# Assessment of water and stream sediment pollution related to artisanal mining in Alga, Burkina Faso – West Africa

## ABSTRACT

Burkina Faso, like several other countries in the Sahelo-Sahelian strip, has seen a significant change in its mining sector in recent years through the development of the industrial and artisanal mining sub-sectors. The purpose of this study is to assess the level of pollution of water and stream sediments in the study area. A total of twenty-eight samples were taken, including three surface water samples, nine groundwater samples, ten stream sediment samples and six mine tailings samples. The analysis of the physico-chemical parameters and the metal content (cadmium, chrome, copper, mercury, nickel, lead, zinc and arsenic) of the water show that the values meet the drinking water standards in force in Burkina Faso. However, the various indices calculated, namely the geo-accumulation index (Igeo), the contamination factor (CF) and the enrichment factor (EF) show that the total metal contents of stream sediments are not dlithogenic (natural) origin but attributable to artisanal mining in the village of Alga. They highlight metal pollution with high levels of arsenic and cadmium and extremely high levels of mercury.

*Keywords: artisanal mining, pollution, water, sediment, Burkina Faso*

## 1. INTRODUCTION

The subsoil of Burkina Faso is full of significant mineral resources, making the mining sector an essential component in the economic and social development of the country.Indeed, the mining sector occupies an important place in the economy of Burkina Faso. As such, it is a major provider of jobs and generates significant resources for the benefit of public revenue. Gold is the main substance exploited and the first export product. In 2022, despite the country's very difficult security situation, this sector represented 16% of gross domestic product (GDP) and 80% of exports.

This situation is attributable to the improvement in the price of gold but also to the significant development of the mining sector in recent years through the development of the sub-sectors of industrial and artisanal mining.

The artisanal mining practiced in Burkina Faso developed from the 1980s, following the drought of 1984 and the poor agricultural production it caused [1]. It is still widespread, as it is practiced throughout the national territory and therefore constitutes a significant source of income for the populations.

Artisanal mining is therefore a means of combating food insecurity and poverty in rural areas, especially during the dry season.

However, it must be recognized that this activity also represents a threat to the environment and health.

Indeed, unlike industrial mining, artisanal mining is most often done in conditions that are not very concerned about the protection of the environment given the technology used on the sites with the use of prohibited chemicals(mercury and cyanide) and explosive substances [2].

The province of Bam, which takes its name from the largest river in the area, namely Lake Bam, was once renowned as a supplier of green beans.

This lake, which offered enormous agricultural and market gardening potential, is nowadays faced with a lot of problems such as silting, pollution by pesticides but also and above all by the chemicals used in artisanal mining, many of whichsites adjoin the watercourse, including that of Alga [2].

The Alga artisanal mining site is one of the oldest gold panning sites in Burkina Faso because this activity lasts more than thirty years continuously with several thousand people working there.

In addition to the pollution of the lake, this activity contributes greatly to the reduction of land available for agriculture and for market gardening, which reduces agricultural productivity and in particular green beans which have always made the reputation of the province.

However, these activities (agriculture and market gardening) therefore constitute a source of income and therefore contribute to the fight against poverty and rural exodus.

In addition, artisanal mining, which causes continuous degradation of the environment and loss of land, is a source of land disputes.

It is in this context that this study is located, which aims to assess the quality and level of pollution of water and stream sediments linked to artisanal mining in the area.

## 2. STUDY AREA

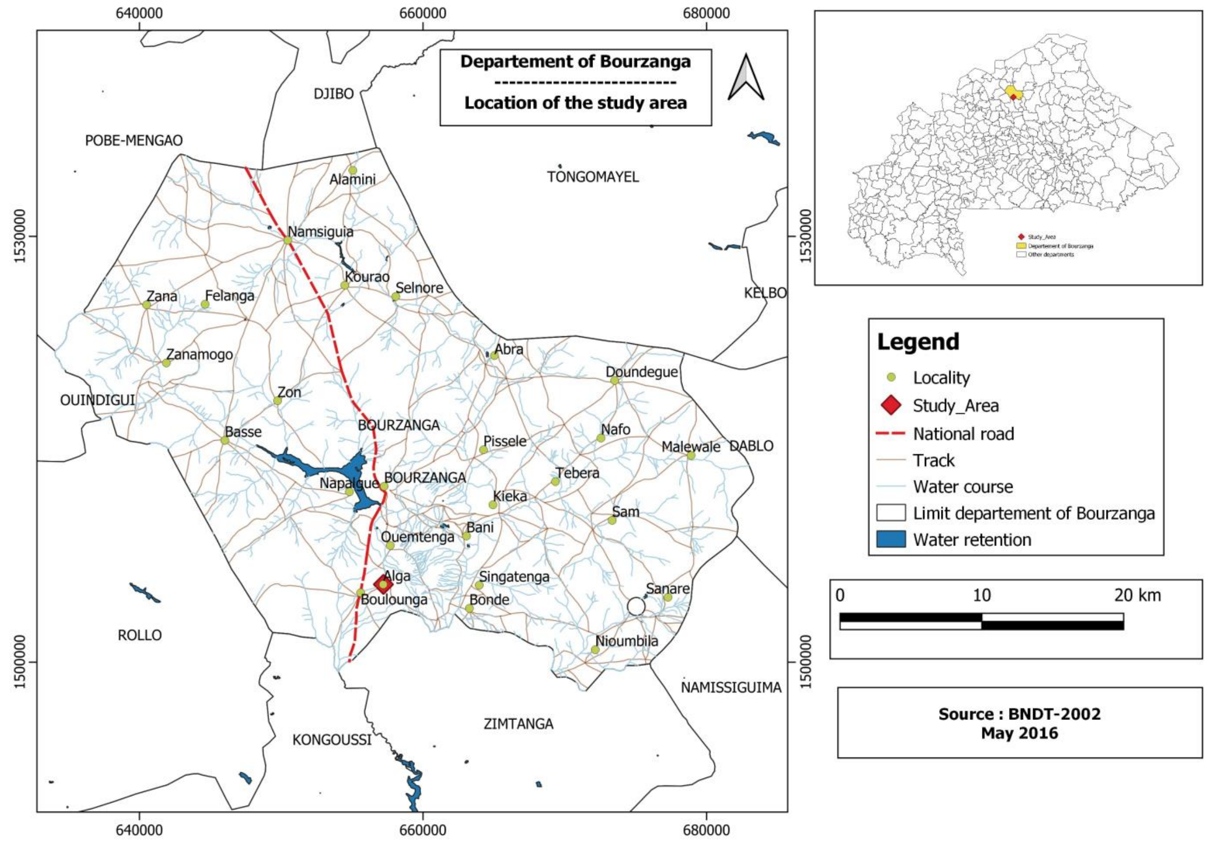
The study area, which concerns the artisanal mining site of Alga (Fig. 1), is located 146 km north of Ouagadougou (Burkina Faso), in the department of Bourzanga (Bam Province). The site is accessible in all seasons by the Ouagadougou-Kongoussi-Djibo road (over 143 km) and by a 3 km track from Boulonga to the east.

