RESEARCH ARTICLE

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# Geochemical Assessment for Trace Metal Contamination of Mining Wastes of Fel and Its Environs in Adamawa Region (Cameroon)

Tonang Zebaze Arnaud, Njueya Kopa Adoua, Nguetnkam Jean Pierre, Tchameni Rigobert, Kwékam Maurice, and Akang Ndelle Brown

**ABSTRACT**

**Mining waste due to gold exploitation has a great consequence for the environment and needs to be assessed where mining sites are developed for good sustainable environmental management because it is responsible for the release of massive amounts of hazardous metals. For this purpose, the diagnosis of the current state of the environment of the mining sites of Fel and its environs was carried out through physical and geochemical analysis to assess evidence of pollutant capacity. Physical analyses focus on the granulometry of wastes while geochemical analyses concern the assessment of the amount 10 Metallic trace elements (MTE) on 9 samples from three mining sites. The results of the granulometric analyses reveal heterogeneity and discontinuity in the sandy gravel texture of the waste. Geochemical analyses show that a fine fraction less than 80 µm presents the best geochemical result for all chemical elements. The geoenvironmental assessment of the wastes according to the Geoaccumulation Index ($Igeo_{max}$=7,14), the Contamination Factor (CFmax=212,45), the Degree of Contamination (DCmax=252,86) and the Sediment Pollution Index (SPI), characterized by low polluted sediment (SPImax=4,07), made it possible to establish the high link between As and Sb with very high concentrations, thus extreme pollution of these elements in the mining waste of the study area, particularly in Foum, Mama Wassande and Fel. Strong to very strong positive correlations observed between As and Cu, Pb, Cd and Cr, suggest that these MTE originated from a common source of contamination. Therefore, these MTE should be assessed on groundwater to prevent and avoid or minimize their effect on human health in this environment.**

**Keywords**: Contamination, Geochemistry, Granulometric Fraction, Mining Wastes, Metallic Traces Elements.

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**T. Z. Arnaud**
Department of Earth Science, Faculty of Sciences, University of Ngaoundéré, Cameroon.
(e-mail: tonangarnaudz@yahoo.fr)
**N. K. Adoua***
Department of Earth Sciences, Faculty of Sciences, University of Dschang, Cameroon.
(e-mail: njuedou@yahoo.fr)
**N. J. Pierre**
Department of Earth Science, Faculty of Sciences, University of Ngaoundéré, Cameroon.
(e-mail: jpnguet@yahoo.fr)
**T. Rigobert**
Department of Earth Science, Faculty of Sciences, University of Ngaoundéré, Cameroon.
(e-mail: rigotchameni@yahoo.fr)
**K. Maurice**
Department of Earth Sciences, Faculty of Sciences, University of Dschang, Cameroon.
(e-mail: mkwekam@yahoo.fr)
**A. N. Brown**
Ministry of Mines, Industry and Technological Development, Cameroon.
(e-mail: ndellebrown@yahoo.com)

***Corresponding Author***

## I. Introduction

In December 31, 2016, there were twelve (12) semi-mechanized artisanal gold mining sites in the Adamawa Region, all located in Meiganga Sub division, compared to zero exploitation sites in December 31, 2014. The exploitation is monometallic (only gold) and takes place mainly in the flats of riverbeds. The other substances were not of importance for exploitation. The method of exploitation permitted the extraction of a greater quantity of gold superior to 100 kg between 2015 and 2020. The mining exploitation took place without any regard to the impact of the activity on the environment. The sulfide minerals which were once confined to the basement of the soil became exposed to the surface and could interact with air and water to form acids. The acidification of the water thus contributed to an increase in the dissolution of metals and the release of Metallic Traces Elements (MTE) into the environment. Mining therefore has great consequences to the environment and is responsible for the release of massive amounts of hazardous metals into the surrounding environments [1]-[2]. According to [3] and [4], heavy metals in our natural environment have received great attention worldwide from scientists in the fields of environment, biology, chemistry as well as the general public certainly because of their unique characteristics such as biological significance, toxic behavior, persistence, bioaccumulation and their tendencies to be incorporated into the food chain in harmful amounts. These elements are not biodegradable and undergo a global ecological cycle [5]. The presence of heavy metals in sediments is imposed by the size of the sediments. This trend is principally attributed to the sorption, co-precipitation, and complexation of metals on particle surfaces [6]. Processing tailings are by-products of ore processing operations using different mineralogical techniques. They are stored on the site in heaps or lagoons. They are coarse to very fine particle size and potentially generate environmental issues (leaching of metals; acid or non-acid mine drainage; siltation of watercourses) requiring appropriate management in the post-mine context. The chemical and physical instability of mine wastes stored in accumulation areas is a source of many environmental and safety problems. Water draining in these areas can also, if not properly managed, be harmful to the public and environment. The main objective of this work is to characterize an environment of mining waste from gold mining exploitation in the locality of Fel and surrounding mining sites in order to appreciate the type of exploitation for the sustainable management of resources on one hand and the impact on the environment on the other hand.

## II. Methodology

### A. *Study Area and Samples Sites*

The study area covers the villages of Kombo Laka, Mborguéné, Mama Wassandé, Ndoyong, Gbatoua and Ngazi, all in Meiganga Subdivision, Mbéré Division, Adamawa Region. It is located about 152 km from Meiganga, about 10 km from the border with the Central African Republic and about 325 km from Ngaoundéré, the regional capital (Fig. 1). This zone covers a surface area of about 750 $km^2$.

Known nationally for its richness in gold, the study area is in the central zone of the East-Cameroon border and can be identified via the coordinates 6°17ʹ10.56ʺ and 6°32ʹ 23,11ʺ North latitudes and 14°28ʹ07.57ʺ and 14°49ʹ 41.47ʺ East longitude.

The geomorphology of the area shows a plateau consisting of a steep cliff to the north, which slopes gently towards the east and south with the peninsula of Meiganga-Bagodo to the southeast. However, the altitude of the study area varies between 875 and 1200m.On the hydrological plan (Fig. 1), it appears that the study area belongs to the Sanaga basin with the Lom as the main collector in its upstream part. The secondary network consisting of the rivers Fel, Foum, Mama, Mifeck, Wantia, Moufeck, Mikila, Bondo and Midal developed in valleys often heavily notched. These rivers belonging to the Upper Lom basin have many common features notably, a torrential regime with floods in August-September and low water levels in January, valleys encased and cut in places by rapids. It should however be noted that it is mainly in these rivers that gold mining takes place in the locality.

