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Small-Scale Mining and the Enrichment of Heavy Metals in Water and Stream Sediments in the Bonsa River Catchment in the Western Region, Ghana

Thomas Ntori[1]; Kwaku Amaning Adjei[1]; Emmanuel Kwesi Nyantakyi[2,3]*, Nana Osei Bonsu Ackerson[2], Saeed Ibn Idris Kofi Yeboah[2], Ebenezer K. Siabi[2,3], Peter Donkor

Abstract
Heavy metals in rocks are usually released into the environment through uncontrolled anthropogenic activities, such as small-scale mining (SSM), where mined waste rock and effluents are disposed of indiscriminately. This study evaluated the effects of heavy metal enrichment in water and stream sediments in the Bonsa River and its tributaries resulting from small-scale mining operations. The concentrations of Copper (Cu), Lead (Pb), Zinc (Zn), Arsenic (As), Mercury (Hg), Iron (Fe), and Manganese (Mn) were measured in a total of 22 water and stream sediment samples. Sediment heavy metal concentrations were evaluated using pollution indices such as the Contamination Factor, Enrichment Factor, Geo-accumulation Index, and Degree of Contamination. Additionally, the concentrations of heavy metals in the water were compared to the WHO guideline values for drinking water quality. The results indicated that the concentrations of arsenic, lead, and manganese in the water samples exceeded the WHO guideline values for drinking water and were highly elevated in the sediments. On the other hand, the concentrations of copper, zinc, and mercury were low in both the water and stream sediments. Pearson correlation analyses showed strong positive correlations among some elemental pairs (Pb–Fe, Zn–Cu, As–Cu, Pb–Cu, and Zn–Fe), indicating similar geochemical behaviour among the analysed heavy metals. In contrast, mercury concentrations were low in both water and stream sediments. They did not correlate with the other metals, likely because Hg is introduced into the environment during the amalgamation of mined ores. Therefore, SSM needs to be regulated to protect the study environment from continuous pollution.

Keywords
Small-scale mining, Heavy metals, Contamination, Arsenic, Bonsa

[1]Regional Water and Environmental Sanitation Centre in Kumasi, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[2]Department of Civil and Environmental Engineering, University of Energy and Natural Resources, Sunyani, Ghana
[3]Earth Observation Research and Innovation Centre (EORIC), University of Energy and Natural Resources, Sunyani, Ghana
[4]Department of Environmental Management, University of Energy and Natural Resources, P. O. Box 214, Sunyani, Ghana
***Corresponding author:** emmanuel.nyantakyi@uenr.edu.gh
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1. Introduction

Small-scale mining (SSM) activities are practised in many countries worldwide. It is estimated that the sector provides livelihoods to over 100 million individuals globally (Chupezi et al., 2009; Stylo & Davis, 2021). Mining contributes approximately 9.1% to Ghana's gross domestic product (GDP); gold alone accounts for 90-96% (Worlanyo et al., 2022). In Ghana, almost 1 million people are directly involved in SSM activities (Akeliwira, 2026; Bansah et al., 2018; Hilson, 2016). SSM operations typically involve extracting alluvial ore minerals deposited along riverbanks and streambeds, employing methods such as panning, washing, and processing. In certain scenarios, miners may need to use explosives to break up hard rock on a small scale, then grind the fragmented ore to extract gold for further processing. Traditional tools commonly used in alluvial gold mining include panning equipment, shovels, pickaxes, sluices, and wooden boxes, among others. Moreover, more advanced equipment, such as excavators, earth-moving machinery, and washing plants, is occasionally employed by miners (Adu-Baffour et al., 2021).