The Sudano-Sahelian tropical type climate is characterized by the alternation of two seasons: the dry season which lasts nine months (October to June) and the rainy season of three months (July to September). During the dry season, the prevailing winds are the continental trade winds or the harmattan which blow over the entire province of Bam. These are hot, dry winds very often laden with dust. During the rainy season, the monsoons replace the harmattan to give rise to precipitation. Monsoons are westerly or southwesterly winds, laden with moisture, that blow from the ocean towards the continent. Extreme temperatures range from 20°C to 43°C.

On the pedological level, there are four types of soils: ferruginous cuirass, clayey-sandy or sandy-clayey soils, gravelly soils and soils with raw minerals.

Hydrographically, the study area is located in the northern watershed of the Nakambé and is served by Lake Bam through Lake Bani and Lake Bohokou as well as the Alga dam.

There is also groundwater exploited from boreholes and wells.



Source : BNDT-2002
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**Fig.1: Location of the study area**

The Alga gold deposit is part of a series of hills of Birimian volcano-sedimentary rocks bounded by granite massifs. These hills offer outcrops that have a major schist structure with a more or less regular N-S orientation with a relatively low dip (60°E) compared to many other Birimian areas. It consists of graphitic meta-pelitic formations, affected by several phases of deformation including the setting up of doleritic veins and quartz sometimes mineralized in gold.

Regarding mineralization, the gold ore consists of quartz-carbonate-sericite-graphite-chalcopyrite-covellite-sphalerite. Native gold is quite common, in free form in quartz (10-250 μm) or included (10-40 μm) in chalcopyrite or in graphite cracks [3]. The main structure, intensely mined by artisanal miners, is a quartz vein located in the EW fracturing, approximately 350 m long and between 0.5 and 2.5 m thick with a NE dip.

## 3. MATERIAL AND METHODS

The methodology adopted consisted of water sampling (surface and underground water), sediments and mine tailings. The analyzes made it possible to highlight the physico-chemical parameters as well as the metal levels which made it possible to assess the quality of the waters, sediments and mine tailings.

## 3.1.Sampling

The type of sampling adopted is that of spot sampling. Spot sampling can be targeted or simple random. Targeted sampling corresponds to the collection of soil samples from a specific location where the information suggests contamination. This type of sampling was used for mine tailings. These were therefore samples taken at random and which were chosen to represent stored mine tailings.

Simple random sampling has been adopted for stream sediments. Samples were randomly taken from several points within the site. It consisted of taking samples from randomly selected locations on the site. From a statistical point of view, this type of sampling makes it possible to assess the average contamination of an environment [4].

For the water samples, certain physico-chemical parameters were measured in situ. These are the pH, temperature and conductivity, then the samples were conditioned in a cooler for their shipment to the analysis laboratory.

### <u>3.1.1 Surface water sampling</u>

Two types of surface (stream) water samples were collected at each site, namely, unfiltered water for major anion analysis and filtered water for cation analysis.This operation required a pre-treatment consisting in filtering the water samples. The latter are then acidified by adding 1.0 ml of super-pure concentrated $HNO_3$ the same day.

### 3.1.2 Groundwater sampling

To obtain reliable results when analyzing groundwater samples, it is important to remove standing water from the well before sampling.Sampling sites concerned wells and boreholes.Groundwater samples are treated in the same way as surface water samples (unfiltered water samples and filtered, acidified water samples).

### 3.1.3 Mine tailings sampling

Each mine tailings sample is a composite of three to five sub-samples taken from sampling sites located 10 to 20 m apart.Samples are collected from the surface or from shallow pits.Samples of mine tailings of 0.5 to 5 kg are dried and sieved.For sieving, plastic sieves fitted with nylon threads (0.15 mm) were used to avoid contamination.For chemical analyses, the fraction less than 2 mm (50 to 100 g) is homogenized in an agate ball mill for the fineness of analysis (less than 0.063 mm).

