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Assessment of metal pollution (Fe, Cu, Cd, Pb, Hg) of an aquatic mining environment: case of the *BOZI* gold panning area (*Marahoué* region)

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Abstract

Water, sediment and soil samples were taken from two sites (S1 and S2) of the *Bandama* River in order to determine the impact of gold panning on the environmental quality of this river which crosses the locality of *Bozi*. The AVIO 200 type ICP analysis results revealed the order of magnitude of overall metal accumulation in the water for the two study sites: [Cu]>[Cd]>[Pb]>[Fe]>[Hg]. In sediments and soils this order is as follows: site S1: [Fe]>[Cu]>[Pb]>[Cd]>[Hg] and site S2: [Fe]>[Pb]>[Cu]>[Cd] > [Hg]. Hg is the least abundant metal in all the studied matrices. In addition, the assessment of water quality and pollution of the study environments showed that the waters studied have a quality unsuitable for consumption with IQE>100 for the two sites. They have a very high contamination of Cu, Cd, Pb and Hg (FC≥6). At the level of the sediments, the Igeo values also show a strong contamination in Cd, Pb and Hg especially in site 1 which is close to the gold panning activities. Furthermore, the values of Enrichment Factor EF (>50) and Pollution Load Index PLI (>1) showed an anthropogenic contamination for Cd, Cu, Pb and Hg. This indicates a progressive deterioration of the estuary sediments of the two sites. of study by the metals studied.

1. Introduction

Mining is one of the most important sources of heavy metal pollution in the environment. Thus, the pollution of the environment, particularly that of aquatic environments by trace metals, has become a subject of global concern, due to their resistance to biodegradation, their toxicity and their ability to incorporate into the food chain [1-4]. Indeed, heavy metals mainly bind to sedimentary particles and can accumulate in sediments. Sediments therefore represent reservoirs for heavy metals in the environment [5]. They serve as mediators for the absorption, storage, release and transfer of contaminants between compartments of the aquatic environment. To this end, they behave as sinks or sources of trace elements for the water column [6-7]. When physico-chemical changes (pH, salinity, suspended solids, turbidity, conductivity, etc.) occur, trace metals trapped in the sediments are likely to be released back into the water column [8-9] and contaminate water and aquatic organisms [10-11]. Thus, sediments could be used as indicators of the level of environmental pollution. They will make it possible to understand the impact of human activities on aquatic environments [9].

In Côte d'Ivoire, particularly in the locality of *Bozi* (*Marahoué* region), artisanal gold mining is one of the major sources likely to degrade the environment. Gold panners process the ore and use mercury near drinking water points, domestic activities or bathing, increasing the risk of pollution of these water resources. However, the use of mercury for the amalgamation of gold, as well as the discharge of effluents resulting from the washing of crushed ore, near water points, are likely to deteriorate the quality of water by the mobilization and the dispersion of heavy metals in the environment, particularly in groundwater by infiltration ([12-13]). It is therefore desirable to measure the physico-chemical parameters and the metal contents in comparison with certain international guide values in the different matrices (water and sediment) of the Bandama River; assess the environmental quality of sediments and water in order to determine the intensity of the pollution generated and the impact of gold panning activities on the degradation of lake environments. This will make it possible to recommend the means of elimination of these inorganic micropollutants and the techniques of remediation of these polluted environments. It is in this context that the research study is located, the purpose of which is to determine the impact of gold panning on the quality of water and sediments of the *Bandama* River in the locality of *Bozi*.

2. Materials and Methods

2.1 Description of the study area

Bozi is a locality in the center west of Côte d'Ivoire and belonging to the department of *Bouaflé*, in the region of *Marahoué*. The locality of *Boz*i is a capital of the commune. It is located on the axis linking the town of *Bouaflé* to that of *Yamoussoukro*. The locality of *Bozi* is located 34 km from the city of *Yamoussoukro* and 27 km from that of Bouaflé. It is crossed by the *Bandama* River. These geographical coordinates are between latitudes 6° 55′ 00″ north, and longitudes 5° 32′ 00″ west. The socio-economic activities of the population are based on the exploitation of natural resources. Two major activities stand out in this locality. These are agriculture and mining activities (clandestine gold panning) because the subsoil in this locality is very rich in gold. Fieldwork was carried out in two sites (S1 and S2) in the locality of *Bozi* along the *Bandama* River (**Figure 1**) where domestic and gold panning activities are commonly carried out. Thus, Site 1 is located upstream of the *Bozi* road bridge near an industrial mining site. Next to this site, clandestine gold washers engage in artisanal mining activities. The rubble obtained from their activities is washed directly into the river. The site S2 is located downstream from the *Bozi* road bridge. It receives water from the river coming from site S1. This site is the place of bathing and laundry of clothes, utensils of the local populations.