The Bonsa River catchment, located within the Ankobra River basin in Ghana's Western Region, has attracted a large influx of unemployed youth due to gold deposits. However, the activities of small-scale miners in this region have led to environmental degradation, particularly from heavy metal contamination. Significantly, the Bonsa River serves as a vital water resource for local communities. It sustains agriculture, provides drinking water, and supports biodiversity. In Ghana, contamination of streams and rivers has become commonplace in mining communities (see, for example, Davis et al., 1994; Aryee et al., 2003). For instance, studies conducted in the Tarkwa region of Ghana have revealed elevated concentrations of ten heavy metals, including Mn, As, Al, Hg, Cd, Co, V, Cu, Th, and Sb, in both water and sediment samples (Fosu et al., 2025). The study further found that the contamination factor for certain metals increased notably, particularly in the sediments at Teberebie and Mile 7, indicating antimony (Sb) pollution. Moreover, the Pollution Load Index underscored a significant association with human activities and natural phenomena as the primary sources of contamination. Contamination of water sources poses significant risks to human health and ecosystems, particularly in communities that rely on these sources for drinking and agriculture (see, for example, Obiri-Yeboah et al., 2021). Similarly, Dartey and Sarpong (2016) investigated trace metal enrichment levels across seven streams in the Tarkwa-Nsuaem Municipality. Utilising Atomic Absorption Spectroscopy (AAS), they analysed the concentrations of Zinc, Arsenic, Cadmium, Lead, Copper, Manganese, and Mercury in both stream sediments and water samples. The concentrations of heavy metals in water samples were compared with the World Health Organisation (WHO) guideline values for drinking water to assess associated risks.

Concurrently, Pollution Load Indices were employed to ascertain the degree of heavy metal enrichment in stream sediments. The findings revealed elevated concentrations of mercury, lead, arsenic, and cadmium, exceeding WHO-recommended standards for potable water. Moreover, the contamination factor and geo-accumulation index for mercury and cadmium in sediments indicated varying degrees of contamination, ranging from heavily contaminated to moderately contaminated to uncontaminated. Ultimately, the study identified a significant risk of heavy metal contamination among individuals consuming water from the six investigated rivers. Also, heavy metal concentrations exceeded EPA guideline values, attributed to discharges from prevalent SSM operations in the region. Generally, SSM has garnered disfavour in recent years due to its significant environmental repercussions stemming from inadequate mining practices along watercourses in Ghana. Additionally, this sector has attracted considerable scrutiny for its adverse impact on the natural environment, including emissions and improper disposal of mercury (Rajaee et al., 2015). One significant source of water body contamination is the discharge of trace and heavy metals, which tend to accumulate in water and stream sediments. Nonetheless, heavy metals are typically introduced into the environment either naturally or through anthropogenic activities (Hariprasad & Dayananda, 2013).

Gold in the Tarkwaian and Birimian rocks in Ghana is associated with arsenopyrite and pyrite as pathfinder minerals (Nyarko et al., 2004). Naturally occurring heavy metals, including copper (Cu), lead (Pb), iron (Fe), and manganese (Mn) among others occur in the rocks within the Tarkwa mining area, and mercury (Hg) may persist in the environment if it is not properly disposed after use by small-scale miners in gold recovery (Boamponsem et al., 2010). These minerals are mobilised by exposure during excavations created by mining activities; hence, some are oxidised, transported, and accumulated in various environmental sinks. Activities of small-scale miners, particularly those engaged in alluvial mining, contribute significantly to the release and mobilisation of heavy metals into the water bodies in which they operate. Heavy metals are released into the environment through smelting, milling, and improper disposal of mining waste. The presence of heavy metals in aquatic environments has profound implications for zooplankton and, in turn, affects the health of organisms that depend on these rivers (Boamponsem et al., 2010). High levels of arsenic are known to cause various health complications, such as malfunction of the white blood cell and gastrointestinal infections (Ferguson, 1990). Exposure to high levels of lead has various health implications, and the impact is the same regardless of which part of the body is affected. Lead primarily affects the nervous system in both infants and the elderly (Ishola & Amuda, 2014). It can also increase blood pressure and cause blood loss in adults (Ishola & Amuda, 2014). Lead poisoning claimed the lives of about 463 children in an SSM community in Nigeria in 2010 (Dooyema et al., 2012). Numerous studies have explored heavy metal enrichment in Ghana, with findings such as those by Cobbina et al. (2015), which highlighted elevated levels of mercury (Hg), arsenic (As), lead (Pb), zinc (Zn), and cadmium (Cd) in water samples from small-scale mining communities like Nangodi and Tinga, often exceeding WHO guidelines and posing significant health risks. Consequently, there is a strong recommendation to continuously monitor drinking water quality in these areas. Studies examining heavy metals, particularly lead and mercury, in the Bonsa River have also indicated concentrations well above permissible limits set by both the Ghana Environmental Protection Agency (EPA) and the WHO, revealing substantial contamination levels in the region, as evidenced in research such as that by Obiri-Yeboah et al. (2021).

