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SOURCES AND CONCENTRATION LEVELS OF HEAVY METALS IN SURFACE WATER AROUND ABANDONED COAL MINES IN NYABA CATCHMENT AREA, ENUGU STATE, NIGERIA

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Keywords: *Heavy metals, Acid Mine Drainage, anthropogenic pollution, water quality, health risk, Enugu State.*

Abstract: *This study assessed the sources, concentration levels, and health risks of heavy metals in surface waters around abandoned coal mines in the Nyaba catchment, Enugu State, Nigeria. Water samples were collected from Ekulu and Nyaba rivers at upstream, midstream, and downstream points during both dry and wet seasons. Eighteen samples from Ekulu River and sixteen from Nyaba River were collected at upstream, midstream, downstream, raw mine discharge, and control points during both wet (August 2023) and dry (January 2024) seasons. Standard Atomic Absorption Spectrophotometry (AAS) was used to analyze concentrations of As, Cd, Co, Fe, Hg, Mn, Ni, Pb, and Se. Data were subjected to descriptive statistics, Pearson correlation, and one-sample t-tests against international and national guideline values from WHO, USEPA, and FEPA/NESREA. The results indicate that both geogenic processes linked to Acid Mine Drainage (AMD) and anthropogenic activities contribute significantly to metal enrichment in the rivers. Correlation analysis suggests that Fe and Mn are strongly associated with AMD inputs from abandoned mine tunnels, while Cd, Pb, and As also reflect contributions from irrigation farming, sand dredging, laundry, and domestic waste disposal. Mean concentrations of Fe (1.181 mg/L in Ekulu dry season; 1.063 mg/L in Nyaba wet season) and Pb consistently exceeded permissible limits, while Cd and As also remained above safety thresholds across seasons. Seasonal variation showed reduced concentrations in Ekulu River during the wet season due to dilution, but increased contamination in Nyaba River during rainfall, reflecting enhanced leaching as well as intensified human activity. Health risk assessment indicated that Hazard Quotient (HQ) and Hazard Index (HI) values exceeded 1 for both adults and children, while Incremental Lifetime Cancer Risk (ILCR) values for As, Pb, and Cd were above 1×10^{-4}, indicating unacceptable lifetime cancer risks. Children were particularly vulnerable, recording higher risk levels due to their greater sensitivity to metal exposure. The study concludes that Ekulu and Nyaba rivers are unsafe for direct domestic and agricultural use without treatment. It recommends urgent remediation of abandoned coal mines, continuous monitoring of water quality, provision of safe alternative water supplies, and public health interventions to protect exposed communities.*

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1. Introduction

Surface water contamination by heavy metals has become one of the most pressing global environmental and public health challenges. Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and iron (Fe) are of particular concern due to their toxicity, 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 in ecosystems, posing long-term risks to human health and biodiversity. Exposure through contaminated water can result in kidney 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 especially vulnerable to heavy metal contamination due to the phenomenon of Acid Mine Drainage (AMD). AMD occurs when sulfide minerals in exposed rocks react with oxygen and water, generating sulfuric acid that leaches metals into adjacent rivers and streams (Gallagher, 2022; Bigham & Cravotta, 2016). Globally, abandoned and poorly managed mines are responsible for widespread ecological degradation and contamination of freshwater resources (Zhao et al., 2020). In sub-Saharan Africa, weak mine closure policies and inadequate monitoring exacerbate the risks, leaving communities dependent on unsafe water sources (Engwa, Ferdinand, Nwalo, & Unachukwu, 2019).

In Nigeria, particularly Enugu State, abandoned coal mines remain a legacy of the colonial and post-colonial mining era. The Onyeama and Okpara coal mines, once central to Nigeria's energy economy, have since been abandoned without proper reclamation, resulting in continual discharge of AMD into Ekulu and Nyaba rivers (Obiadi, Obiadi, Akudinobi, Mmaduweesi, & Ezim, 2016; Ozoko, 2015). These rivers are crucial sources of water for domestic use, small-scale irrigation, laundry, sand dredging, and other artisanal activities that further increase their vulnerability to pollution (Ken-Onukuba et al., 2021). Previous studies have shown that the pH of these rivers ranges between 3.4 and 5.9, classifying them as weakly to strongly acidic, a typical characteristic of AMD-impacted waters (Akpan, Tse, Giadom, & Adamu, 2021). Elevated levels of Fe, Zn, Pb, and Cu in these rivers have consistently exceeded WHO (2017) guideline values, suggesting a high risk of bioaccumulation and biomagnification across the ecosystem.

The health implications of such contamination are severe. Chronic exposure to heavy metals from drinking or domestic water sources has been associated with liver failure, kidney dysfunction, gastrointestinal disorders, and increased incidences of cancer (Qin et al., 2021; Singh et al., 2022). Children are particularly at risk, given their higher vulnerability to metal poisoning due to developing organs and metabolic processes (WHO, 2017). Consequently, assessing the sources, levels, and seasonal variations of heavy metal contamination in the Ekulu and Nyaba rivers is critical to informing water management strategies, environmental policies, and public health interventions in Enugu State.

This study, therefore, aims to investigate the sources and concentration levels of heavy metals in surface water around abandoned coal mines in Nyaba catchment, Enugu State, Nigeria. By comparing measured concentrations with international standards (WHO, USEPA, and FEPA), the research provides evidence of the potential health risks posed to dependent populations and highlights the urgent need for sustainable remediation and monitoring programs.

Aim and Objectives of the Study

Aim

The aim of this study is to assess the sources and concentration levels of heavy metals in surface water around abandoned coal mines in the Nyaba catchment area of Enugu State, Nigeria, and to evaluate their potential implications for environmental quality and human health.

Objectives

The specific objectives are to:

1. Identify the major sources of heavy metal contamination in Ekulu and Nyaba rivers around the abandoned Onyeama and Okpara coal mines.
2. Determine the concentration levels of selected heavy metals (As, Cd, Co, Fe, Hg, Mn, Ni, Pb, and Se) in the rivers and compare them with WHO, USEPA, and FEPA/NESREA standards.
3. Examine the seasonal variations (dry and wet seasons) in heavy metal concentrations and assess their implications for water quality and human health.

Significance of the Study

This study is of great importance both locally and globally. It provides current and reliable evidence on the extent of heavy metal contamination in surface waters around abandoned coal mines in Enugu State, thereby filling a critical knowledge gap in Southeast Nigeria where environmental monitoring has been limited. The research is significant for public health, as it highlights the risks posed to communities that rely on Ekulu and Nyaba rivers for drinking, cooking, bathing, and irrigation. By identifying contaminants that exceed international guideline values, the study offers vital insights into the potential for non-carcinogenic and carcinogenic health effects, particularly among vulnerable groups such as children.

Furthermore, the findings are expected to guide policymakers, regulatory agencies, and environmental managers in designing effective interventions for water resource protection, mine closure, and pollution remediation. The study also raises awareness among local communities on the dangers of consuming untreated river water, encouraging them to seek safer alternatives and engage in advocacy for improved water management. Beyond the local

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context, this work contributes to global efforts toward achieving Sustainable Development Goal 6, which emphasizes access to clean water and sanitation, and strengthens the scientific understanding of the impacts of Acid Mine Drainage on water resources in mining-affected regions worldwide.

2. Literature Review

Conceptual Clarifications

Acid Mine Drainage (AMD) is recognized as one of the major pathways through which heavy metals are introduced into surface waters. It occurs when sulfide-bearing rocks are exposed to oxygen and water, producing sulfuric acid that dissolves and mobilizes metals such as Fe, Pb, Cd, As, and Hg into rivers and streams (Bigham & Cravotta, 2016; Zhao et al., 2020).

Heavy metals, in turn, are of particular concern because they are non-biodegradable and persistent in aquatic ecosystems. They can accumulate in sediments and aquatic organisms, with the potential to biomagnify through food chains. This persistence poses long-term ecological risks and threatens biodiversity (Briffa, Sinagra, & Blundell, 2020).

Bioaccumulation and biomagnification of heavy metals mean that exposure is not limited to direct water contact but also extends to human populations through fish consumption, irrigation, and livestock watering. Even at low concentrations, prolonged exposure to these metals can cause toxicological effects, ranging from kidney and liver dysfunction to neurological damage and carcinogenic outcomes (Tchounwou, Yedjou, Patlolla, & Sutton, 2012).

By clarifying the concepts of AMD and heavy metal persistence, this study establishes the chemical and ecological basis for understanding the contamination of surface waters in coal-mining regions such as Enugu State, Nigeria.

Theoretical Framework

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

The first is the Acid Mine Drainage (AMD) Theory, which explains the geochemical processes responsible for the release of heavy metals into aquatic environments. When sulfide minerals such as pyrite (FeS_2) are exposed to oxygen and water during mining, they oxidize to produce sulfuric acid. This acidic environment accelerates the dissolution of heavy metals, enhancing their solubility and transport in surface waters (Bigham & Cravotta, 2016). The theory provides the basis for understanding why abandoned coal mines remain long-term sources of Fe, Pb, Cd, As, and Hg in rivers such as Ekulu and Nyaba, even decades after mine closure.

The second is the Bioaccumulation and Biomagnification Framework, which emphasizes the pathways through which heavy metals persist in ecosystems and move up the food chain. Metals that accumulate in aquatic organisms can biomagnify in higher trophic levels, ultimately posing risks to human populations through fish consumption,

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irrigation, and livestock watering (Briffa, Sinagra, & Blundell, 2020). This framework is particularly important in assessing the public health implications of AMD contamination.

In addition, this study draws on the Environmental Risk Assessment (ERA) Model, which links environmental contamination to human health outcomes. The ERA framework emphasizes the pathways of exposure such as ingestion and dermal contact and evaluates whether observed contaminant levels exceed regulatory thresholds established by agencies like the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA) (Tchounwou, Yedjou, Patlolla, & Sutton, 2012).

Together, these frameworks provide a comprehensive theoretical lens for analyzing the sources, levels, and health risks of heavy metal contamination in the Nyaba catchment. While the AMD theory explains the geochemical origins of contamination, the bioaccumulation framework situates its ecological and health consequences, and the ERA model guides the interpretation of results against international standards.

Empirical Review

Global Perspectives on Heavy Metal Contamination

Globally, studies have shown that Acid Mine Drainage (AMD) is a persistent environmental problem in mining regions. In Asia and South America, rivers draining abandoned mines often contain Fe, Pb, Cd, and as at concentrations far above WHO and USEPA guidelines (Singh et al., 2022; Zhao et al., 2020). For instance, mining-impacted rivers in China and Peru have been reported to exhibit both low pH and high dissolved metal loads, leading to widespread fish mortality and soil degradation in agricultural zones irrigated with contaminated water (Rehman, Fatima, Waheed, & Akash, 2018). Similar findings in the United States and Europe show that AMD-affected rivers pose long-term risks, since heavy metals remain in sediments and continue to leach for decades after mine closure (Bigham & Cravotta, 2016). These studies confirm the global pattern of heavy metal pollution from AMD, highlighting its ecological persistence and public health consequences.

African Perspectives

In Africa, heavy metal pollution from mining is widespread due to poorly regulated extractive activities and inadequate mine reclamation practices. Research in South Africa has shown that abandoned gold and coal mines discharge AMD into rivers, leading to elevated Fe, Mn, and Pb concentrations that impair drinking water quality and reduce agricultural productivity (Engwa, Ferdinand, Nwalo, & Unachukwu, 2019). In Ghana, rivers draining artisanal and small-scale mines contain high concentrations of As and Hg, directly linked to mining effluents and unsafe disposal practices (Armah et al., 2010). Studies in Zambia also confirm high levels of Pb and Cd in rivers near abandoned mines, with clear evidence of bioaccumulation in fish consumed by local communities (Chileshe et al., 2021). These findings highlight

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a recurring pattern across Africa: mining-induced contamination of surface water, limited treatment capacity, and significant exposure risks for dependent populations.

Nigerian Studies on Heavy Metal Contamination

In Nigeria, abandoned coal mines in Enugu State remain a major source of AMD. Akpan, Tse, Giadom, & Adamu (2021) reported acidic pH values (3.4–5.9) and high Fe and Pb concentrations in the Ekulu and Nyaba rivers, often exceeding WHO standards. Obiadi et al. (2016) similarly observed elevated levels of Zn, Cu, and Cd in these rivers, attributing contamination to both AMD and anthropogenic inputs such as irrigation farming, sand dredging, and domestic effluent discharge. Ozoko (2015) further noted that AMD from Onyeama and Okpara mines continues to impact water quality decades after abandonment, with downstream communities relying on unsafe water for domestic and agricultural use. While these studies confirm the presence of heavy metals in Enugu coalfield rivers, they have often been limited to point measurements, without systematically examining seasonal variation or statistically identifying pollution sources.

