

# Assessment of Trace Metal Contamination and Ecological Risks in the Sediments of Lake Kossou and White Bandama River, Angovia Mining Area (Central-West, Côte d'Ivoire)

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## Abstract

Artisanal gold mining in Angovia (Côte d'Ivoire) exerts pressures on Lake Kossou and the White Bandama River. Six sediment samples (two riverine and four lacustrine) were analyzed for As, Cd, Cu, Zn, Cr, Ni, Hg, Pb, Fe, and Mn using ICP-AES (Hg by CV AAS). Ecological risks were assessed using geochemical indices (Igeo, D<sub>Cm</sub>), the potential Ecological Risk Index (PERI), sediment quality guidelines (TEC/PEC), and Principal Component Analysis (PCA). Sediments show polymetallic (As, Cd, Cu, Cr, Ni, Hg, Fe, and Mn) enrichment relative to the Upper Continental Crust, while Zn, Pb, and Ni remain at background levels. Chromium is the most abundant metal (mean: 145 mg/kg; max: 284 mg/kg). Acidic pH (mean: 5.76) suggests the Acid Mine Drainage process (AMD). PCA confirms the geogenic component (As, Cu, Zn, Cr, Ni, Pb, Fe, Mn) and the anthropogenic component (Hg). Lead shows mixed sources. Geochemical indices indicate low pollution (L1, FL1) to moderate (L2, L3, L4, FL2). Mercury (Er = 107.14 at L3) has the highest individual toxicity, followed by Cd and As. All concentrations of Cd were below the LOQ (<0.2 mg/kg). Using a conservative upper bound substitution (LOQ), Cd's contribution to the PERI ranges from 14% to 40%, with an individual moderate risk Er = 59. Hence, even without precise quantification, Cd may contribute to the ecological risk. Although Cr dominates the sediment load, its low toxicity factor makes it a minor PERI contributor. However, Cr frequently exceeds the TEC/PEC thresholds and can pose a direct biological threat. The combined use of geochemical indices, the PERI, and SQGs is necessary for environmental man-

agement. Close attention should be paid to heavy metal pollution in Lake Kossou and the Bandama River to protect the aquatic ecosystem and the local population.

## Keywords

Contamination, TME, Sediment, Angovia Mining Zone, Ecological Risk

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## 1. Introduction

Heavy metal pollution in aquatic environments, linked to rapid industrial and economic development, has become an important issue worldwide due to the high toxicity, abundance, and persistence of these elements in ecosystems. Heavy metal residues can accumulate in aquatic organisms, then enter the human food chain and cause health problems [1].

In Côte d'Ivoire, the adoption of the 2014 mining code stimulated the extractive sector, but artisanal gold mining also expanded rapidly. Despite government efforts to control it, this activity continues illegally and causes significant damage to watercourses in many regions [2].

River sediments are important vectors and reservoirs for heavy metals released into aquatic environments [3]. Under ecological disturbances such as a decrease in pH or the degradation of organic matter, sediment-bound metals can be remobilized into the water column, leading to secondary pollution [4]. Heavy metals in river sediments originate mainly from rock weathering, erosion, soil runoff, wastewater treatment, and atmospheric deposition. They are transferred and concentrated in sediments through adsorption into organic matter, Fe/Mn oxides, and sulfides, but they are not permanently fixed [2]-[4].

Several studies have shown the degradation of river sediments by heavy metals [5]-[11]. These studies are important and complement each other.

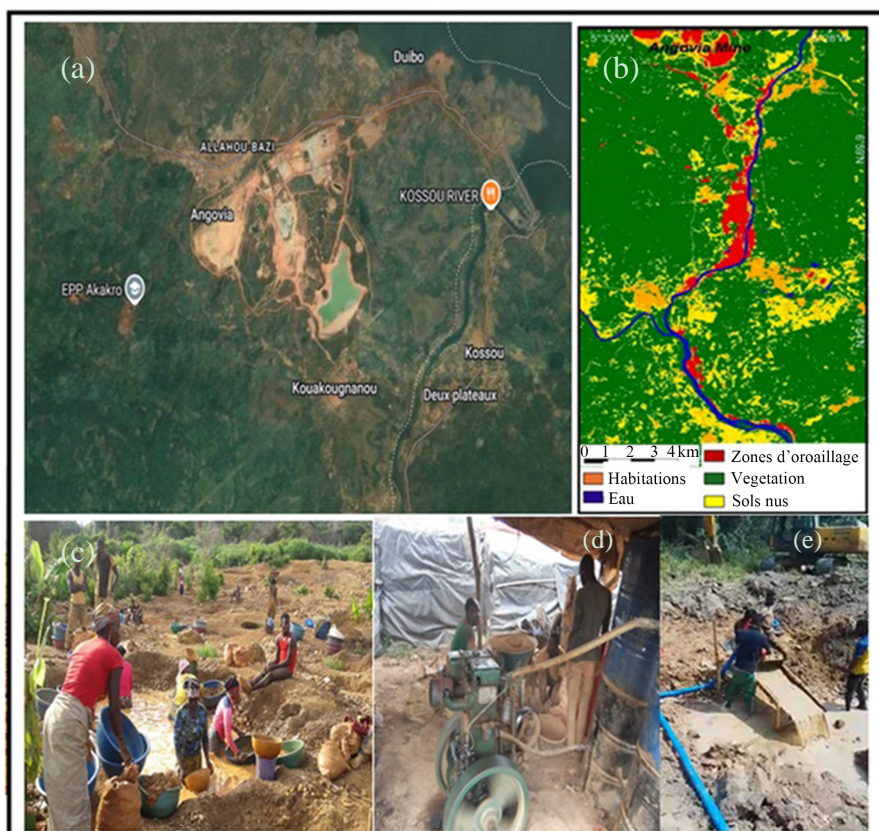
However, previous studies in the region did not consider the full range of metal contamination (As, Cr, Cu, Hg, Ni, Pb, Zn). They also did not assess ecological risk by combining concentration-based approaches (TEC/PEC guidelines) and the potential ecological risk index (PERI) based on intrinsic toxicity. In particular, the role of mechanical ore crushing as a pathway for chromium mobilisation is a potential indicator of mining intensity, which has never been explored.