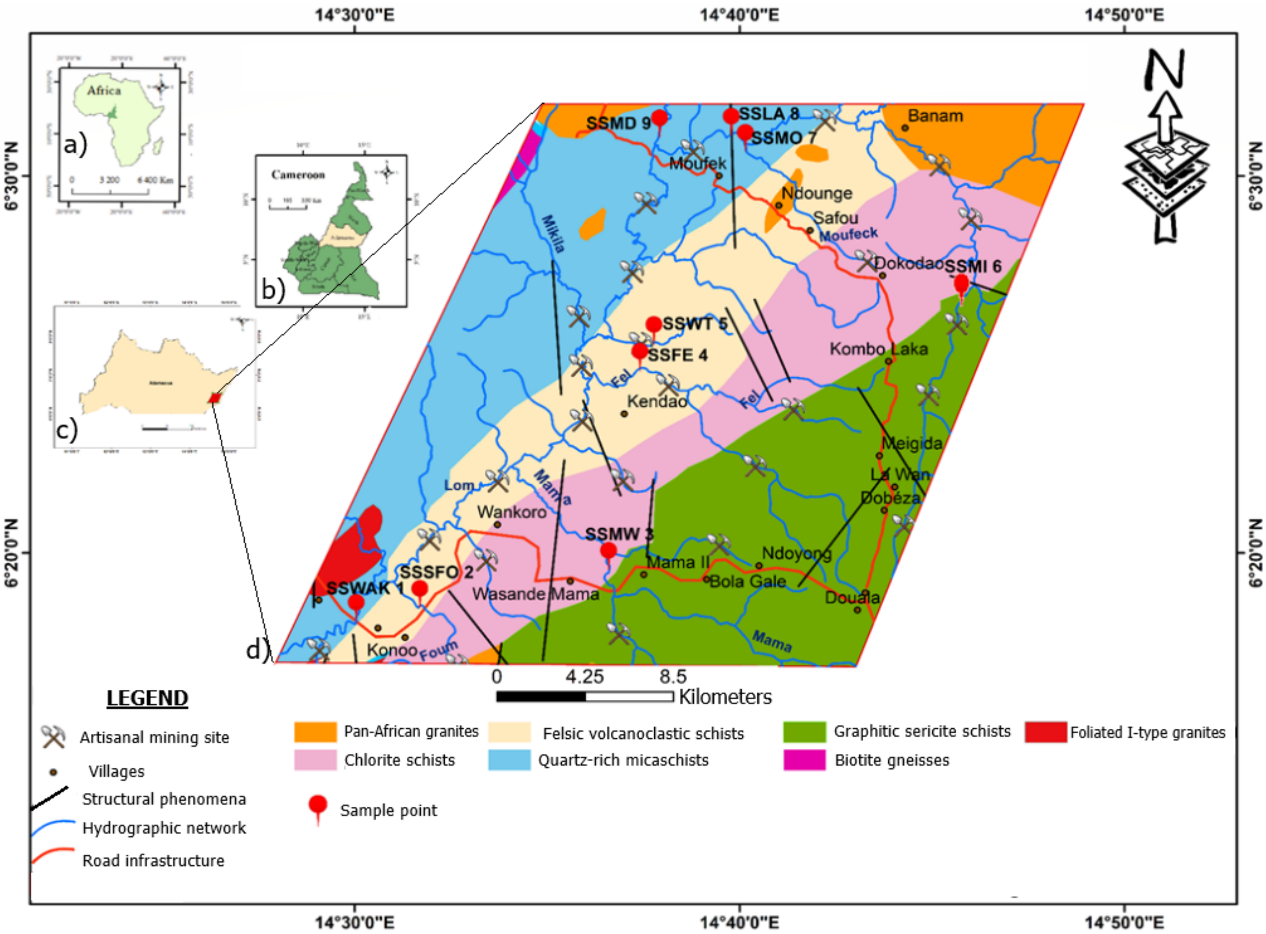


Fig. 1. Location of the study area. a) Cameroon inside Africa; b) Adamawa region inside Cameroon; c) Study area inside Adamawa region; d) Study area showing geologic, hydrographic, tectonic structure and sampling point.

### B. Preparation of Samples and Analytical Method

Several field trips were carried out as part of this study. One of them in January 2017 aimed to identify rivers subject to semi-mechanized artisanal gold mining exploitation, identification of tailings dams (wastes), and assess their extent in space. During this field trip, we were also able to appreciate the method of exploitation of placers and altered formations in the pit. The last field trip took place in April 2021, a period corresponding to the end of the dry season and in addition, a favorable time for accessibility and sampling of the site. During this fieldwork, eight (08) fine waste samples and two (02) stream sediment samples of an unexploited site were collected for geochemical study, and three (03) coarse waste samples were collected for granulometric study.

The wastes of mining sites were progressively formed during the exploitation phase, which lasted only a few months and then remained accumulated for about 05 years. The heterogeneity of the environment is related to two principal phenomena, firstly, we have, grano-classification by the density and size of the particles during decantation and the flow of the pulp from the point of supply to the water drainage weir. Secondly, we have the superposition of successive layers that reflect variations in the characteristics of production. Systematic sampling ensured good representativeness of the granulometric and geochemical characteristics of the wastes. Composite samples of the wastes were taken from the pours of several mining sites namely *Foum, Mama, Fel, Wantia, Mifeck, Moufek, Midal*, and upstream and downstream *Lom* at a place called Pont de Wakasso. Each composite sample was collected manually from several subsamples, taken from different locations and depths of the pours and packaged in clean plastic bags. The samples were dried, demoulding, sieving through a stainless-steel sieve in five particle sizes (< 0,08 mm; 0,08 mm; 0,163 mm; 0,315 mm and 0,5 mm) to study the effects of sediment size on metal absorption [7]-[8], weighing, packaging, and then transported to the laboratory.

