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Quarry Runoff Waters: Potential Risks for Irrigation, Fisheries and Livestock in Akamkpa Communities, Nigeria

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ABSTRACT

Quarry operations contribute significantly to regional development but often lead to environmental degradation, particularly through heavy metal-laden dust and runoffs. This study evaluated the irrigation, fisheries, aquaculture, and livestock water suitability of runoff from major quarries in Akamkpa communities in Southern Nigeria. Water samples were collected between January and July 2024, and analyzed for lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and selenium (Se) using atomic absorption spectrophotometry. Total metal concentrations ranged as follows: Pb (0.92–2.54mg/ L), Cd (0.79–1.96mg/ L), Hg (0.02–0.09mg/L), As (0.02–0.14mg/ L), and Se (0.09–0.24mg/ L). The study revealed heavy metal concentrations exceeding the WHO/FAO irrigation, fisheries and aquaculture and livestock drinking water quality standards across the sites, with significant variations between quarries. Similarly, the runoff's metal levels surpassed ANZECC guidelines for irrigation, freshwater aquaculture and the maximum tolerable limits for livestock drinking water. Lead exhibited notably higher levels during the wet season, potentially driven by runoff dynamics. Ding-Zing quarry had the highest metal concentrations, posing the greatest risk. Strong positive correlations between metals suggest a common source, likely linked to quarry operations. The significant difference in the concentration of each metal between the quarries and the control site suggest that quarry activities may be responsible for the elevated metal levels at the study site. In conclusion, findings underscore the unsuitability of quarry runoff for irrigation, fisheries, and aquaculture. This demonstrates the ecological and public health risks posed, especially bioaccumulation of the toxic metals in crops, fish, and livestock. Recommendations include, implementation of appropriate treatment and management strategies, regular monitoring, and adherence to environmental regulations to mitigate the environmental and health risks associated with quarry runoff.

INTRODUCTION

Quarrying is an industrial activity involving the extraction of rocks, sand, and minerals from the earth's surface. It is a key component of the mining sector, contributing significantly to construction and industrial raw material supply **(Williams & Taylor,**

2018). Quarrying involves a series of processes, including drilling, blasting, crushing, screening, washing, and stockpiling of rock materials extracted from either surface deposits or underground formations **(Langer, 2001)**. The quarrying sector plays a vital role in national economies by providing materials for roads, buildings, and industrial applications **(Mukherjee *et al*., 2020)**. It contributes to GDP, generates employment, and supports related industries such as cement and construction **(Chukwuma & Okoye, 2019)**. In Nigeria, the quarrying industry significantly impacts economic growth, supports infrastructural development and provides employment opportunities for local communities **(Ajayi & Olanrewaju, 2017; Adegbite & Ogunleye, 2021)**. While the quarry industry provides economic benefits, it has several environmental consequences. These include land degradation, habitat destruction, dust pollution, noise pollution, and water contamination **(Nartey *et al*., 2012)**. Quarry runoff, which often contains heavy metals and sediments, poses significant environmental risks **(Akinbile & Yusoff, 2011)**.

Quarry runoff refers to surface water or leachate that flows from quarrying sites due to precipitation, washing processes, or groundwater seepage. Washing operations in quarrying involve using large volumes of water to remove impurities from aggregates. This process generates runoff that often contains high levels of suspended solids, heavy metals, and other contaminants, posing potential environmental hazards **(Tijani *et al*., 2016; Smith *et al*., 2020; Yeboah & Osei, 2020)**. This runoff may infiltrate groundwater or flow into rivers, affecting aquatic life and water quality **(Tijani *et al*., 2016)**. The environmental consequences include water pollution, reduced soil fertility, and risks to aquatic ecosystems **(Umar *et al*., 2018)**. Agricultural impacts include contamination of irrigation water, livestock and aquaculture exposure to toxic metals **(Obiora & Udensi, 2018; Bello *et al*., 2021)**. In aquaculture, bioaccumulation of heavy metals in fish leads to potential human health risks through the consumption of contaminated fish **(Mensah *et al*., 2019)**. Livestock exposed to contaminated water sources may suffer from chronic toxicity, leading to reduced productivity and health issues **(Bassey *et al*., 2021)**. Recent studies have emphasized the need for systematic monitoring and analysis of quarry runoff to determine its potential for irrigation and livestock farming **(Brown & Green, 2019)**. The term 'quarry runoff under the lens' refers to the systematic study and assessment of water that drains from quarrying sites, analyzing its composition, contaminants, and potential risks to the environment and agriculture **(Smith *et al*., 2020)**. Understanding its composition is crucial for determining its suitability for irrigation and aquaculture **(Brown & Green, 2019)**.

