface waters (Engwa, Ferdinand, Nwalo, & Unachukwu, 2019)

In Nigeria, abandoned coal mines in Enugu State represent one of the country's most persistent legacies of environmental degradation. The Onyeama and Okpara coal mines, once central to Nigeria's energy economy, were abandoned without proper reclamation, resulting in continuous AMD discharge into the Ekulu and Nyaba rivers (Obiadi, Obiadi, Akudinobi, Mmaduweesi, & Ezim, 2016; Ozoko, 2015). These rivers provide critical water supplies for domestic consumption, small-scale irrigation, laundry, sand dredging, and artisanal activities, which further heighten their vulnerability to pollution (Ken-Onukuba et al., 2021)

Previous studies in Enugu coalfield rivers reported acidic pH values (3.4–5.9) and elevated concentrations of Fe, Pb, and Cd, consistently above WHO and USEPA guideline values (Akpan, Tse, Giadom, & Adamu, 2021). Such conditions are typical of AMD-impacted rivers and underscore serious health risks for populations that depend on these water sources (Obasi & Akudinobi, 2020). Documented effects of exposure include gastrointestinal problems, kidney and liver damage, reproductive disorders, and increased risks of cancers (Qin, Niu, Ye, Li, Ma, & Xiang, 2021)

Despite these warnings, major gaps remain. Existing Nigerian studies often provide only snapshot data rather than systematic seasonal analyses, leaving uncertainties about how wet and dry seasons influence contamination levels. Moreover, the relative contributions of geogenic AMD sources versus anthropogenic inputs such as irrigation runoff, laundry, and domestic effluents have not been consistently disentangled (Akpan et al., 2021; Obiadi et al., 2016). Finally, most studies have not quantified human health risks in terms of Hazard Quotient (HQ), Hazard Index (HI), or Incremental Lifetime Cancer Risk (ILCR), limiting their relevance for public health policy (Engwa et al., 2019)

This study therefore addresses these gaps by assessing: (i) the concentration levels of heavy metals in Ekulu and Nyaba rivers against WHO/USEPA/FEPA (NESREA) standards; (ii) the seasonal variations in contamination; (iii) the sources of heavy metals using correlation analysis; and (iv) the health risks for adults and children in dependent communities. By integrating water quality monitoring with quantitative risk assessment, this work provides evidence for sustainable water resource management and targeted public health interventions in Enugu and other AMD-affected regions of Nigeria.

Objectives of the Study

The specific objectives of this study are to:

1. Assess the concentrations and seasonal variations of selected heavy metals in Ekulu and Nyaba rivers.
2. Identify the major sources of heavy metal contamination in the rivers.
3. Evaluate the potential non-carcinogenic and carcinogenic health risks to exposed communities.

Significance of the Study

This study is important because it provides evidence of the dangers posed by heavy metal contamination in rivers draining abandoned coal mines in Enugu State. By linking water quality data with health risk assessments, it highlights the real threats faced by local populations who depend on the Ekulu and Nyaba rivers for drinking, irrigation, and domestic activities. The findings will help raise awareness among communities about the risks of prolonged exposure, guide health professionals in diagnosing metal-related illnesses, and support government agencies in designing policies for mine remediation and water resource management. Ultimately, the research contributes to safeguarding public health, ensuring environmental sustainability, and strengthening Nigeria's response to pollution challenges associated with abandoned mining sites.

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2. Literature Review

2.1 Conceptual Issues

Heavy metals are naturally occurring elements with high atomic weights and densities, generally above 5 g/cm³. They are of special concern in environmental studies because many are toxic even at trace concentrations. Metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and iron (Fe) are persistent pollutants that do not degrade, but instead accumulate in sediments, aquatic plants, and animal tissues. This persistence makes them prone to bioaccumulation within organisms and biomagnification through food chains, amplifying health risks to higher trophic levels, including humans (Briffa, Sinagra, & Blundell, 2020; Tchounwou, Yedjou, Patlolla, & Sutton, 2012)

Chronic exposure to these metals has been linked with kidney and liver dysfunction, neurological disorders, immune system suppression, reproductive problems, and carcinogenesis (Balali-Mood et al., 2021; Qin et al., 2021)

Acid Mine Drainage (AMD) is a key pathway through which heavy metals are mobilized into surface waters. AMD occurs when sulfide-bearing minerals such as pyrite (FeS_2) oxidize in the presence of water and oxygen, producing sulfuric acid that dissolves and leaches metals into nearby rivers and streams (Bigham & Cravotta, 2016; Zhao et al., 2020)

. Once formed, AMD is self-sustaining and can persist for decades after mines are abandoned, continually degrading water quality (Ozoko, 2015)

Globally, rivers impaired by AMD are characterized by low pH values (typically 2.5–6.0), elevated concentrations of Fe, Mn, Pb, and Cd, and significant ecological stress, including loss of biodiversity and reduced agricultural productivity (Engwa, Ferdinand, Nwalo, & Unachukwu, 2019)

Within Enugu coalfield, AMD is continuously discharged from abandoned Onyeama and Okpara coal mines into the Ekulu and Nyaba rivers. These rivers, however, are not only ecological sinks for mine effluents but also serve as multi-use resources supplying water for domestic purposes, small-scale irrigation, laundry, fishing, sand dredging, and recreation. This dual role amplifies exposure risks, as untreated contaminated water is directly ingested, used in food preparation, or comes into dermal contact with local populations (Obiadi et al., 2016; Ken-Onukuba et al., 2021)

Recent assessments confirm that pH values in Ekulu and Nyaba rivers range between 3.4 and 5.9, classifying them as weakly to strongly acidic, and that mean concentrations of Fe, Pb, Cd, and Cu frequently exceed WHO guideline values (Akpan, Tse, Giadom, & Adamu, 2021)

In this context, heavy metals and AMD represent interrelated conceptual concerns: the chemical processes of sulfide oxidation create acidified conditions that mobilize metals, while the ecological persistence of those metals translates into long-term risks for both ecosystems and human health. Understanding these mechanisms is critical to evaluating the contamination status of Ekulu and Nyaba rivers and the health risks faced by their dependent populations.

2.2 Theoretical Framework

This study is guided by three interrelated theoretical perspectives that explain the occurrence, mobility, and impacts of heavy metals in surface water systems affected by mining activities.

1. Acid Mine Drainage (AMD) Theory: The AMD theory provides the geochemical basis for understanding heavy metal mobilization from abandoned coal mines into rivers. When sulfide minerals such as pyrite (FeS_2) are exposed to oxygen and water during mining, oxidation reactions generate sulfuric acid. This acidic environment enhances the solubility and transport of metals such as Fe, Pb, Cd, and As, allowing them to be leached into surface waters long after mining activities have ceased (Bigham & Cravotta, 2016; Zhao et al., 2020) The persistence of AMD explains why the abandoned Onyeama and Okpara coal mines remain active sources of contamination decades after closure.

2. Bioaccumulation and Biomagnification Framework: The bioaccumulation and biomagnification framework explains the ecological and health consequences of heavy metal persistence. Heavy metals tend to accumulate in sediments and aquatic organisms; once introduced, they can biomagnify through trophic levels, reaching higher concentrations in fish and livestock. This creates indirect exposure pathways for humans through fish consumption, irrigation of food crops, and livestock watering (Briffa, Sinagra, & Blundell, 2020). The framework highlights that even when metals are not ingested directly via drinking water, they still pose health risks through dietary exposure (kidney and liver dysfunction, neurological disorders, carcinogenesis) (Tchounwou, Yedjou, Patlolla, & Sutton, 2012)

3. Environmental Risk Assessment (ERA) Model: The ERA model links environmental contamination to quantifiable human health outcomes. It emphasizes key exposure pathways such as ingestion of contaminated water, dermal absorption during bathing and laundry, and consumption of contaminated fish or crops. By applying international regulatory benchmarks (WHO, USEPA, and FEPA/NESREA), the ERA framework evaluates whether the observed heavy metal concentrations present non-carcinogenic risks, measured by Hazard Quotient (HQ) and Hazard Index (HI), or carcinogenic risks, measured by Incremental Lifetime Cancer Risk (ILCR). This model is particularly relevant in public health-oriented studies, as it translates scientific measurements into decision-ready information for policymakers and health practitioners (Tchounwou et al., 2012)

Together, these frameworks provide a comprehensive lens for analyzing the situation in Ekulu and Nyaba rivers. While AMD theory explains the geochemical origins of contamination, the bioaccumulation and biomagnification framework situates its ecological and health consequences, and the ERA model provides the methodological tools for quantifying human health risks against international standards. This integration ensures that the study not only identifies contamination sources but also evaluates their implications for both ecosystems and dependent communities.