### 3.1.4 Stream sediment sampling

Each composite stream sediment sample is a sub-sample taken from five points over a distance of 250 to 500 m from the river.From each sampling site, 1 kg of material (extracted from depth 0 to 25 cm) was collected.The mixed samples (composites) were sieved in situ (wet sieving) or after the samples had dried (dry sieving).Plastic sieves fitted with nylon threads (0.15 mm) were also used to avoid contamination. The fraction less than 0.15 mm (50-100 g) was used to be homogenized in an agate ball mill for fineness analysis (less than 0.063 mm).

## 3.2. Analysis

The different analyzes were carried out using an inductively coupled plasma mass spectrometer (ICP-MS: "Inductively Coupled Plasma-Mass Spectrometry").The unfiltered water samples were analyzed for the determination of certain physico-chemical parameters:

pH, temperature, conductivity, alkalinity, mercury and cyanide content.Regarding the samples of filtered and acidified water, several cations were analyzed.For sediments and mine tailings, the analytical quantity required for stream sediment samples is 5 g versus 2.5 g for mine tailings.The particle size of the samples required concerned the fraction less than 0.15 mm.The pulverized samples were digested in a solution of concentrated hydrochloric acid (HCl) and nitric acid ($HNO_3$) (total digestion by aqua regia).

## 4. RESULTS AND DISCUSSION

A total of twenty-eight samples were collected (Fig. 2) including three surface water samples, nine groundwater samples, ten stream sediment samples and six mine tailings samples.

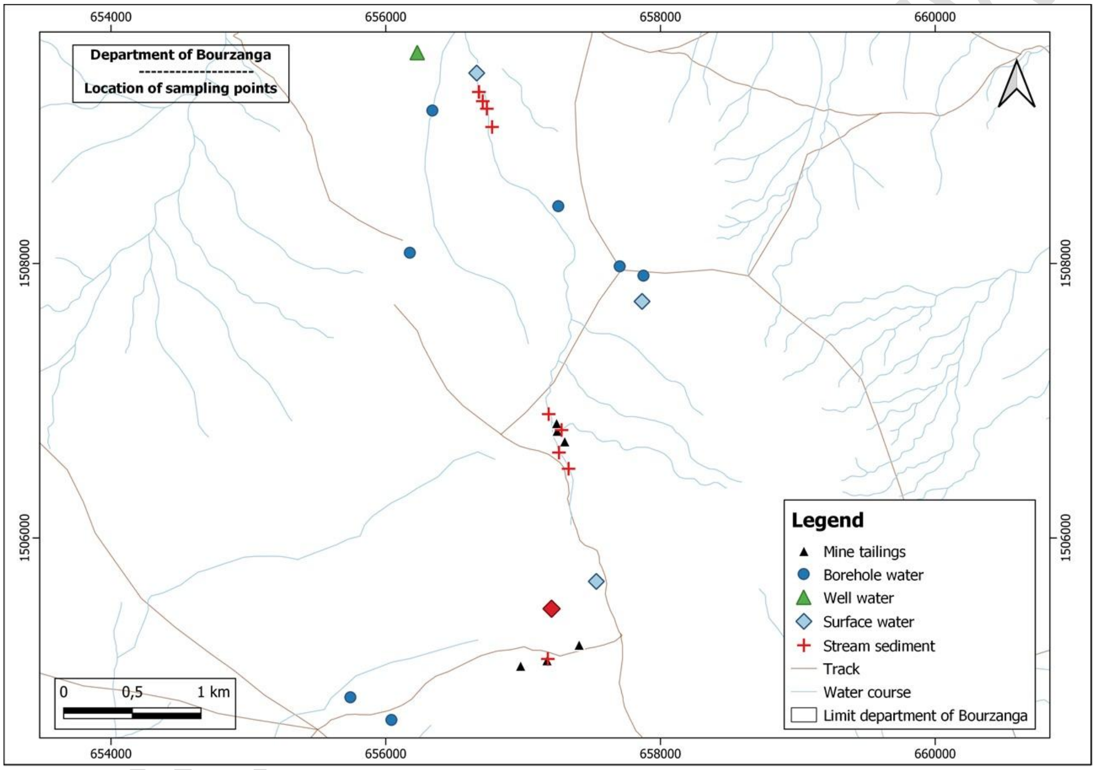

Fig. 2: Location of sampling sites

### 4.1. Physico-chemical parameters of surface water

The physico-chemical parameters of the surface water samples are recorded in the table below.Surface water temperatures reflect the sampling period in the field (month of October) and that of the day.These temperature values of the surface water samples comply with the limit values in force in Burkina Faso for wastewater or discharge of wastewater into the sewers, namely 18 to 40°C.

Regarding the pH values of surface waters, two samples (ES2 and ES3) show values below neutrality (6.28 and 6.43 respectively) unlike ES1 which is very close to neutrality (7.13).These two values do not comply with the standards in force in Burkina Faso, which recommend pH values between 6.5 and 10.5 for wastewater or those for the discharge of wastewater into the sewers. The slight acidity observed for these two samples could be explained by the low levels of alkaline elements such as carbonate which, by its presence in large quantities, would contribute to buffering the water.Indeed, the carbonate contents of these samples are 43 to 91 times lower than those of the ES1 sample (183 mg/l).The alkalinity of water being its ability to resist acid attacks, therefore also linked to its content of alkaline or basic elements.