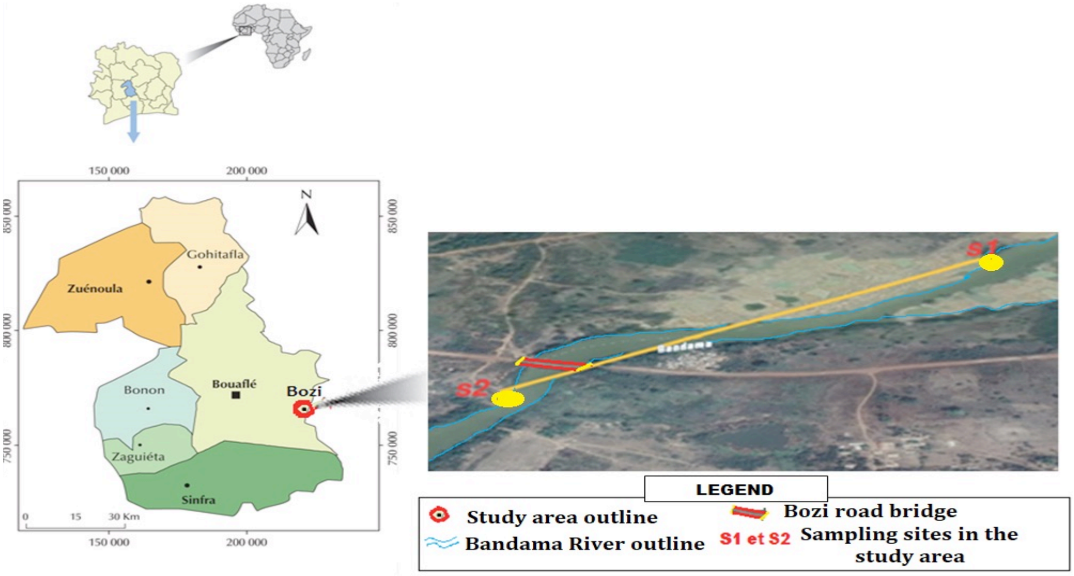

Figure 1. Geographic location of the sampling sites in the study area

2.2 In-situ measurements and sampling

Before the sampling of the different matrices of our study, we proceeded to the measurement of the physico-chemical parameters of the watercourse of the *Bandama* River of the study sites S1 and S2. A portable LEVIBOND multi-parameter equipped with probes was used for the measurement of temperature, pH, dissolved oxygen and conductivity (**Figure 2**). Water and sediment sampling was carried out at two sites S1 and S2. A total of 32 samples were collected at the two sites, including 8 water and sediment samples per site. Water samples are obtained from the *Bandama* River water body near the edge. Water is taken from 1.5 L plastic canisters at a depth of about 10 cm from the water column. After sampling, this water is immediately stabilized with 1 mL of nitric acid and closed tightly for storage until the laboratory. Sediments were collected manually with latex gangs directly from the immediate watercourse of each site approximately 1 m from the river bank. The sediments were stored in plastic jars according to the sampling points of the study sites. Thus, the water and sediment samples were conditioned, then well labeled and then put in a cooler for their conservation in the laboratory.

Figure 2. (a): Multi-parameter; (b) Sample Jars and Canisters

2.3 Mineralization and analysis

Before analysis using an AVIO 200 type ICP (**Figure 3**), the water samples were all filtered using Whatman 45 µm diameter paper to remove unwanted particles. Sediment samples were oven-dried at 80°C for 24 hours. They were then sieved in order to obtain a fine fraction whose particles have a diameter of less than 200 µm. Mineralization by the dry process was carried out. This method begins with the calcination of a 1g mass of sediment at 550°C in a muffle furnace until a whitish ash is formed. This ash will then be assailed by acids (4 mL HNO_3 concentrated at 50% and 10 mL HCl concentrated at 20%) which are heated under reflux on a heating plate without boiling, and covered with a watch glass according to the method of total digestion recommended by the Center of Expertise in Environmental Analysis of Quebec [14]. After cooling in ambient air, the mineral is filtered using Whatman filter paper, then adjusted to 100 ml with distilled water in a volumetric flask and analyzed using an ICP AVIO 200 coupled to a computer. It is an inductively coupled plasma device for the determination of target heavy metals in liquid matrices. The analysis focused mainly on Fe, Cu, Cd, Pb and Hg.

