High arsenic enrichment in water and soils from Sambayourou watershed – Burkina Faso (West Africa)

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Abstract: Sambayourou is one of the main tributary of Mouhoun River in southwest Burkina Faso. Its watershed is part of area affected by mining operations from Poura gold mine in 80s. Investigations on surface water, ground-water and soil from Sambayourou watershed reveal that enormous volume of mine wastes from Poura old gold mine is causing acid mine drainage (AMD). This latter is characterized by a red-brick color, a low pH (2.9) and high contents of arsenic and heavy metals: arsenic (753 ppm), iron (4948 ppm), zinc (51 ppm), copper (38 ppm), cobalt (7 ppm) and lead (4 ppm). The oxidation and acidification of the mine wastes have also resulted in the pollution of some groundwater with concentrations of arsenic and lead beyond acceptable standards. Arsenic is the most polluting element of surface water and ground-water. Concerning ground-water contamination, arsenic come from both mine wastes and host rocks. To assess soil contamination, geo-accumulation indexes (Igeo) and enrichment factor (EF) are used. The use of the index of geo-accumulation is based on seven descriptive classes for increasing geo-accumulation index values. The different values of enrichment factor are divided into five groups corresponding to five categories of contamination. According to geo-accumulation values, the soil in Sambayourou watershed is strongly contaminated by arsenic. This situation is confirmed by enrichment factor which indicates a very high enrichment in arsenic. The very high enrichment in arsenic can derive from erosion of host rocks of ores mineralization which contain sulfide minerals as arsenopyrite (FeAsS) and/or from pedogenesis processes. However, mine wastes are assumed to be the main sources of arsenic contamination of soil in Sambayourou watershed.

Keywords: Arsenic Enrichment, Acid Mine Drainage, Heavy Metals, Environment, Burkina Faso

1. Introduction

Sambayourou, "Petit Balé" and "Grand Balé" are tributaries of Mouhoun which is the main river in southwestern Burkina Faso. Some of these tributaries as Sambayourou drains the site of the old gold mine at Poura. This gold mine was the first industrial mine in Burkina Faso which began operating in the 80s and ended in 1999. Fifteen (15) years after its closure, millions of tons of mine waste (tailings, waste rock) are always stored and exposed to water and weathering. What might generate impacts on the receiving environment and can also cause potential health risks of riparian communities. Apart from gold panning the majority of the population depends on agriculture and livestock breeding. Therefore, contamination of soil and water (ground and surface) can lead

to health problems for both animals and humans through the food chain. In fact, the storage of these wastes has a direct effect on local ecosystems due to the loss of plant and animal communities living in the area in question [1]. In addition, discharges from mineral deposits that contain sulfide minerals have a high potential to generate acid mine drainage which is one of the most important problems for local and regional ecosystems. Acid generation promotes the mobilization of contaminants such as heavy metals and other potentially harmful elements. Heavy metals are a group of highly toxic contaminants to humans, animals and aquatic life [2, 3]. Arsenopyrite (FeAsS) is a sulfo-iron arsenide commonly found in sulfide mineralization especially those operated for gold. With the phenomenon of acid mine drainage (AMD), arsenic in arsenopyrite and other minerals is dissolved. The dissolved arsenic can be absorbed by plants or accumulated in

sediments. Arsenate, As (V) inhibits the synthesis of Adenosine triphosphate (ATP). Its similarity with the phosphate allows it to penetrate the metabolic pathways. Arsenite, As (III) in acid waters is more toxic to aquatic organisms. It reacts with thiol groups present on the actives sites of enzymes and proteins. Some organic arsenic compounds are fat soluble and therefore bio-accumulative. Another major impact of the AMD is the questioning of the use of water downstream of mining sites, such as drinking water, recreational bases, irrigation, fisheries and industrial water use as well as corrosion of mining infrastructure and equipment.
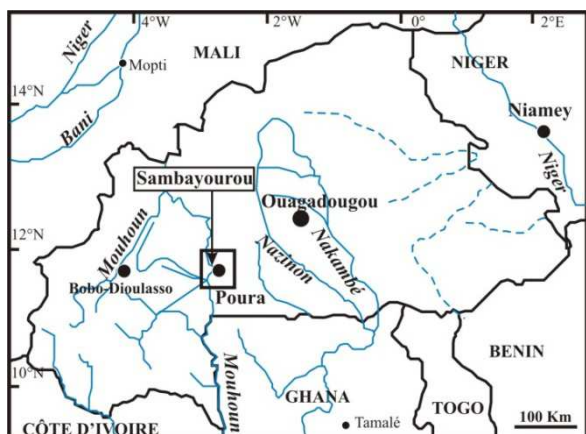

Figure 1. Location of the study area.