Identified Gaps the Study Addresses

Although numerous studies have demonstrated that Acid Mine Drainage (AMD) is a critical source of heavy metal contamination in surface waters worldwide, important research gaps remain in the Nigerian and Enugu contexts.

First, while global literature provides extensive evidence of heavy metals such as Fe, Pb, Cd, and As in mining-impacted rivers (Bigham & Cravotta, 2016; Zhao et al., 2020), there is still limited empirical data from sub-Saharan Africa, where weak mine closure policies and inadequate monitoring exacerbate pollution risks (Engwa et al., 2019).

Second, within Nigeria, particularly in Enugu coalfield areas, existing studies have confirmed the presence of heavy metals in Ekulu and Nyaba rivers (Akpan et al., 2021; Obiadi et al., 2016). However, many of these studies provide only snapshot measurements and do not systematically analyze seasonal variations (dry versus wet season) in contamination levels. Yet, seasonal dynamics play a critical role in water quality, with dilution during wet seasons and concentration during dry seasons affecting exposure risks.

Third, limited efforts have been made to distinguish between geogenic sources (AMD-related leaching of sulfide minerals) and anthropogenic contributions (such as irrigation runoff, sand dredging, laundry, and domestic waste disposal). The lack of correlation and statistical analysis in many Nigerian studies has left uncertainties about the relative contributions of natural versus human-induced contamination.

Finally, although heavy metal concentrations in Enugu rivers have been reported to exceed WHO and USEPA permissible limits, there has been insufficient linkage to health risk implications for local populations who depend on these rivers

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for drinking, bathing, cooking, and irrigation. Without such assessments, policymakers and communities may underestimate the magnitude of public health risks.

This study addresses these gaps by:

1. Systematically assessing the sources of heavy metal contamination in Ekulu and Nyaba rivers using correlation and statistical analysis.
2. Measuring and comparing seasonal variations in heavy metal concentrations against international standards (WHO, USEPA, and FEPA/NESREA).
3. Providing a holistic interpretation of contamination dynamics and their implications for water quality management and public health protection in mining-impacted communities.

3. Methodology

3.1 Study Area

The study was carried out within the Nyaba catchment area, located in Enugu State, Southeast Nigeria. The catchment hosts the abandoned Onyeama and Okpara coal mines, which are historically significant as major contributors to Nigeria's coal industry. These mines have remained unrehabilitated, and their drainage pathways flow into two major rivers Ekulu and Nyaba.

The Ekulu and Nyaba rivers serve as critical water sources for domestic consumption, small-scale irrigation, fishing, laundry, and recreational activities for surrounding communities. However, they are also highly vulnerable to contamination from Acid Mine Drainage (AMD) and anthropogenic inputs such as farming, sand dredging, and effluent discharges.

The region lies within the tropical rainforest climatic zone, characterized by a wet season (April–October) and a dry season (November–March), with annual rainfall ranging from 1,500 to 2,000 mm and average temperatures between 26°C and 30°C (NIMET, 2022). These seasonal variations strongly influence river flow and pollutant concentrations.

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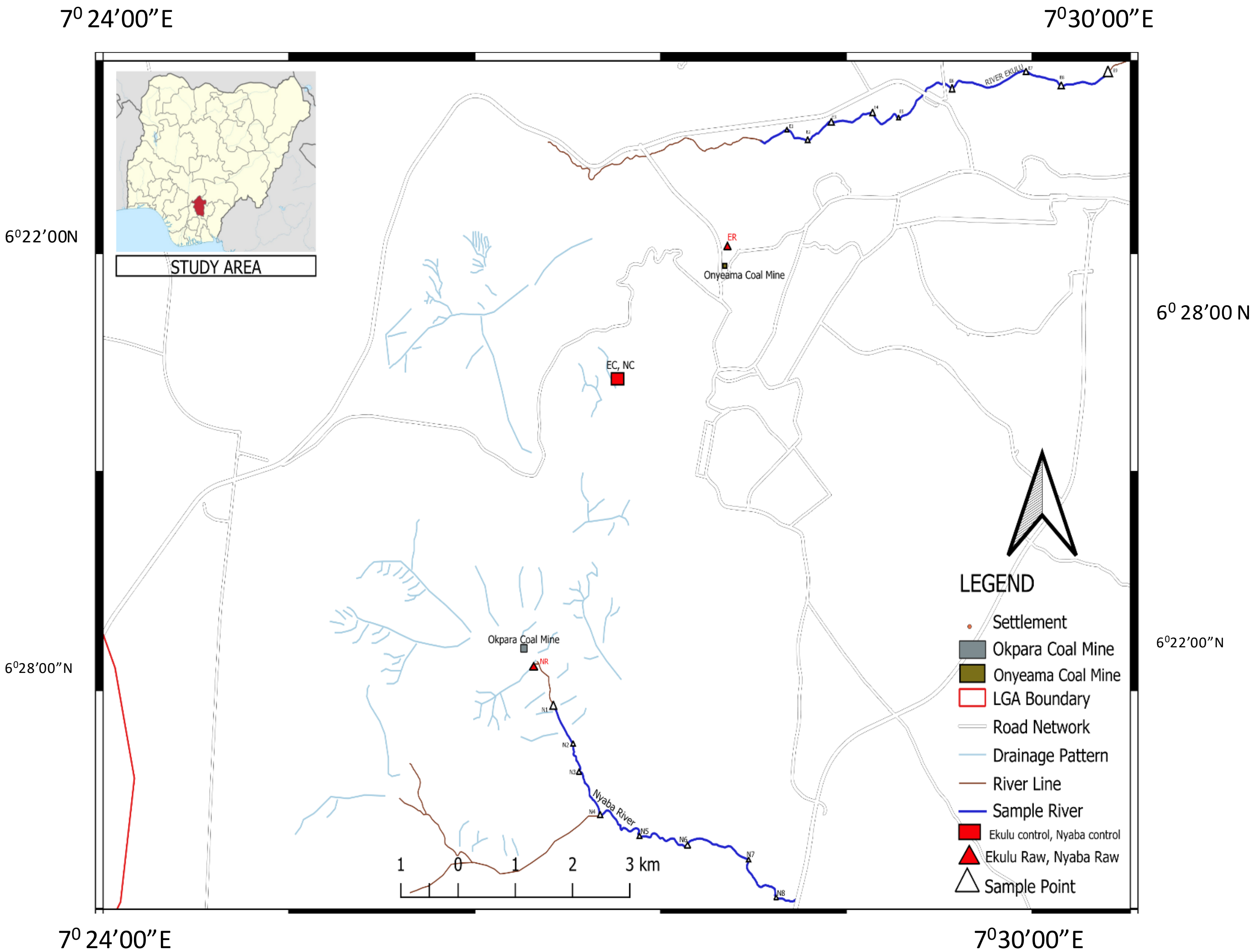

Figure 3.1: Location Map of Onyema Coal Mine, Okpala coal mine, Nyaba River and Ekulu River

Source: Fieldwork, 2023/2024.

3.2 Sampling Design

A stratified sampling approach was employed to capture spatial and seasonal variations in water quality. Sampling points were established at upstream, midstream, and downstream locations along both the Ekulu and Nyaba rivers. This design allowed for the assessment of background water quality (upstream) versus the

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influence of AMD and anthropogenic activities (midstream and downstream).

Sampling was conducted during both the dry season (low-flow conditions) and the wet season (high-flow conditions) to capture seasonal variability. At each point, triplicate water samples were collected, composited, and preserved in pre-cleaned polyethylene bottles. The bottles were rinsed with the river water before final sampling to avoid contamination. Samples were preserved with nitric acid to pH < 2 and stored at 4°C before laboratory analysis. “A total of 18 water samples were collected from Ekulu River (E1–E9, including raw sample ER and control EC) and 16 from Nyaba River (N1–N8, including raw sample NR and control NC) across both wet (August 2023) and dry (January 2024) seasons. Sampling sites were selected at upstream, midstream, and downstream points, as well as at raw mine discharges and distant control locations. The exact coordinates of sampling points are presented in Table 3.1 and Table 3.2.”

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”

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3.3 Laboratory Analysis

Samples were analyzed for arsenic (As), cadmium (Cd), cobalt (Co), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), and selenium (Se) using Atomic Absorption Spectrophotometry (AAS) in accordance with APHA (2017) standard procedures.

Quality assurance and quality control (QA/QC) measures were rigorously applied. These included the use of reagent blanks, calibration with standard solutions, replicate analysis of samples, and recovery checks to ensure accuracy and reliability of results. Each analysis was conducted in triplicate, and mean values were reported.

3.4 Data Analysis

The following statistical techniques were employed:

Descriptive statistics: Means, ranges, and standard deviations were computed to summarize the distribution of heavy metal concentrations. Pearson correlation analysis: Conducted to determine possible relationships among the metals and to distinguish between geogenic (AMD-related) and anthropogenic pollution sources. One-sample t-tests: Used to compare measured heavy metal concentrations with international water quality guidelines, including those of the World Health Organization (WHO, 2017), the United States Environmental Protection Agency (USEPA, 2018), and the Federal Environmental Protection Agency (FEPA/NESREA, 1991), at a significance level of $\alpha = 0.05$. All statistical analyses were carried out using SPSS (version 28).

4. Results

4.1 Sources of Heavy Metals

Pearson correlation analysis was employed to identify the possible sources of heavy metals in the Ekulu and Nyaba rivers during both dry and wet seasons. The results reveal that Acid Mine Drainage (AMD) from the abandoned Onyeama and Okpara coal mines is the dominant source of contamination. This is evidenced by strong positive correlations among Fe, Mn, and other metals typically associated with AMD. At the same time, several weak and negative correlations suggest additional anthropogenic inputs, including irrigation farming, sand dredging, laundry, and domestic effluent disposal

Ekulu River (Dry Season)

Strong positive correlations were observed between Fe and Mn ($r = 0.73$, $p < 0.05$), indicating AMD as a common source. Negative correlations, such as As and Mo ($r = -0.64$), point to multiple sources of contamination.

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Table 4.1: Inter-element correlation matrix among heavy metals in Ekulu river (dry season)

	As	Cd	Co	Fe	Hg	Mn	Mo	Ni	Pb	Se	pH
As	1	0.27	0.43	-0.02	-0.16	-0.03	-0.64*	0.26	-0.24	-0.23	0.05
Cd		1	0.48	-0.04	0.01	0.45	-0.37	-0.14	0.39	-0.82*	-0.30
Co			1	-0.34	0.08	-0.14	-023	-0.45	-0.19	0.34	-0.31
Fe				1	0.34	0.73*	0.04	0.15	0.06	0.06	-0.57
Hg					1	-0.06	0.38	0.06	-0.56*	-0.17	0.53
Mn						1	-0.36	0.17	0.63*	-0.02	0.36
Mo							1	-0.37	-0.25	0.22	0.13
Ni								1	0.09	0.07	0.30
Pb									1	-0.07	0.06
Se										1	-0.34
pH											1

*Significant at 5% alpha level

Source: Field Survey, 2023/2024

Ekulu River (Wet Season)

During the wet season, Cd and Fe (r = 0.85) and As and Cd (r = 0.72) showed strong positive correlations, confirming AMD influence. However, Mn and Cd (r = –0.76) and Mn and Co (r = –0.72) exhibited negative correlations, suggesting additional anthropogenic contributions.

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.

Source: Field Survey, 2023/2024

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Nyaba River (Dry Season)

In Nyaba River, Co and Mn (r = 0.60) and Mn and Pb (r = 0.82) exhibited strong positive correlations, consistent with AMD signatures. Meanwhile, other metals demonstrated weaker associations, indicating localized inputs from human activities.

Table 4.3: 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

Source: Field Survey, 2023/24

Nyaba River (Wet Season)

The wet season results for Nyaba River revealed mixed patterns. While some strong positive correlations persisted (e.g., Pb and Mn), negative correlations between certain metals highlighted additional contamination from domestic and artisanal sources.

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Table 4.4: Inter-element correlation matrix among 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

*Significant at 5% alpha level

Source: Field Survey, 2023/2024

Overall, the correlation matrices confirm that AMD is the principal driver of heavy metal contamination in both rivers, with Fe and Mn showing consistent positive associations typical of mine drainage. However, the presence of weak and negative correlations underscores the contribution of anthropogenic activities such as irrigation, dredging, and waste disposal. This indicates that contamination in the study area is multi-sourced, comprising both geogenic and human-induced pollutants.

