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Impact of an Abandoned Mine on Surrounding Soils, Surface Water and Stream Sediment: Case of SOMIAF Gold Mine, Côte d'Ivoire

Kouadio Assemien François Yao, David Salze, Miguel Lopez-Ferber, Théophile Lasm, and Olivier Belcourt

***Abstract*—The old gold mine of Somiaf in Afema district (Southern of Côte d'Ivoire) ceased operating in 1998 without real site rehabilitation. In 2016, geochemical analyses of the soils, stream sediments and Hydrochemical characterization of waters of the surrounding area were carried out to assess the environmental impact of this mining site.**

The chemical analyses of surface water revealed that almost all the studied water are of poor quality based on the water quality index (WQI). On soils and stream sediments samples the chemical analyses showed Cd, Pb and As pollution. While soil contamination by Pb may be due to mining activity as shown in the water case, Cd and As seems to be coming from agricultural activities due to the widespread contamination. This study allowed us to get an overall view of the state of the environment after the end of the mining activity with the focus on the state of the quality of water consumed by the populations. A more detailed study must be carried out in order to accurately characterize the origin of the metal pollution in the waters.

***Index Terms*—Mining, WQI, metal contamination, Côte d'Ivoire.**

I. Introduction

Mining operations like most human activities (agriculture, the production of residential and industrial wastes and urban wastewater) result in the discharge of dissolved and particulate metals into surrounding soils, rivers and stream sediment which can have a significant impact on the sustainability of water resources [1]. Mining activities are often regarded as a major source of contaminant metals in environment [1]-[4]. Nowadays the mining sector reputation is founded on past examples of environmental degradation and impact on human health [5]. As a result mining operations are increasingly being challenged by local populations and environmental protection organizations. However extraction of minerals, base and precious metals is essential to everyday life, making up numerous products we all use. They are also vital raw materials in a large number of industries, including ceramics, construction, drugs, electronics, glass, automotive and electricity [6]. The mining industry creates also employment and wealth. For these reasons many mining projects have been conducted in recent decades, mainly in African countries.

The SOMIAF (Société des Mines d'Afema) gold mining operations were carried out from 1992 to 1998 in the Afema district, located in the Sud-Comoé Region of Southern Côte d'Ivoire. In 1998 the mine was abandoned without real remediation work. As a result the pits that had been opened are currently flooded by water flowing from the mining area. These waters and others withdrawn in the rivers serve to feed the populations who are not aware of the risk of poisoning incurred. Based on the Hydrochemical of surface water and geochemical (sediment/soil) characterization, the aim of this study is to evaluate (1) the impact of the abandoned mine on surface water resources, sediments and surrounding soils, and (2) the extent of contamination and/or pollution.

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II. Materials and Methods

A. Study Area

The sector of Afema, located south-Est of Côte d'Ivoire (Fig. 1) is characterised by sub-equatorial climate type which is locally called "climat attiéen". In this region, four seasons of unequal length exist: (a) a great rainy season from April to July, (b) a small dry season from August to September, (c) a small rainy season from October to November and (d) a great dry season from December to March. The temperature varies between 21 ℃ and 33 ℃ with annual average of 26 ℃. The annual pluviometry varies between 1400 and 2500 mm, and during the great rainy season periods of river floods are frequent [7].

From a geological perspective, the Afema sector belongs to the Proterozoic domain of Côte d'Ivoire. The formations encountered are grouped into two main sets: métavulcanites and metasediments. For details on geology of the sector, readers are referred to [7]-[10]. The contact zone of these geological formations represents the shear zone, oriented NE-SW [7].

B. Methods

To assess the potential pollution of soils, sediment and surface water by the former gold mine in Afema zone, the study is concerned with:

- The geochemical characterization of sediment and surrounding soils of the Somiaf mine area;
- The hydrochemical characterization of surface water

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comprising mine water and other surface waters positioned downstream and upstream of the abandoned mine.