Several studies have examined the impact of quarry runoff on the environment and agriculture. **Adebayo *et al*. (2020)** investigated quarry runoff in Ogun State, finding Pb and Cd levels exceeding FAO irrigation guidelines. **Koffi and Mensah (2019)** studied quarry runoff in Ghana, linking heavy metal pollution to declining fish populations.

Studies in India and China **(Zhang *et al*., 2018; Patel *et al*., 2020)** highlighted the role of quarrying in water contamination and soil degradation.

Despite extensive research on quarry runoff, critical gaps remain in understanding its long-term impact on soil fertility, crop productivity, and the bioaccumulation of heavy metals in crops, aquaculture, and livestock. The safety of these food sources for human consumption remains largely unexplored. Existing studies have primarily focused on broad environmental consequences, with limited site-specific investigations in Njagachang and Awi, despite their distinct geological and hydrological characteristics. The variability of heavy metal concentrations, their seasonal fluctuations, and their compliance with irrigation and aquaculture standards in these communities remain poorly documented. Furthermore, the health risks associated with consuming contaminated crops, fish, and livestock products have not been systematically assessed. This study seeked to bridge these knowledge gaps by generating empirical data on quarry runoff quality, its implications for agricultural sustainability, and its alignment with international (WHO, FAO) water quality standards. The findings provide critical insights for policymakers, regulatory bodies, and local stakeholders, supporting informed decision-making on quarry runoff and water resource utilization in Njagachang and Awi communities.

MATERIALS AND METHODS

Study area

Cross River State, Nigeria, is situated between latitude 4°28' and 6°55' North, and longitude 7°50' and 9°28' East, with Calabar as its capital. Covering an area of 20,156 km², the state shares borders with Cameroon to the East, Benue State to the North, Ebonyi State to the West, and Akwa Ibom State to the Southwest. It comprises 18 local government areas, among which Akamkpa is the largest, located between latitudes 5.1667°N and 5.5333°N and longitudes 8.2333°E and 8.6333°E. Spanning 5,003km², Akamkpa sits at an elevation of 50–200 meters above sea level and has an estimated population of 200,100 **(Population Stat, 2019; FMEnv, 2020)**. The vegetation in Akamkpa varies from mangrove swamps and tropical rainforests to derived savannah. Geologically, the region consists of Precambrian Basement Complex rocks of the Oban Massif, overlain by sedimentary deposits from the Cretaceous period **(Davidson *et al*., 2019)**. Akamkpa hosts the largest stone deposits in Cross River State, with extensive quarrying activities ranging from small-scale operations to large industrial sites. The local economy is driven by agriculture (both subsistence and commercial), quarrying, fishing, and trade