2.3 Empirical Review

Globally, extensive studies confirm that mining activities are significant contributors to heavy metal pollution in aquatic systems. In Asia, Singh et al. (2022) reported that rivers draining abandoned mines in China contained Fe, Pb, Cd, and As at concentrations far above WHO and USEPA standards, leading to severe ecological damage and human health concerns. Similarly, in South America, rivers in Peru impacted by mine effluents exhibited low pH and high dissolved metal loads, which reduced soil fertility and caused fish mortality (Rehman, Fatima, Waheed, & Akash, 2018). Studies in Europe and the United States show that AMD persists for decades after mine abandonment, with heavy metals continuing to leach from sediments into rivers, thereby sustaining long-term contamination and health risks (Bigham & Cravotta, 2016; Zhao et al., 2020)

In Africa, abandoned and poorly regulated mining activities are a major source of heavy metal contamination. Research in South Africa showed that AMD from gold and coal mines discharged into rivers elevated Fe, Mn, and Pb concentrations beyond drinking-water limits, impairing agricultural productivity and domestic use (Engwa, Ferdinand, Nwalo, & Unachukwu, 2019). In Ghana, rivers draining artisanal and small-scale gold mines recorded unsafe levels of As and Hg, directly linked to unsafe disposal practices and artisanal mining activities (Armah et al., 2010). Likewise, Chileshe et al. (2021) observed high Pb and Cd levels in rivers near abandoned mines in Zambia, with significant bioaccumulation in fish consumed by local communities. These findings collectively underscore the dual challenge of weak mine reclamation policies and high dependence on untreated river water in African contexts

In Nigeria, numerous studies have linked AMD from abandoned coal mines to elevated heavy metal levels in surface water. Adaikpoh, Ogala, and Nwajei (2005) analyzed water and sediments from River Ekulu and reported significant enrichment of Cd, Zn, and Pb. Obiadi, Obiadi, Akudinobi, Mmaduweesi, and Ezim (2016) found elevated Zn, Cu, and Cd in Ekulu and Nyaba rivers, attributing contamination to both AMD and anthropogenic activities such as irrigation farming and domestic effluent discharge. Ozoko (2015) further documented that decades after mine abandonment, AMD from Onyeama and Okpara continues to degrade surface water quality. More recently, Akpan, Tse, Giadom, and Adamu (2021) observed acidic pH values (3.4–5.9) and high Fe and Pb concentrations in Ekulu and Nyaba rivers,

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frequently above WHO permissible limits, confirming persistent AMD influence

Within Enugu State, studies consistently highlight the vulnerability of communities to heavy metal exposure. Ken-Onukuba et al. (2021) documented contributions from anthropogenic activities such as irrigation, sand dredging, and laundry that exacerbate AMD-driven contamination. A thesis-based assessment confirmed that mean Fe, Pb, and Cd values exceeded national and international guidelines in both dry and wet seasons, with higher concentrations often observed in dry seasons due to reduced dilution. Importantly, health risk assessments revealed Hazard Index (HI) values greater than 1 and Incremental Lifetime Cancer Risk (ILCR) values above the threshold of 1×10^{-4}, especially for As, Pb, and Cd, indicating unacceptable risks for both adults and children, with children more vulnerable due to higher exposure sensitivity.

2.4 Identified Research Gaps

Although several studies have investigated heavy metal contamination in rivers draining abandoned mines, important gaps remain in the Nigerian and Enugu contexts. First, many existing studies provide only snapshot measurements, without systematically examining seasonal variations. Yet, seasonal dynamics are critical because dilution during the wet season and concentration during the dry season strongly influence exposure risks.

Second, there is insufficient clarity in source apportionment. While Acid Mine Drainage (AMD) is acknowledged as a major geogenic source, the additional roles of anthropogenic activities such as irrigation runoff, laundry, domestic effluents, and sand dredging are often not disentangled, leaving uncertainties about the relative contributions of natural and human-induced contamination.

Third, most studies stop at reporting exceedances of guideline values without carrying out a formal health risk assessment. As a result, communities and policymakers lack quantifiable measures such as Hazard Quotient (HQ), Hazard Index (HI), or Incremental Lifetime Cancer Risk (ILCR), which are essential for understanding both non-carcinogenic and carcinogenic risks.

Finally, there is a gap in policy relevance and translation. While evidence of contamination exists, few studies link their findings to actionable recommendations for mine remediation, water treatment, or community health interventions. This limits their usefulness in shaping effective environmental management strategies.

By addressing these gaps through season-resolved monitoring, correlation-based source identification, and health risk quantification, the present study strengthens the evidence base for both scientific understanding and policy action in managing heavy metal contamination in Ekulu and Nyaba rivers.

3. Materials and Methods

3.1 Study Area

The study was conducted within the Nyaba catchment, located in Enugu State, Southeast

Nigeria. This catchment hosts the abandoned Onyeama and Okpara coal mines, which are historically significant as part of Nigeria's colonial and post-colonial coal industry. Following decades of abandonment without reclamation, these mines now act as continuous sources of Acid Mine Drainage (AMD), discharging into the Ekulu and Nyaba rivers (Obiadi, Obiadi, Akudinobi, Mmaduweesi, & Ezim, 2016; Ozoko, 2015). Both rivers are vital to surrounding communities, serving as sources for domestic water supply, irrigation, fishing, laundry, sand dredging, and recreational activities (Ken-Onukuba et al., 2021).

The climate of the area is tropical rainforest type, characterized by a wet season (April–October) and a dry season (November–March). Annual rainfall averages between 1,500 and 2,000 mm, while mean annual temperatures range from 26–30°C (NIMET, 2022). These climatic conditions significantly influence river hydrology, with dilution during wet periods and concentration effects during dry periods, thereby affecting heavy metal dynamics (Akpan, Tse, Giadom, & Adamu, 2021).

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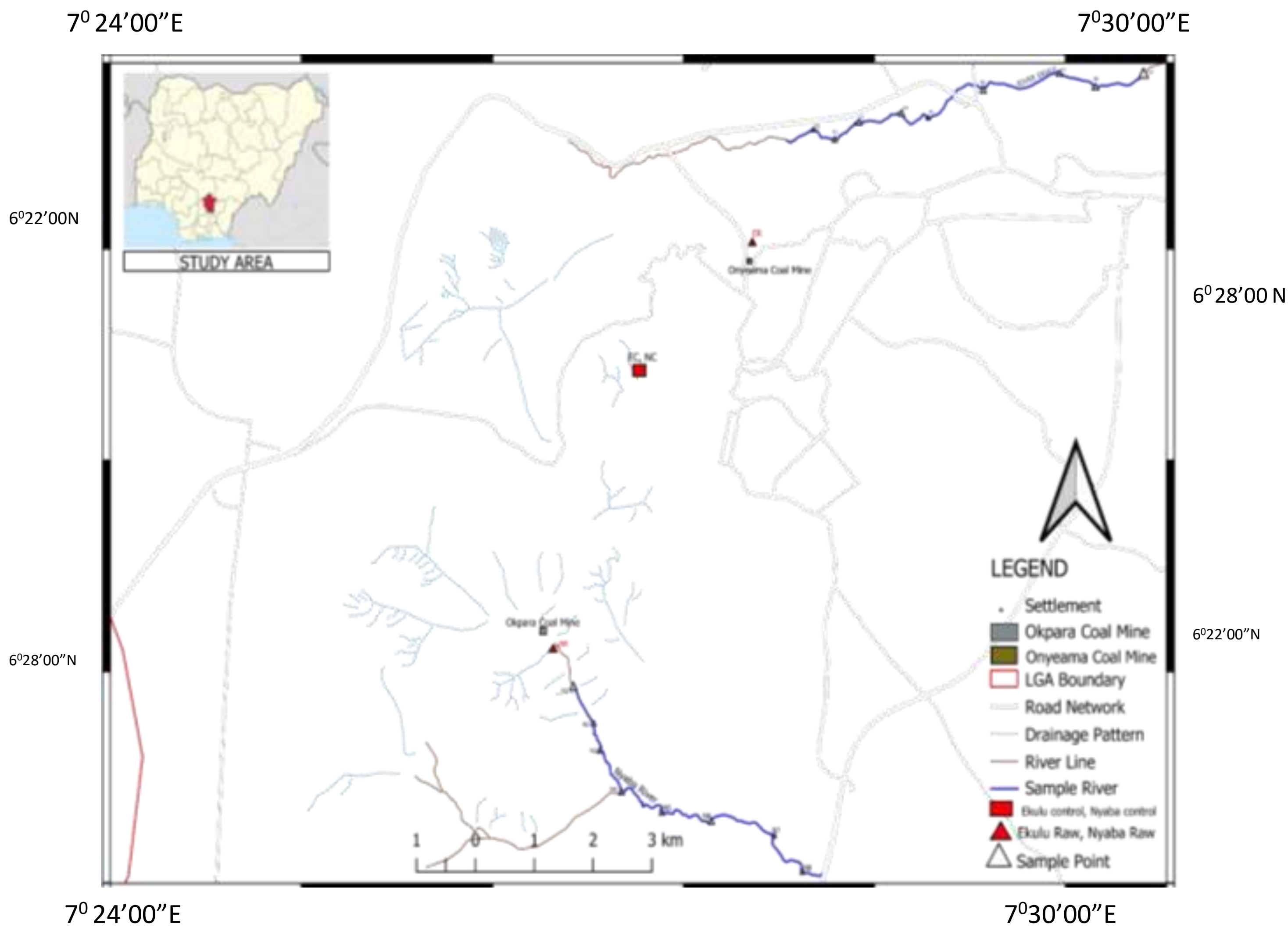