A study conducted by Kpan et al. (2014) in Dunkwa-on-Offin, Central Region of Ghana, highlighted significant levels of heavy metal pollution surpassing the WHO drinking water guideline values. Similarly, Bortey-Sam et al. (2015) assessed metalloid risks in agricultural soils across 19 mining communities, identifying elevated concentrations of heavy metals, ranked as follows: Cd < Hg < Co < Ni < As < Cu < Pb < Cr < Zn. The Bonsa River catchment, a hub of intensive small-scale mining (SSM), serves as a critical water source for residents. Despite extensive documentation of SSM's environmental impacts, gaps persist in understanding specific sources and the extent of heavy metal contamination in this region. This study addresses gaps by evaluating heavy metal enrichment in water and stream sediments within the Bonsa River catchment, specifically mercury, lead, arsenic, and cadmium in aquatic and sediment environments. It aims to provide new insights by identifying sources and quantifying contamination. The research informs evidence-based interventions to mitigate environmental pollution and protect public health in mining-affected areas, promoting sustainable management strategies to ensure environmental resilience and community well-being, as these communities depend on the Bonsa River for drinking water.

2. Methods and Materials

2.1 Study Area

The Bonsa River catchment (Fig. 1) is located in south-western Ghana, within the Ankobra River basin. It covers approximately 1318 km^2 and spans four administrative districts: Tarkwa-Nsuaem, Prestea-Huni Valley, Mpohor, Wassa East, and Twifo-Heman-Lower-Denkyira. The catchment includes several tributaries such as the Subri, Nwiu, and Asenso streams. Geographically, it extends from longitudes 1° 41´ W to 2° 13´ W and latitudes 5° 4´ N to 5° 43´ N. The region experiences two distinct rainy seasons: a major one from May to August and a minor one from September to October. Annual rainfall ranges between approximately 1520 mm and 2200 mm (WRRI, 2003). Annual temperatures range from 22°C to 32°C (WRRI, 2003).

The catchment area is underlain by Birrimian and Tarkwaian rocks (Akabzaa et al., 2009), renowned for their rich mineral deposits (Kortatsi, 2004). The Tarkwaian formation primarily consists of the Banket series and Kawere subgroups. In contrast, the Birimian system is characterised by extensive granitic intrusions and prominent foliation (Asklund & Eldvall, 2005). Mineral deposits in the region are typically located within geological discontinuities and shear zones at the junction of meta-volcanic and meta-sedimentary rocks (Asklund & Eldvall, 2005). The area sees significant mining activities,

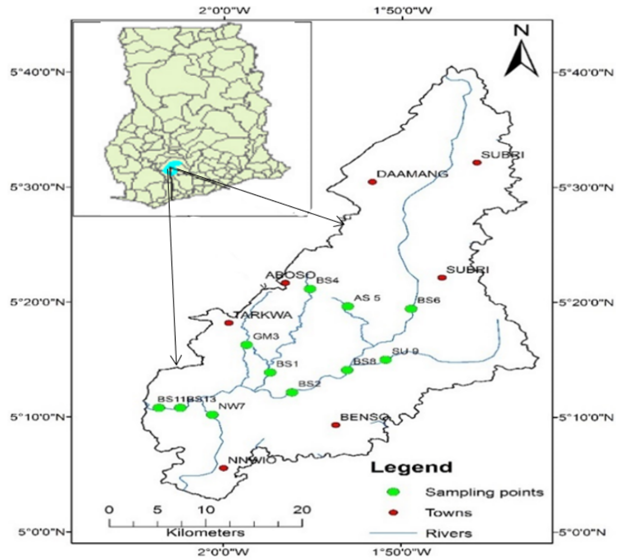

Figure 1. Location map of the study area

including large-scale, small-scale, and illegal operations, owing to the abundant geological resources. Small-scale mining, in particular, is a significant concern due to inadequate regulation. Economic activities in the region also include agriculture, with cash crops such as latex rubber and cocoa, as well as other food crops, being cultivated.