The geochemical analysis carried out covers 10 traces of elements. The method usually consists of two steps including the extraction of the desired elements in solution and the determination of the elements by instrumental analysis of the solution. Extraction was total to measure the total abundance of elements of all minerals in the sample. The method of analysis used is the Induced Coupled Plasma – Mass Spectrometry (ICP-MS) which measures the concentrations of the elements by counting the atoms for each element present in the solution. Generally, the ICP-MS analysis technique provides the widest range of elements associated with the lowest detection limits to ensure maximum exploration power. For the dosage of gold by atomic absorption, the threshold of 0.2 ppb, out of the five fractions was retained. Analysis of the MTE was performed on 10 ml aliquot fractions obtained by mineralization of the samples, with the addition of internal standards (indium, bismuth), $HNO_3$ 15N and $H_2O$ milli-Q, obtained following a cold attack for 168 hours from 0.1 g to 1 g of each solid sample previously crushed. The attack was carried out with 20 ml of ultra-pure concentrated $HNO_3$ acid in polyethylene bottles. The results of analyses are compared with the normal average levels of MTE in the Earth's crust and with the normal levels of uncontaminated soils on one hand and based on the calculation of the geoaccumulation index established by [9] and the Contamination Factor on the other hand.

Evaluation of the degree of metal contamination and toxicity of mining wastes from the study area was based on the calculation of metal and polymetallic enrichment indices, especially the geoaccumulation index (Igeo), contamination factor (CF), the degree of contamination (DC) and the Sediment Toxicity Index or Sediment Pollution Index (SPI).

The Igeo allows the comparison of the concentration of a given metallic element with respect to a reference geochemical background for the same element [10]. The geoaccumulation index (Igeo) was calculated as proposed by [11], using (1).

$$\text{Igeo} = \log_2 \frac{Cx}{1.5 * Bgx} \quad (1)$$

Cx: measured concentration of the metallic trace element x
Bgx: concentration of the geochemical background for the metallic trace element x

The appreciation of geoaccumulation index (Igeo) was defined by [11], on a scale of seven classes. The interpretation of the obtained results is as follows:

class 0: Igeo ≤ 0 unpolluted,
class 1: 0 <Igeo ≤ 1 unpolluted to moderately polluted,
class 2: 1 <Igeo ≤ 2 moderately polluted,
class 3: 2 <Igeo ≤ 3 moderately to strongly polluted,
class 4: 3 <Igeo ≤ 4 strongly polluted,
class 5: 4 <Igeo ≤ 5 strongly to very strongly polluted and
class 6: Igeo> 5 very strongly polluted.

The correction factor "1.5" is introduced to reduce possible variation effects in geochemical background values that could be attributed to lithological variations in sediments.

As for the Contamination Factor (CF), it is defined by the ratio of the content of a given metallic element (Cx) to the geochemical background (Bgx) of the same metallic element taken as a normalizing factor. This contamination factor is calculated by (2) [12]:

$$\text{CF} = \frac{C_x}{Bgx} \quad (2)$$

Cx: measured content for an element x
Bgx: background for a metallic element x

The CF values are interpreted based on seven level of contamination, where:

Level 1: CF < 1 indicates no contamination;
Level 2: 1 < CF < 3 contamination is minor;
Level 3: 3 < CF < 5 contamination is moderate;
Level 4: 5 < CF < 10 contamination is moderately severe;
Level 5: 10 < CF < 25 contamination is severe;
Level 6: 25 < CF < 50 contamination is very severe and
Level 7: CF > 50 contamination is extremely severe.

The Degree of Contamination (DC) is used to assess the polymetallic contamination of sediments at a given station. It is calculated by summing the Contamination Factor (CF) values, as shown in (3).

$$\text{DC} = \Sigma\text{CF} \quad (3)$$

[12] defined the assessment of the Degree of Contamination (DC) according to four (04) classes. Low

contamination for DC < 6; moderate contamination for 6 ≤ DC < 12; considerable contamination for 12 ≤ DC < 24 and very high contamination for 24 ≤ DC.

The Igeo, CF and DC indices are used to assess the degree of enrichment and contamination of sediments in a given MTE but do not take into account its toxicity.

The Sediment Pollution Index (SPI) introduced by [13] and defined by the sum of the CF values, considers the relative toxicity of each MTE by assigning it a weighting factor (W) or toxicity weight. This weighting factor varies depending on the toxicity of the element. Thus, a weight of 1 is assigned to Cr and Zn because they are the least toxic, 2 to Cu and Ni, 5 to Pb and 300 to Cd [13] - [14]. The SPI is expressed by (4).

$$\mathrm{SPI} = \Sigma \frac{FCx * Wx}{W} \quad (4)$$

Where, FCx is the contamination factor of the metallic element x; Wx is the toxicity weight assigned to the metallic element x and W is the sum of Wx.

[14] defined the appreciation of the sediment pollution index (SPI) according to five (05) classes. Unpolluted sediment for 0 ≤ SPI < 2, Less polluted sediment for 2 ≤ SPI < 5, Moderately polluted sediment for 5 ≤ SPI < 10, Highly polluted sediment for 10 ≤ SPI < 20 and Dangerous sediment for SPI ≥ 20. Given the shale nature of the geological coverage of study area, we opted for geochemical background noise of average concentrations specific to shale substrates defined by [15].

## III. Results And Discussion

### A. Granulometric Analysis

The results of granulometric analysis show that the fraction less than 2 mm, according to [16], consists of sands and fines representing 41.1 %; 52.4% and 42.4 % of particulate matter for wastes from Lom, Mama and Fel respectively. The granulometric curve (Fig. 2), indicates that the fraction of ultrafine particles smaller than 80 µm is small and represents less than 5 %.

Granulometric distribution of the wastes (Fig. 3) shows that the fraction of fines is the least represented, varying between 2.9 % and 4.4 % depending on the site. The sandy fraction between 0.08 and 2 mm is intermediate, varying between 38.2 and 48% depending on the site. The gravelly and pebbly fractions are dominant to the previous ones, with a weight percentage varying between 47.6 and 58.9 %. The gravelly nature of waste will thus constitute its main texture.

According to [17], the classification of sediments collected from waste mining in the study area shows that the main texture consists of sandy gravel. Granulometric analysis made it possible to identify the quality, uniformity and continuity of the granulometric classes of our samples. The Finesse Module (Mf) shows that the sandy fraction of our wastes (Mf > 3.2) is not of good quality for civil engineering works. The Hazen coefficient (Cu > 2) shows a spread particle size for the three samples. The spread-out appearance of the curves is characterized by a heterogeneity texture of the material, ranging from fines to pebbles through sand and gravel. The coefficient of curvature less than 1 (Cc < 1) of samples is characteristic of poorly graduated materials. This poor graduation of the particle size is a result of the discontinuity in the texture. The results obtained are comparable to those of [18] as part of their study on the valorization of leaching wastes in heaps from the Amesmessa gold mine in Algeria.