The present study focuses on Lake Kossou and the Bandama river, located downstream of the Angovia mining area, where artisanal gold mining is particularly active [7]. The objectives were to assess sediment contamination by trace metal elements using geochemical indices (Igeo, D<sub>Cm</sub>), the Potential Ecological Risk Index (PERI), sediment quality guidelines (TEC/PEC) for environmental risk, and Principal Component Analysis (PCA) for potential sources and correlation analysis among heavy metals.

## 2. Materials and Methods

### 2.1. Study Area

The study area is located in the Centre-West of Côte d'Ivoire, in the Marahoué region, more specifically in the Sub-prefecture of Gbégbéssou in the department of Bouaflé. It is geographically situated between latitudes 6°50' and 7°15' North and longitudes 5°45' and 6°10' West. The hydrological regime of this region is of the attenuated transitional equatorial type. It is subject to a Baoulean-type climate characterized by alternating two dry seasons and two rainy seasons [12].



**Plate 1.** (a) Industrial mining activities; (b) Artisanal gold mining along the Bandama River [7]; (c)-(e) Artisanal activities in the Angovia mining zone (photos DIBY).

This area has a geological framework composed of Birimian and Archaean greenstone belts rich in gold mineralisation [13] [14]. According to the work of [15], these volcano-sedimentary assemblages, separated by older migmatite and granite massifs, form the basement of the region. The presence of numerous porphyry veins associated with this intrusion confirms the importance of hydro-thermal processes in the geological structuring of the area. These magmatic features have facilitated the concentration and deposition of gold within Birimian greenstone belt shear structures and zones of high structural permeability [16]. This tectonic setting is characterized by typical magmatic mineralization associated with quartz veins and altered zones rich in sulfides (pyrite, arsenopyrite, sometimes ga-

lena and chalcopyrite). It is, therefore, likely to release toxic elements such as Cd, As, Pb, Cr, Zn, Fe, Mn, Co, and Ni [12] [13]. This configuration explains both the existence of the industrial mine located at Angovia and the pervasiveness of artisanal gold mining activities in the area (Plate 1).

### 2.2. Sampling Methodology

The sampling campaign took place in July 2025 during the rainy season. Figure 1 shows the six (6) sediment sampling stations covering the main aquatic environments subject to artisanal gold mining pressure. These include the following stations: each station represents a single grab sample:

- Lake sites (L1 to L4) are distributed from upstream to downstream in an area of the lake heavily exploited by gold panners.
- River stations (FL1 and FL2) are located on the adjacent Bandama River, with FL1 upstream and FL2 immediately downstream of the ore-washing areas.

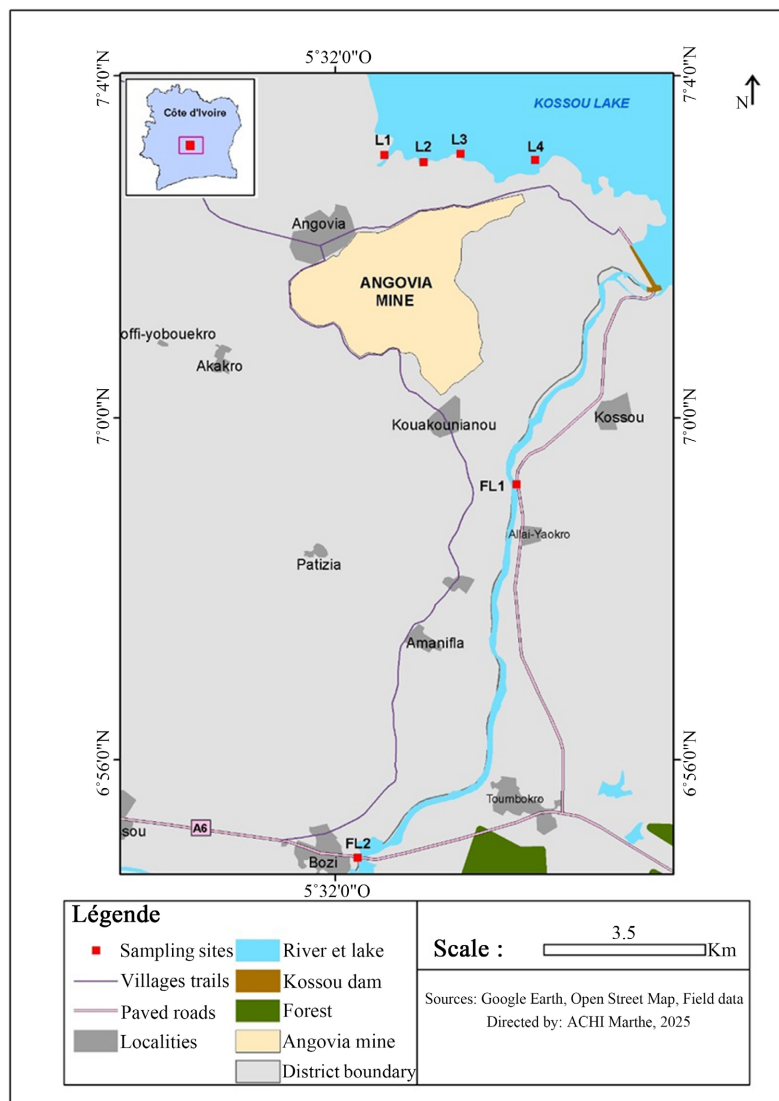


Figure 1. Location of sampling sites in lake kossou and the bandama blanc river.