Figure 3.1: Location Map of Onyema Coal Mine, Okpala coal mine, Nyaba River and Ekulu River
Source: Fieldwork, 2023/2024.

3.2 Sampling Design

A stratified sampling approach was adopted to capture spatial and seasonal variations in water quality. Sampling locations were established at upstream, midstream, and downstream sections of each river to reflect changes along the flow gradient. Additional samples were collected at raw mine discharge points (direct effluents from abandoned mines) and at control sites situated upstream of mining influence.

In total, 34 water samples were collected: 18 from Ekulu River and 16 from Nyaba River, during both the wet season (August 2023) and the dry season (January 2024). At each location, triplicate samples were taken, composited, and preserved in pre-cleaned polyethylene bottles. All bottles were rinsed with river water prior to sampling to prevent contamination, and samples were immediately acidified with nitric acid (HNO_3) to pH < 2 and stored at 4°C until analysis.

The geographical coordinates of all sampling points are presented in Table 3.1 (Ekulu River) and Table 3.2 (Nyaba River).

Table 3.1 Locations of samples collection for Ekulu river

Sampling point	Latitude N (°)			Longitude E (°)		
E1	6°	28’	13.18”	7°	29’	33.29”
E2	6°	28’	9.16”	7°	29’	37.10”
E3	6°	28’	17.25”	7°	29’	58.15”
E4	6°	28’	21.13”	7°	30’	22.00”
E5	6°	28’	18.75”	7°	30’	35.75”
E6	6°	28’	33.28”	7°	31’	6.58”
E7	6°	28’	41.72”	7°	31’	48.46”
E8	6°	28’	34.29”	7°	32’	8.24”
E9	6°	28’	41.48”	7°	32’	35.53”
ER	6°	27’	1.58”	7°	28’	55.61”
EC	6°	26’	12.00”	7°	27’	57.00”

Table 3.2: Locations of samples collected for Nyaba river

Sampling points	Latitude N (°)			Longitude E (°)		
N1	6°	23’	35.24”	7°	27’	20.07”
N2	6°	23’	15.95”	7°	27’	31.51”
N3	6°	23’	2.37”	7°	27’	34,46”
N4	6°	22’	42.19”	7°	27’	46.39”
N5	6°	22’	31.73”	7°	28’	8.92”
N6	6°	22’	26.88”	7°	28’	34.79”
N7	6°	22’	5.77”	7°	29’	25.96”
N8	6°	22’	0.84”	7°	29’	31.93”
NR	6°	23’	54.89”	7°	27’	10.30”
NC	6°	26’	12.00”	7°	27’	57.00”

3.3 Laboratory Analysis

All water samples were analyzed for ten (10) heavy metals As, Cd, Co, Fe, Hg, Mn, Ni, Pb, and Se using Atomic Absorption Spectrophotometry (AAS) in line with APHA (2017) standard methods. Quality Assurance and Quality Control (QA/QC) protocols were strictly followed, including the use of reagent blanks, calibration with certified standards, replicate sample analysis, and recovery checks. Each determination was carried out in triplicate, and mean concentrations were reported. These measures ensured accuracy, reproducibility, and comparability with international studies on heavy metals in mining-impacted rivers (Bigham & Cravotta, 2016; Zhao et al., 2020).

3.4 Data Analysis

Data analysis involved a combination of descriptive and inferential statistical methods. Descriptive statistics (means, ranges, and standard deviations) were computed to summarize concentration levels. Pearson correlation analysis was used to identify relationships among metals, thereby distinguishing between AMD-related (geogenic) and anthropogenic sources of contamination.

To assess compliance with regulatory limits, one-sample t-tests were performed comparing observed concentrations against guideline values from the World Health Organization (WHO, 2017), the United States Environmental Protection Agency (USEPA, 2018), and the Federal Environmental Protection Agency/National Environmental Standards and Regulations Enforcement Agency (FEPA/NESREA, 1991).

Finally, a formal health risk assessment was conducted. Non-carcinogenic risks were evaluated using the Hazard Quotient (HQ) and Hazard Index (HI), while carcinogenic risks were quantified using the Incremental Lifetime Cancer Risk (ILCR) approach, following established procedures in environmental health risk assessment (Tchounwou, Yedjou, Patlolla, & Sutton, 2012). Separate calculations were made for adults and children to account for age-related differences in exposure and susceptibility.

4. Results

4.1 Concentrations and Seasonal Variations of Heavy Metals

The analysis of water samples from Ekulu and Nyaba rivers revealed that several heavy metals, particularly iron (Fe), lead (Pb), cadmium (Cd), and arsenic (As), consistently exceeded permissible limits set by the World Health Organization (WHO, 2017), USEPA (2018), and FEPA/NESREA (1991).

Dry Season

During the dry season, reduced water volume due to low rainfall resulted in higher metal concentrations, particularly in Ekulu River where Fe reached 1.181 mg/L, and Pb and Cd were above permissible thresholds. This pattern reflects the diminished dilution capacity of the rivers, leading to greater pollutant accumulation (Akpan et al., 2021).

Wet Season

In contrast, the wet season exhibited two distinct patterns:

In Ekulu River, dilution from heavy rainfall led to lower concentrations of Fe, Pb, and Cd compared to the dry season.

In Nyaba River, however, rainfall increased leaching from abandoned mine tunnels, raising the concentrations of Fe and As. For instance, Fe recorded 1.063 mg/L in Nyaba during the wet season, still above international standards.

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This divergence indicates that while rainfall can reduce contamination in some rivers, it may also intensify metal mobilization in others, depending on the hydrological connection with mine

Table 4.1: Calculation of correlation coefficients of heavy metals from the raw data for Ekulu river (wet season)

Sample	**Unit in mg/l**	As	Cd	Co	Fe	Hg	Mn	Mo	Ni	Pb	Se	pH
E1	Mg/l	0.017	0.013	0.049	0.405	0.170	0.798	0.098	0.231	0.021	0.033	6.00
E2	Mg/l	0.009	0.026	0.038	0.367	0.201	0.879	0.046	0.399	0.041	0.048	6.10
E3	Mg/l	0.013	0.034	0.037	0.624	0.136	0.907	0.027	0.258	0.014	0.060	6.20
E4	Mg/l	0.014	0.032	0.037	0.443	0.106	0.691	0.079	0.322	0.032	0.054	6.10
E5	Mg/l	0.022	0.031	0.035	0.631	0.084	0.563	0.036	0.573	0.040	0.050	5.90
E6	Mg/l	0.024	0.027	0.015	0.628	0.100	0.745	0.023	0.428	0.045	0.022	6.00
E7	Mg/l	0.021	0.051	0.039	0.884	0.074	0.556	0.020	0.411	0.043	0.044	6.50
E8	Mg/l	0.028	0.067	0.036	1.327	0.121	0.210	0.014	0.539	0.024	0.041	6.40
E9	Mg/l	0.021	0.067	0.030	1.076	0.139	0.750	0.018	0.513	0.042	0.049	5.80
ER	Mg/l	0.032	0.088	0.037	0.975	0.068	0.179	0.116	0.434	0.040	0.090	6.40

Table 4.1 Presents raw concentrations of As, Cd, Co, Fe, Hg, Mn, Mo, Ni, Pb, and Se across sampling stations. Fe, Pb, and Cd values exceed WHO/USEPA limits in multiple locations, showing AMD as the dominant source.