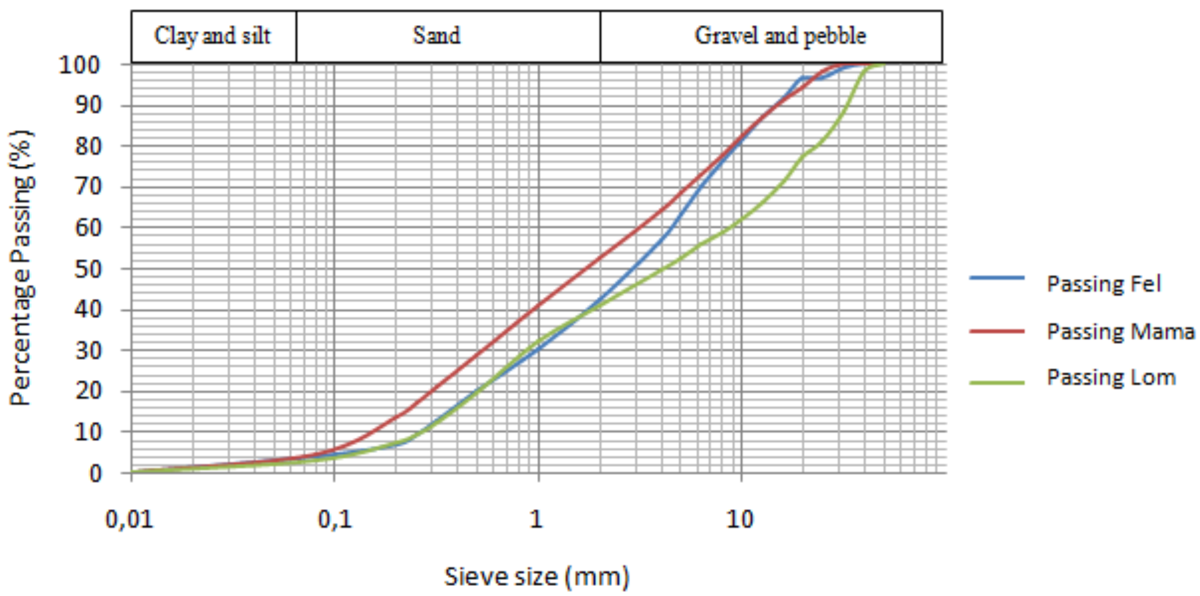


Fig. 2. Granulometric curve of three sampling sites.

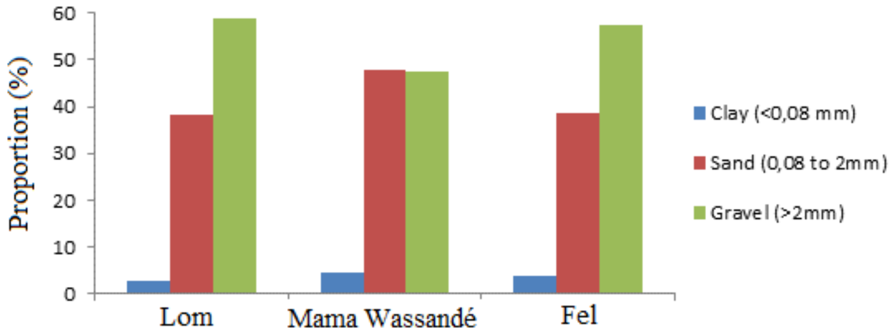

Fig. 3. Distribution of the main fractions in the different samples.

### B. Physical Analysis

Data on the physical properties of samples of sediment is presented in Table I. The pH ranges from 2.8 to 6.4 with an average value of 5.5. This acidity is due to the presence of silicates, precipitation and pollutants in the soil.

Electrical conductivity measurements are used as an indicator of the total amounts of soluble salts in soils. The electrical conductivity of the samples studied varies between 15.9 and 1300 µS/cm with an average value of 197.1 µS/cm. Total Dissolved Solids (TDS) represents the total concentration of dissolved substances in water. TDS is composed of inorganic salts and some organic matter. The TDS of the samples studied vary between 11.2 and 910 ppm with an average value of 138.5 ppm.

A high concentration of TDS indicates that harmful pollutants such as iron, manganese, sulphate, bromide and arsenic may be present in the water. Salinity measures the concentration of water in dissolved salts (sodium chlorides, magnesium chloride, etc.). The soils studied have low salinity. It varies between 15.5 and 637 ppm with an average value of 100.5 ppm. Numerous authors [19]-[21] concluded that physical soil parameters, in particular pH and electrical conductivity, could influence the concentration, behaviour and fate of heavy metals and metalloids. Soil pH is one of the most important factors determining the concentration of metals in soil solution, their mobility and their availability to plants [22]. In highly acidic soils, the mobility of heavy metals is much higher than in neutral and alkaline soils.

In the present study, the soils studied have acidic to neutral properties, therefore, the mobility of heavy metals is pronounced depending on the pH. The most illustrative cases are that of mining wastes from Mama wassandé (SSMW3) which has a pH of 2.8, an electrical conductivity of 1300 µS/cm, TDS of 910 ppm and a salinity of 637 ppm.

This gigantism in terms of proportion is due to the fact that the sediments have recently been reworked and are therefore young compared to all other sediments and mining wastes in the locality. Through redox phenomena, residual sulphides on the surface interact with oxygen and water and are transformed into acid. We are thus witnessing acidification of the waters and a release of heavy metals. The pH of the waters can vary naturally. Certain types of rocks and soils such as limestone and shale can neutralize acidity more effectively than other types of rocks and soils such as granite.

The water pH of the newly reworked wastes is 2.8 while that of the old wastes and sediments from the main collector of the mining zone (Lom) varies between 5 and 6.4.

TABLE I: PHYSICAL CHARACTERISTICS OF SEDIMENTS AND MINING WASTES IN THE STUDY AREA

| Samples | pH | Conductivity (µS/cm) | TDS (ppm) | Salinity (ppm) |
|---|---|---|---|---|
| SSWAK 1 | 6,4 | 63,6 | 45,2 | 35,2 |
| SSFO 2 | 5,5 | 99,1 | 71,3 | 51,2 |
| SSMW 3 | 2,8 | 1300 | 910 | 637 |
| SSFE 4 | 6,1 | 62,9 | 44,6 | 34,6 |
| SSWT 5 | 6,2 | 15,9 | 11,2 | 15,5 |
| SSMI 6 | 5,0 | 61,9 | 43,8 | 34,2 |
| SSMO 7 | 5,9 | 20,2 | 14,4 | 17,2 |
| SSLA 8 | 6,4 | 75,5 | 53,5 | 40,1 |
| SSMD 9 | 5,6 | 74,8 | 53,2 | 39,9 |
| Minimum | 2,8 | 15,9 | 11,2 | 15,5 |
| Average | 5,5 | 197,1 | 138,5 | 100,5 |
| Maximum | 6,4 | 1300 | 910 | 637 |

This tendency to neutralize the waters of the study area may be due to the presence of alkaline minerals that buffer the waters [23] and to the shale formations that have an important neutralizing power on which they are based as demonstrated by the studies of [24]. It should be noted that this neutralization of acidic waters contributes to the hardening of groundwater.