2.2 Sample Collection and Analysis

A total of 22 samples were collected from the Bonsa River and its downstream tributaries, with a focus on areas heavily impacted by small-scale alluvial mining. These samples included 11 water samples and 11 stream sediment samples (refer to Fig. 1). The stream sediment samples were dried and ground into a fine powder. Approximately 2 grams of the powdered sediment were transferred into a 50 ml digestion tube, treated with 2.5 ml each of concentrated hydrochloric acid (HCl) and nitric acid (HNO3), and heated at 110°C for approximately 40 minutes. For the water samples, 50 ml of each sample was placed into a digestion tube, mixed with 5 ml of concentrated nitric acid, and heated at 95°C for about 2.5 hours. The concentrations of the heavy metal parameters in both water and sediment samples were analysed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The liquid samples were analysed directly on the instrument, either in their prepared form or diluted to the instrument's calibration range, with calibration and comparison performed using a 2% HNO3 standard solution.

2.3 Pollution Indices Evaluation

The assessment of heavy metal enrichment levels utilised pollution indices, including the contamination factor, enrichment factor, geo-accumulation index, and degree of contamination. The contamination factor is the ratio of metal concentration or enrichment level to the natural background or crustal concentration. The interpretation classes for heavy metal contamination levels are detailed in Table 1. This factor illustrates the influence of individual metals on sediments (Olatunji et al., 2009). Martin & Meybeck (1979) expressed the contamination factor mathematically as

$$\text{Contamination Factor (CF)} = \frac{C_m}{C_b}, \tag{1}$$

where C_m and C_b represent the measured and background concentrations, respectively.

Table 1. Classification criteria used for interpreting contamination factor (CF) values in stream sediments.

CF	Contamination Levels
CF<1	Low
$1 \leq$ CF<3	Moderate
$3 \leq$ CF<6	Considerate
CF ≥ 6	Very high

The enrichment factor was determined from the ratio of the contamination factor of an element of interest to the ratio of the contamination factor of the reference element. The enrichment factor was used to standardise element concentrations relative to the reference element (Table 2). This method was used to assess the anthropogenic impact on sediments by comparing heavy metal concentrations from anthropogenic and lithogenic sources (Ismaeel & Kusag, 2012). The classes used to interpret heavy metal enrichment levels are listed in Table 2. The mathematical expression (Eq. 2) for the index put forward by Buat-Menard & Chesselet (1979) is defined as:

$$\text{Enrichment Factor} = \frac{C_m/C_b}{C_{m,\text{ref}}/C_{b,\text{ref}}} \tag{2}$$

where C_{mref} and C_{bref} represent the measured and background concentration of the reference element.

The geo-accumulation index (I_geo) quantifies the concentration of a metal relative to that in areas with little or no anthropogenic activity (Table 3). The geo-accumulation index was computed from Equation 3 developed by Muller (1969).

$$I_{\text{geo}} = \log_2\left(\frac{C_n}{1.5B_n}\right) \tag{3}$$

From equation 3, C_n and B_n represent the measured concentration of a metal of interest and the background concentration in mg kg-1. A factor of 1.5 is used to account for anthropogenic effects due to fluctuations in background heavy metal concentrations in environmental media. The value was compared with the geo-accumulation classes in Table 3.

Table 2. Classes for enrichment factor

EF Values	Enrichment level
< 2	Depletion to minimal
$2 - 5$	Moderate
$5 - 20$	Significant
$20 - 40$	Very high
> 40	Extremely high

Table 3. Classes for geo-accumulation index

Igeo Value	Sediment Quality
≤ 0	Not polluted
$0 - 1$	Not polluted to moderate pollution
$1 - 2$	Moderate pollution
$2 - 3$	Moderate to heavy pollution
$3 - 4$	Heavily polluted
$4 - 5$	Heavily to extremely polluted
≥ 5	Extreme pollution