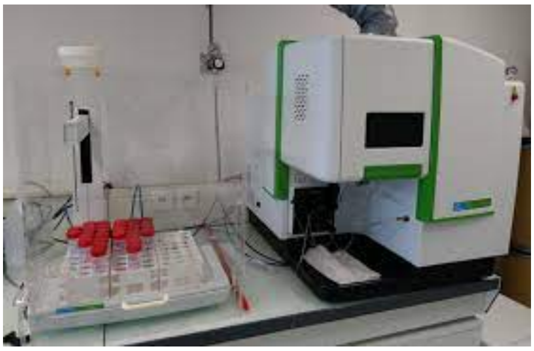

Figure 3. Heavy metal assay device - ICP AVIO 200

2.4. Environmental quality of sediments in the Bandama River

The concentrations of metals were compared with two criteria established according to the guide values (Sediment Quality Guide) proposed by MacDonald and *al.* [15]. These are the TEC and the PEC. The TEC (Threshold Effect Concentration) is the concentration below which there is no harmful effect for burrowing organisms. The PEC (Probable Effect Concentration) is the concentration above which adverse effects are observed on living organisms in the sediment. These criteria, compared to the chemical analyzes of sediments for which eco-toxicological tests have been carried out, indicate that when the measured content is lower than the TEC, the sediment is considered non-toxic. When the measured content is higher than the PEC, the sediment is expected to be toxic.

2.5. Estimation of contamination intensity

The intensity of the contamination of water, sediments and soils by heavy metals of the study sites was evaluated from five indices, namely: the geo-accumulation index, the quality index of the water, the enrichment factor, the contamination factor and the pollutant load index. Their principle is based on the comparison of measured values with reference values such as the average content of elements in the earth's crust (Average Shale).

2.5.1. Geo-accumulation index (Igeo)

To assess the intensity of the metal pollution, we calculated the geo-accumulation index [16]. This empirical character index compares a given concentration versus a value considered as the geochemical background. In addition, Müller [17] defined a scale with six geoaccumulation index classes (**Table I**):

$$I_{géo}=\log_2\left(\frac{C_n}{1,5B_n}\right) \qquad \textbf{Eqn. 1}$$

C_n: *Contents of the metal in the sample* ; B_n*: Metal contents in the global continental crust*

Table I. Distribution of Igeo Classes according to index value (Taken from Müller [17])

I_{geo} value	**I_{geo} class**	**Pollution intensity**
$Igeo < 0$	0	Pollution-free
$0 \leq Igeo < 1$	1	Unpolluted to slightly polluted
$1 \leq Igeo < 2$	2	Slightly to moderately polluted
$2 \leq Igeo < 3$	3	Moderately polluted
$3 \leq Igeo < 4$	4	Moderately to heavily polluted
$4 \leq Igeo < 5$	5	Heavily polluted
$5 \leq Igeo < 6$	6	extremely polluted

2.5.2. Water quality index (WQI)

WQI is a method used to assess the suitability of water for various uses. It indicates water quality in terms of an index that represents the overall water quality for any intended use. It is defined as a score reflecting the composite influence of different water quality parameters taken into account for the WQI calculation. The WQI summarizes large amounts of water quality data in simple terms (Excellent, Good, Poor, Very Poor, Unsuitable). This index was calculated using the weighted arithmetic index method ([18],[19]). In its formulation, the relative importance of the various parameters depends on the intended use of the water. Most often, this is done from the perspective of its suitability for human consumption [20]:

$$WQI=\frac{\sum_{k=1}^{i} W_i \times Q_i}{\sum_{k=1}^{i} W_i} \qquad \textbf{Eqn. 2}$$

$$Q_i = \frac{C_i}{S_i} \times 100$$ **Eqn. 3**

$$W_i = \frac{K}{S_i}$$ **Eqn. 4**

$$K = \frac{1}{\sum_{i=1}^{n} \left({}^{1}/_{S_i} \right)}$$ **Eqn. 5**

Q_i : Quality assessment scale, calculated for each parameter according to the following formula:
C_i: The concentration of each parameter in mg/L.; Si: The norm of the parameter concerned.
W_i : Relative weight specific to each parameter is calculated according to the following formula:
K : Proportionality constant and can be calculated using the following equation..