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Table 4.2: Inter-element correlation matrix among heavy metals in Ekulu river (wet season)

	As	Cd	Co	Fe	Hg	Mn	Mo	Ni	Pb	Se	pH
As	1	0.72*	-0.28	0.75*	-0.68*	0.86*	0.08	-0.15	0.26	0.24	-0.31
Cd		1	-0.09	0.85*	0.48	-0.76*	0.03	0.51	0.22	0.62	-0.02
Co			1	-0.18	0.47	0.76*	0.03	0.51	0.22	0.62	0.40
Fe				1	-0.41	-0.72*	0.35	0.62*	0.07	0.20	0.39
Hg					1	0.62*	-0.02	-0.38	-0.33	-0.32	-0.38
Mn						1	-0.19	-0.54	-0.14	-0.42	-0.59
Mo							1	-0.44	-0.11	0.50	0.40
Ni								1	0.57	0.02	-0.07
Pb									1	-0.02	-0.07
Se										1	-0.49
Ph											1

- *Significant at 5% alpha level (2-tailed).
- Source: Field Survey, 2023/2024

Table 4.2: Demonstrates significant positive correlations ($p < 0.05$) such as Fe–Cd and Fe–Mn, confirming AMD origin. Negative associations indicate anthropogenic influences, e.g., domestic effluent and laundry runoff.

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Table 4.3: Correlation coefficient of heavy metals from the raw data for Nyaba river (dry season)

Sample	Unit mg/L	As	Cd	Co	Fe	Hg	Mn	Mo	Ni	Pb	Se	pH
N1	mg/L	0.303	0.024	0.035	1.152	0.109	0.046	0.053	0.842	0.082	0.424	5.50
N2	mg/L	0.394	0.020	0.022	1.113	0.147	0.246	0.052	0.869	0.035	0.117	5.60
N3	mg/L	0.330	0.037	0.025	0.704	0.164	0.059	0.035	0.798	0.126	0.520	6.50
N4	mg/L	0.320	0.017	0.051	0.517	0.138	0.276	0.056	0.049	0.055	0.233	5.50
N5	mg/L	0.111	0.121	0.041	0.728	0.121	0.076	0.036	0.172	0.072	0.422	5.00
N6	mg/L	0.133	0.021	0.048	0.508	0.130	0.312	0.065	0.710	0.061	0.531	4.50
N7	mg/L	0.372	0.024	0.058	0.490	0.143	0.553	0.068	0.308	0.116	0.004	5.00
N8	mg/L	0.347	0.72	0.056	1.043	0.160	0.956	0.054	0.493	0.880	0.563	5.10
ER	mg/L	0.362	0.027	0.052	0.918	0.144	0.140	0.028	0.835	0.181	0.969	3.80

Table 4.3 Shows higher mean concentrations of Fe and As during the dry season due to reduced dilution. AMD dominance is confirmed, with values exceeding WHO and USEPA guidelines.

Table 4.4: Inter-element correlation matrix among heavy metals in Nyaba river (dry season)

	As	Cd	Co	Fe	Hg	Mn	Mo	Ni	Pb	Se	pH
As	1	-0.53	-0.05	0.37	0.54*	0.27	0.01	0.27	0.23	-0.16	0.21
Cd		1	0.06	0.08	-0.10	0.09	-0.39	-0.41	0.33	0.15	-0.04
Co			1	-0.41	0.01	0.60*	0.33	-0.53	0.41	0.14	0.65*
Fe				1	-0.05	-0.00	-0.31	0.58*	0.34	0.24	0.07
Hg					1	0.46	-0.15	0.11	0.48	0.08	0.25
Mn						1	0.51	-0.26	0.82*	-0.15	-0.15
Mo							1	-0.24	0.03	-0.66*	-0.70
Ni								1	-0.04	0.36	0.01
Pb									1	0.29	-0.09
Se										1	-0.48
Ph											1

- *Significant at 5% alpha level (2-tailed).
- Source: Field Survey, 2023/24

Table 4.4 Highlights positive correlations such as As–Hg and Mn–Pb, showing mixed AMD and anthropogenic influences. Co–Mn correlations reflect sediment–water interactions typical of mine-polluted rivers.

The seasonal assessment shows that Ekulu River is more contaminated during the dry season, while Nyaba River records higher contamination in the wet season due to enhanced mine-water inflows. Across both rivers, Fe, Pb, Cd, and As concentrations remain above international standards, indicating persistent AMD influence and additional anthropogenic contributions.

4.2 Sources of Heavy Metals

The Pearson correlation analysis was employed to determine the sources of heavy metals in both Ekulu and Nyaba rivers. The results confirm that Acid Mine Drainage (AMD) from the abandoned Onyeama and Okpara coal mines is the dominant source of contamination. This was evidenced by strong positive correlations among Fe, Mn, and Cd, metals commonly associated with AMD pathways

At the same time, several weak or negative correlations revealed the influence of anthropogenic activities, such as irrigation farming, laundry, sand dredging, and domestic effluent disposal, which introduce additional heavy metals into the rivers. For instance, As–Mo (−0.64) and Cd–Se (−0.82) correlations in Ekulu River suggest distinct non-AMD sources, while Co–Mn (0.60) and Mn–Pb (0.82) in Nyaba River point to AMD leaching from mine tunnels.

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Table 4.5: Correlation Matrix of Heavy Metals in Ekulu River (Dry Season)

Sample	Unit mg/L	As	Cd	Co	Fe	Hg	Mn	Mo	Ni	Pb	Se	pH
N1	mg/L	0.303	0.024	0.035	1.152	0.109	0.046	0.053	0.842	0.082	0.424	5.50
N2	mg/L	0.394	0.020	0.022	1.113	0.147	0.246	0.052	0.869	0.035	0.117	5.60
N3	mg/L	0.330	0.037	0.025	0.704	0.164	0.059	0.035	0.798	0.126	0.520	6.50
N4	mg/L	0.320	0.017	0.051	0.517	0.138	0.276	0.056	0.049	0.055	0.233	5.50
N5	mg/L	0.111	0.121	0.041	0.728	0.121	0.076	0.036	0.172	0.072	0.422	5.00
N6	mg/L	0.133	0.021	0.048	0.508	0.130	0.312	0.065	0.710	0.061	0.531	4.50
N7	mg/L	0.372	0.024	0.058	0.490	0.143	0.553	0.068	0.308	0.116	0.004	5.00
N8	mg/L	0.347	0.72	0.056	1.043	0.160	0.956	0.054	0.493	0.880	0.563	5.10
ER	mg/L	0.362	0.027	0.052	0.918	0.144	0.140	0.028	0.835	0.181	0.969	3.80

Table 4.5 show Fe–Mn ($r = 0.73$, $p < 0.05$) and Fe–Cd ($r = 0.85$) confirm AMD influence. Negative correlations (As–Mo, Cd–Se) show additional anthropogenic sources.

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Table 4.6: Correlation Matrix of Heavy Metals in Ekulu River (Wet Season)

	As	Cd	Co	Fe	Hg	Mn	Mo	Ni	Pb	Se	pH
As	1	-0.53	-0.05	0.37	0.54*	0.27	0.01	0.27	0.23	-0.16	0.21
Cd		1	0.06	0.08	-0.10	0.09	-0.39	-0.41	0.33	0.15	-0.04
Co			1	-0.41	0.01	0.60*	0.33	-0.53	0.41	0.14	0.65*
Fe				1	-0.05	-0.00	-0.31	0.58*	0.34	0.24	0.07
Hg					1	0.46	-0.15	0.11	0.48	0.08	0.25
Mn						1	0.51	-0.26	0.82*	-0.15	-0.15
Mo							1	-0.24	0.03	-0.66*	-0.70
Ni								1	-0.04	0.36	0.01
Pb									1	0.29	-0.09
Se										1	-0.48
Ph											1

*Significant at 5% alpha level (2-tailed).
Source: Field Survey, 2023/24

Table 4.6 show strong Cd–Fe (r = 0.85) and As–Cd (r = 0.72) correlations reflect common AMD sources. Negative Cd–Mn (r = –0.76) indicates separate inputs, possibly domestic effluents.