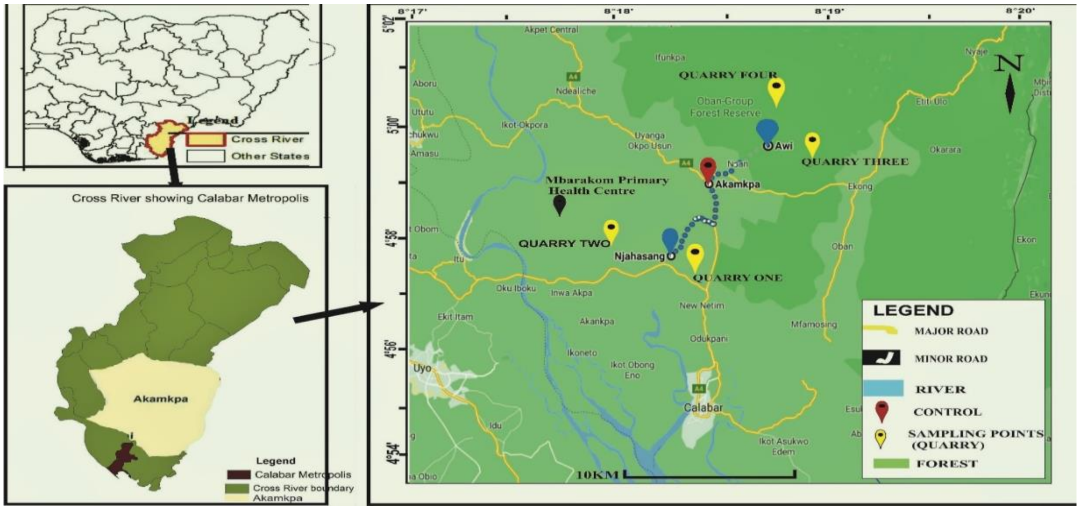

Fig. 1. Map of study area showing sample locations

Sample collection

Sample collection and analysis were carried out following **APHA (2005)**. Four quarry sites were selected for this study: Saturn Quarry and Twin Brother Quarry in Awi, as well as Fuhua and Ding-Zing quarries in Njagachang. Water samples were collected in 1-liter plastic containers that had undergone thorough pre-cleaning. The cleaning process involved washing with detergent and clean water, followed by rinsing with distilled water and soaking in 10% nitric acid for 24 hours to eliminate residual contaminants. At each quarry, runoff water was manually scooped into the containers using a plastic bowl. Sampling points were spaced 100 meters apart along the wastewater flow path, with four collection points per quarry. Additionally, surface water from a flowing stream in Akamkpa main town was collected to serve as a control. All samples were transported to LAB 249 in the Department of Zoology and Environmental Biology, University of Calabar, for further processing and analysis. Sampling was carried out between January and July 2024

Sample preparation and analysis

To obtain a representative sample for each quarry, runoff water from the four collection points was combined into a composite sample. A 50mL portion of each composite sample was transferred into a 250mL acid-washed conical flask for digestion. The digestion process involved adding 20mL of concentrated nitric acid to the sample, followed by gradual heating until the solution was nearly dry. Additional nitric acid was added, when necessary, until a clear solution indicated complete digestion. The digested sample was then filtered into a 50mL volumetric flask and diluted with distilled deionized water **(Ewa *et al*., 2013)**. The concentrations of lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr) were quantified using a Shimadzu Atomic Absorption Spectrophotometer (model AA-6800, Japan).

Analytical quality assurance

To ensure data accuracy and reliability, rigorous quality control protocols were followed throughout the study. Precautions were taken to prevent cross-contamination, including the consistent use of distilled deionized water and thorough cleaning of all glassware. High-purity analytical-grade nitric acid (Riedel-deHaen, Germany) was used for digestion. A blank sample and a set of combined standards were analyzed with each batch to detect potential background contamination and maintain consistency. Additionally, Standard Reference Materials (Lichens coded IAEA-336) underwent the same digestion and analysis procedures. The obtained values were cross-checked against certified reference values to validate the analytical method.

Statistical analysis

Data analysis was performed to determine significant differences in metal concentrations. An independent t-test was conducted to compare metal levels between wet and dry seasons, while analysis of variance test (ANOVA) was used to compare metal levels between quarries. A significance threshold of $P<0.05$ was applied. Statistical computations were executed using IBM SPSS (version 23) for Windows.

RESULTS

Analytical quality assurance

The measured concentrations of elements in the certified reference material (Lichen, IAEA-336) closely matched the certified values, confirming the analytical method's reliability (Table 1).

Table 1. Results of the analysis of the reference material (Lichen IAEA - 336) in comparison with the certified reference values

Metals mg/kg	Pb	Cd	Hg	As	Cr
Analyzed value	4.6	0.123	0.21	0.62	1.10
Reference value	4.3-5.5	0.100-0.134	0.16-0.24	0.55-0.71	0.89-1.23

Total metal concentration in quarry runoff

Total metal concentrations in quarry runoff are presented in Table (2). The differences in metals concentrations between quarries and control for dry and wet seasons are presented in Figs. (2, 3).