Five quality classes can be identified according to the values of the water quality index WQI (**Table II**) [21].

Table II. WQI values and Water Quality Status

Values of WQI	Water quality status
0-25	Excellent water quality
26-50	Good water quality
51-75	Bad water quality
76-100	Very poor water quality
> 100	Unfit for human consumption

2.5.3. Enrichment factor (EF)

Assessing the importance of metal pollution requires the use of an "index", the calculation of which uses standardized concentrations in order to deconvolute the anthropogenic signal from the natural signal. The EF provides the number of times an element is enriched relative to the abundance of that element in the reference material. The reference material used in this study is that defined by Wedepohl [22] and recognized worldwide as the reference concentration in unpolluted areas. The calculation of the EF was defined by relating the content of a contaminant element in the sample to the concentration of an element deemed to be relatively immobile in this sample, compared with the same ratio found in the reference material (Average shale). Iron (Fe) was chosen as the reference immobile element to carry out this calculation. This choice is based on the fact that iron is naturally present in the waters and sediments of the study area. In addition, it is one of the widely used reference materials in the literature ([23],[24]).

$$EF = \frac{([C_{samp}] \div [Fe_{samp}])}{([C_{crust}] \div [Fe_{crust}])}$$ **Eqn. 6**

$[C_{samp}]$**:** *Contents of the metal in the sample;*

$[C_{crust}]$*: Metal contents in the global continental crust;*

$[Fe_{samp}]$*: Iron levels in the sediment;*

$[Fe_{crust}]$*: Iron levels in the crust. This element comes exclusively from the natural terrigenous source. It is often selected from Al, Li, Sc, Zr, Ti and Th or sometimes Fe or Mn.*

EF values between 0.5 and 1.5 indicate a natural origin of metals, whereas those above 1.5 are attributed to anthropogenic inputs [9]. In this study, iron (Fe) was chosen as the normalizing element. The classification is made according to **Table III** [23].

2.5.4. Contamination factor (CF)

The FC makes it possible to know the level of metallic contamination of sediments and waters. It is calculated from the relationship:

$$CF= \frac{[C_{metal}]}{[C_{background}]}$$ **Eqn. 7**

$[C_{metal}]$ *: concentration of the metal in the sediment;*
$[C_{background}]$ *: Geochemical background value for metal.*

Table III. Enrichment Factor Classification

EF values	Enrichment factor level
$EF < 1$	No enrichment
$1 \leq EF < 3$	Low enrichment
$3 \leq EF < 5$	Moderate enrichment
$5 \leq EF < 10$	Moderate to high enrichment
$10 \leq EF < 25$	Fort Enrichment
$25 \leq EF < 50$	Very strong Enrichment
$EF \geq 50$	Extreme enrichment

The different levels of contamination according to FC values are listed in **Table IV** [23].

Table IV. Classification of contamination factor

FC values	Contamination level
$CF < 1$	Low contamination
$1 \leq CF < 3$	Moderate contamination
$3 \leq CF < 6$	Considerable contamination
$CF \geq 6$	Very high contamination

2.5.5. Pollution Load Index (PLI)

The Pollution Load Index makes it possible to estimate the overall degree of contamination of the sediments of the studied area, from the total concentration of all the metals studied. The following equation has been developed for the calculation of the pollutant load index (PLI) [25].

$$PLI= \sqrt[n]{CF_1 \times CF_2 \times CF_3 \times CF_4 \times \ldots.. \times CF_n}$$ **Eqn. 8**

CF_i: *Metal contamination factor i.*

The metal pollution index gives cumulative information on metal pollution in sediments. For PLI=0, there is no deterioration; for PLI=1, only the reference levels of the pollutants are present, and the value of PLI>1 indicates a progressive deterioration of the estuary.

3. Results and Discussion

3.1. Results

3.1.1. Physico-chemical characteristics of the water at the study sites

The results of the in-situ measurements of temperature (T°C), pH, dissolved oxygen (O%) and electrical conductivity (EC) are presented in **Table V**. The analysis of **Table V** shows that the pH of the water of the two study sites is weakly acidic. These waters have almost the same pH approximately equal to 6.4. The water from site 1 has a higher temperature than that from site 2 by more than 4°C. Whatever the site, the pH of the waters is weakly acidic. In terms of conductivity, the average value determined at site 1 is higher than that of site 2. In addition, the average conductivity values determined for the two sites are within the range of values typical of EC of fresh waters (100<EC<1000 µS/cm).