**Table 1.Physico-chemical parameters of surface waters**

| Sample | ES1 | ES2 | ES3 |
|---|---|---|---|
| **Temperature (°C)** | 32 | 35.6 | 26.2 |
| **pH** | 7.13 | 6.28 | 6.43 |
| **Conductivity (µS/cm)** | 634 | 758 | 754 |
| **Total alkalinity (mg/l)** | 290 | 63.6 | 152 |
| **Carbonate (mg/l)** | 183 | < 0.5 | 4.21 |

The conductivity values are substantially equivalent, ranging between 634 µS/cm for ES1 to 754 µS/cm for ES3.Indeed, conductivity provides information on the quantity of ions and therefore of dissolved solids in the water.However, these conductivity values are lower than those of 1000 µS/cm in force in Burkina Faso.

## 4.2. Physico-chemical parameters of groundwater

Groundwater samples include seven samples from water boreholes (EF1, EF2, EF3, EF4, EF5, EF6 and EF7), one well sample (EP) and one standpipe sample (EbF1).The physico-chemical parameters of the groundwater samples are recorded in Table 2.

**Table 2.Physico-chemical parameters of groundwater**

| Sample | EF1 | EF2 | EF3 | EF4 | EF5 | EF6 | EF7 | EP | EbF1 |
|---|---|---|---|---|---|---|---|---|---|
| **Temperature (°C)** | 34 | 33.1 | 32.9 | 32 | 32.3 | 33.2 | 34.4 | 30.9 | 32.8 |
| **pH** | 8.32 | 8.37 | 8.20 | 8.59 | 7.92 | 8.31 | 8.34 | 8.28 | 7.86 |
| **Conductivity (µS/cm)** | 213 | 278 | 275 | 367 | 164 | 225 | 339 | 405 | 101 |
| **Total alkalinity (mg/l)** | 178 | 243 | 165 | 189 | 64.6 | 190 | 152 | 189 | 25.2 |
| **Carbonate (mg/l)** | 4.36 | 2.43 | <0.50 | 3.87 | <0.50 | 3.04 | 2.92 | 2.54 | < 0.50 |

Groundwater temperatures vary very little and comply with current standards, which range from 18 to 40°C.According to the standards governing the potability of water in Burkina Faso, the pH of water suitable for consumption must be between 6.5 and 8.5.The pH values of almost all samples meet these standards, except for EF4 (pH = 8.59).In general, the water sample from the standpipe (EbF1) presents the lowest values for the various physico-chemical parameters except temperature.However, the values of these different parameters analyzed respect the standards in force in Burkina Faso and consequently these waters respect the standards of potability.These values also show that the water from the standpipe (EbF1) is the most drinkable.

## 4.3. Metal contents

### 4.3.1 Surface water metal content

The metal contents of the surface water samples are presented in Table 3.The metal levels of almost all of the surface water samples are below the standards governing surface water quality in Burkina Faso, except for that of the ES3 sample for arsenic (0.55 ppm) which is higher.This value higher than the standard in force in Burkina Faso may result from surface water pollution but may also be explained by the nature of the source rock.Indeed, the geology of Alga is represented by metapellites and schistose and folded metasiltites whose main minerals are: quartz, sericite, hematite and sulphides.Arsenic could therefore come from sulphides which are accompanying minerals of gold and particularly arsenopyrite (FeAsS).In general, the high arsenic levels observed in the waters of the auriferous zones of Burkina Faso come from volcano-sedimentary mineralized Birimian rocks [5, 6].The very low metal contents of the samples can also be linked to pH values which are not far from neutral, which does not allow solubilization of the metals.Because, the lower the pH, the more acidic the environment, thus favoring the solubilization of metals.In addition, the presence of organic matter affects the bioavailability of metals [6, 7, 8, 9-10].It serves as a ligand and therefore reduces their concentration in the aquatic environment.In fact, the metals dissolved in the water, in particular those brought later by human activity, tend to be adsorbed on the surface of the particles in suspension, but can be put back into solution in the event of a change in the physico-chemical conditions of themiddle (Windom, 1988).

**Table 3. Surface water metal content (ppm)**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| LD | 0.0005 | 0.00005 | 0.0005 | 0.0005 | 0.0001 | 0.0002 | 0.0001 | 0.005 |
| Standards (BF) | **0.14** | **0.1** | **2** | **1** | **0.17** | **2** | **0.5** | **5** |
| ES1 | 0.003 | < 0.05 | 0.007 | 0.007 | < 0.1 | 0.003 | 0.011 | 0.244 |
| ES2 | 0.004 | < 0.05 | 0.007 | 0.007 | < 0.1 | 0.001 | 0.003 | 0.130 |
| ES3 | 0.550 | < 0.05 | < 0.5 | 0.006 | < 0.1 | 0.001 | 0.005 | 0.135 |

### 4.3.2 Groundwater metal content

The metal contents of the groundwater samples are presented in the table below.These results show that the groundwater samples analyzed fully meet the standards for metals.The water samples from the borehole (EF7) and from the standpipe (EbF1) show high values of arsenic and zinc.Among all the metals analyzed, arsenic and zinc are those whose values are higher than the standards in force for drinking water in Burkina Faso for EF7 and EbF1.These metals (arsenic and zinc) are believed to come from the host rock.They would be linked to the mineralogical composition of this host rock.Indeed, among the sulphides which accompany gold in the mineralized zones in Burkina Faso, the most frequent are pyrite ($FeS_2$ which is practically encountered in the greenstone belts in Burkina Faso), arsenopyrite (FeAsS),blende (ZnS), galena (PbS) and chalcopyrite (CuFeS) [5,6-11].In short, the groundwater would not present pollution with regard to the metals analyzed but rather an enrichment linked to the source rock in which these boreholes and wells are drilled.