Table 4.7: Correlation Matrix of Heavy Metals in Nyaba River (Dry Season)

Sample	Unit											
	Mg/l	**As**	**Cd**	**Co**	**Fe**	**Hg**	**Mn**	**Mo**	**Ni**	**Pb**	**Se**	**pH**
N1	Mg/l	0.014	0.079	0.038	1.121	0.032	0.344	0.015	0.551	0.042	0.031	5.80
N2	Mg/l	0.016	0.078	0.090	1.041	0.074	0.514	0.021	0.657	0.033	0.028	5.80
N3	Mg/l	0.023	0.087	0.094	0.974	0.047	0.347	0.043	0.595	0.037	0.025	5.50
N4	Mg/l	0.020	0.115	0.070	1.190	0.091	0.413	0.046	0.487	0.035	0.023	5.50
N5	Mg/l	0.023	0.111	0.061	1.114	0.037	0.545	0.035	0.555	0.023	0.035	5.60
N6	Mg/l	0.026	0.101	0.114	1.012	0.026	0.585	0.031	0.681	0.025	0.046	5.50
N7	Mg/l	0.022	0.089	0.047	0.748	0.039	0.383	0.034	0.650	0.030	0.036	5.30
N8	Mg/l	0.018	0.105	0.066	0.916	0.046	0.215	0.030	0.561	0.019	0.029	5.40
NR	Mg/l	0.187	0.091	0.063	0.977	0.044	0.468	0.051	0.353	0.034	0.075	4.10

*Significant at 5% alpha level(2-tailed).
Source: Field Survey, 2023/2024

Table 4.7 show Strong Co–Mn (r = 0.60) and Mn–Pb (r = 0.82) associations confirm AMD leaching. Moderate correlations point to additional contamination from irrigation return flows.

Table 4.8: Correlation Matrix of Heavy Metals in Nyaba River (Wet Season)

	As	Cd	Co	Fe	Hg	Mn	Mo	Ni	Pb	Se	pH
As	1	-0.08	-0.11	-0.11	0.05	0.17	0.59	0.78*	0.13	0.92*	-0.96*
Cd		1	0.14	0.29	0.21	0.08	0.47	-0.21	0.59	-0.08	-0.04
Co			1	0.11	0.26	0.50	0.15	0.40	-0.27	-0.03	-0.05
Fe				1	0.46	0.30	-0.06	-0.28	-0.29	0.21	0.30
Hg					1	0.51	0.01	0.03	0.24	-0.10	0.19
Mn						1	0.07	0.14	-0.07	0.36	-0.04
Mo							1	-0.59	-0.04	0.41	0.70
Ni								1	-0.23	-0.55	0.74*
Pb									1	-0.04	0.01
Se										1	0.26
pH											1

Table 4.8 show Strong As–Ni (r = 0.78) and As–Se (r = 0.92) suggest AMD origin, while weaker relationships (Cd–Mo, Mo–Se) point to anthropogenic sources such as sand dredging and laundry wastewater

Overall, the correlation results confirm that AMD is the principal driver of heavy metal contamination in both rivers, especially for Fe, Mn, and Cd. However, anthropogenic activities significantly intensify contamination, contributing metals such as Pb, As, and Ni. Thus, pollution in Ekulu and Nyaba rivers is multi-sourced, with geogenic AMD inputs reinforced by human-induced activities

4.3 Human Health Risk Assessment

The potential health risks associated with exposure to heavy metals in Ekulu and Nyaba rivers were assessed through the calculation of Hazard Quotient (HQ), Hazard Index (HI) for non-carcinogenic risks, and Incremental Lifetime Cancer Risk (ILCR) for carcinogenic risks. Results were computed separately for adults and children to account for differences in body weight, water ingestion rates, and exposure duration.

4.3.1 Non-Carcinogenic Risks

The HQ values for several metals, particularly Fe, Pb, Cd, and As, exceeded 1.0, indicating a potential for adverse non-carcinogenic effects.

In Ekulu River, the highest HQ values were observed for Pb and Cd, both of which significantly exceeded threshold limits. In Nyaba River, HQ values for As and Fe were particularly elevated, reflecting AMD contributions during both wet and dry seasons.

The cumulative Hazard Index (HI) for both rivers was consistently greater than 1.0, indicating combined health risks from multiple heavy metals. Importantly, HI values were higher for children compared to adults, confirming their greater vulnerability due to lower body mass and higher exposure rates.

Table 4.9: Non-Carcinogenic Risk (HQ and HI) for Adults in Ekulu and Nyaba Rivers

		As(mg/L)	Cd(mg/L)	Co(mg/L)	Fe(mg/L)	Hg(mg/L)	Mn(g/L)	Mo(mg/L)	Ni(mg/L)	Pb(mg/L)	Se(mg/L)
E1	Min	0.014	0.078	0.013	1.914	0.175	0.054	0.085	0.062	0.007	0.062
	Max	0.041	0.048	0.034	2.035	0.218	0.286	0.154	0.613	0.068	0.718
	Mean ± SD	0.024 ± 0.018	0.032 ± 0.018	0.024 ± 0.009	1.970 ± 0.050	0.198 ± 0.018	0.151 ± 0.087	0.128 ± 0.031	0.350 ± 0.226	0.037 ± 0.025	0.469 ± 0.337
E2	Min	0.021	0.038	0.011	1.181	0.175	0.379	0.010	0.527	0.490	0.003
	Max	0.251	0.124	0.038	2.380	0.218	0.402	0.056	1.177	0.570	0.742
	Mean ± SD	0.154 ± 0.097	0.069 ± 0.039	0.028± 0.012	1.956 ± 1.475	0.198± 0.018	0.392± 0.010	0.031± 0.020	0.883± 0.271	0.512± 0.206	0.267± 0.337
E3	Min	0.285	0.065	0.025	0.021	0.024	0.056	0.011	0.057	0.027	0.032
	Max	0.436	0.085	0.047	0.152	0.121	0.118	0.088	0.880	0.055	0.699
	Mean ± SD	0.362 ± 0.062	0.063± 0.014	0.113± 0.137	0.073± 0.052	0.076± 0.040	0.089± 0.026	0.044± 0.033	0.334± 0.386	0.045± 0.013	0.260± 0.311
E4	Min	0.356	0.039	0.009	0.0955	0.099	0.051	0.038	0.615	0.000	0.018
	Max	0.414	0.056	0.068	2.141	0.173	0.497	0.81	1.696	0.082	0.511
	Mean ± SD	0.386 ± 0.202	0.047± 0.007	0.033± 0.006	1.664± 0.572	0.130± 0.031	0.233± 0.019	0.057± 0.018	1.231±0 .454	0.032± 0.036	0.189± 0.207
E5	Min	0.029	0.026	0.003	0.056	0.106	0.061	0.000	0.679	0.000	0.013
	Max	0.456	0.051	0.054	2.931	0.194	0.269	0.049	1.842	0.110	0.665
	Mean ± SD	0.280 ± 0.182	0.039± 0.010	0.036± 0.041	1.022±1. 350	0.160± 0.039	0.167± 0.085	0.020± 0.021	1,316±0 .481	0.049± 0.046	0.433± 0.305
E6	Min	0.022	0.003	0.009	0.077	0.102	0.049	0.041	0.407	0.018	0.799
	Max	0.058	0.016	0.051	0.124	0.231	0.110	0.113	1.101	0.469	0.800
	Mean ± SD	0.145 ± 0.150	0.011± 0.006	0.031± 0.030	0.066± 0.042	0.182± 0.052	0.091± 0.027	0.083± 0.052	0.954± 0.401	0.195± 0.114	0.787± 0.018
E7	Min	0.232	0.013	0.006	0.008	0.051	0.026	0.032	0.463	0.000	0.664
	Max	0.438	0.042	0.024	0.090	0.107	0.056	0.062	1.340	0.304	0.752
	Mean ± SD	0.341 ± 0.085	0.027± 0.016	0.018± 0.008	0.049± 0.034	0.082± 0.040	0.029± 0.018	0.049± 0.013	0.540± 0.366	0.111±0 .137	0.738± 0.056