### C. Geochemical analysis

The composition of certain metallic trace elements of the sediments of Fel mining sites and its surroundings are listed (Table II).

Geochemical response in different particle size fraction shows that fine-grained tend to have relatively high metal contents, in part because of the high specific surface area of the smaller particles. For the ETMs in Mama Wassandé, Fel and High Lom (Fig. 4a, 4b, 4c) as for ten metals in this study, the trend clearly indicates a decrease in concentration with an increase in the granulometry of particles. The fraction with smaller size (< 80 µm) has the highest concentration and higher fraction (315-500 µm) have the lowest concentration, apart from some cases of nugget effect of Cu and Pb encountered in Fel samples for example. [25] also observed this geochemical trend of granulometric fractions in the sediments of the Hara Reserve in Iran.

The results obtained for Geoaccumulation Index (Igeo) show that the environment of the study area is characterized by moderately to extremely polluted sediments (Table III, Fig. 5), much more by arsenic (As) and antimony (Sb) in majority of the sites subject to exploitation.

TABLE II: MTE CONCENTRATION IN SAMPLES OF THE STUDY AREA

| | Cu | Pb | Zn | Ni | Co | As | Cd | Sb | Cr | Hg |
|---|---|---|---|---|---|---|---|---|---|---|
| Unit | PPM | PPM | PPM | PPM | PPM | PPM | PPM | PPM | PPM | PPB |
| MDL | 0,01 | 0,01 | 0,1 | 0,1 | 0,1 | 0,1 | 0,01 | 0,02 | 0,5 | 5 |
| Samples | | | | | | | | | | |
| SSWAK1 | 16,52 | 14,08 | 37,7 | 14,5 | 11,6 | 6,8 | 0,08 | 0,67 | 40,6 | 33 |
| SSF02 | 48,34 | 19,92 | 95,1 | 45,6 | 20,6 | 58,3 | 0,41 | 2,39 | 139,5 | 36 |
| SSMW3 | 36,56 | 17,19 | 242,3 | 83,1 | 27,2 | 40,7 | 0,27 | 42,49 | 74,0 | 15 |
| SSFE4 | 21,10 | 20,95 | 56,8 | 15,2 | 12,8 | 34,2 | 0,10 | 4,01 | 38,3 | 135 |
| SSWT5 | 13,75 | 14,88 | 22,3 | 9,7 | 8,2 | 12,5 | 0,04 | 2,69 | 34,4 | 43 |
| SSMI6 | 28,42 | 14,02 | 46,7 | 13,3 | 8,2 | 10,9 | 0,07 | 1,31 | 34,2 | 34 |
| SSMO7 | 15,90 | 12,61 | 32,4 | 13,8 | 13,7 | 3,4 | 0,04 | 0,23 | 44,6 | 17 |
| SSLA8 | 17,26 | 11,23 | 48,7 | 16,6 | 20,0 | 5,5 | 0,05 | 0,30 | 44,9 | 14 |
| SSMD9 | 17,14 | 20,80 | 35,0 | 17,7 | 11,0 | 1,2 | 0,03 | 0,12 | 59,6 | 29 |
| UCC | 28 | 17 | 67 | 47 | 17,3 | 4,8 | 0,09 | 0,4 | 92 | 50 |
| PAAS (Bgx) | 25 | 17 | 71 | 44 | 17 | 1,5 | 0,098 | 0,2 | 85 | 50[a] |

PAAS: Post-Archean Australian Shale from Taylor & McLennan (1985); UCC: Upper Continental Crust from Rudnick & Gao (2014) = a

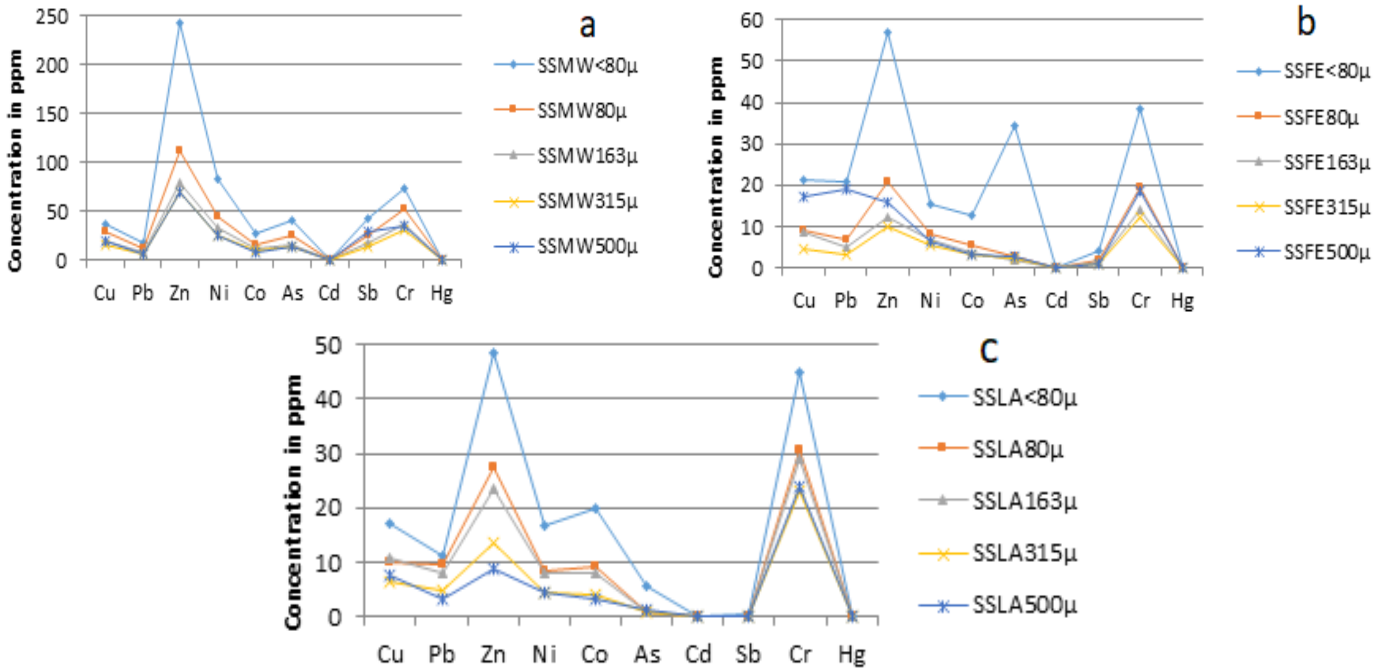


Fig. 4. Geochemical response in different granulometric fractions in study areas, a) Mama Wassandé (SSMW), b) Fel (SSFE) and c) High Lom (SSLA).