Surface sediments were collected from the top five (05) centimeters using a Van Veen grab, in accordance with the reference methods of the Ivorian Anti-Pollution Centre (CIAPOL) [17] applied in the context of marine pollution studies. The samples were packed in hermetically sealed polyethylene bags and stored in a cool box at a temperature of approximately 4°C during transport to the laboratory.

### 2.3. Laboratory Analyses

Laboratory analyses were conducted according to procedures defined by CIAPOL.

#### Mineralization and metal quantification

Sediment samples were processed according to [18]. They were dried at 105°C, ground in an agate mortar to avoid metallic contamination, and sieved to 63 µm to obtain a homogeneous fine fraction. Mineralization was carried out by wet digestion in an open system using aqua regia: three parts hydrochloric acid (3:1, HCl, 37%: HNO<sub>3</sub>, 65%) following [19] and heated until complete dissolution of the target elements. The mixture was heated until complete dissolution of the target element. Finally, the pH of the sediments was measured in a demineralized water/sediment suspension (ratio 1:2.5) using a pH meter.

The concentrations of metallic elements in the digest were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) using argon as the carrier gas. Iron (Fe), manganese (Mn), nickel (Ni), arsenic (As), copper (Cu), zinc (Zn), chromium (Cr), and lead (Pb) were quantified according to [20]. Mercury was determined separately by the cold vapor method (CV-AAS).

#### Quality assurance (QA) and quality control

Laboratory analyses were carried out according to procedures defined by the Ivorian Anti-Pollution Center (CIAPOL) following [20] requirements for ICP-AES. Precision, assessed as relative standard deviation (RSD), was below 5% for all trace metals (n = 6 per batch). Recovery rates ranged from 94% to 105%. Procedure blanks showed no detectable contamination. Duplicate analyses (n = 6; 100% of samples) confirmed reproducibility. Method detection limits ranged from 0.003 mg/kg (Hg) to 2 mg/kg (Fe). All concentrations are expressed in mg/kg dry weight, with a quantification threshold established at 3 × MDL.

#### Substitute method of cadmium

For cadmium, LOD = 0.05 mg/kg, LOQ = 0.2 mg/kg, all measured concentrations were below the limit of quantification (LOQ = 0.2 mg/kg). However, we are also sure that cadmium is present in the samples. In accordance with [21] [22] recommendations for ecotoxicological risk assessment and considering the high toxic response factor of Cd (Tr = 30) in the Hakanson ecological risk index, a conservative upper-bound approach was applied using LOQ = 0.2 mg/kg for all samples. The lower bound (LOD = 0.05 mg/kg) would potentially underestimate the actual risk if true concentrations were close to 0.2 mg/kg. This constant value does not reflect a true measurement, but a substitution based on the LOQ. The actual Cd concentrations lie somewhere between 0.05 and 0.2 mg/kg. Because this value is constant across all stations, it was excluded from the Principal Component

Analysis (PCA) as it brings no variance.

## 2.4. Pollution Assessment Method

To assess sediment contamination and associated ecological risk, the following geochemical indices were used: contamination factor (CF), geoaccumulation index (GeoI), modified contamination degree (DC<sub>m</sub>) for the pollution level; potential ecological risk index (PERI, Er) and sediment quality thresholds (TEC/PEC) for ecological risk.

These indices covered seven heavy metals (As, Cr, Cd, Cu, Hg, Pb, Ni, Zn), excluding Fe/Mn, which are major natural components of the terrestrial matrix. This approach, as explained in [23], avoids masking variations in heavy metals that are indicators of mining activities and pose a real risk to aquatic ecosystems. Concentrations of the sediments obtained were compared with those in unpolluted sediments reported in [24] and background reference values (UCC) [25] according to **Table 1**.

**Table 1.** Concentration of ETMs in uncontaminated sediments.

	As	Cd	Cr	Fe	Mn	Ni	Pb	Zn	Cu	Hg
Persaud <i>et al.</i> (1993)	4.2	1.1	31	31200	400	31	23	65	-	-
Wedepohl, K. H. (1995)	2	0.102	35	30890	527	18.7	17	52	14.3	0.056

### 2.4.1. Müller Geochemical Index (I<sub>geo</sub>)

The geo-accumulation index (I<sub>geo</sub>) proposed by [26] was used to assess the level of pollution. It establishes a relationship between the measured concentration of an ETM in the fine fraction of sediments and the concentration at a geochemical background reference value, often derived from the Earth's crust [25], by including a factor to correct for lithological variations in metallic elements. It is calculated using the following formula:

$$I_{geo} = \log_2 \left[ \frac{c_m \text{ echantillon}}{(1.5 \times c_m \text{ ref})} \right] \quad (1)$$

where  $c_m$  (ref) is the geochemical background concentration of element "m"; 1.5 is the correction factor (variable natural concentration).

- $c_m$ : Measured concentration of element "m" in the sediment sample.
- $c_m$  (ref): Geochemical background concentration of element "m".
- 1.5: A correction factor used to reduce the impact of natural variability.

### 2.4.2. The Contamination Factor (CF) and the Modified Degree of Contamination (DC<sub>m</sub>)

The contamination factor (CF) makes it possible to determine whether sediments are contaminated or uncontaminated by heavy metals and indicates the extent of such contamination [27]. The degree of contamination (DC) refers to the sum of the calculated CFs. The use of this formula is contingent upon considering both

metallic and organic pollutants. [28] modified this formula to generalize it and adapt it to the number of pollutants analyzed. The modified contamination level (DC<sub>m</sub>) is therefore determined at each site by the sum of the contamination factors divided by the number of pollutants analyzed. The values range from one (zero to very low contamination level) to seven (ultra-high contamination level). The formulas are as follows:

$$CF_x = \frac{[M_x]_{mes}}{[M_x]_{ref}} \quad (2)$$

$$DC = \sum CF_x \quad (3)$$

$$DC_m = \sum CF_x / N_x \quad (4)$$

where  $CF_x$  is the contamination factor for metal  $x$ ,  $[M_x]_{(mes)}$  is the measured concentration of element  $x$ ,  $[M_x]_{(ref)}$  is the reference concentration [26],  $N_x$ : the number of pollutants analysed.