**Table 4. Groundwater metal content (ppm)**

| | **As** | **Cd** | **Cr** | **Cu** | **Hg** | **Ni** | **Pb** | **Zn** |
|---|---|---|---|---|---|---|---|---|
| LD | 0.0005 | 0.00005 | 0.0005 | 0.0005 | 0.0001 | 0.0002 | 0.0001 | 0.005 |
| Standards (BF) | **0.01** | **0.001** | **0.05** | **0.02** | **0.0005** | **0.05** | **0.05** | **0.5** |
| EF1 | < LD | < LD | 0.0013 | 0.009 | < LD | 0.0006 | 0.005 | 0.076 |
| EF2 | 0.017 | < LD | 0.0005 | 0.005 | < LD | 0.0004 | 0.004 | 0.270 |
| EF3 | < LD | < LD | 0.0009 | 0.006 | < LD | 0.0008 | 0.003 | 0.190 |
| EF4 | < LD | < LD | 0.0011 | 0.006 | < LD | 0.0006 | 0.001 | 0.161 |
| EF5 | 0.036 | < LD | < LD | 0.005 | < LD | 0.0001 | 0.0007 | 0.131 |
| EF6 | 0.074 | < LD | 0.0005 | 0.006 | < LD | 0.0003 | 0.0014 | 0.150 |
| EF7 | 0.117 | < LD | 0.0019 | 0.006 | < LD | 0.0007 | 0.004 | 0.500 |
| EP | 0.008 | < LD | 0.0014 | 0.007 | < LD | 0.0005 | 0.0006 | 0.250 |
| EbF1 | 0.475 | 0.00022 | 0.009 | 0.011 | < LD | 0.0006 | 0.002 | 0.490 |

### 4.3.3Mine tailings metal content

Several observations can be made from the results of the mine tailings analysis (Table 5).

**Table 5. Mine tailings metal content (ppm)**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| LD | 0.5 | 0.1 | 1 | 0.1 | 0.01 | 0.1 | 0.1 | 1 |
| Standards (BF) | **20** | **30** | **75** | **50** | **0.8** | **50** | **100** | **200** |
| DM1 | 7.3 | < LD | 52 | 23.7 | < LD | 24.4 | 11.8 | 28 |
| DM2 | 432.2 | 0.2 | 51 | 49.7 | 1.04 | 28.7 | 49 | 130 |
| DM3 | 9.9 | < LD | 83 | 29 | < LD | 36.6 | 4.4 | 20 |
| DM4 | 309.6 | 1.7 | 304 | 253.8 | 0.26 | 101.3 | 804 | 604 |
| DM5 | >10000 | 0.9 | 15 | 251.3 | 4.08 | 60.2 | 1339.6 | 107 |
| DM6 | >10000 | 2.8 | 24 | 329.1 | 3.68 | 83.3 | 1069.8 | 364 |

The DM4, DM5 and DM6 samples present, for the majority of the metals, contents higher than the standards in force in Burkina Faso.Conversely, the trace elements of the three other samples, namely DM2 and DM3, have values below these standards, except for arsenic (432.2 ppm for DM2), chromium (83 ppm for DM3) and mercury.(1.04 ppm for DM2).All values for the DM1 sample comply with the standards in force in Burkina Faso.The high levels of these elements can also be explained by the nature of the rock on the one hand, but also by the fact that the DM4, DM5 and DM6 samples did not undergo the cyanidation step, unlike the other three.We can therefore say that during the cyanidation the content of certain elements decreases.This decrease can be attributed to the process of complexation with zinc during gold trapping.This complex is then burned to release the gold.

### 4.3.4 Stream sediment metal content

The metal contents of stream sediments are reported in Table 6.The cadmium contents of all the samples are below the detection limit (DL).The levels of arsenic (SR1, SR3, SR4, SR5 and SR10), chromium (SR2, SR5 and SR6), mercury (SR3 and SR5) and nickel (SR2) are above the acceptable thresholds in Burkina Faso.These samples are taken close to the cyanidation sites, hence the high levels.These metals can be found in the sediments by the leaching of the mining residues stored at the level of the cyanidation sites.

**Table 6. Stream sediment metal content (ppm)**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| LD | 0.5 | 0.1 | 1 | 0.1 | 0.01 | 0.1 | 0.1 | 1 |
| Standards (BF) | **20** | **30** | **75** | **50** | **0.8** | **50** | **100** | **200** |
| SR1 | 30.8 | < LD | 55 | 19 | 0.02 | 11.7 | 4.9 | 11 |
| SR2 | 12.5 | <LD | 299 | 23.8 | 0.01 | 133.6 | 3.8 | 21 |
| SR3 | 76.2 | < LD | 70 | 31.5 | 0.84 | 21.4 | 16.2 | 73 |
| SR4 | 43.9 | < LD | 50 | 23.9 | 0.05 | 25.2 | 4.6 | 35 |
| SR5 | 126.6 | < LD | 283 | 42 | 1.18 | 22.5 | 30.2 | 47 |
| SR6 | 7.5 | < LD | 103 | 18.1 | <LD | 30.8 | 4.8 | 17 |
| SR7 | 24 | < LD | 41 | 18.9 | < LD | 14.8 | 4.9 | 12 |
| SR8 | 7.5 | <LD | 57 | 11.6 | 0.02 | 12.1 | 5.6 | 15 |
| SR9 | 6.3 | < LD | 43 | 1.34 | < LD | 16.7 | 4.1 | 13 |
| SR10 | 21.4 | <LD | 70 | 15.7 | <LD | 15.2 | 5.9 | 13 |

## 4.4. Pollution level assessment

The analytical method for determining total metal content provides quantitative information.In order to assess the level of pollution and to discriminate the contribution related to anthropogenic action, i.e. artisanal mining in Alga, several parameters were calculated.These are the geo-accumulation index (Igeo), the contamination factor (CF) and the enrichment factor (EF).