4.2 Concentration Levels of Heavy Metals

The concentrations of heavy metals in Ekulu and Nyaba rivers were analyzed during the dry and wet seasons and compared with international and national guideline values from the World Health Organization (WHO, 2017), United States Environmental Protection Agency (USEPA, 2018), and the Federal Environmental Protection Agency (FEPA/NESREA, 1991).

Ekulu River (Dry Season)

Results show that Fe recorded the highest mean concentration (1.181 mg/L), significantly exceeding the WHO limit of 0.30 mg/L. Other metals such as Pb and Cd also exceeded permissible limits, indicating serious contamination risks. Arsenic (As) levels, though lower than Fe, were above the guideline values, reflecting AMD influence.

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Table 4.5: Statistical summary of heavy metal concentrations in Ekulu river (mean ± standard deviation, range) (dry season)

		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 Max Mean ± SD	0.014 0.041 0.024 ± 0.018	0.078 0.048 0.032 ± 0.018	0.013 0.034 0.024 ± 0.009	1.914 2.035 1.970 ± 0.050	0.175 0.218 0.198 ± 0.018	0.054 0.286 0.151 ± 0.087	0.085 0.154 0.128 ± 0.031	0.062 0.613 0.350 ± 0.226	0.007 0.068 0.037 ± 0.025	0.062 0.718 0.469 ± 0.337
E2	Min Max Mean ± SD	0.021 0.251 0.154 ± 0.097	0.038 0.124 0.069 ± 0.039	0.011 0.038 0.028± 0.012	1.181 2.380 1.956 ± 1.475	0.175 0.218 0.198 ± 0.018	0.379 0.402 0.392 ± 0.010	0.010 0.056 0.031 ± 0.020	0.527 1.177 0.883 ±0.271	0.490 0.570 0.512 ±0.206	0.003 0.742 0.267 ±0.337
E3	Min Max Mean ±	0.285 0.436 0.362 ± 0.062	0.065 0.085 0.063± 0.014	0.025 0.047 0.113 ± 0.137	0.021 0.152 0.073 ± 0.052	0.024 0.121 0.076 ± 0.040	0.056 0.118 0.089 ± 0.026	0.011 0.088 0.044 ± 0.033	0.057 0.880 0.334 ±0.386	0.027 0.055 0.045 ±0.013	0.032 0.699 0.260 ±0.311

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	S D										
E4	Mi n M ax M ea n ± S D	0.35 6 0.414 0.38 6 ± 0.20 2	0.03 9 0.05 6 0.04 7± 0.00 7	0.00 9 0.06 8 0.03 3± 0.00 6	0.095 5 2.141 1.664 ± 0.572	0.09 9 0.173 0.130 ± 0.031	0.051 0.497 0.233 ± 0.019	0.038 0.81 0.057 ± 0.018	0.615 1.696 1.231± 0.454	0.000 0.082 0.032 ±0.03 6	0.018 0.511 0.189 ±0.20 7
E5	Mi n M ax M ea n ± S D	0.02 9 0.45 6 0.28 0 ± 0.182	0.02 6 0.051 0.03 9± 0.01 0	0.00 3 0.05 4 0.03 6± 0.041	0.056 2.931 1.022 ±1.35 0	0.106 0.194 0.160 ± 0.03 9	0.061 0.269 0.167 ± 0.085	0.00 0 0.049 0.020 ± 0.021	0.679 1.842 1,316± 0.481	0.000 0.110 0.049 ±0.04 6	0.013 0.665 0.433 ±0.30 5
E6	Mi n M ax M ea n ± S D	0.02 2 0.05 8 0.145 ± 0.150	0.00 3 0.016 0.011 ± 0.00 6	0.00 9 0.051 0.031 ± 0.03 0	0.077 0.124 0.066 ± 0.042	0.102 0.231 0.182 ± 0.052	0.049 0.110 0.091 ±0.02 7	0.041 0.113 0.083 ± 0.052	0.407 1.101 0.954 ±0.40 1	0.018 0.469 0.195 ±0.114	0.799 0.800 0.787 ±0.01 8
E7	Mi n	0.23 2	0.013	0.00 6	0.008 0.090	0.051 0.107	0.026 0.056	0.032 0.062	0.463 1.340	0.000 0.304	0.664 0.752

	Max Mean ± SD	0.438 0.341 ± 0.085	0.042 0.027± 0.016	0.024 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
E8	Min Max Mean ± SD	0.152 0.215 0.174 ± 0.029	0.002 0.053 0.031 ± 0.023	0.021 0.048 0.031 ± 0.037	0.029 2.588 0.907 ± 1.597	0.030 0.111 0.064± 0.001	0.057 0.291 0.144 ±0.105	0.016 0.079 0.040± 0.019	0.274 0.931 0.681 ±0.299	0.040 0.077 0.062 ±0.066	0.004 0.613 0.223 ±0.314
E9	Min Max Mean ± SD	0.094 0.121 0.104 ± 0.012	0.006 0.042 0.021 ± 0.015	0.009 0.044 0.027± 0.014	0.086 2.502 0.913 ± 1.124	0.074 0.106 0.087± 0.014	0.014 0.081 0.037 ±0.031	0.079 0.097 0.089 ± 0.008	0.846 1.136 1.014 ±0.389	0.006 0.133 0.067 ±0.052	0.564 0.628 0.608 ±0.024
ER	Min Max Mea	0.106 0.395 0.265 ±	0.000 0.020 0.007±	0.017 0.054 0.032± 0.051	2.766 2.895 2.811 ± 0.060	0.119 0.235 0.163 ± 0.055	0.200 0.263 0.239 ±0.028	0.018 0.086 0.044 ± 0.030	0.274 1.322 0.814 ±0.428	0.052 0.117 0.088 ±0.027	0.890 1.006 0.962 ±0.061

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	n ± SD	0.120	0.009								
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 ± SD	0.213 ± 0.008	0.019 ± 0.018	0.045± 0.009	0.920 ± 1.300	0.123 ± 0.018	0.929 ±0.099	0.060± 0.033	1.090 ±0.462	0.197 ±0.104	0.006 ±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	0.07	0.07	0.050	0.04
USEPA		0.010	0.005	0.100	0.300	0.002	0.300	0.01	0.02	0.150	0.05
FEPA(NESREA)		0.050	0.003		0.300	0.002	0.200		0.05	0.010	0.01

Source: WHO 2017
USEPA 2018
FEPA (NESREA) 1991

Ekulu River (Wet Season)

During the wet season, Fe (0.736 mg/L) remained the dominant contaminant, still above WHO standards, though slightly reduced compared to the dry season due to dilution from higher rainfall and river discharge. Pb and Cd also remained above permissible limits, confirming persistent contamination.

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Table 4.6: Statistical summary of heavy metal concentration in Ekulu river (mean ± standard deviation range) (wet season)

		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 Max Mean ± SD	0.013 0.020 0.017 ± 0.004	0.004 0.016 0.013 ± 0.008	0.030 0.059 0.049 ± 0.017	0.141 0.569 0.405± 0.231	0.068 0.267 0.170 ± 0.100	0.660 0.941 0.798 ± 0.138	0.086 0.122 0.098 ± 0.021	0.119 0.337 0.231 ± 0.109	0.015 0.055 0.021 ± 0.039	0.024 0.044 0.033± 0.010
E2	Min Max Mean ± SD	0.009 0.012 0.009 ±0.003	0.018 0.041 0.026 ± 0.013	0.005 0.076 0.038± 0.036	0.164 0.571 0.367 ± 0.288	0.108 0.298 0.201 ± 0.095	0.420 1.197 0.879 ± 0.407	0.038 0.056 0.046 ± 0.009	0.275 0.637 0.399± 0.206	0.027 0.051 0.041 ± 0.012	0.045 0.051 0.048± 0.003
E3	Min Max Mean ±	0.011 0.016 0.013± 0.003	0.024 0.043 0.034 ± 0.010	0.013 0.057 0.037 ± 0.022	0.159 0.957 0.624 ± 0.415	0.103 0.176 0.136 ± 0.037	0.330 1.297 0.907 ± 0.510	0.021 0.033 0.027 ± 0.006	0.271 0.052 0.258± 0.200	0.003 0.022 0.014 ± 0.010	0.055 0.068 0.060± 0.007

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	SD										
E4	Min Max Mean ± SD	0.010 0.020 0.014± 0.006	0.022 0.043 0.032 ± 0.011	0.001 0.093 0.037 ± 0.044	0.331 0.642 0.443 ± 0.173	0.053 0.119 0.106 ± 0.048	0.316 0.885 0.691 ± 0.325	0.022 0.189 0.079 ± 0.095	0.260 0.425 0.322 ± 0.090	0.005 0.054 0.032 ± 0.025	0.049 0.058 0.054± 0.005
E5	Min Max Mean ± SD	0.010 0.037 0.022 ±0.014	0.011 0.049 0.031 ± 0.019	0.013 0.051 0.035 ± 0.020	0.520 0.850 0.631 ± 0.189	0.015 0.161 0.084 ± 0.073	0.226 1.092 0.563 ± 0.564	0.019 0.063 0.036 ± 0.024	0.406 0.735 0.573 ± 0.165	0.027 0.062 0.040± 0.019	0.044 0.059 0.050± 0.008
E6	Min Max Mean ± SD	0.019 0.028 0.024 ±0.005	0.003 0.051 0.027 ± 0.024	0.011 0.019 0.015 ± 0.004	0.430 0.799 0.628± 0.186	0.074 0.114 0.100 ± 0.023	0.619 0.950 0.745 ± 0.179	0.017 0.029 0.023 ± 0.006	0.190 0.751 0.428± 0.290	0.020 0.071 0.045 ± 0.026	0.018 0.025 0.022± 0.004

E7	Min Max Mean ± SD	0.017 0.023 0.021± 0.003	0.032 0.065 0.051 ± 0.017	0.000 0.094 0.039 ± 0.049	0.539 1.140 0.884± 0.310	0.058 0.094 0.074 ± 0.018	0.389 1.022 0.556 ± 0.410	0.017 0.023 0.020 ± 0.003	0.332 0.490 0.411 ± 0.079	0.026 0.062 0.043 ± 0.018	0.037 0.046 0.044± 0.006
E8	Min Max Mean ± SD	0.024 0.032 0.028 ±0.004	0.051 0.075 0.067 ± 0.011	0.028 0.048 0.036 ± 0.011	1.127 1.610 1.327 ± 0.252	0.083 0.147 0.121 ± 0.034	0.109 0.277 0.210 ± 0.089	0.012 0.016 0.014 ± 0.002	0.482 0.634 0.539 ± 0.083	0.018 0.029 0.024 ± 0.006	0.036 0.049 0.041 ± 0.007
E9	Min Max Mean ± SD	0.019 0.022 0.021± 0.002	0.055 0.075 0.067 ± 0.011	0.023 0.039 0.030± 0.008	0.900 1.398 1.076 ± 0.280	0.073 0.184 0.139 ± 0.058	0.360 1.257 0.750 ± 0.460	0.011 0.022 0.018 ± 0.006	0.250 0.834 0.513 ± 0.296	0.021 0.081 0.042 ± 0.034	0.033 0.061 0.049± 0.015
ER	Min Max	0.027 0.038	0.072 0.098	0.018 0.069 0.037 ±	0.780 1.352	0.030 0.119	0.094 0.343	0.108 0.122 0.116	0.339 0.549	0.010 0.067	0.074 0.108

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	Mean ± SD	0.032 ±0.006	0.088± 0.014	0.028	0.975 ± 0.326	0.068 ± 0.046	0.179 ± 0.142	± 0.007	0.434± 0.106	0.040± 0.029	0.090± 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 ± SD	0.011± 0.002	0.099 ± 0.011	0.053 ± 0.049	0.470 ± 0.182	0.044 ± 0.038	0.092 ± 0.022	0.016 ± 0.002	0.453 ± 0.084	0.022 ± 0.017	0.019 ± 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

Nyaba River (Dry Season)

For Nyaba River, Fe averaged 0.797 mg/L in the dry season, again above the WHO limit. Pb and As were also above safe thresholds, while Ni and Mn concentrations fluctuated within borderline limits. The results confirm Nyaba River as highly impacted by AMD and additional anthropogenic sources.