#### 2.4.3. Potential Ecological Risk Index (RI) and Potential Risk for Each Metal Er (Håkanson)

The Potential Ecological Risk Index (RI or PERI) measures the integrated potential risk by considering its concentration and toxicity response. It is determined by the linear sum of all individual ecological risks (Er). Er allows the ecological risk posed by a contaminant in each sample to be expressed quantitatively [27]; [29] by counting the contamination factor and the toxicity response of the metallic element. These are represented by the following formulas:

$$RI = \sum E_r \quad (5)$$

$$E_r = CF_x \times W_x \quad (6)$$

$$RI = \sum (CF_x \times W_x) \quad (7)$$

where  $W_x$  is the toxicity response coefficient for the heavy metal, as proposed by Håkanson, and  $CF$  is the contamination factor. Equation (6) reveals the hazards of heavy metals to both human and aquatic ecosystems. The Håkanson toxicity coefficients (Hg = 40; Cd = 30; As = 10; Pb = 5; Cu = 5; Ni = 2; Cr = 2; Zn = 1) were adopted as the evaluation criteria. Risk values range according to **Table 2**.

**Table 2.** Risk level for potential ecological risks.

Risk level	Low	Moderate	High	Very high	Disastrous
<b>Er</b>	40	40 - 80	80 - 160	160 - 320	>320
<b>RI</b>	<150	150 - 300	300 - 600	>600	

In this study, the percentage contribution (%) of each metal to the overall risk (PERI) at each monitoring station and across the study area was determined. This enables the risk to be refined and the impact of pollutants to be prioritized, thereby

facilitating better environmental management.

#### 2.4.4. Toxicity Assessment of HEAVY Metals in Sediments Based on the SQGs

SQGs (Sediment Quality Guidelines) established by [30], developed for freshwater ecosystems, were applied to evaluate sediment quality and the ecotoxicological risks caused by heavy metals in sediment. TEC (Threshold Effect Concentration), a low range value, is the concentration below which adverse effects are not expected to occur. However, PEC (Probable Effect Concentration) is the concentration above which adverse effects are expected to occur more often than not (Table 3).

**Table 3.** US Sediment Quality Guidelines (SQGs) for TEC and PEC from [30].

ETM	As	Cd	Cr	Cu	Pb	Ni	Zn	Hg
TEC (mg/kg)	9.79	0.99	43.4	31.6	35.8	22.7	121	0.18
PEC (mg/kg)	33	4.98	111	149	128	48.6	459	1.06

#### 2.4.5. Determination of Sources of Heavy Metals

To identify the common pollution sources, a factor analysis was performed by PCA (Principal Component Analysis), including eigenvector analysis and a correlation matrix. Due to its natural abundance in the country's soils, particularly in the study area [31], iron was used as a reference relative to the other heavy metals for determining pollution sources. All statistical analyses were performed using Statistica 7.1.

### 3. Results

#### 3.1. Concentrations of Heavy Metals in Sediments from Lake Kossou and the Bandama River

The results of the physicochemical analyses of sediments from Lake Kossou and the Bandama River are presented in Table 4. They reveal the presence of heavy metals (Cd, Cr, As, Cu, Pb, Ni, Zn, Hg, Fe, and Mn) in all samples, which are generally characterised by significant spatial variability in concentrations. The sediments in the study area occur in a slightly acidic environment with a pH ranging from 5.33 (L4) to 6.14 (L1) and an average of 5.76.

When compared with the values for the upper continental crust (UCC), the heavy metals (HM) Fe, Mn, As, Cd, Cr, Cu, Ni, and Hg exceed at least one sampling point. Conversely, across all the sediments analysed, lead (Pb) and zinc (Zn) show no such exceedance. The order of abundance of the average raw concentrations (mg/kg) of ETMs in the sediments is as follows: Fe > Mn > Cr > Cu > Zn > Ni > As > Pb > Cd > Hg.

Arsenic concentrations range from 2 mg/kg (L1, FL1) to 10.8 mg/kg (FL2). L3 and L4 stations also show high levels. Although mercury is present at low levels (0.008 to 0.15 mg/kg), it is characterized by higher values at the lake stations L2 (0.10 mg/kg) and L3 (0.15 mg/kg). Cadmium levels are consistent across the entire

sample set. Copper and zinc show a similar trend, with maximum levels at L3 (51.84 mg/kg for copper and 35.65 mg/kg for zinc). Their lowest values are observed at stations L1 and FL1.

**Table 4.** Statistics on the physicochemical parameters of sediments from Lake Kossou and the Bandama River (concentration in mg/kg).

Station	L1	L2	L3	L4	FL1	FL2	Min	Max	Mean	Std Dev
As	2	3.86	7.95	7.31	2	10.08	2.00	10.08	5.53	2.91
Cd	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	-	-	-	-
Cr	26.99	64.01	184.25	272.17	40.32	283.92	26.99	283.92	145.28	101.50
Cu	12.43	28.13	51.84	32.43	7.44	39.82	7.44	51.84	28.68	12.68
Mn	283.70	343.80	535.90	502.00	171.80	639.90	171.80	639.90	412.85	146.42
Ni	2	11.51	29.62	13.28	2	16.40	2.00	29.62	12.47	7.30
Pb	2.00	2.00	3.04	6.93	3.20	9.49	2.00	9.49	4.44	2.51
Zn	6.22	16.02	35.65	30.40	7.82	25.89	6.22	35.65	20.33	10.31
Hg	0.02	0.1	0.15	0.02	0.01	0.008	0.01	0.15	0.05	0.05
Fe	5525.20	18110.24	50393.70	70078.74	9448.82	66141.73	5525.20	70078.74	36616.40	25588.32
pH	6.14	5.6	5.6	5.33	5.96	5.93	5.33	6.14	5.76	0.25

Chromium stands out as the most abundant element. The highest values are observed at stations FL2 (283.92 mg/kg), L4 (272.17 mg/kg), and L3 (184.25 mg/kg), representing concentrations 7 to 10 times higher than those measured upstream (L1, FL1). Its average value (145 mg/kg) is significantly higher than those determined in certain mining areas of the country. However, in **Table 5**, the concentration range is well below that obtained in China and relatively comparable to that of Ghana.