The contamination factor and degree of contamination were used to assess the extent of heavy metal enrichment in water samples. The metal ratio was computed by dividing the measured concentration of the metal under consideration by the WHO-recommended standard threshold limit for drinking water. The degree of contamination for the various sites was computed using the contamination factors. The degree of heavy metal contamination at each site was calculated as the sum of the contamination factors for the various heavy metals at that site. Mathematically, the degree of contamination is expressed as:

$$\text{Degree of Contamination}\,(C_d) = \sum CF \tag{4}$$

Where CF is referred to as the ratio of the level of enrichment or concentration of a metal to the natural background or crustal concentration. Hakanson (1980) categorised contamination levels into four classes: Cd < 6 for low contamination, $6 \leq$ Cd ≤ 12 for moderate contamination, $12 <$ Cd ≤ 24 indicating considerable contamination, and Cd > 24 representing very high contamination. Spatial assessment of contamination levels involved interpolating the sum of contamination factors at each sampling point. The Inverse Distance Weighting (IDW) technique was used to spatially interpolate contamination levels across sampling points, generating a heavy metal contamination map for the catchment area. The IDW interpolation method was adopted because it is a simple and widely used deterministic approach that provides reliable spatial estimates from point-based environmental data and is particularly suitable for visualizing spatial patterns of contamination across a study area (Ibrahim & Nasser, 2017).

2.4 Data Analysis

Descriptive statistics were employed to summarise the concentrations of arsenic (As), manganese (Mn), copper (Cu), iron (Fe), lead (Pb), zinc (Zn), and mercury (Hg) in water and sediment samples collected from the Bonsa River catchment. Measures such as mean, median, standard deviation, and range provided insights into central tendencies and variability across sampling sites. Inferential statistics, specifically analysis of variance (ANOVA), were used to assess significant differences in heavy metal concentrations among sampling locations and between water and sediment samples. Spatial analysis involved interpolating contamination levels across the catchment area using the Inverse Distance Weighting (IDW) method, based on contamination factors calculated for individual metals. This spatial mapping illustrated the geographical distribution of heavy metal contamination within the study area. All statistical analyses were performed using SPSS (Statistical Package for the Social Sciences), version 26 and Excel 2019.

3. Results and Discussion

Table 4 presents the concentrations of heavy metals detected in water samples collected from the River Bonsa. Various metals were identified in different water samples across the study area, particularly in SB9, where levels of arsenic (As), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), mercury (Hg), and zinc (Zn) were compared to the WHO (2011) drinking water guideline values. Most metals were below detectable limits (DL), except for Mn and Pb. In SB9, concentrations exceeded the recommended guidelines for all parameters except Zn and Hg, which were present in very low amounts. There were isolated instances in which Mn, Fe, and Pb levels exceeded permissible limits for drinking water.

Similarly, concentrations of Fe and Mn in streams often exceeded acceptable WHO (2011) drinking water standards. This situation is attributed to the direct pumping of water from mine pits into streams during mining operations, resulting in elevated Fe and Mn levels that exceed permissible limits for river water quality. These metals are commonly found in mining communities because they are associated with gold-bearing rocks, including those in the study area (Bhattacharya et al., 2012; Dorleku et al., 2018). The weathering of these rocks, exacerbated by mining activities, likely contributes to the release of metals into surface water.

Pollution indices such as the contamination factor, enrichment factor, geoaccumulation index, and degree of contamination were used to evaluate heavy metal concentrations in water. Figures 2 and 3 illustrate the results of contamination and enrichment factors for heavy metals in sediments. The concentrations of heavy metals in water varied significantly across sampling sites, possibly influenced by the intensity of small-scale mining activities. Additionally, during transport along watercourses, metals can be absorbed or adsorbed by aquatic organisms and other environmental components. Adsorption onto environmental surfaces plays a critical role in the transport of heavy metals.

Table 4. Heavy metal concentrations (mg/l) in water samples

ID	As	Cu	Fe	Mn	Pb	Zn	Hg
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
BSW1	0.024	0.381	0.817	1.02	0.11	0.08	0.001
BSS2	0.01	0.212	0.214	0.04	0.03	0.03	0.001
GMC3	0.048	0.781	0.685	0.12	0.04	0.16	0.001
BSW4	0.012	0.366	0.766	2.06	0.13	0.07	0.001
AS5	0.038	0.426	0.643	1.07	0.11	0.07	0.001
BSS6	0.005	0.233	0.199	0.04	0.02	0.03	0.001
NW7	0.043	0.433	0.652	2.03	0.15	0.05	0.001
BSS8	0.004	0.217	0.236	0.02	0.02	0.04	0.001
SB9	0.044	2.061	0.711	3.12	0.15	0.06	0.001
BSS11	0.008	0.186	0.232	0.01	0.04	0.01	0.001
BSS13	0.007	0.181	0.196	0.03	0.03	0.01	0.001
WHO Limit	**0.01**	**1**	**0.3**	**0.4**	**0.01**	**3**	**0.006**