TABLE III: EVOLUTION OF IGEO IN SAMPLES OF THE STUDY AREA

| Indice | MTE | SSWAK1 | SSF02 | SSMW3 | SSFE4 | SSWT5 | SSMI6 | SSMO7 | SSLA8 | SSMD9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Igeo | Cu | - 1,18 | 0,36 | - 0,04 | - 0,83 | - 1,43 | - 0,39 | - 1,25 | - 1,12 | - 1,12 |
| | Pb | - 0,85 | - 0,35 | - 0,56 | - 0,28 | - 0,77 | - 0,86 | - 1,01 | - 1,18 | - 0,29 |
| | Zn | - 1,49 | - 0,16 | 1,18 | - 0,90 | - 2,25 | - 1,18 | - 1,71 | - 1,12 | - 1,60 |
| | Ni | - 2,18 | - 0,53 | 0,33 | - 2,11 | - 2,76 | - 2,31 | - 2,25 | - 1,99 | - 1,89 |
| | Co | - 1,13 | - 0,30 | 0,09 | - 0,99 | - 1,63 | - 1,63 | - 0,89 | - 0,35 | - 1,21 |
| | As | 1,59 | 4,69 | 4,17 | 3,92 | 2,47 | 2,27 | 0,59 | 1,29 | - 0,90 |
| | Cd | - 0,87 | 1,47 | 0,87 | - 0,55 | - 1,87 | - 1,07 | - 1,87 | - 1,55 | - 2,29 |
| | Sb | 1,15 | 2,99 | 7,14 | 3,74 | 3,16 | 2,12 | - 0,38 | - 0,0 | - 1,32 |
| | Cr | - 1,65 | 0,12 | - 0,78 | - 1,73 | - 1,89 | - 1,89 | - 1,51 | - 1,50 | - 1,09 |
| | Hg | - 1,18 | - 1,05 | - 2,32 | 0,84 | - 0,80 | - 1,14 | - 2,14 | - 2,42 | - 1,37 |

Studies by [26] in the soils of Fel and Wantia also show moderate to extreme pollution in As and Sb. On the other hand, in the context of studies conducted by [27] in the mine tailings of Zaida in Morocco, extreme pollution is observed in Pd, Cr and Cd. The results reveal arsenic and antimony pollution at all sites except the control site (SSMD9) from the Midal sediments where no mining activity was identified upstream. Thus, in all sites, mining sediments evolve from unpolluted to very strongly polluted for these two elements. The Igeo calculated for lead does not reflect any pollution; the latter being negative. In addition, those calculated for copper, zinc, nickel, cobalt, chromium and mercury present for each of the elements mentioned, the only polluting element of each site.

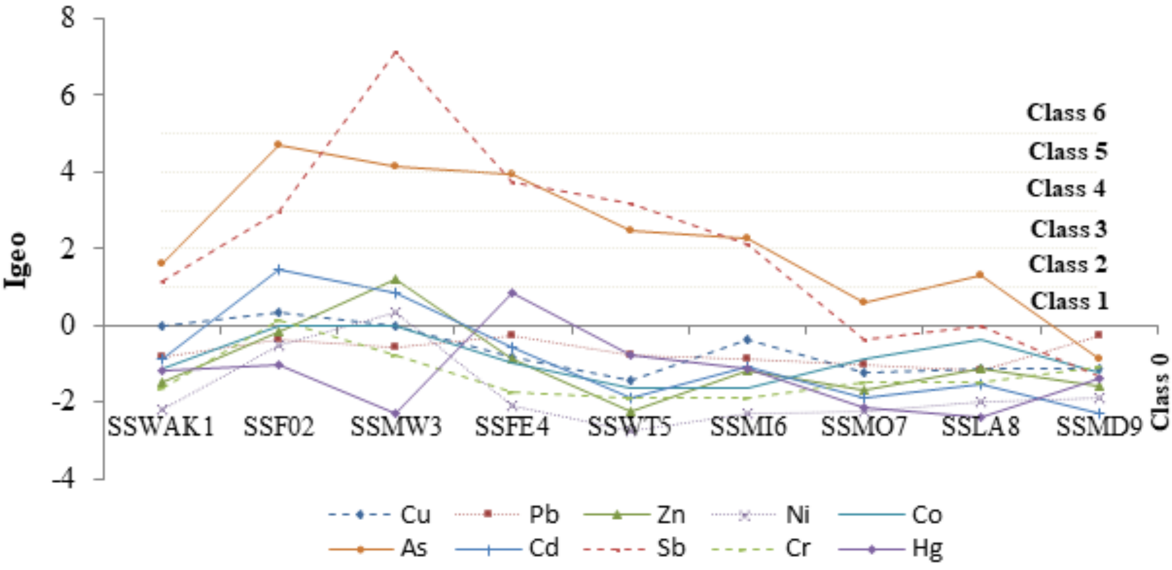


Fig. 5. Evolution of Igeo in the study area.