The aim of this study is to assess the impact of mine waste on the watershed of Sambayourou (Fig. 1): pollution of surface water, groundwater (wells and hand-pumped boreholes) and of soils then to identify contaminated areas as well as the elements (such as arsenic) responsible for the pollution.

2. Methodology

The methodology consisted in sampling of surface water, groundwater from hand-pumped boreholes, and soil in the watershed of Sambayourou. Each sample of water was directly filtered (with 0.45 μm membrane pore diameter) into pre-acid-washed polyethylene bottles and acidified with ultra-pure HNO_3 (pH < 2) for subsequent analyses of their major cations and trace element concentrations. The sampling was carried out under ultra-trace element conditions [4]. Thus, plastic glove were worn throughout the sampling, and contact with metallic tools was minimized. Samples were subsequently stored in double-zip lock bags.

Soil samples were collected. Each sample is a composite of three sub-samples collected from sampling sites located at the distance of 10-20 m from each other. About 3 kg of each sample was air-dried and sieved through a 2 mm stainless steel sieve, and homogenized. The fine fractions (< 2mm) were used for analysis.

Analyzes were performed in the laboratory "AcmeLabs" in Johannesburg" (South Africa).

3. Results and Discussions

3.1. Sampling

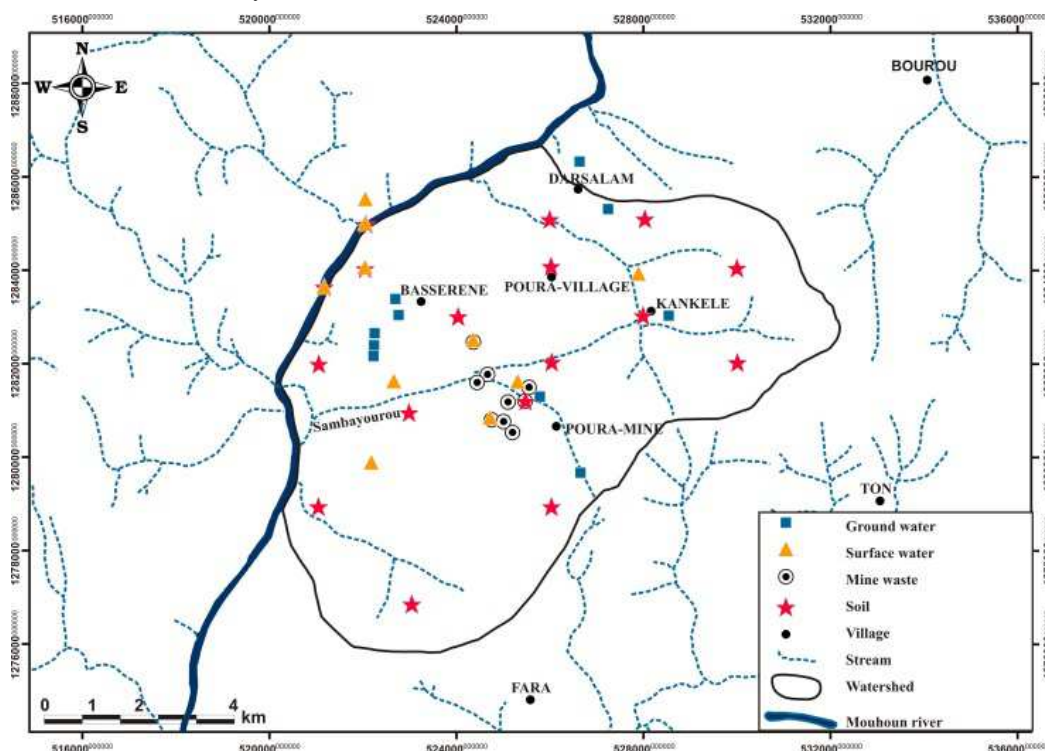The different sampling sites through the watershed are reported in Figure 2.