### 4.4.1 Geo-accumulation index (Igeo)

The geo-accumulation index, which quantifies the state of pollution, was used to determine the level of metal pollution in mine tailings and stream sediments.The geo-accumulation index was therefore calculated in order to determine the degree of pollution linked to artisanal mining in the study area.Proposed by [12] then modified by [13], the geo-accumulation index is calculated as follows:

$$I_{geo} = \log_2 [\frac{Cm}{1.5\ XBV}]$$

*Cm* = concentration of a given element in the tested soil;

BV = concentration of the element in the Earth's crust; the background values (background value) [14,15-16].

1.5 = a constant accounting for fluctuations in the content of a given substance in theenvironment [17,18].

[13] then propose the following descriptive classes (Table 7) for numerical values of the geo-accumulation index.

**Table 7. Descriptive classes according to Igeo value**

| Igeo value | Classes | Quality |
|---|---|---|
| > 5 | 6 | **Extremely contaminated** |
| 4-5 | 5 | **Strongly to extremely contaminated** |
| 3-4 | 4 | **Strongly contaminated** |
| 2-3 | 3 | **Moderately to strongly contaminated** |
| 1-2 | 2 | **Moderately contaminated** |
| 0-1 | 1 | **Uncontaminated to moderately contaminated** |
| 0 | 0 | **Uncontaminated** |

### *4.4.1.1 Mine tailings Geo-accumulation index*

The values of the mine tailings geoaccumulation index (Table 8) make it possible to distinguish the following classes [14, 19]:

- original and unpolluted concentration for all samples for cadmium, chromium, copper, nickel and zinc;
- Unpolluted to moderately polluted with arsenic (DM2 and DM3), mercury (DM4) and lead (DM4, DM5 and DM6);
- Moderately polluted with arsenic (DM5 and DM6) and mercury (DM2, DM5 and DM6).

**Table 8. Mine tailings Geo-accumulation index**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| DM1 | -0.21 | - | -0.31 | -0.31 | - | -0.48 | -0.31 | -0.83 |
| DM2 | 1.56 | -0.18 | -0.32 | 0.02 | 2.06 | -0.41 | 0.31 | -0.17 |
| DM3 | -0.08 | - | -0.11 | -0.22 | - | -0.30 | -0.74 | -0.98 |
| DM4 | 1.42 | 0.75 | 0.46 | 0.72 | 1.46 | 0.14 | 1.53 | 0.50 |
| DM5 | 2.93 | 0.48 | -0.85 | 0.72 | 2.66 | -0.09 | 1.75 | -0.25 |
| DM6 | 2.93 | 0.97 | -0.65 | 0.84 | 2.61 | 0.05 | 1.65 | 0.28 |

By comparing the values of the geo-accumulation index with those of the metal contents, we realize that for elements such as chromium (DM3 and DM4), copper (DM4, DM5 and DM6), nickel (DM4, DM5 and DM6) and zinc (DM4 and DM6) where some samples showed contents above the threshold values accepted in Burkina Faso, the values of the geo-accumulation index show that these contents are of lithogenic origin.These contents therefore do not come from artisanal mining.On the other hand, for metals such as arsenic, mercury and lead, the values of the geo-accumulation index show that the total metal contents above the standards in force in Burkina Faso are attributable to pollution resulting from artisanal mining in the locality.In addition, the DM4 sample which shows a mercury content (0.26 ppm) lower than the standard in force in Burkina Faso (0.80 ppm) is on the other hand linked to pollution and not of lithogenic origin (natural).

### *4.4.1.2 Stream sediments Geo-accumulation index*

To assess the degree of pollution of the sediments, the geo-accumulation indices of the sediment samples were also calculated and the results are presented in the following table.

**Table 9. Stream sediments Geo-accumulation index**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| SR1 | 0.41 | - | -0.29 | -0.40 | 0.35 | -0.80 | -0.69 | -1.24 |
| SR2 | 0.02 | - | 0.45 | -0.30 | 0.05 | - | -0.80 | -0.96 |
| SR3 | 0.81 | - | -0.18 | -0.18 | 1.97 | -0.54 | -0.17 | -0.42 |
| SR4 | 0.57 | - | -0.33 | -0.30 | 0.74 | -0.46 | -0.72 | -0.74 |
| SR5 | 1.03 | - | 0.42 | -0.06 | 2.12 | -0.51 | 0.10 | -0.61 |
| SR6 | -0.20 | - | -0.01 | -0.42 | - | -0.38 | -0.70 | -1.05 |
| SR7 | 0.31 | - | -0.41 | -0.40 | - | -0.70 | -0.69 | -1.20 |
| SR8 | -0.20 | - | -0.27 | - | 0.35 | -0.78 | -0.63 | -1.10 |
| SR9 | -0.27 | - | -0.39 | -1.55 | - | -0.64 | -0.77 | -1.17 |
| SR10 | 0.26 | - | -0.18 | -0.49 | - | -0.68 | -0.61 | -1.17 |

The values of the stream sediment geo-accumulation indices show that with the exception of the SR3 samples for mercury and SR5 for arsenic and mercury, all the other samples are unpolluted.SR3 and SR5 are unpolluted to moderately polluted in arsenic.
However, SR5 is also moderately polluted with mercury.For the other samples whose arsenic, chromium and nickel contents are higher than the standards, the values of the geo-accumulation index show that they are of lithogenic origin.