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Table 4.7: Statistical summary of heavy metal concentrations in Nyaba river (mean ± standard deviation range) (dry season)

		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

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N5	Min Max Mean ± SD	0.28 9 0.371 0.111 ±0.2 24	0.07 5 0.181 0.121 ±0.0 45	0.03 0 0.04 8 0.04 1±0. 008	0.068 1.956 0.728 ± 1.187	0.10 6 0.138 0.121 ±0.0 13	0.00 5 0.20 1 0.07 6±0. 089	0.02 0 0.06 0 0.03 6±0. 017	1.06 4 0.29 3 0.172 ±0.5 20	0.05 0 0.10 0 0.02 2±0. 021	0.02 0 0.64 8 0.42 2±0. 282
N6	Min Max Mean ± SD	0.371 0.42 7 0.133 ±0.2 67	0.00 4 0.04 1 0.02 1±0. 015	0.03 7 0.06 7 0.04 8±0. 013	1.081 0.222 0.508 ± 0.405	0.10 4 0.162 0.130 ±0.0 24	0.217 0.44 7 0.312 ±0.0 98	0.03 8 0.10 5 0.06 5±0. 030	1.46 0 0.38 8 0.71 0±0. 532	0.05 4 0.07 0 0.06 1±0. 007	0.31 9 0.64 1 0.531 ±0.1 50
N7	Min Max Mean ± SD	0.331 0.46 5 0.37 7±0. 365	0.01 8 0.03 1 0.02 4±0. 005	0.04 6 0.05 9 0.05 8±0. 005	0.271 0.431 0.490 ± 0.179	0.10 0 0.176 0.143 ±0.0 32	0.30 4 1.015 0.55 3±0. 333	0.02 7 0.14 6 0.06 8±0. 055	0.10 2 0.411 0.30 8±0. 143	0.07 7 0.141 0.116 ±0.0 31	0.00 0 0.00 7 0.00 4±0. 003
N8	Min Max Mean ± SD	0.26 4 0.43 3 0.34 7±0. 069	0.01 6 0.10 3 0.07 2±0. 040	0.04 0 0.07 6 0.05 6±0. 015	0.462 2.200 1.043 ± 0.818	0.135 0.185 0.16 0±0. 025	0.88 2 1.037 0.95 6±0. 064	0.03 9 0.07 8 0.05 4±0. 017	0.26 8 0.68 2 0.49 3±0. 177	0.05 8 0.09 8 0.08 0±0. 017	0.53 2 0.58 2 0.56 3±0. 022
NR	Min Max Mean ± SD	0.31 8 0.38 8	0.01 2 0.04 0	0.03 8 0.06 0	0.122 0.263 0.918 ±0.05 8	0.103 0.210 0.144 ±0.0 48	0.00 9 0.33 5	0.01 9 0.03 3	0.22 3 1.526 0.83 5±0. 927	0.153 0.19 9 0.181 ±0.0 20	0.88 6 1.055 0.96 9±0. 069

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		0.362±0.032	0.027±0.012	0.052±0.009			0.140±0.140	0.028±0.006			
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

Source: WHO 2017
USEPA 2018
FEPA (NESREA) 1991

Nyaba River (Wet Season)

In the wet season, Fe levels (1.063 mg/L) were higher than in the dry season, contrary to the Ekulu River trend. This may be attributed to increased leaching of mine water into the Nyaba River during high rainfall periods. Pb, Cd, and As remained above guideline values, while Co and Ni were moderately elevated.

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Table 4.8: Statistical summary of heavy metal concentrations in Nyaba river (mean ± standard deviation range) (wet season)

		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 ± SD	0.023 ±0.003	0.087 ±0.017	0.094 ±0.034	0.974 ±0.339	0.047 ±0.019	0.347 ±0.209	0.043 ±0.004	0.595 ±0.223	0.037 ±0.024	0.025 ±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 ± SD	0.020 ±0.001	0.115 ±0.010	0.070 ±0.031	1.190 ±0.263	0.047 ±0.034	0.413 ±0.333	0.046 ±0.007	0.487 ±0.123	0.035 ±0.008	0.023 ±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 ± SD	0.023 ±0.004	0.111 ±0.013	0.069 ±0.041	1.114 ±0.293	0.091 ±0.100	0.545 ±0.130	0.035 ±0.006	0.555 ±0.080	0.023 ±0.036	0.035 ±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 ± SD										

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		0.026 ±0.004	0.101 ±0.008	0.114 ±0.031	1.012 ±0.235	0.037 ±0.011	0.585 ±0.339	0.031 ±0.005	0.681 ±0.249	0.025 ±0.023	0.046 ±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..04	0.748	0.026	0.383	0.034	0.650	0.030	0.036
	± SD	±0.003	±0.010	7±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

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FEPA(NESREA)	0.100	0.003	0.300	0.050	0.050	0.010	0.010

Source: WHO 2017
USEPA 2018
FEPA (NESREA) 1991

Across both rivers, Fe consistently emerged as the most dominant contaminant, with mean concentrations exceeding WHO, USEPA, and FEPA standards in all seasons. Pb and Cd were also consistently above permissible limits, underscoring their significance as health-threatening pollutants. Seasonal variations showed higher Fe in the Ekulu River during the dry season (low dilution effect) and higher Fe in the Nyaba River during the wet season (increased leaching effect). These results demonstrate that both rivers are significantly contaminated and unsuitable for direct domestic or agricultural use without treatment.

4.3 Health Risk Assessment

The health risks of heavy metal exposure from Ekulu and Nyaba rivers were assessed for both non-carcinogenic and carcinogenic effects, considering two exposure pathways: ingestion of water and dermal absorption during bathing/washing. The risks were estimated for both adults and children, using standard exposure equations and guideline reference doses.

4.3.1 Non-Carcinogenic Risk (Hazard Quotient and Hazard Index)

The Hazard Quotient (HQ) values for Fe, Pb, Cd, and As in both rivers exceeded the safety threshold of HQ > 1, indicating potential non-carcinogenic health effects. Children were found to be more vulnerable than adults due to their lower body weight and higher relative exposure rates.

In Ekulu River (dry season), Pb and Cd recorded HQ values greater than 2 for both adults and children, while Fe exceeded the limit marginally. The Hazard Index (HI), representing the cumulative effect of multiple metals, was well above 1 in all cases.

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Table 4.9: Chronic daily intake of heavy metals for ingestion and dermal routes for Ekulu river (dry season) (mg/kg-day)

Site/parameter		E1	E2	E3	E4	E5	E6	E7	E8	E9	ER	RfD
Ingestion												
As	Adult	6.60E - 03	4.2E - 03	9.9E - 03	1.10E – 02	7.70E – 03	4.00E – 03	9.30E – 03	4.80E - 03	2.60E - 03	7.30E – 03	3.0 0E – 04
	Children	1.50E - 03	9.8E - 03	2.3E - 02	2.5E - 02	7.9E - 02	9.30E - 03	2.20E - 02	1.10E – 02	6.60E – 03	1.70E - 02	
Cd	Adult	8.8E – 04	1.9E – 03	1.7E – 03	1.30E – 03	1.10E – 03	3.00E – 04	7.40E – 04	8.40E - 04	5.60E – 04	2.00E – 04	5.0 0E – 04
	Children	2.0E – 03	4.4E – 03	4.0E – 03	3.00E – 03	2.50E – 03	7.00E – 04	1.70E – 03	2.00E - 03	1.30E – 03	4.50E – 04	
Co	Adult	6.6E - 04	7.7E 04	3.1E - 03	9.00E – 04	9.90E – 04	859 0E – 04	4.90E – 04	8.50E – 04	7.40E – 04	8.80E – 04	3.0 0E – 04
	Children	1.5E - 03	1.8E – 03	7.2E – 03	2.10E – 03	2.30E – 03	2.00E – 03	1.20E – 03	2.00E – 03	1.70E – 03	2.00E – 03	
Fe	Adult	5.4E – 03	5.4 E – 02	2.0E – 03	4.60E – 02	2.80E – 02	1.80E – 03	1.30E – 03	2.50E – 02	2.50E – 02	7.70E – 02	7.0 0E – 01
	Children	1.3E – 01	1.3E – 01	4.7E – 03	1.10E - 01	6.50E - 02	4.20E - 03	3.10E - 03	5.80E – 02	5.50E – 02	1.80E – 01	
Hg	Adult	5.4E – 03	2.1E – 03	3.6E – 03	4.40E - 03	5.00E - 03	2.20E - 03	1.80E - 03	2.20E – 03	4.50E – 03	3.40E - 03	3.0 0E – 04
	Children	1.3E – 02	4.9E – 03	8.3E – 03								

					1.00E - 02	1.20E - 02	5.20E - 03	4.10E - 03	5.10E – 03	1.00E – 02	7.90E – 03	
Mn	Adult Children	4.1E – 03 9.6E – 03	1.1E – 02 2.5E – 02	2.4E – 03 5.7E – 03	6.40E - 03 1.50E - 02	4.60E - 03 1.10E - 02	2.50E - 03 5.80E - 03	7.10E - 04 1.90E - 03	3.90E – 03 9.20E – 02	1.00E – 03 2.40E – 03	6.50E – 03 1.50E – 02	2.40E – 02
Mo	Adult Children	3.5E – 03 8.2E - 03	8.4E – 04 2.0E – 03	1.2E – 03 2.8E – 03	1.60E - 03 3.60E – 03	5.50E - 04 1.30E – 03	2.20E - 03 5.30E – 03	1.30E - 03 3.10E – 03	1.10E – 03 2.60E – 03	2.40E – 03 5.70E – 03	1.20E – 03 2.80E – 03	5.00E – 03
Ni	Adult Children	9.6E – 03 2.2E – 02	2.4E – 02 5.6E – 02	9.2E – 03 2.10E – 02	3.40E - 02 7.90E - 02	3.60E - 02 8.40E – 02	2.60E - 02 6.10E – 02	2.30E - 02 5.40E – 02	1.70E – 02 4.40E – 02	2.80E - 02 6.50E – 02	2.20E – 02 5.20E – 02	2.00E – 02
Pb	Adult Children	1.0E – 03 2.4E – 03	1.4E – 02 3.3E – 02	1.20 – 03 2.90E – 03	8.80E - 04 2.00E - 03	1.30E - 03 3.10E – 03	5.30E - 03 1.20E - 02	3.00E - 03 7.10E – 03	1.70E – 03 4.00E – 03	1.80E – 03 4.30E – 03	2.30E – 03 5.40E – 30	1.40E – 03
Se	Adult Children	1.3E – 02 3.0E - 02	7.3E – 03 1.7E - 02	7.10E – 03 1.70E - 02	5.20E - 03 1.20E - 02	1.20E - 02 2.80E – 02	2.20E - 02 5.00E - 02	2.00E - 02 4.70E - 02	6.10E – 03 1.40E – 02	1.70E – 02 3.90E - 02	2,60E – 02 6.10E – 02	5.00E – 03
Dermal												

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As	Adult Children	3.40 E - 06 1.00 E - 05	2.20 E - 05 6.50 E - 05	5.20 E - 05 1.50 E - 04	5.50 E - 05 1.60 E - 04	4.00 E – 05 1.20 E - 04	2.10 E - 05 6.10 E - 05	4.90 E - 05 1.40 E - 04	2.50 E - 05 7.30 E – 05	1.50 E - 05 4.40 E - 05	8.80 E – 05 1.10 E - 04	2.85E – 04
Cd	Adult Children	4.60 E - 06 1.10 E - 05	9.90 E - 06 3.00 E - 05	9.90 E - 06 2.70 E - 05	6.70 E - 06 2.00 E - 05	5.60 E – 06 1.60 E - 05	1.60 E - 06 4.60 E - 06	3.90 E - 06 1.10 E - 05	4.40 E - 06 1.30 E – 05	3.00 E - 06 8.90 E - 06	1.00 E – 06 3.00 E - 05	2.50E - 05
Co	Adult Children	3.40 E-06 1.00 E-05	4.00 E-06 1.20 E-05	1.60 E-05 4.80 E-05	4.70 E-06 1.40 E-05	5.10 E-06 1.50 E-05	4.40 E-06 1.30 E-05	2.60 E-06 7.60 E-06	4.40 E-06 1.30 E-05	3.90 E-06 1.10 E-05	4.60 E-06 1.40 E-05	6.00E – 05
Fe	Adult Children	2.80 E - 04 8.30 E - 04	2.80 E - 04 8.30 E - 04	1.00 E - 05 3.10 E - 05	2.40 E - 04 7.10 E - 04	1.50 E – 04 4.30 E - 04	9.40 E - 06 2.80 E - 05	7.00 E - 06 2.10 E - 04	1.60 E - 04 3.80 E – 04	1.30 E - 04 3.90 E - 04	4.00 E – 04 1.20 E - 03	1.40 E – 01
Hg	Adult Children	2.80 E - 04 8.30 E - 04	1.10 E - 05 3.20 E - 05	1.90 E - 05 5.50 E - 05	2.30 E - 05 6.80 E – 05	2.60 E – 05 7.70 E - 05	1.20 E - 05 3.50 E - 05	9.20 E - 05 2.70 E - 05	1.20 E - 05 3.70 E – 05	2.3E - 05 6.90 E - 05	1.80 E – 05 5.20 E - 05	2.10 E – 05
Mn	Adult Children	2.20 E - 05	5.60 E - 05	1.30 E - 05	3.30 E - 05	2.40 E – 05	1.30 E - 05	4.10 E - 06	2.10 E - 05	5.30 E - 06	3.40 E – 05	8.30E – 04