Table 5. Heavy metal concentrations (mg/kg) in river sediments

Sn NO.	As	Cu	Fe	Mn	Pb	Zn	Hg
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
S-1	9.41	17.33	2568.13	3471.7	5.05	31.29	0.003
S-2	5.11	9.71	1864.6	114	4.29	21.59	0.003
S-3	6.55	25.6	29999.1	1310.49	11.31	37.28	0.003
S-4	1.8	6.28	7272.43	68.61	3.95	14.11	0.003
S-5	2.81	10.3	16850.6	518.47	3.99	13.32	0.003
S-6	1.86	5.51	10541.4	39.99	3.95	5.04	0.003
S-7	10.59	14.85	26214.5	2214.35	7.99	22.88	0.003
S-8	5.52	10.74	1573.26	91.39	3.45	19.88	0.003
S-9	6.31	11.8	2562.62	44.35	3.62	18.92	0.003
S-10	1.9	1.37	1846.61	55.55	0.65	13.04	0.003
S-11	1.07	1.25	1391.4	45.96	0.35	2.4	0.003

The concentrations of heavy metals in the river sediment varied significantly: Arsenic (As) ranged from 1.07 to 10.59 mg/kg, Copper (Cu) from 1.25 to 25.6 mg/kg, Iron (Fe) from 1391.4 to 29999.06 mg/kg, Manganese (Mn) from 39.99 to 3471.7 mg/kg, Lead (Pb) from 0.35 to 11.31 mg/kg, Zinc (Zn) from 2.4 to 37.28 mg/kg, while Mercury (Hg) was detected below the analytical detection limit (<0.0006 mg/kg). The concentrations of As, Cu, Fe, Mn, Pb and Zn are comparable to those reported in mining-impacted environments in the Obuasi area (Bempah & Ewusi, 2016; Bempah et al., 2013; Kwarteng, 2012). The low Hg concentrations observed in this study may suggest limited mercury inputs to the sampled sites during the study period, effective dilution and transport processes, or the absence of substantial mercury accumulation in the river sediments despite ongoing mining activities within the catchment.

Assessment of contamination factors (Fig. 2) revealed that 82% of sampling sites exhibited moderate to considerable levels of arsenic contamination, while 27% showed similar trends for manganese. The geo-accumulation index (Fig. 3) indicated moderate to high pollution levels at 55% of sites for arsenic, with manganese and copper levels classified as extremely polluted across all sampling sites based on the geo-accumulation index (Fig. 4). Arsenic primarily associates with arsenopyrite (FeAsS) in the gold mineralisation within Birimian and Tarkwaian rocks (Akabzaa et al., 2007; Coakley, 1996). Previous studies have reported elevated arsenic levels in water in the Tarkwa mining area, attributed to small-scale alluvial mining along riverbanks, which facilitates heavy metal exposure and transport in the environment. Lead, zinc, and mercury displayed low contamination factors across all sites (Fig. 2). Sites S1, S2, S8, and S9 exhibited extremely high arsenic enrichment, with significant enrichment of lead at S1, S2, and S8, and zinc at S1, as indicated by enrichment factors. Manganese enrichment was notably high at sites S1 and S8, while copper showed moderate enrichment at S1, S2, S8, and S9, and minimal to depleted enrichment at other sites. These findings underscore the pervasive impact of mining activities on heavy metal contamination in the Bonsa River catchment, requiring robust environmental management strategies to mitigate risks to aquatic ecosystems and public health.