### 4.4.2 Contamination Factor (CF)

The contamination factor (CF) expresses the level of contamination by each metal in the sediments [14,20].This factor is used to confirm or invalidate the pollution hypotheses detected from the geo-accumulation index. It is expressed as follows:

$$\mathbf{CF} = \frac{\mathbf{Cm}}{\mathbf{Bm}}$$

Where:
- Cm is the concentration of a given element in the tested soil.
- Bm is the concentration (at the origin or primitive value) of the element in the earth's crust [14]. According to [20], the contamination factor is subdivided into four (4) levels or classes (Table 10).

**Table 10. Different Contamination Factor classes**

| CF value | Classes | Contamination |
|---|---|---|
| CF > 6 | 4 | **Very high contamination** |
| 3 ≤ CF ≤ 6 | 3 | **High contamination** |
| 1 ≤ CF ≤ 3 | 2 | **Moderate contamination** |
| CF < 1 | 1 | **Low contamination** |

#### *4.4.2.1 Mine tailings Contamination Factor*

The values of the mine tailings contamination factors are recorded in Table 11.The values of the contamination factor make it possible to distinguish:

- samples slightly contaminated with arsenic (DM1), chromium (DM1, DM2, DM3 and DM4), copper (DM1 and DM3), nickel (DM1, DM2 and DM3), lead (DM1 and DM3) and zinc(DM1, DM3 and DM5);
- samples moderately contaminated with arsenic (DM3), cadmium (DM2), chromium (DM3), copper (DM2), nickel (DM4, DM5 and DM6) and zinc (DM2 and DM6);
- samples whose contamination is high in cadmium (DM5), lead (DM2), chromium and zinc (DM4);
- samples with very high contamination in arsenic (DM2, DM4, DM5 and DM6), cadmium (DM4 and DM6), copper (DM4, DM5 and DM6), mercury (DM2, DM4, DM5 and DM6) andin lead (DM4, DM5 and DM6).

These values confirm those of the geo-accumulation index and also show that the level of contamination is high (high to very high) for elements such as arsenic, cadmium, chromium, mercury, lead andzinc, with the exception of nickel where the samples are in the low contamination (DM1, DM2, and DM3) and moderate contamination (DM4, DM5 and DM6) classes.

**Table 11. Mine tailings Contamination Factor**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| DM1 | 0.92 | - | 0.73 | 0.74 | - | 0.50 | 0.74 | 0.22 |
| DM2 | 54.71 | 1.00 | 0.72 | 1.55 | 173.33 | 0.59 | 3.06 | 1.02 |
| DM3 | 1.25 | - | 1.17 | 0.91 | - | 0.75 | 0.28 | 0.16 |
| DM4 | 39.19 | 8.50 | 4.28 | 7.93 | 43.33 | 2.07 | 50.25 | 4.76 |
| DM5 | 1265.82 | 4.50 | 0.21 | 7.85 | 680.00 | 1.23 | 83.73 | 0.84 |
| DM6 | 1265.82 | 14.00 | 0.34 | 10.28 | 613.33 | 1.70 | 66.86 | 2.87 |

### *4.4.2.2 Stream sediment Contamination Factor*

Concerning the stream sediment samples, the values of the contamination factor show that all the samples are weakly contaminated with nickel and zinc.

With regard to copper, apart from the SR5 sample which is moderately contaminated, the rest of the samples are slightly contaminated.For lead, all the samples are weakly contaminated except SR3 and SR5 which are moderately contaminated.Compared to chromium, apart from SR6 which is weakly contaminated, SR2 and SR5 which show high contamination, the other samples are weakly contaminated.High to very high contamination is mainly observed at the level of arsenic and mercury.

**Table 12. Stream sediment Contamination Factor**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| SR1 | 3.90 | - | 0.77 | 0.59 | 3.33 | 0.24 | 0.31 | 0.09 |
| SR2 | 1.58 | - | 4.21 | 0.74 | 1.67 | - | 0.24 | 0.17 |
| SR3 | 9.65 | - | 0.99 | 0.98 | 140.00 | 0.44 | 1.01 | 0.57 |
| SR4 | 5.56 | - | 0.70 | 0.75 | 8.33 | 0.51 | 0.29 | 0.28 |
| SR5 | 16.03 | - | 3.99 | 1.31 | 196.67 | 0.46 | 1.89 | 0.37 |
| SR6 | 0.95 | - | 1.45 | 0.57 | - | 0.63 | 0.30 | 0.13 |
| SR7 | 3.04 | - | 0.58 | 0.59 | - | 0.30 | 0.31 | 0.09 |
| SR8 | 0.95 | - | 0.80 | - | 3.33 | 0.25 | 0.35 | 0.12 |
| SR9 | 0.80 | - | 0.61 | 0.04 | - | 0.34 | 0.26 | 0.10 |
| SR10 | 2.71 | - | 0.99 | 0.49 | - | 0.31 | 0.37 | 0.10 |

### 4.4.3 Enrichment Factor (EF)

Proposed by [21], then [22], the enrichment factor (EF) was used just like the geo-accumulation index (Igeo) and the contamination factor (CF) to estimatethe level of metal pollution.The main purpose of the enrichment factor is to distribute the degree of contamination and to understand the distribution of anthropogenic elements in the sediments.The enrichment factor is obtained using the following formula [22]:

$$EF = \frac{\mathbf{Cm/CFe}}{\mathbf{Bm/BFe}}$$

Where:
- Cm is the content of the metal in the sediments
- CFe is the iron content in the sediments
- Bm is the average content of the metal in the earth's crust
- BFe is the average content of iron in the earth's crust.