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		6.40 E - 05	1.70 E - 04	3.80 E - 05	9.80 E – 05	7.00 E - 05	3.80 E - 05	1.20 E - 05	6.10 E - 05	1.60 E - 05	1.00 E - 04	
Mo	Adult Children	1.0E – 05 5.40 E - 05	4.40 E - 06 1.30 E - 05	6.30 E - 06 1.90 E - 05	8.20 E - 06 2.40 E – 05	2.90 E – 06 8.40 E - 06	1.20 E - 05 3.50 E - 05	7.00 E - 06 2.10 E - 05	5.70 E - 06 1.60 E - 05	1.30 E - 05 3.80 E - 05	6.30 E – 06 1.90 E - 05	5.0 0E – 03
Ni	Adult Children	5.00 E - 05 1.50 E - 04	1.30 E-04 3.50 E-04	4.80 E-05 1.40 E-04	1.80 E-04 5.20 E-04	1.90 E-04 5.60 E-04	1.40 E-04 4.00 E-04	1.20 E-04 3.50 E-04	9.70 E-05 2.90 E-04	1.50 E-04 4.30 E-04	1.20 E-04 3.40 E-04	8.0 0E – 04
Pb	Adult Children	5.30 E - 06 1.60 E - 05	7.40 E - 05 2.20 E - 04	6.40 E - 06 1.90 E - 05	4.60 E - 06 1.40 E – 05	7.00 E - 06 2.00 E - 05	2.80 E - 05 8.20 E - 04	1.60 E - 05 4.70 E - 05	8.90 E - 06 2.60 E - 05	9.60 E - 06 2.80 E - 05	1.20 E – 05 3.60 E - 05	4.2 0E – 04
Se	Adult Children	6.70 E - 05 2.00 E – 04	3.80 E - 05 1.10 E - 04	3.70 E - 05 1.10 E - 04	2,70 E - 05 8.00 E – 05	6.20 E - 05 1.80 E - 04	1.10 E - 04 3.30 E - 04	1.10 E - 04 3.10 E - 04	3.20 E - 05 9.40 E - 04	8.60 E - 05 2.50 E - 04	1.40 E – 04 4.00 E - 04	5.0 0E – 03

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Table 4.10: Ingestion/ dermal hazard quotients and hazard index for adult and children in the stations (Ekulu river), (dry season)

Sites/ parameter	E1		E2		E3		E4		E5		E6		E7		E8		E9		ER	
Ingestion	HQ Adult	HQ Children	HQ Adult	HQ children	HQ Adult	HQ Children	HQ Adult	HQ Children	HQ Adult	HQ children	HQ Adult	HQ children	HQ Adult	HQ children	HQ Adult	HQ Children	HQ Adult	HQ children	HQ Adult	HQ Children
As	2.20E+00	5.00E+00	14.00E+00	32.00E+00	33.00E+00	36.70E+00	36.70E+00	83.30E+00	25.70E+00	263.00E+00	13.30E+00	31.00E+00	31.00E+00	73.00E+00	16.00E+00	36.70E+00	9.30E+00	22.00E+00	24.30E+00	56.70E+00
Cd	1.70E+00	4.00E+00	3.80E+00	8.80E+00	3.40E+00	8.00E+00	2.60E+00	6.00E+00	2.20E+00	5.00E+00	6.00E-01	1.40E+00	1.50E+00	3.40E+00	1.70E+00	4.00E+00	1.10E+00	2.60E+00	4.00E-01	9.00E-01
Co	2.20E+00	5.00E+00	2.60E+00	6.00E+00	10.30E+00	24.00E+00	3.00E+00	7.00E+00	3.30E+00	7.70E+00	33.00E+00	6.70E+00	16.30E+	4.00E+00	2.80E+00	6.70E+00	2.50E+00	5.70E+00	2.90E+00	6.70E+00

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													00							
Fe	1.00E-01	2.00E-01	1.00E-01	2.00E-01	2.90E-03	6.70E-03	1.00E-01	2.00E-01	4.00E-00	1.00E-01	2.60E-03	6.00E-03	1.90E-03	4.40E-03	3.60E-02	8.30E-02	3.60E-02	8.30E-02	1.10E-01	2.60E-01
Hg	18.00E+00	43.00E+00	7.00E+00	16.30E+00	12.00E+00	27.70E+00	14.70E+00	33.30E+00	16.70E+00	4.00E+00	7.30E+00	17.30E+00	6.00E+00	13.70E+00	7.30E+00	17.00E+00	15.00E+00	33.00E+00	11.30E+00	26.30E+00
Mn	1.70E-01	4.00E-00	4.60E-00	1.00E+00	1.00E-01	2.40E-00	2.70E-00	6.30E-00	2.00E-00	4.60E-01	1.00E-01	2.40E-01	3.30E-02	7.90E-02	1.60E-01	3.80E+00	4.20E-02	1.00E-01	2.70E-01	6.30E-01
Mo	7.00E-01	1.60E+00	1.70E-00	4.00E-00	2.40E-00	5.60E-00	3.20E-01	7.20E-01	1.10E-01	2.60E-01	4.40E-01	1.10E+00	2.60E-01	6.20E-01	2.20E-01	5.20E-01	4.80E-01	1.10E+00	2.40E-01	5.60E-01
Ni	4.80E-	1.10E+00	1.20E+	2.80E+00	4.60E+00	1.10E+00	1.70E+	4.00E+00	1.80E+	4.20E+00	1.30E+	3.10E+00	1.20E+	2.76E+00	8.50E-	2.20E+00	1.40E+	3.30E+00	1.10E+	2.60E+00

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	01		00				00		00		00		00		01		00		00	
Pb	7.10E-01	1.70E+00	10.0E+00	23.60E+00	8.60E-01	2.10E+00	6.30E-00	1.40E+00	9.30E-01	2.20E+00	3.80E+00	8.60E+00	2.10E+00	5.10E+00	1.20E+00	2.90E+00	1.30E+00	3.10E+00	1.60E+00	3.90E+00
Se	2.60E+00	6.00E+00	1.50E+00	3.40E+00	1.40E+00	3.40E+00	1.00E+00	2.40E+00	2.40E+00	5.60E+00	4.40E+00	10.00E+00	4.00E+00	9.40E+00	1.20E+00	2.80E+00	3.80E+00	7.80E+00	5.20E+00	12.20E+00
HI	28.90E+00	68.30E+00	40.80E+00	95.20E+00	65.90E+00	143.80E+00	61.00E+00	139.00E+00	53.40E+00	329.0E+00	64.00E+00	79.40E+00	61.20E+00	112.30E+00	31.50E+00	76.90E+00	35.00E+00	78.00E+00	47.00E+00	110.10E+00
Dermal																				
AS	1.20E-02	3.50E-02	7.70E-02	2.30E-01	1.80E-01	5.30E-01	1.90E-01	5.60E-01	1.40E-01	4.20E-01	7.40E-02	2.10E-01	1.70E-01	4.90E-01	8.80E-01	2.60E-01	5.30E-02	1.50E-01	1.30E-01	3.90E-01

Cd	1.80E-01	5.60E-01	4.00E-01	1.20E+00	3.60E-01	1.10E+00	2.70E-01	8.00E-01	2.20E-01	6.40E-01	6.40E-02	1.80E-01	1.60E-01	4.40E-01	1.80E-01	5.20E-01	1.20E-01	3.60E-01	4.00E-02	1.20E-01
Co	5.90E-02	1.70E-01	6.70E-02	2.00E-01	2.70E-01	8.00E-01	7.80E-02	2.30E-01	8.50E-02	2.50E-01	7.30E-02	2.20E-01	4.30E-02	1.30E-01	7.30E-01	2.20E-01	6.50E-01	1.80E-01	7.70E-02	2.30E-01
Fe	2.00E-03	5.90E-03	2.00E-03	5.90E-03	7.10E-05	2.20E-04	1.70E-03	5.10E-01	1.10E-03	3.10E-03	6.70E-05	2.00E-04	5.00E-05	1.50E-04	1.10E-01	2.70E-03	9.30E-04	2.10E-03	2.90E-01	8.60E-03
Hg	1.30E+00	4.00E+00	5.20E-01	1.50E+00	9.00E+00	2.60E+00	1.10E+00	3.20E+00	1.20E+00	3.70E+00	5.70E+00	1.90E+00	4.40E-01	1.30E+00	5.70E-01	1.80E+00	1.10E-01	3.30E+00	8.60E-01	2.50E+00
Mn	2.70E-02	7.70E-02	6.70E-02	2.00E-01	1.60E-02	4.60E-02	4.00E-02	1.20E-01	2.90E-02	8.40E-02	1.60E-02	4.60E-02	5.00E-03	1.40E-02	2.50E-02	7.30E-02	6.40E-03	1.90E-02	4.10E-02	1.20E-01

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Mo	3.60E-03	1.10E-02	8.80E-04	2.60E-02	1.30E-03	3.80E-03	1.60E-03	4.80E-03	5.80E-04	1.70E-03	2.40E-03	7.00E-03	1.40E-03	4.20E-03	1.10E-03	3.20E-03	2.60E-03	7.60E-03	1.30E-03	3.80E-03
Ni	6.30E-02	1.90E-01	1.60E-01	4.40E-01	6.00E-02	1.80E-01	2.30E-01	6.50E-01	2.40E-01	7.00E-01	1.80E-01	5.00E-01	1.50E-01	4.40E-01	1.20E-01	3.60E-01	1.90E-01	5.40E-01	1.50E-01	4.30E-01

Table 4.10 Ingestion/ dermal hazard quotients and hazard index for adult and children in the stations (Ekulu river), (dry season) Contd.

Pb	**1.30E-02**	**3.80E-02**	**1.80E-01**	**5.20E-01**	**1.50E-02**	**4.50E-02**	**1.10E-02**	**3.30E-02**	**1.70E-02**	**4.80E-02**	**6.70E-02**	**2.00E-01**	**3.80E-02**	**1.10E-01**	**2.10E-02**	**6.20E-02**	**2.30E-02**	**6.70E-02**	**2.90E-02**	**8.60E-02**
Se	1.30E-02	4.00E-02	7.60E-03	2.20E-02	7.40E-03	2.20E-02	5.40E-03	1.60E-02	1.20E-02	3.60E-02	2.20E-02	6.60E-02	2.20E-02	6.20E-02	0.40E-03	1.90E-02	1.70E-02	5.00E-02	2.80E-02	8.00E-02
HI	1.70E+00	5.10E+00	1.50E+00	4.30E+00	1.80E+00	5.30E+00	1.90E+00	5.60E+00	1.70E+00	5.90E+00	6.20E+00	3.10E+00	9.90E-01	3.00E+00	1.10E+00	3.00E+00	5.90E-01	4.70E+00	1.40E+00	4.00E+00

In Nyaba River (dry season), HQ values for Pb, Fe, and As were particularly high, with children showing HI values above 3, signaling significant health risks.