**Table 5.** Comparison of chromium contamination with that in other regions.

Locality	Concentration (Min-Max) in mg/Kg	Mean	Reference
Angovia	26.99 - 283.92	145.25	This study
Kokumbo	1.08 - 20.76	6.35	[5]
Bocanda	12.40 - 48.10	30.25	[10]
Korhogo	43.24 - 174.98		[8]
Tengrela	59.42 - 60.58		
Bouaflé	68.31 - 117.52		[9]
Ghana	9.84 - 281		[32]
Chine	24.1 - 726		[33]

### 3.2. Contamination Factor (CF)

The average contamination factor values (**Table 6**) obtained from the sediments

of the two waterways (Lake Kossou and the Bandama) are in the following order: Cr > As > Cu > Cd > Hg > Ni > Zn > Pb. At the sampling level, Cr shows a considerable level of contamination (FC > 3), while As, Cd, and Cu show moderate contamination ( $1 < FC < 3$ ), whereas Ni, Pb, Zn, and Hg show low contamination ( $FC < 1$ ).

On the river, the average FC values for the eight ETMs that correspond to the modified contamination degree (DCm) range from very low (FL1: 0.66) to moderate (FL2: 2.5). On Lake Kossou, the DCm is very low at station L1 (0.66), low at L2 (1.31), and moderate at L3 and L4 (2.21 - 2.49).

**Table 6.** Contamination factor values for sediments in lake kossou and the white bandama river.

	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg	DC	DCm
<b>FL1</b>	1.00	1.96	1.15	0.52	0.11	0.19	0.15	0.18	5.26	0.66
<b>FL2</b>	5.04	1.96	8.11	2.78	0.88	0.56	0.50	0.14	19.97	2.50
<b>L1</b>	1.00	1.96	0.77	0.87	0.11	0.12	0.12	0.36	5.30	0.66
<b>L2</b>	1.93	1.96	1.83	1.97	0.62	0.12	0.31	1.79	10.51	1.31
<b>L3</b>	3.98	1.96	5.26	3.63	1.58	0.18	0.69	2.68	19.95	2.49
<b>L4</b>	3.66	1.96	7.78	2.27	0.71	0.41	0.58	0.36	17.72	2.21
<b>FC (Mean)</b>	2.77	1.96	4.15	2.01	0.67	0.26	0.39	0.92	13.12	1.64

At the station level, the highest contamination factors (CF) are observed for chromium at FL2 (8.11), L4 (7.78), and L3 (5.26), confirming its significant contribution to contamination. Arsenic also reaches significant values at FL2 (5.04) and L3 (3.98). Although the average contamination factor (CF) for mercury is below 1, values exceeding this threshold are observed at stations L2 (CF: 1.72) and L3 (CF: 2.63), indicating moderate contamination at these points. Analysis of the CF results indicates polymetallic contamination (Cr, As, Cu, Cd, Hg) of the sediments in Lake Kossou and the Bandama River. Arsenic and chromium stand out due to their high factors. The river station FL2 and the lake stations L2, L3, and L4 are the most affected by this contamination.

### 3.3. Muller's Geoaccumulation Index (1969)

The results of this index confirm the trends observed with the sediment contamination factor for Lake Kossou and the White Bandama River. The Igeo values for Ni, Pb, and Zn are below zero at all stations. These values indicate that the sediments are not contaminated by these elements and demonstrate their crustal origin. However, the results reveal slight pollution ( $0 < Igeo < 1$ ) of cadmium at all stations and of mercury in the sediments at stations L2 and L3. They also show slight ( $Igeo > 1$ ) to moderate ( $Igeo > 2$ ) contamination of the sediments by As, Cr, and Cu at stations FL2, L2, L3, and L4. Chromium (Cr) remains the predominant pollutant, reaching the highest pollution level (moderately polluted) at stations

FL2 (2.44) and L4 (2.37). These results indicate a significant anthropogenic input of Cr and a moderate input of Cd, Hg, As, and Cu in both waterways. No station recorded contamination classified as heavily polluted ( $I_{geo} > 3$ ), which places the overall pollution within a moderate range.

### 3.4. Individual Ecological Risk Index (Er) and Potential Ecological Risk Index (PERI)

The results (Table 7) for the individual ecological risk factor (Er), which considers the toxicity factor (Tr) of each metal, reveal a different hierarchy from that determined by the geochemical indices (FC and  $I_{geo}$ ): an ecological risk dominated by Hg, Cd, and As. Despite its low concentration, mercury has the highest Er values. Its risk is moderate ( $40 < Er < 80$ ) at L2 (71.43) and considerable ( $80 < Er < 160$ ) at station L3 (107.14). As presents a moderate risk only at station FL2. Cadmium with its unique value, presents a moderate risk. Its high toxicity factor (Tr: 30) makes it a significant contributor to the PERI.