TABLE IV: EVOLUTION OF CF IN SAMPLES OF THE STUDY AREA

| Indice | MTE | SSWAK1 | SSF02 | SSMW3 | SSFE4 | SSWT5 | SSMI6 | SSMO7 | SSLA8 | SSMD9 |
|---|---|---|---|---|---|---|---|---|---|---|
| CF | Cu | 0,66 | 1,93 | 1,46 | 0,84 | 0,55 | 1,13 | 0,63 | 0,69 | 0,68 |
| | Pb | 0,82 | 1,17 | 1,01 | 1,23 | 0,87 | 0,82 | 0,74 | 0,66 | 1,22 |
| | Zn | 0,53 | 1,33 | 3,41 | 0,80 | 0,31 | 0,65 | 0,45 | 0,68 | 0,49 |
| | Ni | 0,32 | 1,03 | 1,88 | 0,34 | 0,22 | 0,30 | 0,31 | 0,37 | 0,40 |
| | Co | 0,68 | 1,21 | 1,60 | 0,75 | 0,48 | 0,48 | 0,80 | 1,17 | 0,64 |
| | As | 4,53 | 38,86 | 27,13 | 22,8 | 8,33 | 7,26 | 2,22 | 3,66 | 0,80 |
| | Cd | 0,81 | 4,18 | 2,75 | 1,02 | 0,40 | 0,71 | 0,40 | 0,51 | 0,30 |
| | Sb | 3,35 | 11,95 | 212,45 | 20,05 | 13,45 | 6,55 | 1,15 | 1,50 | 0,60 |
| | Cr | 0,47 | 1,64 | 0,87 | 0,45 | 0,40 | 0,40 | 0,52 | 0,52 | 0,70 |
| | Hg | 0,66 | 0,72 | 0,30 | 2,70 | 0,86 | 0,68 | 0,34 | 0,28 | 0,58 |

TABLE V: MTE CORRELATION MATRIX

| | *Cu* | *Pb* | *Zn* | *Ni* | *Co* | *As* | *Cd* | *Sb* | *Cr* | *Hg* |
|---|---|---|---|---|---|---|---|---|---|---|
| Cu | 1 | – | – | – | – | – | – | – | – | – |
| Pb | 0,593 | 1 | – | – | – | – | – | – | – | – |
| Zn | 0,629 | 0,367 | 1 | – | – | – | – | – | – | – |
| Ni | 0,724 | 0,397 | 0,979 | 1 | – | – | – | – | – | – |
| Co | 0,585 | 0,213 | 0,829 | 0,863 | 1 | – | – | – | – | – |
| As | 0,870 | 0,872 | 0,611 | 0,691 | 0,566 | 1 | – | – | – | – |
| Cd | 0,947 | 0,652 | 0,646 | 0,765 | 0,669 | 0,923 | 1 | – | – | – |
| Sb | 0,411 | 0,262 | 0,957 | 0,900 | 0,703 | 0,435 | 0,435 | 1 | – | – |
| Cr | 0,883 | 0,519 | 0,449 | 0,608 | 0,611 | 0,829 | 0,952 | 0,212 | 1 | – |
| Hg | -0,099 | 0,682 | -0,202 | -0,269 | -0,319 | 0,276 | -0,077 | -0,188 | -0,175 | 1 |

The Contamination Factor (CF) confirms the results of Igeo, through arsenic and antimony enrichments, thus indicating an absent to extremely severe contamination in all sampling points (Table IV, Fig. 6). These results corroborate with those obtained by [26] in soils of the locality, where concentrations of Cd, As and Sb are moderate to very high.

The only contamination recorded for our control sample (SSMD9) where no mining activity exists upstream is that of lead. This low contamination in lead would surely be an anomaly of the geochemical background. For mercury, only one site is contaminated (SSFE4), while the other sites have no contamination. This mercury contamination was of anthropogenic origin. Apart from sediments (SSMD9) from an unexploited area, there is high arsenic and antimony contamination at all other sampling points, indicating low to very severe arsenic contamination and low to extremely severe antimony contamination, reflecting anthropogenic contamination by these elements considered extremely toxic to benthic fauna.

Average DC (Fig. 7) far exceed maximum threshold for the fourth class defined by Hakanson (1980) indicating very high polymetallic contamination (25,87 to 252,86) for wastes of Foum (SSFO2), Mama Wassandé (SSMW3), Fel (SSFE4) and Wantia (SSWT5).

This critical value is mainly due to arsenic and antimony, whose contributions alone represent 79.4 %, 94.7 % 84.1 % and 84.2 % of contamination respectively. For Wakasso sediments (SSWAK1) and wastes from Mifeck (SSMI6) the contaminations are considerable (12,83 to 18,98) while for the other three samples (Moufeck, Lom upstream and Midal), the contamination is moderate (6,41 to 10,04).

The results of the sediment pollution indices (Fig. 8) show overall unpolluted to less polluted sediments. The highest sediment pollution index (SPI), characterized by low polluted sediment, are recorded at the level of the mining wastes of Foum (SSFO2) and Mama Wassandé (SSMW3), with values of 4.07 and 2.7 respectively. The lowest SPI, characterized by unpolluted sediment, are recorded at the level of other sediments, with the lowest value registered at the control sediment level at the Midal Water course (SSMD9). Generally, the results indicate non to low polluted mining sediments.

Pearson correlation coefficients calculated for ten elements (Cu, Pb, Zn, Ni, Co, As, Cd, Sb, Cr, and Hg) show positive correlations between them, with exception of some correlations with mercury (Hg) (Table V). Inter-element relationships in sediments provide information on sources and their mobility in geoenvironments ([28], [29]). Significantly positive correlations indicate that the elements are coming from similar sources and equally moves together [30].

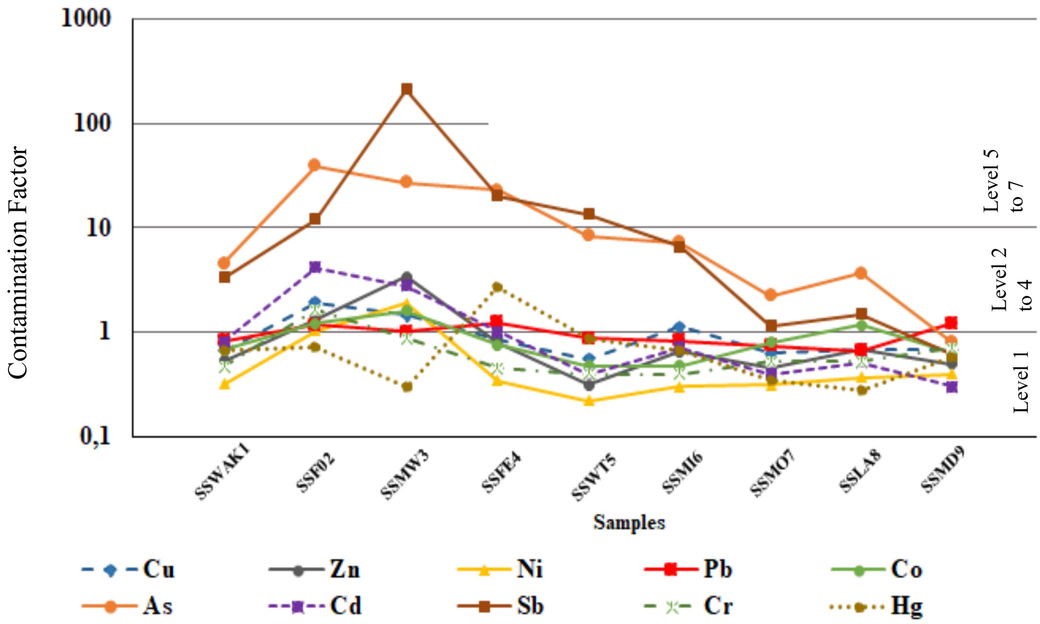


Fig. 6. Variation of contamination factors.