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Table 4.11: Chronic daily intake of heavy metals for ingestion and dermal routes for Nyaba river (dry season) (mg/kg-day)

Site/parameter		N1	N2	N3	N4	N5	N6	N7	N8	NR	RfD
Ingestion											
AS	Adult	8.30 E - 03	1.10 E – 02	9.00 E – 03	8.90 E – 03	3.00 E – 03	3.60 E – 03	1.30 E – 02	9.50 E – 03	9.90 E – 03	3.00 E – 04
	Children	1.90 E - 02	2.50 E – 02	2.10 E – 02	2.10 E – 02	7.10 E – 03	8.50 E – 03	2.40 E - 02	2.20 E - 02	2.30 E - 02	
Cd	Adult	6.60 E - 04	5.50 – 04	8.80 E – 04	4.90 E – 04	3.30 E – 03	5.80 E – 04	6.60 E – 04	2.00 E – 03	7.40 E – 04	5.00 E – 04
	Children	1.50E - 03	1.30 E – 03	2.00 E – 03	1.10 E – 03	7.70 E – 03	1.30 E – 04	1.50 E - 03	4.60 E - 03	1.70 E - 30	
Co	Adult	9.60 E - 04	6.00 E – 04	6.80 E – 04	1.40 E – 03	1.10 E – 03	1.30 E – 03	1.50 E – 03	1.50 E – 03	1.40 E – 03	3.00 E – 04
	Children	2.20 E- 03	1.40 E – 03	1.60 E – 03	3.30 E – 03	2.60 E – 03	3.10 E – 03	3.40 E - 03	3.60 E - 03	3.30 E - 03	
Fe	Adult	3.20 E - 02	3.00 E – 02	1.90 E – 02	1.40 E – 02	2.00 E – 02	1.40 E – 02	1.30 E – 02	2.90 E 0.2	2.50 E – 02	7.00 E – 01
	Children	7.40 E - 02	7.10 – 02	4.50 E – 02	3.30 E – 02	4.70 E – 02	3.20 E – 02	3.10 E - 02	6.70 E - 02	5.90 E – 02	
Hg	Adult Children	3.00 E - 03	4.00 E – 03	4.50 E – 03	3.80 E – 03	3.30 E – 03	3.60 E – 03	3.90 E – 03	4.40 E – 03	3.90 E – 03	3.00 E – 04

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		7.00E-03	9.40E–03	1.00E–02	8.50E–03	7.70E–03	8.30E–03	9.10E-03	1.00E-02	9.20E-03	
Mn	Adult	1.30E-03	6.70E–03	1.60E–03	7.60E–03	2.10E–03	8.50E–02	1.50E–02	2.60E–02	3.80E–03	2.40E–02
	Children	2.90E-03	5.70E–02	3.80E–03	1.80E–02	4.90E–03	2.00E–02	3.50E-02	6.10E-02	8.90E-03	
Mo	Adult	1.50E–03	1.40E–03	9.60E–04	1.50E 03	9.90E–04	1.80E–03	1.90E–03	1.50E–03	7.70E–04	5.00E–03
	Children	3.40E–03	3.30E–03	2.20E–03	3.60E-03	2.30E–03	4.20E–03	4.30E-03	3.50E-03	1.80E-03	
Ni	Adult	2.30E–02	2.40E–02	2.20E–02	1.30E–03	4.70E–03	1.90E–02	8.40E–03	1.30E–02	2.30E–02	2.00E–02
	Children	5.40–02	5.60E–02	5.10E–02	3.10E–03	1.10E–02	4.50E–02	1.90E-02	3.00E-02	5.30E-02	
Pb	Adult	2.20E–03	9.60E–04	3.50E–03	1.50E–03	2.00E–03	1.70E-03	3.20E–03	2.20E–03	5.00E–03	1.40E–03
	Children	5.20E–03	2.20E–03	8.10E–03	3.50E–03	4.60E–03	3.90E–03	7.40E-03	5.10E-03	1.20E-02	
Se	Adult	7.50E--02	3.20E–03	1.40E–02	6.40E–03	1.20E–02	1.50E–02	1.10E–04	1.50E–02	2.70E–02	5.00E–03
	Children	2.70E-02	7.50E–03	3.30E–02	1.50E–02	2.70E-02	3.40E–02	2.60E-04	3.60E-02	6.20E-02	
Dermal											

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As	Adult Children	4.30E–05 1.30E–04	5.60E–05 1.70E–04	4.70E–05 1.40E–04	4.70E–05 1.40E–04	1.60E–05 4.70E–05	1.90E-05 5.60E–05	5.40E–05 1.60E-04	5.00E–05 1.50E-04	5.20E–05 1.50E–04	2.85E–04
Cd	Adult Children	3.40E–06 1.00E–05	2.90E–06 8.40E–06	5.30E–06 1.60E–05	2.40E–06 7.20E–06	1.70E–05 5.10E–05	3.00E–05 5.60E–05	3.40E–06 1.00E-05	1.00E–05 3.00E-05	3.90E–06 1.10E-05	2.50E-05
Co	Adult Children	5.00E–06 1.50E–05	3.0E–06 9.30E–06	3.60E–06 1.00E–05	7.30E-06 7.20E-05	5.90E–06 1.70E–05	3.00E–06 8.90E–06	7.60E–60 2.00E-05	8.00E–06 2.40E-05	7.40E–06 2.20E-05	6.00E–05
Fe	Adult Children	1.60E–04 4.90E–04	1.60E–04 4.70E-04	1.00E–04 3.00E–04	7.40E–05 2.20E–04	1.00E–04 3.00E–04	6.90E–06 2.00E–05	7.00E–05 2.10E-04	1.50E–04 4.40E-04	1.30E–04 3.90E-04	1.40E–01
Hg	Adult Children	1.60E–05 4.60E–05	2.10E–05 6.20E–50	2.30E–05 7.00E–05	2.00E–05 5.80E–05	1.70E–05 5.10E–05	7.30E–05 2.10E–04	2.00E–05 6.00E–05	2.30E–05 6.80E–05	2.10E–05 6.10E–05	2.10E–05
Mn	Adult Children	6.60E–06	3.50E–05	8.40E–06	3.90E–05	1.10E–05	1.90E–05	7.90E–05	1.70E–05	2.00E–05	8.30E–04

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		1.90E – 05	1.00E - 04	2.50E - 05	1.10E - 04	3.20E - 05	5.50E – 05	2.30E - 04	4.00E - 04	5.90 – 05	
Mo	Adult	7.60E – 06	7.40E – 06	5.00E 06	8.00E – 06	5.10E – 06	9.30E – 06	9.70E – 06	7.70E – 06	4.00E – 06	5.00E – 03
	Children	2.20E – 05	2.20E – 05	1.50E – 05	2.40E - 05	1.50E – 05	2.70E – 05	2.90E – 05	2.30E – 05	1.20E – 05	
Ni	Adult	1.20E – 04	1.20E – 04	1.10E – 04	7.00E – 06	2.50E – 05	1.00E – 04	4.40E – 05	7.10E – 05	1.20E – 04	8.00E – 04
	Children	3.60E – 04	3.70E – 04	3.40E – 04	2.10E – 05	7.30E – 05	3.00E – 04	1.30E – 04	2.10E – 04	3.50E – 04	
Pb	Adult	1.20E – 05	5.00E – 06	1.80E – 05	7.90E – 06	1.00E – 5	8.70E – 60	1.70E – 05	1.10E – 05	2.60E – 05	4.20E – 04
	Children	3.50E – 05	1.50E -- 05	5.30E – 05	2.30E – 05	3.00E – 05	2.60E – 05	4.90E – 05	3.40E – 05	7.60E – 05	
Se	Adult	6.00E – 05	1.70E - 05	7.50E – 05	3.30E – 05	6.00E – 05	7.60E – 50	5.70E – 07	8.00E – 05	1.40E – 04	5.00E – 03
	Children	1.80E – 04	4.90E - 05	2.20E - 04	9.80E - 05	1.80E - 40	2.20E - 04	1.70E - 06	2.40E - 04	4.10E – 04	

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Table 4.12 Ingestion /dermal hazard quotients and hazard index for adult and children in the stations (Nyaba river) (dry season)

Sites/Parameter	N1		N2		N3		N4		N5		N6		N7		N8		ER	
Ingestion	HQ Adult	HQ Children	HQ Adult	HQ children	HQ Adult	HQ Children	HQ Adult	HQ Children	HQ Adult	HQ Children	HQ Adult	HQ children	HQ Adult	HQ children	HQ Adult	HQ Children	HQ Adult	HQ Children
As	27.70E+00	63.30E+00	36.70E+00	83.30E+00	30.00E+00	70.00E+00	29.70E+00	70.00E+00	10.00E+00	23.70E+00	12.00E+00	28.30E+00	43.30E+00	80.00E+00	31.70E+00	73.30E+00	33.00E+00	76.70E+00
Cd	1.32E+00	3.00E+00	1.10E+00	2.60E+00	1.80E+00	4.00E+00	9.80E-01	2.20E+00	6.60E+00	15.40E+00	1.20E+00	2.60E-01	1.30E+00	3.00E+00	4.00E+00	9.20E+00	1.50E+00	3.40E+00
Co	3.20E+	7.30E+00	2.00E+	4.70E+00	2.30E+	5.30E+00	4.70E+	11.00E+00	3.70E+	8.70E+00	4.30E+	10.30E+00	5.00E+	11.30E+00	5.00E+	12.00E+00	4.70E+	11.00E+00

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	00		00		00		00		00		00		00		00		00	
Fe	4.60E-02	1.10E-01	4.30E-02	1.00E-01	2.70E-02	6.40E-02	2.00E-01	4.70E-02	2.90E-02	6.70E-02	2.00E-02	4.60E-02	1.90E-02	4.40E-02	4.00E-02	9.60E-02	3.60E-02	8.40E-02
Hg	1.00E+00	23.30E+00	13.30E+00	31.30E+00	15.00E+00	33.30E+00	12.70E+00	28.30E+00	11.00E+00	25.70E+00	12.00E+00	27.70E+00	13.00E+00	30.30E+00	14.70E+00	33.30E+00	13.00E+00	30.70E+00
Mn	5.40E-02	1.10E-01	2.80E-01	2.40E-01	6.70E-02	1.60E-01	3.20E-01	7.50E-01	8.80E-02	2.00E-01	1.04E+00	8.30E-01	6.30E-01	1.50E+00	1.10E+00	2.50E+00	1.60E-01	3.70E-01
Mo	3.00E-01	6.80E-01	2.80E-01	6.60E-01	1.90E-01	4.40E-01	3.20E-01	7.20E-01	2.00E-01	4.00E-01	3.60E-01	8.40E-01	3.80E-01	8.60E-01	3.00E-01	7.00E-01	1.50E-01	3.60E-01
Ni	1.20	2.70E+00	1.20	2.80E+00	1.10E+	2.60E+00	6.50	1.60E-01	2.40	5.50E-01	9.50	2.30E+00	4.20	9.50E-01	6.50	1.50E+00	1.20	2.60E+00

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	E+000		E+000		00		E-02		E-01		E-01		E-01		E-01		E+00	
Pb	1.60E+00	3.70E+00	6.90E-01	1.60E+00	2.50E+00	5.80E+00	1.10E+00	2.50E+00	1.40E+00	3.30E+00	1.20E+00	2.80E+00	2.30E+03	5.30E+00	1.60E+00	3.60E+00	3.60E+00	8.60E+00
Se	15.00E+00	5.40E+00	6.40E-01	1.50E+00	2.30E+00	6.60E+00	1.30E+00	3.00E+00	2.40E+00	5.40E+00	3.00E+00	7.80E+00	2.20E-02	5.20E-02	3.00E+00	7.20E+00	5.40E+00	12.40E+00
HI	60.0E+00	109.60E+00	56.0E+00	129.0E+00	55.30E+00	128.0E+00	51.20E+00	118.70E+00	35.70E+00	3.30E+00	36.10E+00	81.20E+00	66.40E+00	133.30E+00	62.10E+00	152.90E+00	62.70E+00	146.20E+00
Dermal																		
As	1.50E-	4.60E-01	2.00E-	6.00E+00	1.60E-01	4.90E-01	1.60E-	4.90E-01	5.60E-02	1.60E-01	6.70E-	2.00E-01	1.90E-01	5.60E-01	1.80E-	5.30E-01	1.80E-01	5.30E-01

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	01		01				01				02				01			
Cd	1.40E-01	4.00E-01	1.20E-01	3.40E-01	2.10E-01	6.40E-01	9.60E-02	2.90E-01	6.80E-01	2.00E+00	1.20E-01	3.60E-01	1.40E-01	4.00E-01	2.00E+00	6.00E-01	2.00E+00	6.00E+00
Co	8.30E-02	2.50E-01	5.00E-01	1.60E-01	6.00E-02	1.70E-01	1.20E-01	3.70E-01	9.80E-02	2.80E-01	1.20E-01	3.30E-01	1.30E-01	3.30E-01	1.30E-01	4.00E-01	1.20E-01	3.70E-01
Fe	1.10E-03	3.50E-03	1.10E-03	3.40E-03	7.10E-04	2.10E-03	5.30E-04	1.60E-03	7.10E-04	2.10E-03	5.20E-04	1.50E-03	5.00E-03	1.50E-33	1.10E-03	3.10E-03	9.30E-04	2.80E-03
Hg	7.60E-01	2.20E+00	1.00E+00	3.00E+00	1.10E+00	3.30E+00	9.50E-01	2.80E+00	8.10E+00	2.40E+00	9.00E-01	2.60E+00	9.50E-01	2.90E+00	1.10E+00	3.20E+00	1.00E+00	2.90E+00
Mn	8.00	2.30E-02	4.20	1.20E-01	1.00	3.00E-02	4.70	1.30E-01	1.30	3.90E-02	5.40	1.60E-01	9.50	2.80E-01	2.00	4.80E-01	2.40	7.00E-02