**Table 7.** Individual ecological risk factor (Er) and potential ecological risk index (PERI).

Stations	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg	RI
FL1	10	58.82	2.30	2.60	0.53	0.94	0.15	7.14	82.50
FL2	50.4	58.82	16.22	13.92	4.39	2.79	0.50	5.71	152.76
L1	10	58.82	1.54	4.35	0.53	0.59	0.12	14.29	90.24
L2	19.3	58.82	3.66	9.84	3.08	0.59	0.31	71.43	167.02
L3	39.75	58.82	10.53	18.13	7.92	0.89	0.69	107.14	243.87
L4	36.55	58.82	15.55	11.34	3.55	2.04	0.58	14.29	142.72
<b>RI (%) UB</b>	19	40	6	7	2	1	0	25	
<b>RI (%) LB</b>	17	14	8	10	3	1	1	36	

All other trace metals (Cr, Cu, Ni, Pb, Zn) present a low risk ( $<40$ ) at all monitoring stations. This analysis reveals that Cr is no longer the priority element despite its raw concentration, high “ $I_{geo}$ ” and “FC” values. Mercury, cadmium, and arsenic are becoming major pollutants in terms of risk despite their low concentrations. The (PERI), calculated as the sum of the value of Er for each monitoring site, ranges from 82.50 to 243.87. Stations FL1 (82.5) and L1 (90.2) present a low risk ( $RI < 150$ ), whereas FL2 (152.8), L4 (142.7), L2 (167) and L3 (243.9) demonstrate a moderate risk ( $150 < RI < 300$ ). The results show a very low PERI upstream (L1, FL1) of the watercourses, contrasting with a high PERI observed downstream (L4, FL2). In the lake area, the highest PERI values directly coincide with the highest mercury levels at L2 and L3.

Figure 2 presents the relative contribution (%) of each trace metal to the PERI at the scale of the entire study area, calculated with the upper bound (LOQ = 0.2 mg/kg). Cadmium’s contribution rises to 40%, becoming the dominant element, while Hg (25%) and As (19%) remain significant. Other metals (Cr, Cu, Ni, Pb, Zn)

contribute less than 10% each, with Cr around 6%. This ranking highlights that Cd, Hg, and As, despite their low absolute concentrations, are the major contributors to the overall ecological risk due to their elevated toxic response factors. Conversely, Cr (6%), although present at much higher bulk concentrations, contributes minimally to the total PERI because of its low toxic factor.

The uncertainty in Cd concentration (0.05 - 0.20 mg/kg) leads to a large variation in its contribution (14% - 40%). In the conservative upper-bound scenario, Er (Cd) = 59 is a moderate risk (40 - 80) for every station. This shows that even without precise quantification, Cd could actively contribute to the overall ecological risk.

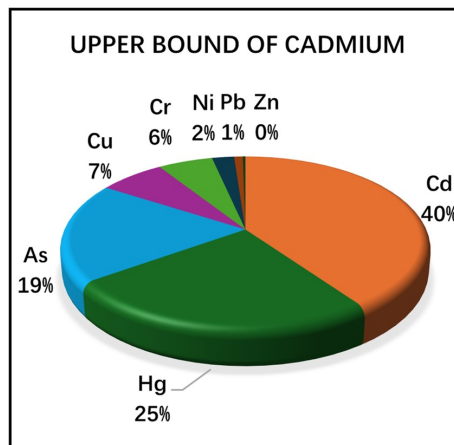


Figure 2. Risk contribution (%) according to the upper bound of cadmium.

These results also show a lack of direct correlation between elemental concentrations and the ecological risk (Figure 3). A high concentration does not systematically entail a high risk, and conversely, a low concentration does not preclude a low risk. Mercury, even at trace levels, poses a substantial threat due to its high intrinsic toxicity.

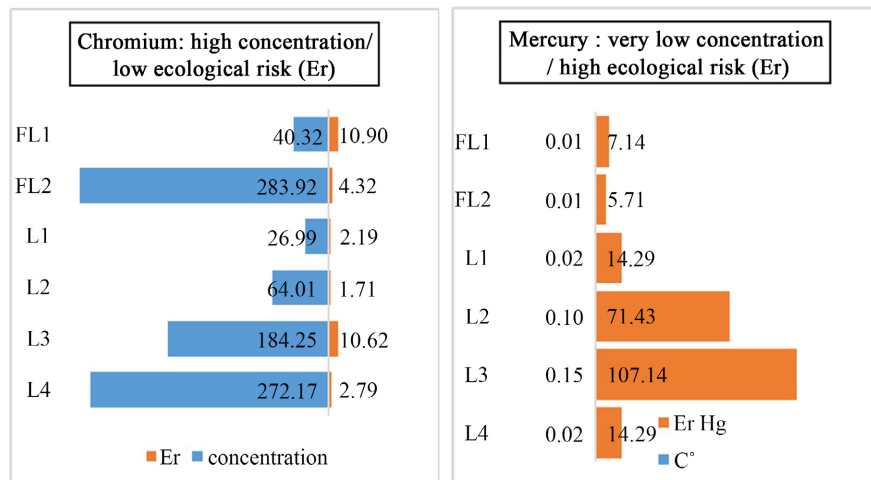


Figure 3. Relationship between the concentration and toxicity of chromium and mercury.

### 3.5. Ecotoxicological Risk Assessment Based on Sediment Quality Guidelines (SQG: TEC/PEC)

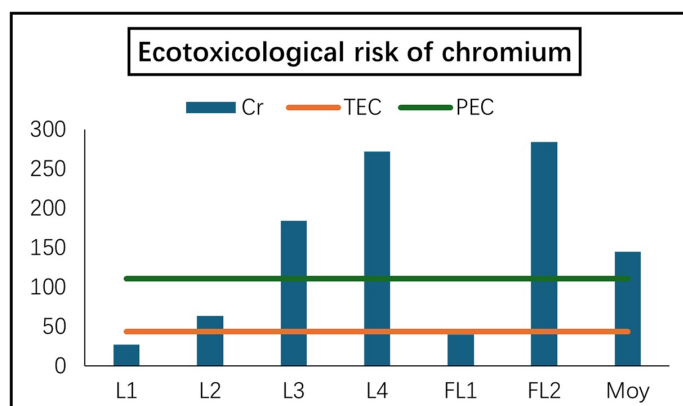
Compared with TEC and PEC according to **Table 8**, the concentrations of Pb, Zn, Ni, and Hg are below the TEC threshold in all samples. These sites might cause toxicity infrequently. For Cu, 50% of the stations have concentrations below the TEC, while 50% are between the TEC and the PEC. It might cause adverse effects occasionally. Arsenic shows a similar profile: 83.33% of stations are below TEC and 16.7% are between TEC and PEC with an occasional adverse effect probability.