The results also show that the average value of the dissolved oxygen rate for the two sites is less than 60% and with a minimum value found in the water of site S1 of 46.70%.

Table V. Average values of the physico-chemical parameters of the water according to the study sites

Sites	T (°C)	pH	O%	EC (µs/cm)
S1	28.70	6.44	46.70	134.00
S2	24.73	6.36	58.50	121.00

3.1.2. Average concentrations of heavy metals in the study matrices

3.1.2.1. In water

The values of the average concentration levels of heavy metals Fe, Cu, Cd, Pb and Hg measured in the water column of the Bandama study sites (site S1 and site S2) are listed in **Table VI**.

Table VI. Levels of average concentrations of heavy metals in water

Heavy metals	Average concentration (mg/L)		Standard in mg/L
	Site S1	Site S2	
Hg	0.036	0.014	0.006
Pb	0.745	1.450	0.010
Cd	1.424	2.470	0.003
Cu	9.681	7.543	2.000
Fe	0.195	0.297	-

The results in **Table VI** show that the metals Fe, Cu, Cd, Pb and Hg were all identified in the water column of sites S1 and S2 at varying levels of concentration from one site to another. These data clearly show that the average Cu concentration is higher than that of other heavy metals, regardless of the site. The data also indicate that the lowest levels are those of Hg. Furthermore, analysis of the data in the table shows that Cu and Hg reach a maximum average level at site 1, respectively 9.681 mg/L and 0.036 mg/L. In addition, we observe that it is at site 2 that the heavy metals Fe, Cd and Pb reach a maximum average concentration of 0.297 mg/L, 2.470 mg/L and 1.450 mg/L respectively. Thus, the order of magnitude of overall metal accumulation in the water column for the two study sites is as follows: [Cu]>[Cd]>[Pb]>[Fe]>[Hg].

3.1.2.2. in sediment

Table VII below presents the values of the average concentration levels of heavy metals in the sediments of the *Bandama* River of the sites S1 and S2 on the other hand. The average concentration levels of the studied metals detected in the sediments show higher levels for Fe for both sites, with a maximum value of 321.477 mg/kg (S2). The lowest levels of average content are observed at the level of Hg, with a minimum value of 0.042 mg/kg (S2). The analysis of **Tables VII** and **VIII** shows that Fe is the most abundant in the sediments of all the sites studied. It is noted that the trace elements (Fe and Cu) have almost a high concentration in the different sediments of the study sites compared to other metals. Thus, the order of magnitude of metal accumulation in the sediments for the two study sites is as follows:

Site S1: [Fe]>[Cu]>[Pb]>[Cd]>[Hg] and Site S2: [Fe]>[Pb]>[Cu]>[Cd]>[Hg]

Table VII. Mean concentrations of heavy metals in sediments and guide values of TEC and PEC

Heavy metals	Average concentration (mg/kg)		TEC mg/kg	PEC mg/kg
	Site S1	Site S2		
Hg	0.906	0.042	0.18	1.06
Pb	40.250	54.580	35.80	128.0
Cd	3.258	5.452	0.99	4.98
Cu	55.670	38.750	31.90	149.00
Fe	310.796	321.477	-	-

Table VIIII. Heavy metal levels in the continental crust [22]

Heavy metals	Fe	Cu	Cd	Pb	Hg	AL
UCC (mg/kg)	30890	14	0.1	17	0.056	77440

Also, the analysis of the Table shows that the soils near the two study sites have an average maximum value of 158.234 mg/kg for Fe (S2). Similarly, the smallest average values are observed at the level of Hg of the order of 0.015 mg/kg (S2). Thus, the order of magnitude of metal accumulation in the soil for the two study sites is as follows:

Site S1: [Fe]>[Cu]>[Pb]>[Cd]>[Hg] and Site S2: [Fe]>[Pb]>[Cu]>[Cd]>[Hg].

3.1.3. Environmental quality of sediments

The contents of Hg, Pb, Cd and Cu in these sediments were compared to the TEC and PEC quality criteria (**Table VII**). The metals detected (Hg, Pb, Cd and Cu) in the sediments of site S1 and S2 showed a concentration higher than the TEC except for Hg only for site S2. Thus, the sediments of sites S1 and S2 can be considered as a whole toxic. One can have a detrimental effect of these heavy metals on the burrowing organisms. It is noted however, that the only Cd (site S2) has a concentration in the sediment, higher than the PEC.