Mean lead concentrations (mg/L) in runoff during the dry and wet seasons were respectively as follows: Saturn (1.41 ± 0.13; 1.90 ± 0.05), Twin Brothers (0.97 ± 0.04; 1.57 ± 0.01), Fuhua (1.75 ± 0.05; 1.96 ± 0.08), and Ding Zing (1.94 ± 0.03; 2.18 ± 0.23) (Table 2). Mean cadmium concentration for both wet and dry seasons were 0.95±0.08 and 1.26±0.21mg/ L for Saturn, 0.89±0.11 and 1.07±0.02mg/ L for Twin Brother, 1.31±0.28 and 1.66±0.07mg/ L for Fuhua, and 1.74±0.12 and 1.91±0.04mg/ L for Ding Zing (Table 2). Mean concentration of mercury in runoff across the quarries for both dry and wet seasons were 0.03±0.01 and 0.04±0.01mg/ L, 0.02±0.01 and 0.04±0.01mg/ L, 0.05±0.01 and 0.08±0.01mg/ L, and 0.06±0.02 and 0.08±0.01mg/ L for Saturn, Twin Brothers, Fuhua and Ding Zing, respectively (Table 2). Arsenic concentrations across the quarries for both dry and wet seasons recorded the mean values: 0.03±0.01 and 0.05±0.01mg/ L, 0.03±0.01 and 0.05±0.01mg/ L, 0.06±0.01 and 0.07±0.06mg/ L, and 0.08±0.01 and 0.10±0.03mg/ L for Saturn, Twin Brothers, Fuhua and Ding Zing, respectively. The mean concentration of selenium for both wet and dry seasons were 0.13±0.02 and 0.15±0.012mg/ L for Saturn, 0.11±0.02 and 0.14±0.01mg/ L for Twin Brother, 0.17±0.01 and 0.20±0.03mg/ L for Fuhua, and 0.18±0.04 and 0.22±0.01mg/ L for Ding Zing.

Ding Zing quarry recorded the highest concentrations of all metals during the peak wet season (July), while the lowest concentrations were recorded at the peak of dry season (January-February at Twin Brother Quarry, except for arsenic, which was the lowest at Saturn Quarry. The differences in metals concentration between dry and wet seasons were not significant ($P > 0.05$), except for lead which displayed wet season values that were significantly ($P \leq 0.05$) higher than dry season values (Table 2). Total metals concentrations at the control station were significantly lower than all the quarry communities, except for mercury which displayed no significant variation between the quarry runoffs and the control. Significant variations in total metal concentrations were observed across quarry sites during both dry and wet seasons ($P \leq 0.05$; Figs. 2 and 3).

Relationship between heavy metal in runoff across quarries

There were strong, statistically significant positive correlations ($P < 0.01$) between lead and cadmium (r = 0.952), lead and mercury (r = 0.687), lead and arsenic (r = 0.887) and between lead and selenium (r = 0.951), as shown in Table (3). A significant ($P <$ 0.01) strong positive correlation was also observed between cadmium and mercury (r = 0.738), cadmium and arsenic (r = 0.898) and between cadmium and selenium (r = 0.943). Strong positive correlation was also observed between mercury and arsenic (r = 0.772), mercury and selenium (r = 0.807) and between arsenic and selenium (r = 0.914), the correlations were significant at 99% confidence level.

Table 2. Total heavy metal concentration (mg/L) in runoff across quarries for both dry and wet season