**Table 8.** Proportion (%) of ETMs in sediments relative to the TEC and PEC thresholds.

	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg
<b>TEC</b>	9.79	0.99	43.4	31.6	22.7	35.8	121	0.18
<b>PEC</b>	33	4.98	111	149	48.6	128	459	1.06
<b>% less than TEC</b>	83.3	100	33.3	50	100	100	100	100
<b>% between TEC and PEC</b>	16.7	0	16.7	50	0	0	0	0
<b>% Greater PEC</b>	0.0	0	50.0	0	0	0	0	0
<b>&lt;PEC</b>	FL2		L2	L3-L4-FL2				
<b>&gt;PEC</b>			L3-L4-FL2					

In contrast, chromium presents a much more concerning profile. Only 33.33% of stations have concentrations below TEC, and 16.7% fall between TEC and PEC. However, 50% of the sampled sites were greater than PEC value, indicating that sites could frequently cause adverse effects on organisms.

Station FL2 (283.92 mg/kg) and L4 (272.17 mg/kg), located respectively at the downstream of the Bandama River and Lake Kossou, show severe contamination exceeding 2.5 times PEC (111 mg/kg). Chromium emerges as the element of greatest concern. Thus, although chromium contributes only marginally to PERI, it could pose a very high probability of frequent adverse effects to living organisms (**Figure 4**).



**Figure 4.** Toxicity level of the metal of greatest concern: chromium.

Field observations show a strong spatial correlation between high chromium concentrations and the presence of crushers at the sampling sites (**Plate 2**). The appearance of the slurry flowing into the waterway also reflects the intensity of the mechanical crushing of the ore.



**Plate 2.** (a) Abandoned crusher on the banks of Lake Kossou; (b) Sludge discharged into the lake (photos: DIBY).

### 3.6. Source of Heavy Metals in Lake Kossou and Bandama River

Two main components with eigenvalues greater than one were determined, explaining 92.03% of the total variance, which is sufficient to account for almost the entire structure of the data (**Table 9**).

The first component (PC1), with 70.73% of the total variance, has strong negative loadings on (As, Cr, Cu, Pb, Zn, Fe, Mn) and a strong positive loading on pH (**Table 10**). Since iron and manganese are of natural origin and abundant in the study area, their strong association with this metal assemblage indicates that these metals share the same origin. The negative correlation with pH suggests that more acidic conditions favor the mobilization and accumulation of this natural metal assemblage. This component was called the geogenic factor.

The correlation matrix (**Table 11**) confirms very close links between Fe/Mn and the following elements: Cr (0.99/0.91); As (0.94/0.98); Zn (0.89/0.86); Pb (0.82/0.73); Cu (0.77/0.89); Ni (0.67/0.78).

**Table 9.** PCA eigenvalues and explained variance.

Components	Eigenvalues	% variance	Cumulative variance %
F1	7.07	70.73	70.73
F2	2.13	21.29	92.03

The second component (PC2), with a variance of 21.29%, opposes Hg (+0.94) to Pb (−0.73). Hg, which does not follow iron ( $r = 0.026$ ) and manganese ( $r = 0.2$ ) indicates a different origin from the local geochemical background. This isolation suggests a point-source anthropogenic input. Although Pb is correlated with Fe-Mn ( $r = 0.82$ ;  $r = 0.73$ ) and is part of the natural group on PC1 (0.67), it distinguishes itself on PC2 (0.73), revealing a different input pathway. Thus, Pb has a

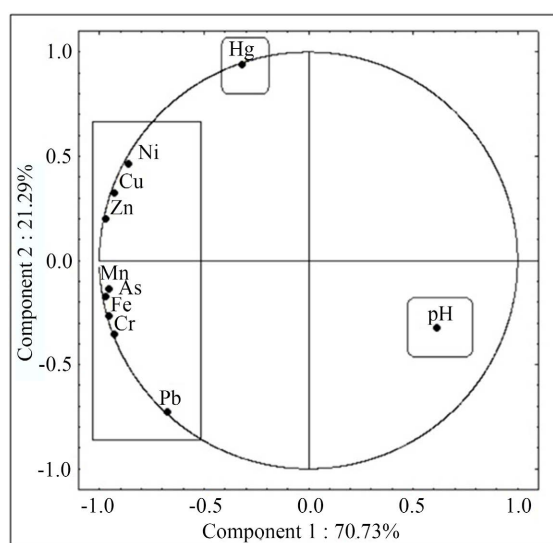
dual origin: a natural part linked to Fe-Mn and an anthropogenic origin. This component was called the anthropogenic factor.