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E8	Min	0.152	0.002	0.021	0.029	0.030	0.057	0.016	0.274	0.040	0.004
	Max	0.215	0.053	0.048	2.588	0.111	0.291	0.079	0.931	0.077	0.613
	Mean ±	0.174 ±	0.031±	0.031±	0.907±	0.064±	0.144±	0.040±	0.681±	0.062±	0.223±
	SD	0.029	0.023	0.037	1.597	0.001	0.105	0.019	0.299	0.066	0.314
E9	Min	0.094	0.006	0.009	0.086	0.074	0.014	0.079	0.846	0.006	0.564
	Max	0.121	0.042	0.044	2.502	0.106	0.081	0.097	1.136	0.133	0.628
	Mean ±	0.104 ±	0.021±	0.027±	0.913±	0.087±	0.037±	0.089±	1.014±	0.067±	0.608±
	SD	0.012	0.015	0.014	1.124	0.014	0.031	0.008	0.389	0.052	0.024
ER	Min	0.106	0.000	0.017	2.766	0.119	0.200	0.018	0.274	0.052	0.890
	Max	0.395	0.020	0.054	2.895	0.235	0.263	0.086	1.322	0.117	1.006
	Mean ±	0.265 ±	0.007±	0.032±	2.811±	0.163±	0.239±	0.044±	0.814±	0.088±	0.962±
	SD	0.120	0.009	0.051	0.060	0.055	0.028	0.030	0.428	0.027	0.061
EC	Min	0.206	0.003	0.034	0.001	0.100	0.805	0.030	0.651	0.177	0.002
	Max	0.225	0.044	0.057	2.748	0.145	1.047	0.108	1.727	0.216	0.012
	Mean ±	0.213 ±	0.019±	0.045±	0.920±	0.123±	0.929±	0.060±	1.090±	0.197±	0.006±
	SD	0.008	0.018	0.009	1.300	0.018	0.099	0.033	0.462	0.104	0.004
TOTAL		2.253	0.284	0.373	11.812	1.265	1.244	0.645	7.817	1.208	4.936
Average		0.224	0.028	0.037	1.181	0.127	0.124	0.665	0.782	0.121	0.494
WHO		0.010	0.003		0.300	0.006	0.400	0.070	0.070	0.050	0.040
USEPA		0.010	0.005	0.100	0.300	0.002	0.300	0.010	0.020	0.150	0.050
FEPA(NESREA)		0.050	0.003		0.300	0.001	0.200		0.050	0.010	0.010

Source : WHO 2017
USEPA 2018
FEPA(NESREA) 1991

Table 4.9 Shows HQ values for individual metals; Pb and Cd > 1 in Ekulu, As > 1 in Nyaba. HI > 1 for both rivers, indicating cumulative risk.

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Table 4.10: Non-Carcinogenic Risk (HQ and HI) for Children in Ekulu and Nyaba Rivers

		As (mg/L)	Cd(mg/L)	Co(mg/L)	Fe(mg/L)	Hg(mg/L)	Mn(mg/L)	Mo(mg/L)	Ni(mg/L)	Pb(mg/L)	Se(mg/L)
E1	Min	0.013	0.004	0.030	0.141	0.068	0.660	0.086	0.119	0.015	0.024
	Max	0.020	0.016	0.059	0.569	0.267	0.941	0.122	0.337	0.055	0.044
	Mean ±	0.017	0.013±	0.049±	0.405±	0.170±	0.798±	0.098±	0.231±	0.021±	0.033±
	SD	± 0.004	0.008	0.017	0.231	0.100	0.138	0.021	0.109	0.039	0.010
E2	Min	0.009	0.018	0.005	0.164	0.108	0.420	0.038	0.275	0.027	0.045
	Max	0.012	0.041	0.076	0.571	0.298	1.197	0.056	0.637	0.051	0.051
	Mean ±	0.009	0.026±	0.038±	0.367±	0.201±	0.879±	0.046±	0.399±	0.041±	0.048±
	SD	±0.003	0.013	0.036	0.288	0.095	0.407	0.009	0.206	0.012	0.003
E3	Min	0.011	0.024	0.013	0.159	0.103	0.330	0.021	0.271	0.003	0.055
	Max	0.016	0.043	0.057	0.957	0.176	1.297	0.033	0.052	0.022	0.068
	Mean ±	0.013±	0.034±	0.037±	0.624±	0.136±	0.907±	0.027±	0.258±	0.014±	0.060±
	SD	0.003	0.010	0.022	0.415	0.037	0.510	0.006	0.200	0.010	0.007
E4	Min	0.010	0.022	0.001	0.331	0.053	0.316	0.022	0.260	0.005	0.049
	Max	0.020	0.043	0.093	0.642	0.119	0.885	0.189	0.425	0.054	0.058
	Mean ±	0.014±	0.032±	0.037±	0.443±	0.106±	0.691±	0.079±	0.322±	0.032±	0.054±
	SD	0.006	0.011	0.044	0.173	0.048	0.325	0.095	0.090	0.025	0 .005
E5	Min	0.010	0.011	0.013	0.520	0.015	0.226	0.019	0.406	0.027	0.044
	Max	0.037	0.049	0.051	0.850	0.161	1.092	0.063	0.735	0.062	0.059
	Mean ±	0.022	0.031±	0.035±	0.631±	0.084±	0.563±	0.036±	0.573±	0.040±	0.050±
	SD	±0.014	0.019	0.020	0.189	0.073	0.564	0.024	0.165	0.019	0.008
E6	Min	0.019	0.003	0.011	0.430	0.074	0.619	0.017	0.190	0.020	0.018
	Max	0.028	0.051	0.019	0.799	0.114	0.950	0.029	0.751	0.071	0.025
	Mean ±	0.024	0.027±	0.015±	0.628±	0.100±	0.745±	0.023±	0.428±	0.045±	0.022±
	SD	±0.005	0.024	0.004	0.186	0.023	0.179	0.006	0.290	0.026	0.004
E7	Min	0.017	0.032	0.000	0.539	0.058	0.389	0.017	0.332	0.026	0.037
	Max	0.023	0.065	0.094	1.140	0.094	1.022	0.023	0.490	0.062	0.046
	Mean ±	0.021±	0.051±	0.039±	0.884±	0.074±	0.556±	0.020±	0.411±	0.043±	0.044±
	SD	0.003	0.017	0.049	0.310	0.018	0.410	0.003	0.079	0.018	0.006
E8	Min	0.024	0.051	0.028	1.127	0.083	0.109	0.012	0.482	0.018	0.036
	Max	0.032	0.075	0.048	1.610	0.147	0.277	0.016	0.634	0.029	0.049
	Mean ±	0.028	0.067±	0.036±	1.327±	0.121±	0.210±	0.014±	0.539±	0.024±	0.041±
	SD	±0.004	0.011	0.011	0.252	0.034	0.089	0.002	0.083	0.006	0.007

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E9	Min	0.019	0.055	0.023	0.900	0.073	0.360	0.011	0.250	0.021	0.033
	Max	0.022	0.075	0.039	1.398	0.184	1.257	0.022	0.834	0.081	0.061
	Mean ±	0.021±	0.067±	0.030±	1.076±	0.139±	0.750±	0.018±	0.513±	0.042±	0.049±
	SD	0.002	0.011	0.008	0.280	0.058	0.460	0.006	0.296	0.034	0.015
ER	Min	0.027	0.072	0.018	0.780	0.030	0.094	0.108	0.339	0.010	0.074
	Max	0.038	0.098	0.069	1.352	0.119	0.343	0.122	0.549	0.067	0.108
	Mean ±	0.032	0.088	0.037±	0.975±	0.068±	0.179±	0.116±	0.434±	0.040±	0.090±
	SD	±0.006	± 0.014	0.028	0.326	0.046	0.142	0.007	0.106	0.029	0.017
EC	Min	0.010	0.091	0.015	0.334	0.017	0.068	0.014	0.356	0.008	0.016
	Max	0.013	0.111	0.109	0.676	0.087	0.110	0.018	0.505	0.041	0.021
	Mean ±	0.011±	0.099±	0.053±	0.470±	0.044±	0.092±	0.016±	0.453±	0.022±	0.019±
	SD	0.002	0.011	0.049	0.182	0.038	0.022	0.002	0.084	0.017	0.003
Total		0.201	0.436	0.316	7.360	1.199	6.278	0.441	4.108	0.342	0.491
Average		0.020	0.044	0.032	0.736	0.120	0.628	0.044	0.411	0.034	0.049
WHO		0.010	0.030	0.005	0.300	0.006	0.050	0.070	0.070	0.050	0.040
USEPA		0.010	0.005	0.100	0.300	0.001	0.050	0.010	0.020	0.150	0.050
FEPA(NESREA)		0.010	0.030		0.300		0.050		0.050	0.010	0.010

Source : WHO 2017

USEPA 2018

FEPA(NESREA) 1991

Table 4.10 show HQ values for As, Pb, and Cd all exceeded 1 in both rivers. HI values were significantly higher than in adults, underscoring children's susceptibility.