Iron (Fe) being one of the major elements of the acid mine drainage phenomenon, it was chosen as a normalizing element for the determination of EF values.Moreover, iron is one of the widely used reference elements for calculating the distribution of elements of anthropogenic origin [23].

The different values of the EF were divided into five (5) groups corresponding to the categories of contamination [24, 25] and presented in the following table.

**Table 13. Enrichment level according to EF value**

| EF value | Enrichment level |
|---|---|
| 40 ≥ EF | **Extremely enriched** |
| 20 ≤ EF < 40 | **Very highly enriched** |
| 5 ≤ EF < 20 | **Considerable enrichment** |
| 2 ≤ EF < 5 | **Moderate enrichment** |
| EF < 2 | **Low enrichment** |

#### *4.4.3.1 Mine tailings Enrichment Factor*

For the mine tailings, the values of the enrichment factor (Table 14) show that all the samples are slightly enriched in chromium, copper, nickel, lead and zinc.For arsenic, the samples are in the "low enrichment" (DM1 and DM3), "considerable enrichment" (DM4) and "extremely enriched" (DM2, DM5 and DM6) levels.Similar classes are also observed at the level of cadmium with "moderate enrichment" (DM5), "considerable enrichment" (DM6), "very highly enriched" (DM2) and "extremely enriched" (DM3 and DM4).All mine tailings samples are extremely enriched in mercury with extremely high values.These enrichments of mine tailings are attributable to artisanal mining, especially for mercury, which is prohibited but used for amalgamation.

**Table 14. Mine tailings Enrichment Factor**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| DM1 | 1.44 | 45.02 | 0.13 | 0.28 | - | 0.12 | 0.38 | 0.02 |
| DM2 | 57.02 | 29.57 | 0.08 | 0.40 | 237869.52 | 0.10 | 0.30 | 0.07 |
| DM3 | 1.69 | 62.27 | 0.18 | 0.30 | - | 0.16 | 0.50 | 0.01 |
| DM4 | 13.83 | 59.67 | 0.17 | 0.69 | 20130.26 | 0.12 | 0.36 | 0.10 |
| DM5 | 622.54 | 4.10 | 0.01 | 0.95 | 440331.89 | 0.10 | 0.30 | 0.03 |
| DM6 | 524.36 | 5.53 | 0.02 | 1.05 | 334528.51 | 0.11 | 0.35 | 0.07 |

#### ***4.4.3.2 Stream sediments Enrichment Factor***

Almost similar observations can be made with the values of stream sediment enrichment factors (Table 15).These values show that all the samples, as in the case of the mine tailings, are weakly enriched in chromium, copper, nickel, lead and zinc.Two classes of enrichment can be distinguished at the level of arsenic with samples slightly enriched (SR2, SR6, SR8 and SR9) and considerably enriched (SR1, SR3, SR4, SR5, SR7 and SR10).Two classes are also observed at the level of cadmium for which all the samples are extremely enriched except for SR4 which is very highly enriched.All stream sediment samples are extremely enriched in mercury with extremely high values.Despite the generally low contents of the various metals and arsenic in the sediments which comply with the standards in force in Burkina Faso, the values of the enrichment factor show that they are not of lithogenic origin but linked to theanthropogenic action (artisanal mining).The case of mercury clearly shows that sediments are problematic.These potentially harmful elements can therefore be transferred from sediments to water [26, 27].They will therefore represent a major risk to human health due to possible indirect poisoning from the consumption of contaminated fish [10] or agricultural and market garden products.

**Table 15. Stream sediments Enrichment Factor**

| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| SR1 | 7.44 | 58.42 | 0.16 | 0.28 | 8380.02 | 0.07 | 0.23 | 0.01 |
| SR2 | 1.98 | 208.24 | 0.59 | 0.23 | 2747.17 | - | - | 0.01 |
| SR3 | 10.54 | 42.54 | 0.12 | 0.27 | 201362.18 | 0.08 | 0.24 | 0.04 |
| SR4 | 7.17 | 35.91 | 0.10 | 0.24 | 14165.09 | 0.11 | 0.33 | 0.02 |
| SR5 | 5.65 | 55.51 | 0.16 | 0.11 | 91289.54 | 0.03 | 0.08 | 0.01 |
| SR6 | 1.69 | 102.12 | 0.29 | 0.25 | - | 0.18 | 0.55 | 0.01 |
| SR7 | 6.36 | 47.77 | 0.13 | 0.31 | - | 0.10 | 0.31 | 0.01 |
| SR8 | 1.48 | 49.35 | 0.14 | - | 6830.29 | 0.06 | 0.19 | 0.01 |
| SR9 | 1.36 | 40.72 | 0.11 | 0.02 | - | 0.09 | 0.29 | 0.01 |
| SR10 | 5.07 | 72.83 | 0.21 | 0.23 | - | 0.09 | 0.29 | 0.01 |

## 5. CONCLUSION

This study carried out on the Alga gold site made it possible to assess the level of pollution of water and stream sediments and, in general, that of the environment.

Sampling of water, mining residues from artisanal miners and sediment has shown that while the quality of the water remains acceptable, the same cannot be said for that of the sediment.Sampling of water, mine tailings from artisanal miners and sediment has shown that while the quality of the water remains acceptable, the same cannot be said for that of the sediment.

The various indices calculated (Igeo, CF, EF) show that the sediments record very problematic arsenic, cadmium and especially mercury pollution.The various results indicate that even the generally low levels and lower than the standards in force in Burkina Faso for certain metals are attributable to anthropogenic action and therefore to artisanal mining in the Alga area.

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