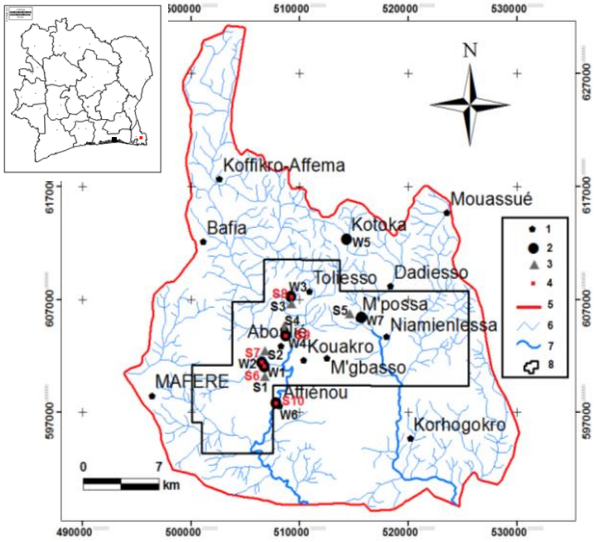


Fig. 1. Location of the study area: 1- Village; 2- Surface water sample; 3- Soil samples; 4- Sediment samples; 5- Study area boundary; 6- Non-perennial watercourses; 7- Main watercourses; 8- Operating license boundary.

C. Sampling of Soils Sediments and Water

Samples of soils, sediments and water were collected in February 2016. Five samples of soils referenced S1 to S5 were taken. Three samples were obtained in the immediate area of the mine and two others outside of this area. Samples were taken down to a depth of 10 cm and packed in polyethylene (PE) bags. Surface water quality study concerned with 7 collection points. One sample was taken in each of the two main pits and one in the former leaching pond. The remaining samples were collected upstream and downstream of Ehania and Noé watercourses (Figure 1). In addition, for each of these surface waters, stream sediment was collected. Field analyses on these waters concerned parameters such as *T*, pH, Eh and EC turbidity, and major ions. Elements such as Cd, As, Cr, and Pb were also targeted in this study. Samples for metal analyses were acidified with HNO_3 while those for ions analyses were not. Each of the two types of samples was collected in PE bottles. For solids samples (soils and stream sediments), analyses concerned Cd, As, Cr, and Pb. Parameters: pH, CE, and Eh were also investigated in soils.

Chemical analyses were carried out at the laboratory of the Centre Ivoirien Anti-Pollution (CIAPOL). In soils and sediments, measurements were performed after sample drying, grinding and digestion with a HNO_3–HCl–HF acid mixture according to the methodology proposed by [11]. Quantification was performed on an atomic absorption spectrophotometer (AAS). The surface water samples were analyzed on a Hach DR6000 spectrophotometer.

D. Assessment of Potential Environmental Risk

In order to evaluate the quality of soils a significant number of indicators were developed [12]-[14]. In this study the assessment of soils and sediment contamination level was performed by the quantification of the contamination factor (CF) and the pollution load index (PLI).

For each soil/sediment sample and each heavy metal the CF has been calculated as the ratio between the metal concentrations with its background values as expressed by (1).

$$CF = C_{heavy\ metal}/C_{Background} \quad (1)$$

$CF < 1$ indicates low contamination; $1 < CF < 3$ is moderate contamination; $3 < CF < 6$ is considerable contamination and $CF > 6$ is very high contamination [12].

For the entire sampling site, PLI has been determined as the nth root of the product of the n CF as indicate in (2):

$$PLI = (CF_1 \times CF_2 \times \ldots \times CF_n)^{1/n} \quad (2)$$

The background concentrations of metal (of interest) in soil/sediments come usually from samples taken in the same or close areas, where there was no anthropogenic input. However in the Afema area in addition to mining activity, agricultural activity is strongly practiced. Therefore, it was impossible to find soils not subject to human influence. Accordingly, background values were assumed equal to the element concentrations (in ppm) in the Upper Continental Crust [15].

To estimate the pollution level of the surface water of Afema, World Health Organization (WHO) Standards for waters were adopted. Then the quality index (WQI) was performed for each samples. It is defined as an estimate of water quality based on the influence of several parameters [16]. More information about WQI calculus principles can be found in [16]. The calculation is based on the suitability of given water for human consumption. WQI < 50 indicates excellent quality; 50 < WQI < 100 is good quality; 100 < WQI < 200 poor water; 200 < WQI < 300 is very poor water and WQI > 300 is water unsuitable for drinking.