4.3.2 Carcinogenic Risks

The ILCR results indicated significant cancer risks associated with exposure to As, Cd, Ni, and Pb in both rivers. For adults, ILCR values exceeded the acceptable threshold of 1×10^{-4} for As (8.0×10^{-4}), Cd (1.3×10^{-4}), Ni (8.0×10^{-3}), and Pb (2.7×10^{-4}) in Ekulu River, indicating elevated cancer risks primarily via the ingestion pathway. For children, ILCR values were even higher, with As (2.9×10^{-4}), Ni (7.5×10^{-3}), and Pb (2.7×10^{-3}) surpassing safe limits.

In Nyaba River, similar trends were observed. ILCR values for adults exceeded thresholds for As, Cd, and Ni, while in children, both ingestion and dermal exposure pathways yielded unacceptable risks.

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Table 4.11: Carcinogenic Risk (ILCR) for Adults in Ekulu and Nyaba Rivers

		As(mg/L)	Cd(mg/L)	Co(mg/L)	Fe(mg/L)	Hg(mg/L)	Ma(mg/L)	Mo(mg/L)	Ni(mg/L)	Pb(mg/L)	Se(mg/L)
N1	Min	0.221	0.006	0.025	0.214	0.078	0.007	0.024	0.547	0.078	0.125
	Max	0.383	0.041	0.045	1.586	0.112	0.114	0.071	1.405	0.088	0.628
	Mean ± SD	0.303 ±0.066	0.024 ±0.014	0.035 ±0.007	1.152±0.664	0.109 ± 0.025	0.046 ±0.048	0.053 ±0.021	0.042 ±0.400	0.082 ±0.004	0.424 ±0.216
N2	Min	0.297	0.006	0.018	0.045	0.092	0.070	0.008	0.218	0.000	0.000
	Max	0.456	0.036	0.029	2.099	0.186	0.362	0.107	1.896	0.102	0.841
	Mean ± SD	0.394 ±0.154	0.020 ±0.012	0.022 ±0.005	1.113±0.841	0.147± 0.083	0.246 ±0.127	0.052 ±0.041	0.869 ±0.735	0.035 ±0.055	0.117± 0.461
N3	Min	0.301	0.005	0.022	0.126	0.442	0.027	0.009	0.040	0.053	0.002
	Max	0.366	0.020	0.029	1.937	0.178	0.099	0.057	0.518	0.234	0.793
	Mean ± SD	0.330 ±0.028	0.037 ±0.006	0.025 ±0.003	0.704± 0.554	0.164± 0.016	0.059 ±0.094	0.035 ±0.020	0.798 ±0.760	0.126 ±0.081	0.520 ±0.363
N4	Min	0.270	0.001	0.024	0.024	0.078	0.127	0.023	0.021	0.036	0.001
	Max	0.395	0.038	0.078	1.451	0.207	0.521	0.102	0.071	0.074	0.677
	Mean ± SD	0.320 ±0.052	0.017 ±0.016	0.051± 0.022	0.517± 0.661	0.138± 0.007	0.276 ±0.173	0.056 ±0.034	0.049 ±0.034	0.055 ±0.021	0.233 ±0.314
N5	Min	0.289	0.075	0.030	0.068	0.106	0.005	0.020	1.064	0.050	0.020
	Max	0.371	0.181	0.048	1.956	0.138	0.201	0.060	0.293	0.100	0.648
	Mean ± SD	0.111± 0.224	0.121± 0.045	0.041 ±0.008	0.728± 1.187	0.121± 0.013	0.076 ±0.089	0.036 ±0.017	0.172± 0.520	0.022 ±0.021	0.422 ±0.282
N6	Min	0.371	0.004	0.037	1.081	0.104	0.217	0.038	1.460	0.054	0.319
	Max	0.427	0.041	0.067	0.222	0.162	0.447	0.105	0.388	0.070	0.641
	Mean ± SD	0.133 ±0.267	0.021 ±0.015	0.048 ±0.013	0.508± 0.405	0.130 ±0.024	0.312 ±0.098	0.065 ±0.030	0.710 ±0.532	0.061 ±0.007	0.531± 0.150
N7	Min	0.331	0.018	0.046	0.271	0.100	0.304	0.027	0.102	0.077	0.000
	Max	0.465	0.031	0.059	0.431	0.176	1.015	0.146	0.411	0.141	0.007
	Mean ± SD	0.377 ±0.365	0.024 ±0.005	0.058 ±0.005	0.490± 0.179	0.143± 0.032	0.553 ±0.333	0.068 ±0.055	0.308 ±0.143	0.116± 0.031	0.004 ±0.003

N8	Min	0.264	0.016	0.040	0.462	0.135	0.882	0.039	0.268	0.058	0.532
	Max	0.433	0.103	0.076	2.200	0.185	1.037	0.078	0.682	0.098	0.582
	Mean ± SD	0.347 ±0.069	0.072 ±0.040	0.056 ±0.015	1.043± 0.818	0.160 ±0.025	0.956 ±0.064	0.054 ±0.017	0.493 ±0.177	0.080 ±0.017	0.563 ±0.022
NR	Min	0.318	0.012	0.038	0.122	0.103	0.009	0.019	0.223	0.153	0.886
	Max	0.388	0.040	0.060	0.263	0.210	0.335	0.033	1.526	0.199	1.055
	Mean ± SD	0.362 ±0.032	0.027 ±0.012	0.052 ±0.009	0.918± 0.058	0.144± 0.048	0.140 ±0.140	0.028 ±0.006	0.835 ±0.927	0.181± 0.020	0.969 ±0.069
NC	Min	0.206	0.003	0.034	0.001	0.107	0.805	0.030	0.651	0.177	0.002
	Max	0.225	0.044	0.057	2.748	0.116	1.047	0.108	1.727	0.216	0.012
	Mean ± SD	0.213 ±0.008	0.019 ±0.018	0.045 ±0.009	0.920± 1.300	0.112± 0.002	0.929 ±0.099	0.060 ±0.033	1.090 ±0.462	0.197± 0.104	0.006 ±0.004
TOTAL		2.583	0.363	0.388	7.173	1.256	2.664	0.447	5.076	0.703	3.777
Average		0.287	0.040	0.043	0.797	0.139	0.296	0.050	0.564	0.078	0.420
WHO		0.010	0.003		0.300	0.006	0.400	0.070	0.070	0.050	0.040
USEPA		0.010	0.005	0.100	0.300	0.002	0.300	0.010	0.020	0.150	0.050
FEPA(NESREA)		0.050	0.003		0.300	0.002	0.200		0.050	0.010	0.010

Table 4.11 show ILCR values for As, Cd, Ni, and Pb are all > 1 × 10^{-4}, confirming cancer risk.