		Dry Season					Wet Season				
Station	Metals	Jan	Feb	March	Mean±SD	Range	May	June	July	Mean±SD	Range
Saturn	Pb	1.23	1.46	1.53	1.41±0.13^{a}	1.23-1.53	1.86	1.87	1.98	1.90±0.05^{b}	1.85-1.98
	Cd	1.03	0.83	0.98	0.95±0.08^{a}	0.83-1.03	1.21	1.02	1.54	1.26±0.21^{a}	1.02-1.54
	Hg	0.03	0.03	0.04	0.03±0.01^{a}	0.03-0.04	0.04	0.05	0.04	0.04±0.01^{a}	0.04-0.05
	As	0.02	0.02	0.05	0.03±0.01^{a}	0.02-0.05	0.04	0.06	0.06	0.05±0.01^{a}	0.04-0.06
	Se	0.11	0.13	0.15	0.13±0.02^{a}	0.11-0.15	0.15	0.17	0.14	0.15±0.012^{a}	0.14-0.17
Twin Brother	Pb	0.92	0.98	1.02	0.97±0.04^{a}	0.92-1.02	1.56	1.58	1.58	1.57±0.01^{b}	1.56-1.58
	Cd	0.79	0.85	1.04	0.89±0.11^{a}	0.79-1.04	1.05	1.08	1.09	1.07±0.02^{a}	1.05-1.09
	Hg	0.02	0.02	0.03	0.02±0.01^{a}	0.02-0.03	0.03	0.04	0.05	0.04±0.01^{a}	0.03-0.05
	As	0.03	0.03	0.04	0.03±0.01^{a}	0.03-0.04	0.05	0.05	0.06	0.05±0.01^{a}	0.05-0.06
	Se	0.09	0.11	0.13	0.11±0.02^{a}	0.09-0.13	0.13	0.13	0.15	0.14±0.01^{a}	0.13-0.15
Fuhua	Pb	1.67	1.78	1.79	1.75±0.05^{a}	1.67-1.79	1.85	1.98	2.04	1.96±0.08^{b}	1.85-2.04
	Cd	0.92	1.46	1.56	1.31±0.28^{a}	0.92-1.56	1.57	1.67	1.74	1.66±0.07^{a}	1.57-1.74
	Hg	0.04	0.06	0.06	0.05±0.01^{a}	0.04-0.06	0.06	0.08	0.09	0.08±0.01^{a}	0.06-0.09
	As	0.06	0.05	0.07	0.06±0.01^{a}	0.05-0.07	0.06	0.07	0.09	0.07±0.06^{a}	0.06-0.09
	Se	0.16	0.18	0.17	0.17±0.01^{a}	0.16-0.18	0.17	0.18	0.24	0.20±0.03^{a}	0.17-0.24
Ding/Zing	Pb	1.89	1.94	1.98	1.94±0.03^{a}	1.89-1.98	1.98	2.03	2.54	2.18±0.23^{a}	1.08-2.54
	Cd	1.57	1.79	1.87	1.74±0.12^{a}	1.57-1.87	1.88	1.88	1.96	1.91±0.04^{a}	1.88-1.96
	Hg	0.04	0.08	0.07	0.06±0.02^{a}	0.04-0.08	0.08	0.08	0.09	0.08±0.01^{a}	0.08-0.09
	As	0.07	0.08	0.08	0.08±0.01^{a}	0.07-0.08	0.08	0.09	0.14	0.10±0.03^{a}	0.08-0.14
	Se	0.18	0.18	0.19	0.18±0.04^{a}	0.18-0.19	0.21	0.21	0.24	0.22±0.01^{a}	0.21-0.24
Control	Pb	0.09	0.09	0.09	0.09±0.00^{a}	0.09-0.09	0.08	0.09	0.09	0.09±0.00^{a}	0.08-0.09
	Cd	0.01	0.01	0.01	0.01±0.00^{a}	0.01-0.01	0.02	0.01	0.01	0.01±0.01^{a}	0.01-0.02
	Hg	0.007	0.005	0.006	0.01±0.01^{a}	0.05-0.07	0.008	0.008	0.09	0.04±0.04^{a}	0.08-0.09
	As	0.005	0.006	0.008	0.006±0.00^{a}	0.005-008	0.009	0.008	0.009	0.009±0.00^{a}	0.008-0.009
	Se	0.01	0.03	0.01	0.02±0.00^{a}	0.01-0.03	0.02	0.05	0.07	0.05±0.02^{a}	0.02-0.07

Means with the different superscripts across the row indicates significant (*P* < 0.05, ANOVA) difference in metals concentratiom.