III. Results and Discussion

A. Physicochemical Parameters and Metal Concentration

All soil samples presented an acidic pH regardless of their origin - in the immediate mining area or outside (Table I). The pH average value is 5 and indicates a relatively low acidity. These soil samples showed electrical conductivity values between 25.6 and 57.9 µs/cm. In contrast, sediment samples showed near-neutral pH (6.7- 6.9) and EC values of freshwater sediment are almost normal (CE < 1000 µs/cm).

Heavy metal contents show a variation of the average concentrations in soils in the following ascending order:

The studied soils are rich in Pb with an average of 58.2 mg/kg. Conversely, they have relatively low concentrations of As with an average of 2.1 mg/kg. In the sediments analyzed, we also observed high concentrations of Pb (65 mg/kg) followed by Cd (20 mg/kg), Cr (5.4 mg/kg) and As which is less abundant with 3.8 mg/kg average concentration (Fig. 2).

B. Intensity of Heavy Metal Pollution

The contamination factor (CF) and the pollution load index (PLI) are showed in Table II. CF values for Cd are very high in all samples both in soils and in sediments. For Pb, the

lower CF value (0.83) was obtained in sample S2 from soil collected near the pond of the former leaching basin. The same is true (0.90) for the CF obtained in the sediments of this pond.

TABLE I: CADMIUM, LEAD, CHROMIUM, AND ARSENIC CONCENTRATIONS AND PH, EC IN SOILS AND SEDIMENTS OF AFEMA AREA

Samples		pH	EC	Cd	Pb	Cr	As
Soils	S1	4.9	44.7	16.2	99.8	11.7	1.6
	S2	5.1	47.7	16.3	14.2	3.7	2.3
	S3	5.1	25.6	8.7	32.3	2.0	1.8
	S4	5.0	29.5	29.7	59.7	5.3	2.5
	S5	5.1	57.9	19.3	84.8	2.0	2.3
	Min	4.9	25.6	8.7	14.2	2.0	1.6
	Max	5.1	57.9	29.7	99.8	11.7	2.5
	Moy	5.0	41.1	18.0	58.2	4.9	2.1
Sediments	S6	6.8	74.7	18.3	80.1	12.5	2.0
	S7	6.9	58.8	14.3	15.3	1.8	1.3
	S8	6.8	35.4	23.7	98.8	6.2	4.3
	S9	6.7	150.3	16.2	74.7	3.8	5.1
	S10	6.7	143.3	27.7	56.2	2.7	6.3
	Min	6.7	35.4	14.3	15.3	1.8	1.3
	Max	6.8	150.3	27.7	98.8	12.5	6.3
	Moy	6.7	92.5	20.0	65.0	5.4	3.8

As <Cr <Cd <Pb.

Soils S1, S4 and S5 have high values of CF for Pb (3 <CF <6). S4 and S5 correspond to the soil sampled a little farther from the immediate area of the old mine. The contamination of these soils by Pb would suggest a non-mining origin. However, S1 which was taken close to the Anuiri pit reveals a CF of 5.87. In addition, the CF values quantified in the sediment from this pit (S6) and those of the Jonction pit (S8) indicate a high Pb contamination.

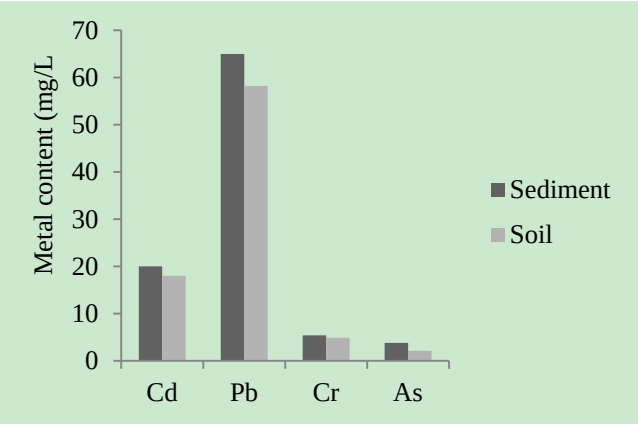


Fig. 2. Average metal content in soils and sediments of Afema area.