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	E.03		E-02		E-02		E-02		E-02		E-02		E-02		E-02		E-02	
Mo	1.50E-03	4.40E-03	1.50E-03	4.40E-03	1.00E-03	3.00E-03	1.60E-03	4.80E-03	1.00E-03	3.00E-03	1.90E-03	5.40E-03	2.00E-03	5.80E-03	1.50E-03	4.60E-03	8.00E-04	2.40E-03
Ni	1.50E-01	4.50E-01	1.50E-01	4.60E-01	1.40E-01	4.30E-01	8.80E-03	2.60E-02	3.10E-02	9.10E-02	1.30E-01	3.80E-01	5.50E-02	1.60E-01	8.90E-02	2.60E-01	1.50E-01	4.40E-01

Table 4.12: Ingestion /dermal hazard quotients and hazard index for adult and children in the stations (Nyaba river) (dry season) Contd

Pb	2.90E-02	8.30E-02	1.20E-02	3.60E-02	4.30E-02	1.30E-01	1.90E-02	5.50E-02	2.40E-02	7.10E-02	2.10E-02	6.20E-02	4.00E-02	1.20E-01	2.60E-02	8.10E-02	6.20E-02	1.80E-01
Se	1.20E-02	3.60E –02	3.40E-03	9.80E-03	1.50E-02	4.40E-02	6.60E-03	2.00E-02	1.20E-02	3.60E-02	1.50E-02	4.40E-02	1.10Eo4	3.40E-04	1.60E-02	4.80E-02	2.80E-02	8.20E-02
HI	1.30E+00	4.00E+00	1.58E+00	4.70E+00	1.70E+00	5.20E+00	1.40E+00	4.20E+00	1.70E+00	5.20E+00	1.32E+00	4.10E+00	1.60E+00	4.80E+00	3.60E+00	5.60E+00	3.60E+00	10.60E+00

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In the wet season, HQ and HI values generally decreased compared to the dry season for Ekulu River due to dilution effects, but still remained above 1 for Pb and Cd. Conversely, Nyaba River showed consistently high HQ and HI values even in the wet season, confirming persistent contamination.

4.3.2 Carcinogenic Risk (Incremental Lifetime Cancer Risk – ILCR)

The Incremental Lifetime Cancer Risk (ILCR) was calculated for carcinogenic metals such as As, Cd, Pb, and Ni. Acceptable risk thresholds are typically within 1×10^{-6} to 1×10^{-4}, while values above 1×10^{-4} indicate high cancer risk. For Ekulu River (dry season), ILCR values for As and Pb exceeded the acceptable threshold, particularly for children ($ILCR > 1 \times 10^{-3}$), indicating elevated lifetime cancer risks

Table 4.13: Chronic daily intake for carcinogenic heavy metals for cancer risk assessment for Ekulu river (dry season) (mg/kg-day)

Sites/ Parameter	As		Cd		Ni		Pb	
Ingestion	HQ Adult	HQ Children	HQ Adult	HQ Children	HQ Adult	HQ Children	HQ Adult	HQ Children
E1	2.80 E-04	1.30 E-04	3.80 E-04	1.80 E-04	4.10 E-03	1.90 E-03	4.30 E-04	2.00 E-04
E2	1.80 E-03	8.40 E-40	8.10 E-04	3.80 E-04	1.00 E-02	4.80 E-03	6.10 E-03	2.80 E-03
E3	4.30 E-03	2.00 E-03	7.40 E-04	3.50 E-04	3.90 E-03	1.80 E-03	5.30 E-04	2.50 E-04
E4	4.50 E-03	2.10 E-03	5.50 E-04	2.60 E-04	1.40 E-02	6.70 E-03	3.80 E-04	1.80 E-04
E5	8.30 E-03	1.50 E-03	4.60 E-04	2.10 E-04	1.50 E-02	7.20 E-03	5.80 E-04	2.70 E-04
E6	1.70 E-03	7.90 E-03	1.30 E-04	6.00 E-05	1.10 E-02	5.20 E-03	2.30 E-03	1.10 E-03
E7	4.00 E-03	1.90 E-03	3.20 E-04	1.50 E-04	9.90 E-03	4.60 E-03	1.30 E-03	6.10 E-04
E8	2.00 E-03	9.50 E-03	3.60 E-04	1.70 E-04	8.00 E-03	3.70 E-03	7.30 E-04	3.40 E-04
E9	1.20 E.03	5.70 E-04	1.20 E-04	1.20 E-04	1.20 E-02	5.60 E-03	7.90 E-04	3.70 E-04
ER	3.00	1.50	3.80	3.80	9.60	4.50	10.00	4.70

	E-03	E-03	E-05	E-04	E-03	E-03	E-04	E-04
Dermal								
E1	1.50 E-06	8.70 E-07	2.80 E-06	1.20 E-06	2.00 E-05	1.30 E-06	2.30 E-06	1.30 E-06
E2	9.40 E-06	5.60 E-06	4.20 E-06	2.50 E-06	5.40 E-05	3.20 E-05	3.20 E-06	1.90 E-05
E3	2.20 E-05	1.30 E-05	3.90 E-06	2.30 E-06	2.00 E-05	9.60 E-05	2.80 E-06	1.60 E-06
E4	2.40 E-05	1.40 E-05	2.90 E-06	1.70 E-06	7.50 E-05	4.50 E-05	2.00 E-06	1.20 E-06
E5	1.70 E-05	1.00 E-05	2.40 E-06	1.40 E-06	8.10 E-05	4.80 E-05	3.00 E-06	1.80 E-06
E6	8.90 E-06	5.20 E-06	6.70 E-07	4.00 E-07	5.80 E-05	3.50 E-05	1.20 E-05	7.10 E-06
E7	2.10 E-05	1.20 E-05	1.70 E-06	9.80 E-07	5.00 E-05	3.00 E-05	6.80 E-06	4.00 E-06
E8	1.10 E-05	6.30 E-06	1.90 E-06	1.10 E-06	4.20 E-05	2.50 E-05	3.80 E-06	2.20 E-06
E9	6.40 E-06	3.80 E-06	1.30 E-06	7.60 E-07	6.20 E-05	3.70 E-05	4.10 E-06	2.40 E-06
ER	1.60 E-05	9.60 E-06	4.30 E-07	2.50 E-07	5.00 E-05	2.90 E-05	5.20 E-06	3.10 E-06

Table 4.14: Incremental lifetime cancer risks for carcinogenic heavy metals in Ekulu river for adults and children (dry season)

Sites/ Parameter	**As**		**Cd**		**Ni**		**Pb**	
Ingestion	Adult	Children	Adult	Children	Adult	Children	Adult	Children
E1	4.20 E-04	2.00 E-03	1.40 E-04	6.30 E-05	7.00 E-03	3.20 E-03	3.70 E-06	1.70 E-06
E2	2.70 E-03	1.30 E-03	3.10 E-04	1.40 E-04	1.70 E-02	8.20 E-30	5.20 E-05	2.40 E-05
E3	6.50 E-03	3.00 E-03	2.80 E-04	1.30 E-04	6.60 E-03	3.10 E-03	4.50 E-06	2.10 E-06

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E4	6.80 E-03	3.20 E-03	2.10 E-04	9.90 E-05	2.40 E-03	1.10 E-02	3.20 E-06	1.50 E-06
E5	5.00 E-03	2.30 E-03	1.70 E-04	8.00 E-05	2.60 E-02	1.20 E-02	4.90 E-06	2.30 E-06
E6	2.60 E-03	1.20 E-03	4.90 E-50	2.30 E-05	1.90 E-02	8.80 E-03	2.00 E-05	9.40 E-06
E7	6.00 E-03	2.90 E-03	1.20 E-04	5.70 E-05	1.70 E-02	7.80 E-03	1.10 E-05	5.20 E-06
E8	3.00 E-03	1.40 E-03	1.40 E-04	6.50 E-05	1.40 E-02	6.30 E-03	6.20 E-06	2.90 E-06
E9	1.80 E-03	8.60 E-04	9.50 E-05	4.60 E-05	2.00 E-02	9.50 E-03	6.70 E-06	3.10 E-06
ER	4.50 E-03	2.30 E-03	3.00 E-05	1.40 E-05	1.60 E-02	7.70 E-03	8.50 E-07	4.00 E-06
Total	3.40 E-02	2.00 E-02	1.50 E-03	7.20 E-04	1.50 E-01	7.80 E-02	1.10 E-04	5.60 E-05
Mean	3.40 E-03	2.00 E-03	1.50 E-04	7.20 E-05	1.50 E-02	7.80 E-03	1.10 E-05	5.60 E-06
Total adult/children	5.	40	2.	20	2	.30	1.	70
	E -	02	E	-03	E	-01	E	-40
Dermal								
E1	5.50 E-06	3.20 E-06	1.20 E-05	7.30 E-06	4.00 E-04	2.60 E-05	9.80 E-05	5.50 E-05
E2	3.40 E-05	2.00 E-05	2.60 E-05	1.50 E-05	1.00 E-03	6.40 E-04	1.40 E-03	8.00 E-04
E3	8.10 E-05	4.80 E-05	2.40 E-05	1.40 E-05	4.00 E-04	1.90 E-03	1.20 E-04	6.80 E-05
E4	8.80 E-05	5.10 E-05	1.80 E-05	1.00 E-05	1.50 E-03	9.00 E-04	8.50 E-05	5.10 E-05
E5	6.20 E-06	3.70 E-05	1.50 E-05	8.50 E-06	1.60 E-04	9.60 E-04	1.30 E-04	7.70 E-05
E6	3.30 E-05	1.90 E-05	4.00 E-06	2.40 E-06	1.20 E-03	7.00 E-04	5.10 E-05	3.00 E-04
E7	7.70	4.40	1.00	6.00	1.00	6.00	2.90	1.70

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	E-05	E-05	E-05	E-06	E-03	E-04	E-04	E-04
E8	4.00 E-05	2.30 E-05	1.20 E-05	6.70 E-06	8.40 E-04	5.00 E-04	1.60 E-04	9.40 E-05
E9	2.30 E-05	1.40 E-05	7.90 E-06	4.60 E-06	1.20 E-03	7.40 E-04	1.70 E-04	1.00 E-04
ER	5.90 E-05	3.50 E-05	2.60 E-06	1.50 E-06	1.00 E-03	5.80 E-04	2.20 E-04	1.30 E-04
Total	8.00 E-04	2.90 E-05	1.30 E-04	7.60 E-05	8.70 E-03	7.50 E-03	2.70 E-03	2.70 E-03
Mean	8.00 E-05	2.90 E-05	1.30 E-05	7.60 E-06	8.70 E-04	7.50 E-04	2.70 E-04	2.70 E-04
Total adult/children	1.	10 E-04	2	.00 E-04	1.	60 E-02	5.	40 E-03
Total Ing + dermal	3.50 E-03	2.00 E-03	1.60 E-05	8.00 E-05	1.60 E-02	8.60 E-03	2.80 E-04	2.80 E-04

In Nyaba River (dry season), ILCR values were even higher, with As and Pb again showing the strongest cancer risks. Both adults and children fell into the "unacceptable risk" range.