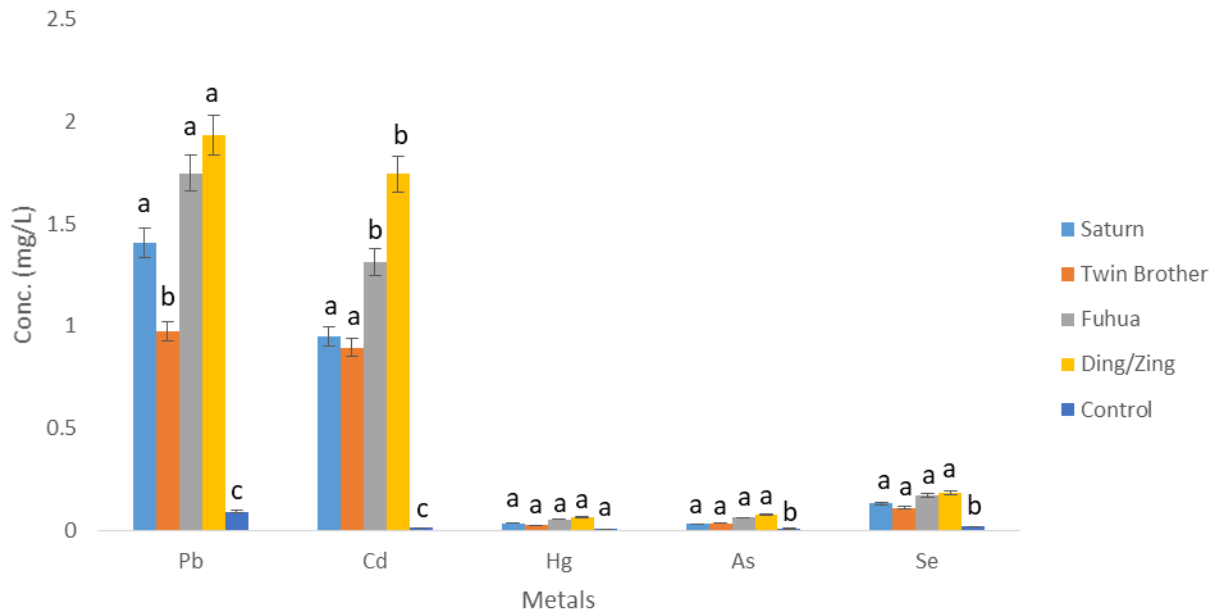

Fig. 2. Comparison of heavy metal concentration in runoff across quarries and control for dry season.

Quarries with different superscript per metal indicates significant difference (ANOVA, $P< 0.05$) in concentration

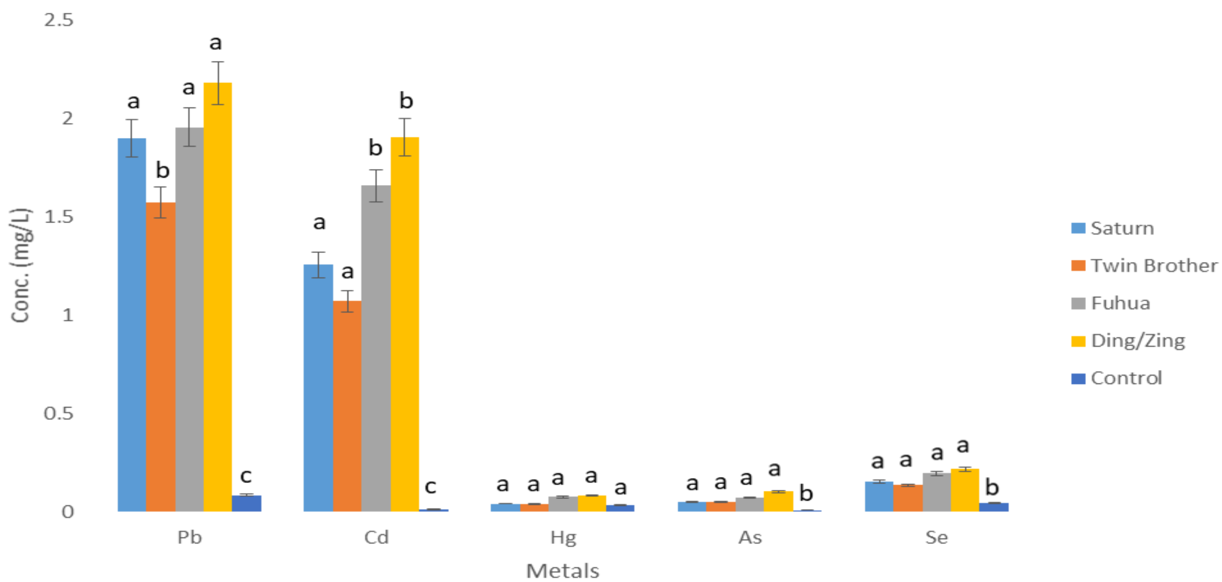

Fig. 3. Comparison of heavy metal concentration in runoff across quarries and control for wet season.

Quarries with different superscript per metal indicates significant difference (ANOVA, $P < 0.05$) in concentration

Table 3. Relationship between heavy metals concentrations in runoffs across quarries

		Lead	Cadmium	Mercury	Arsenic	Selenium
Lead	Pearson Correlation	1				
	Sig. (2-tailed)					
	N	30				
Cadmium	Pearson Correlation	0.952**	1			
	Sig. (2-tailed)	0.000				
	N	30	30			
Mercury	Pearson Correlation	0.687**	0.738**	1		
	Sig. (2-tailed)	0.000	0.000			
	N	30	30	30		
Arsenic	Pearson Correlation	0.887**	0.898**	0.772**	1	
	Sig. (2-tailed)	0.000	0.000	0.000		
	N	30	30	30	30	
Selenium	Pearson Correlation	0.951**	0.943**	0.807**	0.914**	1
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	
	N	30	30	30	30	30

**. Correlation is significant at the 0.01 level (2-tailed).

DISCUSSION

Total metal concentration in quarry runoff (Surface water)

Quarry operations rely heavily on water, particularly for washing aggregates after drilling, blasting, crushing, and screening. In the quarries examined in this study, wastewater from this process serves as the primary irrigation source for nearby vegetable farms. Given the potential risk of heavy metal contamination, evaluating this runoffs against international irrigation standards is crucial for safeguarding public health.