Table 4.12: Carcinogenic Risk (ILCR) for Children in Ekulu and Nyaba Rivers

		As(mg/L)	**Cd(mg/L)**	**Co(mg/L)**	**Fe(mg/L)**	**Hg(mg/L)**	**Mn(mg/L)**	**Mo(mg/L)**	**Ni(mg/L)**	**Pb(mg/L)**	**Se(mg/L)**
N1	Min	0.011	0.073	0.020	0.980	0.017	0.013	0.014	0.509	0.019	0.029
	Max	0.018	0.085	0.060	1.334	0.051	0.573	0.016	0.594	0.064	0.033
	Mean ± SD	0.014± 0.004	0.079± 0.00	0.038± 0.020	1.121±0 .187	0.032± 0.017	0.344± 0.294	0.015± 0.001	0.551± 0.043	0.042± 0.023	0.031± 0.002
N2	Min	0.008	0.057	0.030	0.637	0.013	0.254	0.014	0.526	0.016	0.024
	Max	0.020	0.092	0.163	1.274	0.056	0.667	0.034	0.789	0.042	0.031
	Mean ± SD	0.016± 0.012	0.078± 0.019	0.090± 0.068	1.041± 0.351	0.074± 0.072	0.514± 0.226	0.021± 0.011	0.657± 0.132	0.033± 0.015	0.028± 0.004

N3	Min	0.021	0.070	0.057	0.585	0.029	0.142	0.038	0.344	0.011	0.023
	Max	0.027	0.105	0.124	1.209	0.066	0.560	0.046	0.770	0.058	0.027
	Mean ±	0.023±	0.087±	0.094±	0.974±	0.047±	0.347±	0.043±	0.595±	0.037±	0.025±
	SD	0.003	0.017	0.034	0.339	0.019	0.209	0.004	0.223	0.024	0.002
N4	Min	0.019	0.103	0.049	0.906	0.021	0.048	0.033	0.354	0.026	0.022
	Max	0.021	0.122	0.105	1.424	0.067	0.699	0.051	0.596	0.041	0.024
	Mean ±	0.020±	0.115±	0.070±	1.190±	0.047±	0.413±	0.046±	0.487±	0.035±	0.023±
	SD	0.001	0.010	0.031	0.263	0.034	0.333	0.007	0.123	0.008	0.001
N5	Min	0.019	0.100	0.027	0.829	0.028	0.419	0.028	0.500	0.002	0.018
	Max	0.026	0.126	0.109	1.414	0.106	0.679	0.040	0.647	0.065	0.065
	Mean ±	0.023±	0.111±0	0.069±	1.114±0	0.091±	0.545±	0.035±	0.555±	0.023±	0.035±
	SD	0.004	.013	0.041	.293	0.100	0.130	0.006	0.080	0.036	0.026
N6	Min	0.022	0.094	0.080	0.746	0.024	0.299	0.027	0.521	0.001	0.039
	Max	0.029	0.110	0.140	1.193	0.045	0.960	0.036	0.968	0.046	0.053
	Mean ±	0.026±	0.101±	0.114±	1.012±	0.037±	0.585±	0.031±	0.681±	0.025±	0.046±
	SD	0.004	0.008	0.031	0.235	0.011	0.339	0.005	0.249	0.023	0.007
N7	Min	0.019	0.083	0.036	0.233	0.001	0.316	0.026	0.412	0.018	0.032
	Max	0.024	0.100	0.056	1.286	0.059	0.419	0.039	0.852	0.040	0.043
	Mean ±	0.022±	0.089±	0..047	0.748±	0.026±	0.383±	0.034±	0.650±	0.030±	0.036±
	SD	0.003	0.010	±0.010	0.527	0.030	0.058	0.007	0.222	0.011	0.006
N8	Min	0.015	0.092	0.033	0.532	0.020	0.198	0.019	0.526	0.013	0.021
	Max	0.021	0.118	0.114	1.338	0.060	0.234	0.039	0.597	0.029	0.042
	Mean ±	0.018±	0.105±	0.066±	0.916±	0.039±	0.215±	0.030±	0.561±	0.019±	0.029±
	SD	0.003	0.013	0.043	0.404	0.020	0.018	0.010	0.036	0.009	0.011
NR	Min	0.118	0.084	0.025	0.752	0.004	0.414	0.049	0.302	0.026	0.065
	Max	0.321	0.101	0.081	1.154	0.077	0.556	0.053	0.434	0.041	0.084
	Mean ±	0.187±		0.063±	0.977±	0.046±	0.468±	0.051±	0.353±	0.034±	0.075±
	SD	0.116		0.033	0.205	0.038	0.077	0.002	0.071	0.008	0010
NC	Min	0.010	0.091	0.036	0.334	0.017	0.068	0.014	0.356	0.008	0.016
	Max	0.013	0.111	0.109	0.676	0.087	0.110	0.018	0.505	0.041	0.021
	Mean ±	0.011±	0.099±	0.053±	0.470±	0.044±	0.092±	0.016±	0.453±	0.022±	0.019±
	SD	0.002	0.011	0.049	0.182	0.038	0.022	0.002	0.084	0.017	0.003
Total		0.379	0.955	0.704	9.563	0.392	3.814	0.306	5.09	0.278	0.328
Average		0.035	0.106	0.078	1.063	0.044	0.424	0.034	0.566	0.031	0.036
WHO		0.010	0.003	0.005	0.300	0.001	0.050	0.070	0.070	0.050	0.040
USEPA		0.100	0.005	0.100	0.300	0.001	0.050	0.010	0.020	0.015	0.050
FEPA(NESREA)		0.100	0.003		0.300		0.050		0.050	0.010	0.010

Table 4.12 show ILCR values even higher than adults, with Ni and Pb showing the greatest risks. Children are the most vulnerable group.

The health risk assessment demonstrates that:
Non-carcinogenic risks (HQ and HI): Both rivers pose significant health hazards, with HI > 1 in all cases. Children face higher risks than adults.
Carcinogenic risks (ILCR): ILCR values for As, Cd, Ni, and Pb in both rivers exceed acceptable thresholds, indicating unacceptable lifetime cancer risks, especially for children.
Risk pathways: Ingestion of contaminated water is the dominant pathway, but dermal exposure also contributes to cumulative risk.

5. Discussion

5.1 Concentrations and Seasonal Variations

The results revealed that heavy metals such as Fe, Pb, Cd, and As consistently exceeded WHO, USEPA, and FEPA/NESREA standards in both Ekulu and Nyaba rivers. These findings align with global studies reporting elevated Fe, Pb, and Cd in mining-impacted rivers, often linked to Acid Mine Drainage (AMD) processes (Bigham & Cravotta, 2016; Zhao et al., 2020). The seasonal dynamics observed higher concentrations during the dry season in Ekulu due to limited dilution, and increased contamination during the wet season in Nyaba due to enhanced leaching reflect the hydrological influence on pollutant transport. Similar patterns were reported in Chinese and Peruvian mine-impacted rivers, where rainfall either diluted contaminants or mobilized them depending on hydrogeological settings (Singh et al., 2022; Rehman et al., 2018). In the Nigerian context, Akpan et al. (2021) also observed acidic pH and elevated Fe and Pb levels in Ekulu and Nyaba rivers, corroborating the current study's evidence of persistent AMD contamination. The consistent exceedance of permissible limits indicates that both rivers pose significant ecological and health risks regardless of season.

5.2 Sources of Heavy Metal Contamination

Correlation analysis confirmed that AMD from the abandoned Onyeama and Okpara coal mines is the dominant source of heavy metal contamination, particularly for Fe, Mn, and Cd. This supports theoretical expectations that sulfide oxidation in coal-bearing rocks produces acidic effluents enriched in metals (Gallagher, 2022). However, the presence of weak or negative correlations among certain metals suggests anthropogenic contributions, including irrigation runoff, domestic wastewater, laundry activities, and sand dredging along riverbanks.

This mixed source profile parallels findings in South Africa and Ghana, where AMD interacts with artisanal mining and agricultural effluents to amplify contamination (Engwa et al., 2019; Armah et al., 2010). In Enugu, Obiadi et al. (2016) similarly attributed elevated Zn, Cu, and Cd in coalfield rivers to both AMD and anthropogenic activities. The implication is that while AMD provides the baseline contamination load, human practices act as secondary drivers that worsen river water quality.

5.3 Human Health Risks

The health risk assessment demonstrated that non-carcinogenic risks (HQ and HI) were significant in both rivers, with HI values exceeding 1 for both adults and children. The risks were notably higher for children due to their greater sensitivity, higher intake-to-body-mass ratios, and developing physiological systems. This aligns with WHO (2017), which emphasizes children's heightened vulnerability to metal exposure.

The carcinogenic risk assessment (ILCR) further confirmed unacceptable lifetime cancer risks from As, Cd, Ni, and Pb, with values surpassing the acceptable threshold of 1×10^{-4}. These findings are consistent with studies in Zambia and Peru, where ILCR values for As and Pb in mining-impacted rivers indicated high cancer risks in local populations (Chileshe et al., 2021; Zhao et al., 2020). In Nigeria, Ozoko (2015) also noted that AMD from abandoned mines continues to degrade water quality and poses long-term health hazards.

The persistence of elevated ILCR values underscores the public health emergency facing communities dependent on Ekulu and Nyaba rivers. Ingestion of untreated river water is the primary risk pathway, although dermal exposure during laundry and bathing also contributes. Without intervention, chronic exposure could manifest in increased cases of kidney dysfunction, developmental disorders, and cancers, especially among children.

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