Except for S2 (soil close to the leaching basin) and S7 (sediment in the leaching pond), there is a generalized contamination in Pb. In the case of Cr, all CF values are less than 1 in soils and sediments. For As, CF values indicate low to medium contamination. Soils contamination is lower than sediment contamination.

The pollution load index was calculated to evaluate the degree of contamination. The results of PLI for the selected elements confirm anthropogenic action in the area since all values are > 1. These results show that soil from the immediate area of mining are relatively less polluted than those collected on sites somewhat distant from this area. For sediments, this variation in pollution seems to be reversed. It is more pronounced in the sediments of the mining pits (S6 and S8) than in the river sediments (S9 and S10). This could be explained by the fact that these reservoirs are larger than rivers and constitute run-off points. This is justified by the low PLI value (1.42) in sediments of the former leaching basin which is very small in extent.

TABLE II: CONTAMINATION FACTOR AND POLLUTION LOAD INDEX IN SOILS AND SEDIMENTS OF AFEMA AREA

Samples		CF				PLI
		Cd	Pb	Cr	As	
Soils	S1	161.67	5.87	0.33	0.79	3.96
	S2	163.30	0.83	0.10	1.16	1.99
	S3	86.67	1.90	0.06	0.91	1.73
	S4	296.70	3.51	0.15	1.26	3.74
	S5	193.33	4.99	0.06	1.15	2.85
Sediments	S6	182.50	4.71	0.36	1.02	4.21
	S7	143.33	0.90	0.05	0.63	1.42
	S8	236.70	5.81	0.18	2.16	4.81
	S9	161.70	4.39	0.11	2.57	3.76
	S10	276.70	3.30	0.08	3.16	3.90
Upper Continental Crust (UCC)		*0.10*	*17*	*35*	*2*	

The results obtained also strongly depend on the background values used in the study. The average concentrations in the UCC remain very general and may not correspond to the actual context of studied area. Thus, the values obtained may be either undervalued or overvalued. In the case of an overvaluation this would not constitute a real problem (from a health point of view) because the present results already reveal pollution. However, in the case of undervaluation, this would be detrimental to the health of local populations because the health risk associated with the use of the soil (consumption of plants) and the consumption of water would have been underestimated.

C. Assessment of Surface Water Quality

The pH values of the studied water range from 6.2 to 7.1. Curiously the waters of the old pits (W1, W2 and W3) are closer to neutrality than those of rivers (W4... W7). These values are respectively 7.0, 6.8, 7.1, 6.5, 6.8, 6.2 and 6.4. The EC of these waters is low and oscillates between 19.6 (W3: Junction pit) and 58.85 (W7: Noé River at Kotoka). These low conductivity value reflect low water mineralization as evidenced by major ion concentrations (Fig. 3A). Indeed, the concentrations of major ions are low for all waters. Only bicarbonate ions stand out a bit of the set with higher values in the waters of rivers over the waters from mining pits.

For the trace metal content, analyses do not indicate the presence of As, Cr, and Hg in the waters, while Cd and CN were found in all waters (except W5 for CN) and Pb in the Anuiri pit and leach basin (Fig. 3B). The presence of Pb only in mine waters with high values shows that it's due the mining activities. The obtained values fall far beyond those recommended by WHO (0.01 mg/L). It is the same to the CN with the highest values are obtained in these waters but nevertheless remain below the WHO standard (0.05 mg/L). Furthermore, the Cd concentrations are all above the tolerance limit (0.003 mg/L).

Thus the contamination of water by the Cd could originate either from agricultural activities that use phosphate fertilizers, or from domestic waste.