The quarries studied are active operations where wastewater from aggregate washing is discharged into surrounding environments. Over time, these discharges have evolved into flowing surface waters that now feed into local agricultural and fisheries systems. This raises important public health concerns due to the potential accumulation of heavy metals in these ecosystems.

Suitability of the quarry runoffs for irrigation purposes

The mean concentrations of heavy metals in the quarry runoff were compared with WHO and FAO/WHO irrigation water quality standards to assess their suitability for irrigation, fisheries, and aquaculture purposes.

Comparing mean heavy metal concentrations in quarry runoff against WHO and FAO/WHO irrigation water quality guidelines revealed excess compared to permissible limits. Lead concentrations surpassed the WHO threshold of 0.01mg/ L, posing risks of bioaccumulation in crops and soil microorganisms **(FAO, 1994; Alloway, 2013; FAO/WHO, 2017)**. Similarly, cadmium levels exceeded the FAO/WHO limit of 0.005 mg/L, threatening crop yield and soil integrity **(Kabata-Pendias, 2011)**. Mercury concentrations also exceeded WHO's 0.001mg/ L limit, raising concerns about its bioaccumulation in crops and aquatic organisms **(Khan *et al*., 2018)**. Arsenic was below the FAO/WHO limit of 0.1mg/ L, while selenium concentrations exceeded the WHO threshold of 0.02mg/ L, increasing phytotoxicity risks **(Fordyce, 2013)**. These findings indicate that quarry runoff may not be suitable for irrigation due to heavy metal contamination and its long-term ecological and health risks.

To further evaluate irrigation suitability, the study applied Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) guidelines. This comprehensive irrigation water quality guidelines include the Agricultural Irrigation Long-term Trigger Value (LTV), Short-term Trigger Value (STV), and Soil Cumulative Contaminant Loading (CCL) for heavy metals and metalloids. The LTV (mg/L) represents the maximum permissible contaminant concentration over a 100-year irrigation period, ensuring minimal soil accumulation. The STV (mg/L) sets a higher threshold, tolerable for up to 20 years under maximum irrigation loading to prevent acute toxicity to crops. Meanwhile, the CCL (kg/ha) defines the cumulative contaminant threshold, beyond which further risk assessment is necessary if irrigation persists. These benchmarks aim to prevent toxic build-up in soil and ensure the long-term viability of agricultural land irrigated with quarry wastewater **(ANZECC, 2000)**.

The mean concentration of lead in water across the four quarries were found to be below Australia and New Zealand uses Agricultural Irrigation Long-term Trigger Value (LTV) of 5mg/ l and short-term trigger value (STV) of 2mg/ kg, except for Ding Zing quarry during wet season where the mean value was slightly above the STV **(ANZECC, 2000)**. Mean concentration arsenic in water from the different quarries were also below the LTV (0.1mg/ L) and the STV (2.0mg/ l), except at Ding Zing quarry during wet season where the mean value was equal to the LTV. On the other hand, the mean concentration of cadmium, mercury and selenium in runoffs from the different quarries exceeded the LTV and STV thresholds of, 0.01 and 0.05mg/ kg for cadmium, 0.002 and 0.002mg/ kg for mercury and 0.02 and 0.05mg/ kg for selenium respectively, during both dry and wet seasons, suggesting long-term toxicity risks to crops and soil microbial communities **(ANZECC, 2000)**. Repeated irrigation with metal-contaminated runoff can lead to heavy metal accumulation in soils, ultimately affecting soil fertility and plant growth **(McLaughlin *et al*., 2000)**. However, the metals levels in the runoffs were below the Soil Cumulative Contaminant Loading (CCL) limits, indicating minimal immediate risk of soil contamination build-up.