3.1.4. Determination of water quality and metal pollution in study environments

3.1.4.1. Water quality index of water from study sites

The calculated values of the WQI are recorded in **Table IX** according to the study sites. The results recorded in **Table IX** show that the WQI calculated at each of the sampling sites is greater than 100 the limit value for the state of the quality of drinking water. The Table shows that the water from the *Bandama* River near sites S1 and S2 is unfit for consumption.

Table IX. Water quality index values

Sites	WQI	Water quality status
S1	408.58	Unfit for consumption
S2	429.64	Unfit for consumption

3.1.4.2. Contamination factor (CF) of water by heavy metals

The CF values were calculated by the ratio between the average content of the metallic element measured in the water and their reference content (guide value) [26] are given in **Table X**. Analysis of **Table X** reveals that the values of $CF_{(Fe)}$ calculated for the water from the stream of sites S1 and S2 are all less than 1. This indicates contamination with low iron content. On the other hand, the values calculated for the other heavy metals are all greater than 6 for all the study sites. However, when CF is greater than or equal to 6, there is a very strong metallic contamination (Cu, Cd, Pb and Hg).

Table X. Values of water contamination factors

Sites	$CF_{(Fe)}$	$CF_{(Cd)}$	$CF_{(Pb)}$	$CF_{(Hg)}$	$CF_{(Cu)}$
S1	0.65	193.62	284.77	14.90	35.70
S2	0.99	150.86	494.00	29.00	14.30

3.1.4.3. Metallic geo-accumulation index (I_{geo}) of sediments

The tables below show the average values of the geoaccumulation index (**Table XI**) calculated for each metal and the class of metal pollution intensity (**Table XII**) in the sediment of sites S1 and S2. Analysis of **Tables XI** and **XII** shows that the values of the geo-accumulation index calculated for heavy metals (Cu, Cd and Pb) are all positive, regardless of the site (S1 or S2). We also observe that all the calculated values of I_{geo} for Fe are negative (Class 0). For Hg, there is a positive Igeo value for site 1 (class 4) and a negative value (class 0) for site 2. There is no proven pollution for Fe regardless of the study site on the one hand (Class 0). Also, there is no Hg pollution of the sediments of Site 2 (Class 0). The Hg pollution intensity class (Class 4) shows a moderately to heavily polluted intensity of Site 1. There is also an intensity class (Class 1) for Cu and Pb, from unpolluted to slightly polluted respectively for Site 2 and Site 1 on the one hand.

Table XI. Mean I_{geo} values calculated in sediments

Sites	$I_{geo(Fe)}$	$I_{geo(Cu)}$	$I_{geo(Cd)}$	$I_{geo(Pb)}$	$I_{geo(Hg)}$
S1	-7.21	1.41	4.44	0.66	3.43
S2	-7.17	0.88	5.18	1.10	-1.00

Table XII. Classes of metal pollution intensities of sediments

	Intensity classes				
Sites	**Fe**	**Cu**	**Cd**	**Pb**	**Hg**
S1	Classe 0	Classe 2	Classe 5	Classe 1	Classe 4
S2	Classe 0	Classe 1	Classe 6	Classe 2	Classe 0

Also, Cu and Pb have a pollution intensity of class 2 respectively for Site 1 and Site 2. Finally, the results of **Tables XII** indicate an intensity of heavily polluted (Class 5) to extremely polluted (Class 6) for Cd in the sediments of Site 1 and Site 2 respectively.

3.1.4.4. Enrichment factor (EF) of sediments by heavy metals

The calculated values of the EF are shown in **Table XIII**. All the EF values recorded in **Table XIII** calculated for the heavy metals Cu, Cd, Pb and Hg are all well above 50. These results show extreme enrichment of the *Bandama* River sediment by these metals regardless of the site of study. Moreover, the EFs calculated for the Cu and the Hg of the S1 site are higher than those calculated for the S2 site. However, those calculated for the Cd, Pb metals of this S1 are lower than the respective EF of the S2 site.

Tableau XIII. Valeurs du Facteur d'enrichissement

Sites	$EF_{(Fe)}$	$EF_{(Cu)}$	$EF_{(Cd)}$	$EF_{(Pb)}$	$EF_{(Hg)}$
S1	-	335.22	3298.12	236.78	1607.99
S2	-	265.96	5238.70	308.45	72.07

3.1.4.5. Metal Contamination Factor (CF) and Pollution Load Index (PLI) of sediments

Mean CF and PLI values of heavy metals in the sediments of the two sites are listed in **Table XIV**.