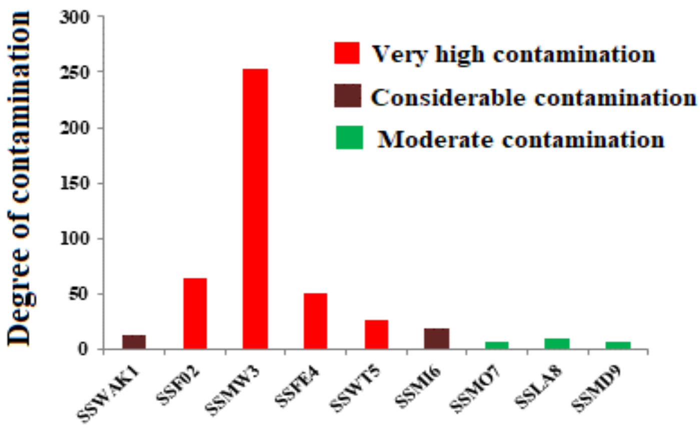


Fig. 7. Evolution of DC in samples of the study area.

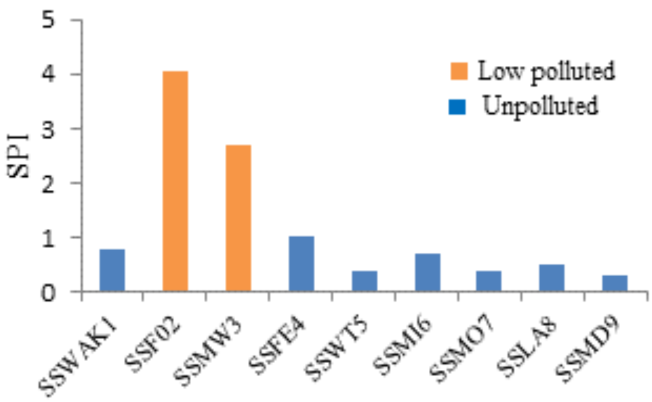


Fig. 8. Evolution of the SPI in samples of the study area.

Cu has a strong to very strong correlation with Cd, Cr, As and Ni (0.721 – 0.947). Pb has a strong correlation with As (0.872). Zn has a strong to very strong correlation with Ni, Sb and Co (0.829 – 0.979). Ni has a strong to very strong correlation with Sb, Co, Zn and Cd (0.765 – 0.979). Co has a strong correlation with Sb, Zn and Ni (0.703 – 0.863). As has a strong to very strong correlation with Cr, Cu, Pb and Cd (0.829 – 0.923). Cd has a very strong correlation with Cr. As and Sb are positively correlated. However, their degree of correlation is quite poor and is in the order of 0.435. Mercury (Hg) is negatively correlated with Cu, Zn, Ni, Co, Cd, Sb and Cr but positively correlated with Pb and As. The strong to very strong correlations recorded in this work indicates a common origin of the elements. The positive correlation between the elements may reflect similarity in their occurrences or the geochemical processes that control their behavior in soils. [26] and [27] made the same observation respectively, in the soils of Kombo Laka and the mine tailings of Zaida in Morocco.

## IV. Conclusion

The objective of this work was to make an environmental characterization of mining wastes from gold exploitation in the locality of Fel and surrounding mining sites. To achieve this objective, direct observations and systematic sampling of sediments and mine wastes were conducted to determine their degree of pollution based on certain MTE (Cu, Pb, Zn, Ni, Co, As, Cd, Sb, Cr, Hg). The results of the granulometric analyses show a heterogeneous and discontinuous texture of the sandy-gravel mine wastes. The sediments and mining wastes studied have acidic to neutral properties. The tendency to neutralize the waters of the study area may be due to the presence of alkaline minerals that buffer the waters and to the shale formations that have an important neutralizing power. For all metals in this study, the trend clearly indicates a decrease in concentration with an increase in the granulometry of sediments. The fraction of sediments with smaller size (< 80 μm) has the highest concentration while sediments of higher fraction (315 - 500 μm) have the lowest concentrations, except for cases with nugget effect of Cu and Pb encountered in samples of Fel. The Geoaccumulation Index (Igeo) shows unpolluted sediments to very strongly polluted by arsenic (As) and antimony (Sb). The Contamination Factor confirms the results of Igeo, through the enrichments in arsenic and antimony that are high, thus indicating no contamination to extremely severe contamination in sampling points subject to exploitation, a reflection of anthropogenic pollution. The Degrees of Contamination indicate moderate to very high polymetallic contamination for sediments and mining wastes. The results of Sediment Pollution Index show unpolluted to low-polluted sediments. These geoenvironmental indicators show that Foum, Mama Wassandé and Fel are the most polluted sites. Pearson correlation coefficients show positive correlations between all elements except for some correlations with mercury (Hg). The strong to very strong correlations of As and Sb with another elements recorded in this work is an indicator of a common origin of these elements.

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## Conflict of Interest

The authors declare that they have no conflict of interest.

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**Tonang Zebaze Arnaud** is a Ph.D student in water, soil and environmental resource management at the Earth Science Department in the Faculty of Science at the University of Ngaoundéré, Cameroon, 2018. Mr Tonang Zebaze Arnaud is the Regional Head of Services of Mines, Geology and Mining Cadastre at the Ministry of Mines, Industry and Technological Development.

**Njueya Kopa Adoua** is a Ph.D holder in Hydrology and water management at the Earth Science Department in the Faculty of Science at the University of Dschang, Cameroon, 2018. Dr. Njueya Kopa Adoua is a Lecturer at the Earth Science Department of the University of Dschang, Cameroon.