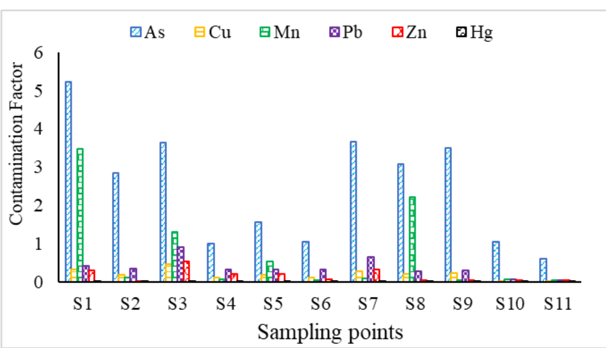

Figure 2. Contamination factor of Heavy metals

The high concentration of manganese observed in sediment samples within the catchment is consistent with findings reported by Boamponsem et al. (2010) in the Tarkwa mining area. The geological composition of the study area is predominantly greenstone rich in manganese ore. When these rocks are exposed by mining, manganese and other metals are mobilised and subsequently accumulate in environmental reservoirs, such as river sediments. In contrast, copper concentrations in sediment samples were higher than in water samples, indicating potential sources from both anthropogenic activities and natural processes within the local rock formations. Copper, a base metal commonly associated with gold mineralisation in the Birimian and Tarkwaian rocks underlying the catchment (Kortatsi, 2004), leaches into rivers and accumulates in stream sediments through excavation processes associated with small-scale mining.

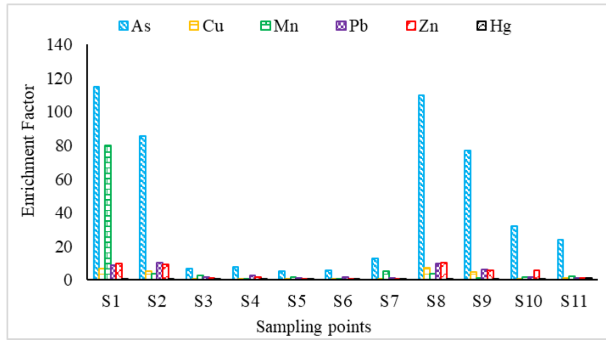

Figure 3. Enrichment factor of Heavy metals

The contamination level was evaluated at 11 sampling sites to assess the pollution burden in water samples across the catchment area. Figure 5 shows a spatial map of varying levels of heavy-metal contamination. Sampling points BS4, SU9, and S7 showed very high contamination levels. Sites BS1, GM3, and AS5 showed high contamination, while BS2 and BS11 showed moderate contamination. Sampling locations BS6, BS8, and BS13 showed low contamination levels. Notably, SU9 showed the highest contamination level at 32.65, highlighting the significant impact of small-scale alluvial mining activities along the Subri stream. These activities contribute to the release and spread of heavy metals in the aquatic environment. In contrast, BS8 reported the lowest contamination level at 4.47.

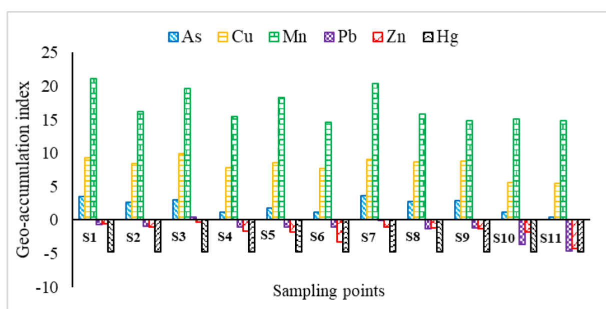

Figure 4. Geo-accumulation index of Heavy metals

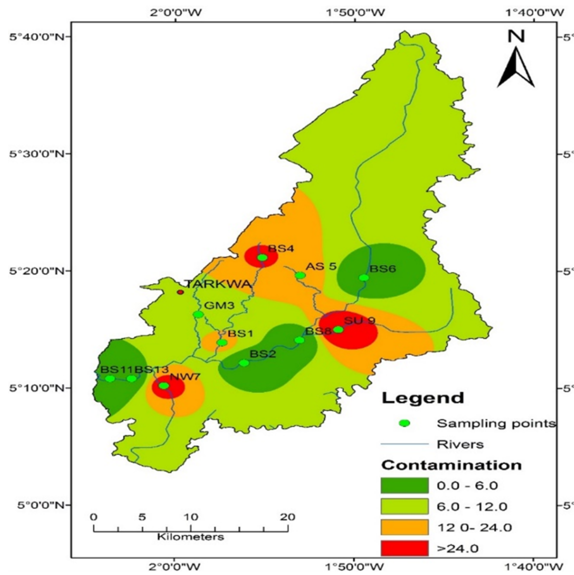

Figure 5. Spatial Degree of contamination map

3.1 Correlation Matrix

Pearson correlation analysis was performed to investigate associations between heavy metal concentrations in water and sediments and to identify potential sources of contamination. Table 6 outlines the results of the Pearson correlation analysis for heavy metals in sediments, while Table 7 details the correlations observed in water samples.