Table XIV. CF and PLI values of metals in sediments

Sites	$CF_{(Cu)}$	$CF_{(Cd)}$	$CF_{(Pb)}$	$CF_{(Hg)}$	PLI
S1	3.98	32.58	2.36	16.18	**2.18**
S2	2.75	54.52	3.21	0.75	**1.29**

Analysis of calculated CF values shows that Fe ($CF_{(Fe)}=0.01<1$) any study site and Hg ($CF_{(Hg)}=0.75<1$) for site 2. This indicates low Fe and Hg concentrations in the sediments at these locations. In addition, the metals Cu and Pb show values in the interval $2<FC<3$ respectively for the S2 site ($CF_{(Cu)}=2.75$) and the Site S1 ($CF_{(Pb)}=2.36$). This shows a moderate contamination of these sites by these heavy metals. On the other hand, the contamination by Cu and Pb at the S1 site is considerable ($CF_{(Cu)}=3.98$) and the S2 site ($CF_{(Pb)}=3.21$). Cd and Hg are the metals that most contaminate the sediments of the various sites. Indeed, there is a very strong Cd contamination on all the sites with $CF_{(Cd)}\gg6$. Sediment contamination is also high only at site S1 by Hg with $CF_{(Hg)}=16.18\gg6$. The results indicate that the PLI values are all greater than PLI>1 for all study sites S1 and S2.

3.2 Discussion

This study revealed that the pH of the waters of the *Bandama* River in the locality of *Bozi*, at sites S1 and S2, is weakly acidic. The average pH value of the water at the two sites (pH= 6.4 ± 0.04) is below the pH range allowed for surface water and ideal (6.5 to 8.5) for aquatic organisms recommended by the EPA (Environmental Protection Agency) [26]. The pH variation is the factor whose action on the mobility of metals is the most determining [27]. Indeed, according to Faurie [28], the pH of continental waters is linked to the structure of the soil. According to this author, the pH of continental waters is less than 7 with a non-calcareous soil whose cation exchange capacity is essentially made up of H^+ ions. This pH value could make the sediments of the *Bandama* River rich in metals. Indeed, the alkaline pH of surface waters promotes the precipitation of metals and limits their release into the waters, which induces an intense metal enrichment of the sediments of these waters ([8],[27],[29]). On the other hand, the lowering of the pH also favored the mobility of heavy metals [30]. Thus, acidic waters make these elements more soluble, i.e. they dissolve more easily in water and thus become more biologically available to fish and other organisms. As for the electrical conductivity (EC), the average of 127.5 ± 6.5 µS/cm is typical of the conductivity of fresh waters. This result shows that the waters studied are highly mineralized [29]. These results are similar to those of Yao & Ahoussi [31] who focused on the physico-chemical characterization of surface water in a mining environment at Divo. As regards dissolved oxygen, the recorded average is 52.6 ± 5.9, which is less than 60%. This shows that the oxygen level is low and is not acceptable to most common water organisms. However, dissolved oxygen influences the forms and toxicity of certain metals and the concentrations of certain chemical constituents (sulphide and ammonia). This rate would be due to the low rate of renewal of water [32] which would be one of the consequences of the eutrophication of the watercourse due to increased anthropogenic activities. The results of water and sediment analysis collected from the waters of the *Bandama* River revealed the presence of heavy metals such as Hg, Cd, Pb, Cu and Fe.

Thus, to determine the environmental quality of the sediments of sites S1 and S2, the average values of the concentrations of the heavy metals studied were compared to the values of TEC and PEC. The results showed that except Hg in site S2, all the other metals have their average concentration higher than the value of the TEC of the metal concerned whatever the site S1 and S2. This indicates that the metals in question may have adverse effects through the sediments on burrowing organisms. Thus, these sediments could present a risk of metal bioaccumulation and bioconcentration in these organisms. On the other hand, Hg does not constitute a danger for burrowing organisms only at the level of the sediments of S2. The result at site S2 of [Cd]>PEC shows that the sediments are toxic in Cd for burrowing organisms. This indicates the occurrence of harmful effects due to Cd for the sediments of this site. However, this site receives the stream coming from site S1, therefore probably the mobilized metals emanating from site S1. It is also noted that the sediments for all the study sites have a high intensity of Cd pollution (class 6 for S1 and class 4 for S2). Only Fe has concentrations below the limit values of metals in water and those of unpolluted sediments indicating that the major source of Fe is of natural origin. The results showed a high content of Cu, Cd, Pb and Hg in the sediments at the two sites, well above the residual value of the upper continental crust [22]. This high content suggests contamination of anthropogenic origin [33-34]. This accumulation may be due to local activities such as the use of herbicides and fertilizers, domestic activities and an intensification of gold panning activities along the *Bandama* River.