Figure 2. Location of sampling sites.
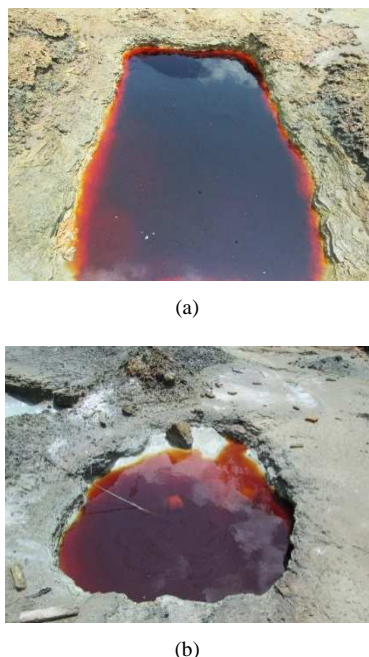
3.2. Surface Water

(a)

(b)

Figure 3. *Surface water resulting from oxidation of mine wastes.*

The surface water in some areas is characterized by a red-brick color (Fig. 3), a pH of 2.9 and a large amount of dissolved metals. Distribution of various elements in surface water is: iron (0.062-4948 ppm), arsenic (0.001-753 ppm), zinc (0.018-51 ppm), and lead (0.001-4 ppm). Sample SW13 has the highest levels for the different elements (Table 1). Indeed the acidification of the environment has the effect of promoting the solubilization of these elements and particularly of metals. This is the case of iron (4948 ppm), arsenic (753 ppm), zinc (51 ppm), copper (38 ppm), cobalt (7 ppm) and lead (4 ppm).

These results indicate oxidation and acidification levels which vary considerably from one place to another. Acid mine drainage is generally characterized by a pH value of about 4.5. Acidification of the medium leads to the solubilization of these elements in the surface water and therefore in the environment.

Regarding the mineralogical composition, the mine wastes resulting from the mineralization of host rocks comprise pyrite (FeS), chalcopyrite (CuFeS), arsenopyrite (FeAsS). As a result, when the pH is sufficiently low (pH <4), ferric iron remains in solution, and thus playing the role of a highly reactive oxidant (the so-called indirect reaction). The indirect oxidation of pyrite produces more protons, and thus exacerbates acidification of the receiving environment [5-7].

This acid mine drainage and dissolved metals within the watershed can contaminate agricultural soils and water table but also convey in the Mouhoun River. The Mouhoun is the largest river in the region, which results in a vulnerability of aquatic living beings, animals and people.

3.3. Ground-Water

Ground-water is characterized (Table 2) by a pH close to neutrality (6.62-7.29) compared to the surface water. Analysis of results from Table 2 which summarizes the various physic-chemical parameters shows low pH (pH = 5.6) for the sample GW9. This is due to the geographical location of the sample GW9. Indeed it is at a close distance of the old mine and mine waste. It is therefore under the influence of surface water that is to say those phenomena from runoff and seepage from the mine. This pH also certify that beyond acidification and contamination of surface water, leachate from the different processes acid mine drainage may extend to deeper waters and have significant environmental consequences. The concentrations of various elements are below acceptable standards except for lead and arsenic. High levels of arsenic and lead are found in the drinking water. They exceed the standards accepted by the Burkina Faso (quality guidelines for drinking water, 2005) through the recommendations of the World Health Organization (WHO). This concerns the GW8 and GW10 samples for arsenic and GW1 for lead (Fig. 4). These elements have adverse effects to humans [8, 9]. Indeed, exposure to low levels of arsenic in the water may cause the risk of cancer of the skin while that a daily absorption of 3 to 6 mg or a dose of 70 to 180 mg is a deadly poison. Regarding lead, chronic exposure may cause toxic effects on the central and peripheral nervous systems, reproductive disorders, kidney failure and encephalopathy. Arsenic and lead found in the groundwater may come in part from the migration of these elements after solubilization following oxidation of arsenopyrite (FeAsS) and galena (PbS) from mine wastes and to lower pH but also from the host rock of groundwater which have the same mineralogical composition.
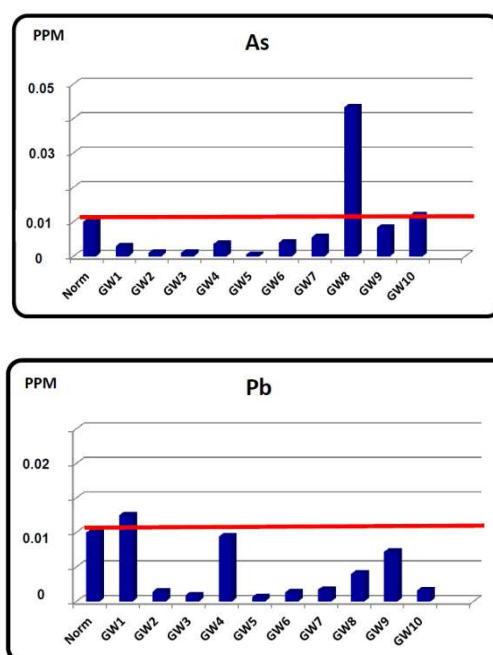

Figure 4. *Levels of lead and arsenic above the accepted standards from Burkina Faso (after WHO) in certain drinking water.*

Although the oxidation of wastes and water contamination (surface and groundwater) are not yet widespread throughout the watershed, the effects are already significant and problematic.