**Table 10.** Sample contributions (%) to components.

	PC1	PC2
As	-0.97	-0.18
Cr	-0.93	-0.36
Cu	-0.93	0.32
Ni	-0.86	0.46
Pb	<b>-0.67</b>	<b>-0.73</b>
Zn	-0.97	0.20
Hg	<b>-0.31</b>	<b>0.94</b>
Fe	-0.95	-0.27
Mn	-0.95	-0.14
pH	0.62	-0.33

**Table 11.** Correlation matrix of heavy metals, Fe-Mn, and pH in sediments from lake kossou and the bandama river.

Variables	As	Cr	Cu	Ni	Pb	Zn	Hg	Fe	Mn	pH
As	1.000									
Cr	0.945	1.000								
Cu	0.873	0.730	1.000							
Ni	0.781	0.619	0.975	1.000						
Pb	0.790	0.879	0.392	0.245	1.000					
Zn	0.879	0.839	0.938	0.918	0.493	1.000				
Hg	0.160	-0.059	0.615	0.722	-0.467	0.471	1.000			
Fe	0.941	0.994	0.770	0.673	0.824	0.887	0.026	1.000		
Mn	0.978	0.913	0.886	0.776	0.734	0.859	0.195	0.910	1.000	
pH	-0.425	-0.514	-0.551	-0.540	-0.167	-0.713	-0.423	-0.593	-0.401	1.000



**Figure 5.** Loading plot of the first two components obtained.

**Figure 5** shows the result of factor analysis for total heavy metals in sediments from Lake Kossou and Bandama River.

#### 4. Discussion

Sediment analysis from Lake Kossou and the Bandama River revealed polymetallic contamination (As, Cr, Cu, Cd, Hg, Fe, Mn), with average values exceeding the Upper Continental Crust (UCC) reference [25] and unpolluted sediments from [24]. Lead (Pb), nickel (Ni), and zinc (Zn) do not exceed background levels [25]. Chromium is the most abundant trace metal. Geochemical indices (CF, DC<sub>m</sub>, and Igeo) indicate moderate overall pollution with significant anthropogenic Cr input and moderate Hg, As, and Cu inputs. Station FL2 (river) and stations L2, L3, and L4 (lake) are the most affected.

While Cd, Hg, and As dominate the PERI (84.18%) due to their high toxicity factors, the direct comparison with SQGs identifies Cr as the only element frequently exceeding effect thresholds, thus posing a potential biological threat. These results show a lack of direct correlation between elemental concentrations and the ecological risk: a high concentration (Cr) does not systematically imply a high risk, and a low concentration (Hg, Cd) does not preclude a high risk.

In the conservative upperbound scenario, uncertainty in Cd concentration (0.05 - 0.2 mg/kg) leads to a large variation in its contribution (14% - 40%). This confirms that, even without precise quantification, Cd could actively contribute to the overall ecological risk.

The first component (PC1) shows a strong association between (As, Cr, Cu, Pb, Zn) and Fe/Mn, which are naturally abundant in the study area, confirming their natural origin. Consequently, PC1 is interpreted as a geogenic factor [13]-[16]. The negative correlation between metals and pH (mean 5.76) suggests their solubilization and mobility under acidic conditions, characteristic of the Acid Mine Drainage process (AMD) [28] [29]. The second component (PC2), dominated by Hg, is interpreted as an anthropogenic factor.

The use of mercury for gold amalgamation in artisanal gold mining is a primary contributor to mercury contamination. The clear singularity of mercury observed on PC2 of the PCA confirms that its occurrence is not natural and it could be directly linked to gold mining effluent [34]-[36]. Lead exhibits a partially natural background; it may also be enriched by other sources.

Chromium levels in Angovia (mean: 145 mg/kg; max: 284 mg/kg) are among the highest recorded in Côte d'Ivoire, exceeding values (68.31 - 117.52 mg/kg) reported in Bouaflé [9], Kokumbo [5] and Korhogo [8]. They are comparable to Ghanaian values (9.84 - 281 mg/kg) in [32] but significantly lower than the extreme levels (24.1 - 726 mg/kg) observed in China [33]. It likely reflects different geological contexts and anthropogenic pressures. Mercury concentration (mean: 0.05 mg/kg) is higher than at Bocanda (0.001 mg/kg) in [10] but lower than at Ity (0.51 mg/kg at Yinhi and 0.33 mg/kg at Douhou) in [37]. These results suggest either less intensive use of mercury or dilution within the watercourses.

Artisanal gold mining generates large volumes of waste (waste rock, tailings, and fine refinery residues) that mobilize metals through geochemical and mechanical pathways. Sulfide oxidation generates acidity, releasing trace elements such as As, Cr, Cu, Fe, and Mn. Excavation, crushing, and grinding produce fine particles bearing trace metal elements (ETMs) that are readily transported to watercourses [2] [38]. The strong spatial co-occurrence of crushers and high Cr levels indicates that crushing intensity is a key driver of sedimentary Cr enrichment. Moreover, exposed sulfide surfaces from crushing accelerate oxidation, and the acidic condition further enhances metal solubilization and transfer to the water column [34]-[36]. Consequently, while the geochemical background explains the natural presence of metals, mechanical crushing could be one of the factors contributing to their abundance and mobility.

With the exception of Cd (not quantified), polymetallic enrichment (As, Cr, Cu, Hg) occurs at stations L2 - L4, reflecting lacustrine accumulation. Station FL2 (river mouth) shows the highest Cr, As, and Pb, receiving runoff and leachates from artisanal gold mining [7]. Iron and manganese are abundant at all stations, particularly in the downstream section of the watercourses.

This study is based on a single sampling campaign conducted during the rainy season, which does not allow us to document seasonal variability. A conservative upper-bound approach was applied for cadmium due to analytical limitation (value < LOQ). Nevertheless, the results reveal sediment degradation and ecological risks that could indirectly expose local populations. Multi-seasonal sampling, using ICP MS combined with an integrated approach (sediment-water-biota), is needed to refine the assessment of environmental and human health risks.

## 5. Conclusion

Artisanal gold mining in Angovia leads to polymetallic sediment contamination, with moderate ecological risk dominated by Hg and As. Unquantified Cd may also contribute; under the conservative scenario, it reaches 40% of PERI ( $Er = 59$ ). Chromium is present at high levels, yet its low toxic response factor makes it a minor contributor to the PERI. However, its exceedance of toxicity thresholds (TEC/PEC) is likely to pose a direct biological threat. The combination of geochemical indices, the PERI, and sediment quality guidelines is therefore necessary for effective environmental management, including the protection of Lake Kossou, the Bandama River, and local populations.

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## Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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