Table 6. Correlation of metals in sediment samples

	As	Cu	Mn	Pb	Zn	Hg
As	**1**					
Cu	0.811**	**1**				
Mn	0.686*	0.532	**1**			
Pb	0.594	0.914**	0.247	**1**		
Zn	0.486	0.821**	0.347	0.874**	**1**	
Hg	0	0	0	0	0	**1**

**Correlation is significant at the level 0.01 *Correlation is significant at the 0.05 level.

Table 6 illustrates strong positive correlations (r > 0.80) among several pairs of heavy metals in sediment samples, specifically As-Cu, Pb-Cu, Zn-Cu, and Zn-Pb. The correlation coefficient between Mn and As was 0.686, indicating a moderately positive relationship. However, no significant correlation (r = 0) was found between Hg and any other metals in sediment samples. In water samples (Table 7), weak correlations were observed among Pb-Mn, Mn-Zn, and As-Zn pairs of elements.

Table 7 reveals positive correlations among several pairs of heavy metals in water samples, with the pairs Pb-Mn significant at the p=0.01 level, and Cu-As, Mn-Cu, Pb-As, and Zn-As significant at the p=0.05 level. Weak correlations (r < 0.5) were observed for Zn-Pb, Zn-Mn, Zn-Cu, Mn-As, and Pb-Cu pairs. A positive correlation of 0.686 was observed for the Zn-Pb and Mn-As pairs, suggesting these elements may share a common source or exhibit similar geochemical behaviour influenced by regional rock types such as the Birimian and Tarkwaian formations, which are known for their natural concentrations of these metals (Kortatsi, 2004). Notably, no correlation (r = 0) was found between mercury and other metals in sediments, likely due to its non-crustal origin and association with small-scale mining activities that use mercury in amalgamation processes (Pfeiffer & Larceda, 1998). Similarly, strong positive correlations (r > 0.80) were observed among most elemental pairs in water samples, with mercury showing no correlation with other metals (r = 0), indicating a distinct source of mercury in the water environment.

Table 7. Correlation of metals in water samples

	As	Cu	Mn	Pb	Zn	Hg
As	**1**					
Cu	0.644*	**1**				
Mn	0.567	0.713*	**1**			
Pb	0.628*	0.529	0.941**	**1**		
Zn	0.695*	0.34	0.178	0.241	**1**	
Hg	0	0	0	0	0	**1**

**Correlation is significant at the level 0.01 *Correlation is significant at the 0.05 level.

4. Conclusion

The study examined heavy metal concentrations in water and stream sediments in the Bonsa River and its tributaries, revealing elevated enrichment levels attributable to small-scale mining (SSM) activities along the riverbanks. Arsenic, lead, and manganese concentrations in water exceeded WHO drinking water guidelines, and elevated levels were also observed in sediment, as indicated by pollution indices. Conversely, copper, zinc, and mercury concentrations were relatively low in both water and sediment samples. Near the Bonsa-Subri confluence, increased metal contamination pointed to escalating SSM activities. Pearson correlation analysis highlighted strong correlations among base metals, suggesting similar environmental behaviour. In contrast, mercury showed no correlation with other metals, indicating that it was introduced through SSM amalgamation processes. The findings underscore the need for stringent environmental oversight of SSM, particularly alluvial mining, to mitigate pollution risks and safeguard ecosystem and human health.

5. CRediT authorship contribution statement

Thomas Ntori: Conceptualisation and design of the research work, Methodology, Software, Writing – original draft. Kwaku Amaning Adjei: Supervision, Literature

Search, Visualisation, Investigation. Emmanuel Kwesi Nyantakyi: Literature Search, Visualisation, Investigation, Validation, Writing – review & editing. Nana Osei Bonsu Ackerson: Data curation, Software, Visualisation. Saeed Ibn Idris Kofi Yeboah: Validation, Writing – review & editing. Ebenezer K. Siabi: Writing – review & editing. Peter Donkor: Writing – review & editing. All co-authors have agreed to be accountable for all aspects of the research work. All authors read and approved this manuscript.

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7. Conflict of Interest Statement

There is no conflict of interest.

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