Table 4.15: Chronic daily intake for carcinogenic heavy metals for cancer risk assessment for Nyaba river (dry season)

Sites/ Parameter	As		Cd		Ni		Pb	
Ingestion	Adult	Children	Adult	children	Adult	Children	Adult	Children
N1	3.60 E-03	1.70 E-03	2.80 E-04	1.30 E-0	9.90 E-03	4.60 E-02	9.60 E-04	4.50 E-04
N2	4.60 E-03	2.20 E-03	2.30 E-04	1.10 E-04	1.00 E-02	4.80 E-03	4.10 E-04	1.90 E-04
N3	3.90 E-03	1.80 E-04	3.80 E-04	1.80 E-04	9.40 E-03	4.40 E-03	1.50 E-03	6.90 E-03
N4	3.80 E-03	1.80 E-03	2.00 E-04	9.30 E-05	5.80 E-04	2.70 E-04	6.50 E-04	3.00 E-04
N5	1.30 E-03	6.10 E-04	1.40 E-03	6.60 E-04	2.00 E-03	9.40 E-04	8.50 E-04	3.90 E-04
N6	1.60 E-03	7.30 E-04	2.50 E-04	1.20 E-04	8.30 E-04	3.90 E-03	7.20 E-04	3.30 E-04

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N7	4.40 E-03	2.10 E-03	2.80 E-04	1.30 E-04	3.60 E-03	1.90 E-03	1.40 E-03	6.40 E-04
N8	4.10 E-03	1.70 E-03	8.50 E-04	3.90 E-04	5.60 E-03	2.60 E-03	9.40 E-04	4.40 E-03
NR	4.30 E-03	2.00 E-03	3.20 E-04	1.50 E-04	9.80 E-03	4.60 E-03	2.10 E-03	9.90 E-04
Dermal								
N1	1.90 E-05	1.10 E-05	1.50 E-06	8.70 E-07	5.20 E-05	3.00 E-05	5.00 E-06	3.00 E-06
N2	2.40 E-05	1.40 E-05	1.20 E-06	7.20 E-07	5.30 E-05	3.10 E-05	2.10 E-05	1.30 E-06
N3	2.00 E-05	1.20 E-05	2.30 E-06	1.30 E-06	4.90 E-05	1.80 E-06	7.70 E-06	4.60 E-06
N4	2.00 E-05	1.20 E-05	1.00 E-06	6.10 E-07	3.00 E-06	1.80 E-06	3.40 E-06	2.00 E-06
N5	6.80 E-06	4.00 E-06	7.40 E-06	4.40 E-06	1.10 E-05	6.20 E-06	4.40 E-06	2.90 E-06
N6	8.20 E-06	4.80 E-06	1.30 E-06	7.60 E-07	4.40 E-05	2.60 E-05	3.70 E-06	2.20 E-06
N7	2.30 E-05	1.40 E-05	1.60 E-07	8.70 E-07	1.90 E-05	1.10 E-05	7.10 E-06	4.20 E-06
N8	2.10 E-05	1.30 E-05	4.40 E-06	2.60 E-06	3.00 E-05	1.60 E-05	4.90 E-06	2.90 E-06
NR	2.20 E-05	1.30 E-05	1.70 E-06	9.07 E-07	5.10 E-05	1.80 E-05	1.10 E-05	6.50 E-06

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Table 4.16: Incremental Lifetime Cancer Risk (ILCR) for carcinogenic heavy metals in Nyaba river for adults and children (dry season)

Sites/ Parameter	**As**		**Cd**		**Ni**			**Pb**
Ingestion	Adult	Children	Adult	children	Adult	Children	Adult	Children
N1	5.40 E-03	2.60 E-03	1.10 E-04	4.90 E-05	1.70 E-02	7.80 E-02	8.20 E-06	3.80 E-06
N2	6.90 E-03	3.30 E-03	8.70 E-05	4.20 E-05	1.70 E-02	8.20 E-03	3.50 E-06	1.60 E-06
N3	5.90 E-03	2.70 E-04	1.40 E-04	6.80 E-05	1.60 E-02	7.50 E-03	1.30 E-06	5.90 E-06
N4	5.70 E-03	2.70 E-03	7.60 E-05	3.50 E-03	9.90 E-04	4.60 E-04	5.50 E-06	2.60 E-06
N5	2.00 E-03	9.20 E-04	5.30 E-04	2.50 E-04	3.40 E-03	1.60 E-03	7.20 E-06	3.30 E-06
N6	2.40 E-03	1.10 E-03	6.60 E-04	4.60 E-05	1.40 E-03	6.60 E-03	6.10 E-06	2.80 E-06
N7	6.80 E-03	3.20 E-03	1.10 E-04	4.90 E-05	6.10 E-03	2.90 E-03	1.20 E-05	5.40 E-06
N8	6.20 E-03	2.60 E-03	3.20 E-04	1.50 E-04	9.50 E-03	4.40 E-03	8.00 E-06	1.80 E.05
NR	6.50 E-03	3.00 E-03	1.20 E-04	5.70 E-05	1.70 E-02	7.80 E-03	1.80 E-05	5.20 E-05
Total	4.80 E-02	2.00 E-02	2.20 E-03	7.50 E-04	8.80 E-02	1.30 E-02	7.00 E-05	5.80 E-06
Mean	5.30 E-03	2.20 E-03	2.40 E-04	8.30 E-05	9.80 E-03	10 E-01	7.80 E-06	E-04
Total adult/children	6.00	E-02	3.	00 E-04	2.	10E-01	1.20	E-04
Dermal								
N1	7.00 E-05	3.00 E-06	9.20 E.06	5.30 E-06	1.00 E-03	6.00 E-04	2.10 E-04	1.30 E-04
N2	8.80 E-05	5.10 E-05	7.30 E-05	4.40 E-06	1.10 E-03	6.20 E-04	8.90 E-04	5.50 E-05

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N3	7.30E-05	4.40E-05	1.40E-05	7.90E-06	9.80E-04	3.60E-05	3.30E-04	2.00E-04
N4	7.30E-05	4.40E-05	6.10E-06	3.70E-06	6.00E-05	3.60E-05	1.40E-04	8.50E-05
N5	2.50E-05	1.50E-05	4.50E-05	2.70E-05	2.20E-04	1.20E-04	1.90E-04	1.20E-04
N6	3.00E-05	1.80E-05	7.90E-06	4.60E-06	8.80E-04	5.20E-04	1.60E-04	9.60E-05
N7	8.40E-05	5.10E-05	9.80E-07	5.80E-06	3.80E-04	2.20E-04	3.00E-04	1.80E-04
N8	7.70E-05	4.80E-05	2.70E-05	1.60E-05	6.00E-04	3.20E-04	2.10E-04	1.20E-04
NR	8.10E-05	4.80E-05	1.00E-05	6.00E-06	1.00E-03	3.60E-03	4.70E-04	2.80E-04
Total	6.00E-04	3.20E-04	1.90E-04	8.10E-05	6.20E-03	6.10E-03	2.90E-03	1.30E-03
Mean	6.70E-05	3.60E-05	2.10E-05	9.00E-06	6.90E-04	6.70E-04	3.20E-04	1.40E-04

Seasonal comparison shows that while dilution during the wet season reduced some ILCR values, they still remained above permissible limits, meaning cancer risks persist across seasons.

The health risk assessment reveals that both non-carcinogenic and carcinogenic risks from heavy metals are significant in Ekulu and Nyaba rivers. Children are the most at risk, with higher HQ, HI, and ILCR values compared to adults. Pb, Cd, and As emerged as the most critical metals driving both non-carcinogenic and carcinogenic risks. Seasonal variation reduced risk levels slightly in Ekulu River during the wet season but not in Nyaba River, where AMD inflows intensified during rainfall.

These findings indicate that direct use of Ekulu and Nyaba river water for drinking, cooking, or bathing poses severe health risks to exposed populations and highlights the urgent need for water treatment interventions and alternative safe water supplies.

5. Discussion of Findings

5.1 Sources of Heavy Metals

The correlation analyses from Ekulu and Nyaba rivers confirmed that Acid Mine Drainage (AMD) is the dominant source of Fe, Mn, and other heavy metals, consistent with global studies (Bigham & Cravotta, 2016; Zhao et al., 2020). The strong positive correlations among Fe and Mn in both rivers align with AMD signatures observed in rivers draining

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abandoned coal mines in the United States, South Africa, and Ghana (Singh et al., 2022; Engwa et al., 2019).

However, the presence of negative correlations and weaker associations suggests that anthropogenic inputs such as irrigation farming, laundry, domestic effluent discharge, and sand dredging also contribute significantly to contamination. This mixed geogenic and anthropogenic influence mirrors findings in Zambia and Ghana, where rivers adjacent to abandoned mines showed multiple pollution pathways (Chileshe et al., 2021; Armah et al., 2010).

Thus, while AMD remains the principal contamination source, the contribution of human activities around the rivers exacerbates the water quality challenges.

5.2 Concentration Levels of Heavy Metals

Across both rivers and seasons, Fe consistently recorded concentrations exceeding WHO, USEPA, and FEPA guideline values. In Ekulu River, Fe peaked in the dry season due to reduced dilution, while in Nyaba River it was higher during the wet season, reflecting increased leaching from mine water during rainfall. These findings support previous studies in Enugu coalfields that reported persistently acidic pH (3.4–5.9) and elevated Fe levels (Akpan et al., 2021).

Pb and Cd also consistently exceeded permissible limits, aligning with studies from global mining regions where Pb toxicity is a recurrent problem (Rehman et al., 2018). As contamination was also notable in both rivers, echoing findings from Ghana and South Africa where As from mine drainage poses long-term risks (Armah et al., 2010; Engwa et al., 2019).

These results demonstrate that the surface waters in Nyaba catchment are unsafe for domestic and agricultural use without treatment.

5.3 Health Risk Assessment

The hazard quotient (HQ) and hazard index (HI) values above 1 indicate that non-carcinogenic health risks are present for both adults and children. Children were especially vulnerable, with HI values exceeding 3 in some cases, reflecting their higher exposure per unit body weight. Similar child-focused vulnerability has been documented in heavy metal studies in Asia and Africa (Balali-Mood et al., 2021).

Carcinogenic risks (ILCR) for As, Cd, and Pb exceeded the permissible threshold of 1×10^{-4} in both rivers and seasons. This places exposed populations at unacceptable lifetime cancer risks, consistent with findings from Zambia, where ILCR values for Pb and Cd in rivers near abandoned mines were similarly high (Chileshe et al., 2021). In Enugu, these results confirm earlier warnings by Obiadi et al. (2016) and Ozoko (2015) that abandoned mines pose long-term health threats to surrounding communities.

The fact that both non-carcinogenic and carcinogenic risks persist across seasons underscores the severity of contamination and the inadequacy of natural dilution processes to mitigate exposure risks.

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6. Conclusion and Recommendations

6.1 Conclusion

This study assessed the sources, concentration levels, and health risks of heavy metals in surface waters of Ekulu and Nyaba rivers draining the abandoned Onyeama and Okpara coal mines in Enugu State, Nigeria. The findings revealed that Acid Mine Drainage (AMD) is the dominant source of contamination, supported by strong positive correlations among Fe, Mn, and other metals typical of mine effluents. However, anthropogenic activities such as irrigation, sand dredging, laundry, and domestic waste disposal also contributed significantly, indicating a multi-sourced pollution problem.

Concentration analysis showed that Fe, Pb, Cd, and As consistently exceeded WHO, USEPA, and FEPA/NESREA standards across both dry and wet seasons. Seasonal patterns highlighted dilution effects in Ekulu River during the wet season and intensified leaching in Nyaba River during rainfall, but in all cases, concentrations remained above safe limits.

The health risk assessment further demonstrated that both non-carcinogenic (HQ, HI > 1) and carcinogenic risks (ILCR > 1×10^{-4}) are present, with children facing significantly higher risks than adults. These findings confirm that the rivers are unsafe for domestic and agricultural uses without treatment, and long-term exposure poses serious public health threats, including cancer, kidney dysfunction, and neurological disorders.

Overall, the study concludes that the abandoned coal mines in Enugu State continue to generate AMD and heavy metal pollution, with severe implications for water resources, public health, and sustainable development in the region.

6.2 Recommendations

This study identified Acid Mine Drainage (AMD) from the abandoned Onyeama and Okpara coal mines as the dominant source of heavy metal contamination in Ekulu and Nyaba rivers, with additional contributions from irrigation farming, laundry, dredging, and domestic effluents. In line with this finding, it is recommended that remediation measures such as lime neutralization, anoxic limestone drains, and constructed wetlands be introduced to minimize acid generation and heavy metal leaching from the mines. At the same time, local authorities should strengthen regulations to control anthropogenic activities along the rivers, particularly sand dredging, indiscriminate laundry, and unregulated agricultural runoff.

The study further revealed that concentrations of Fe, Pb, Cd, and As consistently exceeded the permissible limits of WHO, USEPA, and FEPA standards across seasons. To address this, there is urgent need for continuous monitoring of water quality in the study area, coordinated by agencies such as NESREA and the Enugu State Ministry of Environment, with special attention to seasonal variations. Given that the rivers are unsuitable for direct domestic and agricultural use, government and development partners should prioritize the provision of safe alternative water supplies, such as treated boreholes and piped municipal systems, to the dependent communities.

Seasonal analysis also highlighted important dynamics: while Ekulu River showed reduced concentrations during the wet season due to dilution, Nyaba River became more contaminated in the wet season as a result of increased leaching from mine water. In response, health-focused interventions are necessary, including periodic medical screening of exposed populations, especially children, for heavy metal poisoning. Public health campaigns should also be launched to discourage the direct use of untreated river water, emphasizing the risks associated with both seasons and the heightened vulnerability of children.

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