For the evaluation of the water quality and the intensity of the metal pollution of the sediments of the study area, the WQI, the I_{geo}, the EF and of contamination and the metal PLI were calculated. For the evaluation of water quality, based on the evaluation grid of Shweta et al. [21], the results revealed that the waters studied have a quality unsuitable for consumption (WQI>100). In addition, the Igeo values show that the sediments of sites S1 and S2 are preferentially polluted with Hg and Cd compared to other metals. Indeed, the Hg pollution intensity class shows a moderately to heavily polluted intensity for site 1 due to gold panning activities near this site. The same is true for Cd, which shows an intensity of highly polluted to extremely polluted in the sediments.

In addition, the EF values show an extreme enrichment of the sediments in Hg, Pb, Cd, Cu and Fe. Also, these values indicate the anthropogenic origin of the metals in the sediments of the *Bandama* River. This result testifies well to the influence and impact of activities, in particular gold panning, on the banks of the *Bandama* River in the locality of *Bozi*. Moreover, these results agree quite well with those obtained by the evaluation of the CF. Indeed, CF showed a strong anthropogenic contribution for Cd on both sites and Hg on site 1 in the sediments. These sites are areas where the main activity is gold panning, hence the heavy contamination of the sediments. The results of the average calculated PLI values (PLI>1) indicate a progressive deterioration of the estuary of the sediments of the two study sites by the metals studied. Thus, gold panning activities on the banks of the river and uncontrolled domestic activities will lead to a gradual deterioration of the environmental framework of the *Bandama* River in the locality of *Bozi*. Because, therefore, the development of these intense gold panning activities near the *Bandama* River will bring considerable quantities of heavy metals into surface waters [35]. Thus, once in the aquatic environment, heavy metals are distributed between the aqueous phase, sediments and aquatic organisms ([4],[36]). The extreme contamination of sediments and the degradation of water quality by the metal pollutants studied are, on the one hand, a risk of intoxication through the food chain for the populations who use them for their domestic uses and consumption and to on the other hand, a risk for the contamination of groundwater.

Conclusion

The results of this study show that the water and sediments of the *Bandama* River which passes through the locality of *Bozi* are under the influence of anthropogenic activities in its immediate environment. The waters of the river are weakly acidic and have a high mineralization. In addition, the metals Cu, Cd, Pb and Hg have all been detected in water and sediments at levels well above the international guideline values. These high metal levels in the aquatic environment of the river suggest contamination of anthropogenic origin. The analysis of the contents of the heavy metals detected in the sediments and the values of the TEC and PEC showed that the sediments are toxic in heavy metals more, particularly in Cd for the burrowing organisms. This indicates the occurrence of harmful effects due to Cd for the sediments.

The water quality assessment showed that the waters of the *Bandama* River from sites S1 (WQI_{S1}=408.58) and S2 (WQI_{S2}=429.64) are classified as unfit for consumption (WQI>100). These results also revealed an extreme enrichment (EF>100) of the sediments in Hg, Pb, Cd, Cu and Fe for all the study sites. A strong anthropogenic input for Cd at both sites and Hg at the S1 site in the sediments was indicated by the CF values. In addition, the sediments for all the study sites have a high intensity of Cd pollution. study by the metals studied. The order of magnitude of overall metal accumulation in the water for the two study sites: [Cu]>[Cd]>[Pb]>[Fe]>[Hg]. In sediments this order is as follows: Site 1: [Fe]>[Cu]>[Pb]>[Cd]>[Hg]" and Site 2: [Fe]>[Pb]>[Cu]>[Cd]>[Hg].

The extreme contamination of the sediments and the degradation of the quality of the water by the metal pollutants studied will therefore present environmental and health risks endangering the local populations. The enrichment of heavy metals in the sediments of the *Bandama* River underlines the need for the protection of this environment to preserve water resources, to protect living species and to avoid public health problems. It is therefore necessary to assess the toxicity of metals by studies that will take into account their bioavailability. It is also necessary that the population be made aware of the pollution of waterways caused by gold panning activities in order to avoid intense contamination of these waters.

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