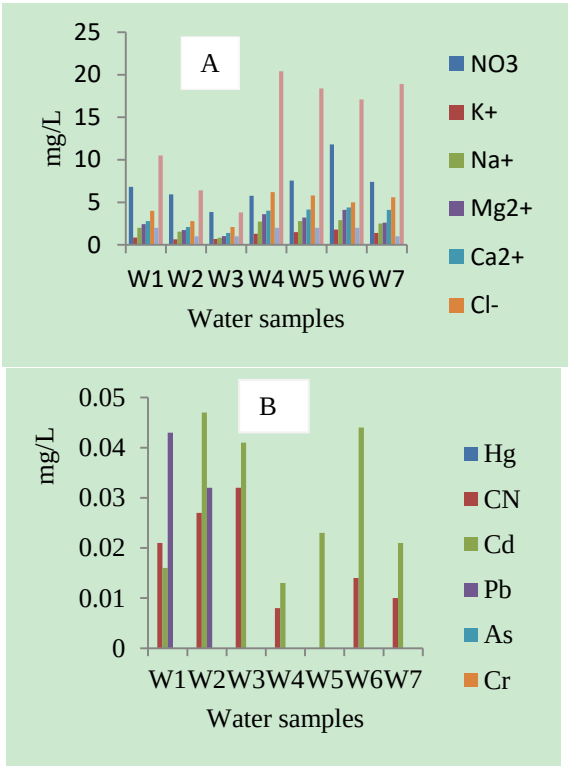


Fig. 3. Chemical composition of water samples: (A) Ions content, (B) Metal content.

Last, the WQI was evaluated to determine water quality. The WQI results show that most of the waters are of poor quality (Fig. 4). Only W4 (Ehania river at Abouliè) has a WQI of less than 100 (i.e. good quality). The highest value is obtained at W2 (leaching basin). Also, the waters of the Ehania and Noé rivers and the Anuiri pit are of poor quality (100<WQI<200) and yet they are consumed by the populations.

Based on these results, we suggest recommendations to improve environmental conditions and water quality:

- Stopping the consumption of polluted water,
- Stopping or reducing the use of fertilizers in agricultural practices,
- Rehabilitation of the former mine site to prevent the flow of polluted water,
- Involvement of authorities (local/national) for taking a firm decision to fight against pollution.

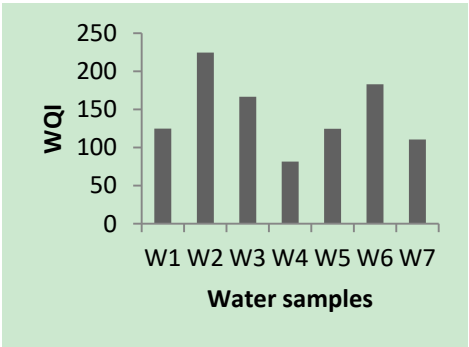


Fig. 4. Water quality index of surface water of Afema area.

IV. Conclusion

After this study, it should be noted that soils and sediment in the study area are contaminated with Cd, Pb and As. This contamination is expressed by high contamination factor and PLI values. These results reflect an enrichment of elements of anthropic origin in comparison with average levels in the UCC. Pb enrichment would be linked to mining activity whereas Cd and As would be derived from other human activities such as agriculture.

The study also revealed that, like the waters in the old mining works (pits and leach basin), Noé River waters are of poor quality. While it is true that the pollution of the water in the pits is due to the mining, the origin of river pollution is not clear. It could come from agricultural activity or from domestic waste. More detailed studies of water and types of fertilizer used in the area will substantiate these presumptions. In the meantime, it is evident that these waters are not suitable for human consumption. Their consumption without prior treatment exposes the population to health risks.

Acknowledgment

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Dr. Salze present researches include environmental impacts assessment and numerical modelling of the extractive industry.



Miguel Lopez-ferber graduated (PhD degree) in Pathology and Parasitology. After his PhD, he worked on the reduction of chemical pesticide pollution by developing bio-insecticides at the Laboratory of Industrial and Environmental Engineering, Ecole des mines d'Alès, France. He is currently full professor of environmental engineering at the same Laboratory.

Pr. Lopez-Ferber present research aims to analyse the interactions between organisms or groups and the main drivers conditioning the final response (antagonisms, synergies…), both from the Biological Ecology and from the Industrial Ecology perspectives.



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