Suitability for the quarry runoffs for fisheries and aquaculture purposes

The WHO/FAO standards for fisheries and aquaculture is ≤ 0.01mg/ L for lead, cadmium, and arsenic, ≤ 0.002 for mercury, and ≤ 0.01-0.02 for selenium **(FAO, 1992; Lemly, 2002; ATSDR, 2007; WHO, 2011; WHO, 2017)**. ANZECC toxicant guidelines for the protection of freshwater aquaculture species stipulate limits for lead (0.001–0.007mg/ L), cadmium (0.0002–0.0018mg/ L), mercury (<0.001mg/ L), arsenic (<0.05mg/ L), and selenium (0.01mg/ L) **(ANZECC, 2000)**. The measured concentrations in the runoff exceed these limits, posing toxicity risks to aquatic organisms. Elevated metal concentrations in water can impair fish reproduction, growth, and immune response **(Almeida *et al*., 2018)**. Consumption of fish exposed to high metal concentrations can lead to bioaccumulation, resulting in neurological and renal disorders in humans **(Jarup, 2003)**. The findings suggest that quarry runoff could compromise aquatic ecosystems, warranting mitigation measures to reduce metal contamination.

Suitability for the quarry runoffs for livestock drinking water

The study area supports pastoral activities, making it essential to assess runoff suitability for livestock consumption, in order to safeguard animal and human health. The WHO/FAO standards for livestock drinking water is ≤ 0.1mg/ L for lead, ≤ 0.01 for cadmium and mercury, and ≤ 0.05 for arsenic and selenium **(FAO, 1992; Lemly, 2002; NRC, 2005; ATSDR, 2007; WHO, 2011; WHO, 2017)**. ANZECC guidelines set tolerable limits for lead (0.1mg/ L), cadmium (0.01mg/ L), mercury (0.002mg/ L), arsenic (0.5mg/ L), and selenium (0.02mg/ L) **(ANZECC, 2000)**. Exceeding values were observed for most metals, implying risks of chronic toxicity in livestock, which could manifest as reduced weight gain, organ damage, and reproductive disorders **(Smith *et al*., 2017)**. Moreover, metal-contaminated livestock products could expose humans to secondary heavy metal ingestion **(FAO, 2020)**.

Seasonal and spatial comparison of metal levels in runoff from the different quarries

Metal levels did not display significant ($P > 0.05$) seasonal variation in the study, except for lead which displayed significantly ($P \leq 0.05$) higher wet season values in Saturn, Twin Brother and Fuhua quarry runoffs. This observation may be attributed to the influence of the rains. Seasonal rainfall significantly influences metal mobility in quarry runoff by increasing surface erosion and leaching, especially during the wet season. Lower pH conditions caused by rain enhance the solubility of metals like lead, explaining its higher wet season concentrations. While rainfall can dilute pollutants, in quarry environments it more often mobilizes metals from exposed rock and soil surfaces. The observed variation across sites and seasons suggests strong anthropogenic inputs, likely intensified by rainfall-driven runoff. The significant difference in the concentration of each metal between the quarries and the control site suggest that quarry activities may be responsible for the higher metal levels at the study site. The significant difference in the concentration lead, cadmium and selenium across quarries for both dry and wet season suggests anthropogenic influence.

Relationship between heavy metals in quarries runoffs

The strong, positive correlations among lead, cadmium, mercury, arsenic, and selenium (Table 4) suggest a shared anthropogenic origin, likely from quarrying processes and associated waste discharge. This co-occurrence implies potential for synergistic toxicity and highlights the importance of addressing multiple contaminants concurrently. The significant, strong and positive correlation observed between cadmium and mercury, cadmium and arsenic and between cadmium and selenium also indicates that an increase in the concentration of cadmium is accompanied by a corresponding increase in the concentration of mercury, arsenic and selenium suggesting that same source is responsible for their presence at the concentration determined. Strong, positive correlation was also observed between mercury and arsenic, mercury and selenium and between arsenic and selenium, which indicates that an increase in the concentration of any one of the metals is accompanied by a corresponding increase in the other metals suggesting that they came from the same source.

CONCLUSION

This research provides a systematic assessment of quarry runoff quality in Njagachang and Awi communities, offering critical site-specific data. The results indicate that heavy metal concentrations exceeded WHO and FAO/WHO irrigation water quality standards, the ANZECC guidelines for freshwater aquaculture, and the maximum tolerable limits for livestock drinking water. The exceeding values pose long-term risks to agriculture, aquatic ecosystems, and human health through bioaccumulation. To mitigate these risks and ensure water safety for various uses, targeted regulatory interventions and the implementation of sustainable quarry waste management practices are strongly recommended.

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Competing interest

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