Table 1. Physical parameters and levels of some potentially harmful elements in surface water samples.

Element	pH	As	Cd	Co	Cr	Cu	Fe	Hg	Ni	Pb	Zn
Unit		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
*LD		0.0005	0.00005	0.00002	0.0005	0.0001	0.01	0.0001	0.0002	0.0001	0.0005
SW1	6.88	0.003	<LD	0.017	0.001	0.007	0.518	<LD	0.003	0.002	0.245
SW2	6.94	0.004	<LD	0.017	0.001	0.007	0.104	<LD	0.002	0.003	0.130
SW3	8.59	0.056	<LD	0.012	<LD	0.006	0.062	<LD	0.002	0.006	0.136
SW4	6.74	<LD	<LD	0.014	0.001	0.010	0.373	<LD	0.044	0.005	0.076
SW5	6.41	0.002	<LD	0.014	0.001	0.006	0.521	<LD	0.004	0.004	0.270
SW6	6.81	< LD	<LD	0.012	0.001	0.006	0.354	<LD	0.021	0.004	0.190
SW7	6.68	< LD	<LD	0.015	0.001	0.006	0.389	<LD	0.002	0.001	0.162
SW8	6.49	0.004	<LD	0.016	<LD	0.005	0.098	<LD	0.002	0.001	0.131
SW9	7.34	0.007	<LD	0.012	0.001	0.006	0.091	<LD	0.002	0.001	0.151
SW10	5.15	0.111	<LD	0.015	0.002	0.006	0.256	<LD	0.006	0.004	0.501
SW11	5.87	0.001	<LD	0.014	0.001	0.008	0.413	<LD	0.007	0.001	0.250
SW12	5.30	0.048	0.0002	0.016	0.009	0.011	9.314	<LD	0.010	0.012	0.490
SW13	2.90	753.710	0.700	7.429	1.329	38.924	4948.079	<LD	13.982	4.000	51.413
SW14	6.93	0.001	<LD	<LD	0.004	0.003	1.418	<LD	0.006	0.001	0.018

*LD : Limit of detection

Table 2. Physical parameters and levels of some potentially harmful elements in ground water samples.

Element	pH	As	Cd	Co	Cr	Cu	Fe	Hg	Ni	Pb	Zn
Unit		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
*LD		0.0005	0.00005	0.00002	0.0005	0.0001	0.01	0.0001	0.0002	0.0001	0.0005
GW1	6.81	0.003	<LD	0.012	<LD	0.005	0.052	<LD	0.002	0.013	0.222
GW2	6.84	0.001	<LD	0.012	<LD	0.005	0.074	<LD	0.001	0.001	0.185
GW3	6.62	0.001	<LD	0.013	<LD	0.006	0.069	<LD	0.001	0.001	0.183
GW4	6.80	0.004	<LD	0.013	<LD	0.005	0.031	<LD	<LD	0.009	0.183
GW5	6.78	< LD	<LD	0.012	<LD	0.005	0.022	<LD	0.002	0.001	0.127
GW6	6.90	0.004	<LD	0.012	<LD	0.004	0.016	<LD	<LD	0.001	0.681
GW7	6.92	0.006	<LD	0.013	<LD	0.006	<LD	<LD	<LD	0.002	0.149
GW8	6.90	0.043	0.001	0.011	0.001	0.004	0.027	<LD	<LD	0.004	0.506
GW9	5.60	0.008	<LD	0.013	0.001	0.005	0.116	<LD	0.002	0.007	0.205
GW10	7.29	0.012	<LD	0.016	0.001	0.006	0.086	<LD	<LD	0.002	0.276

3.4. Heavy Metals Contamination Levels in Soil

To assess the level of soil contamination, the index of geo-accumulation (I_{geo}) of various elements is estimated [10, 11].

$$I_{geo} = \log_2 \left[\frac{Cm}{1.5 \times BV} \right]$$

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) [12, 13].

1.5 = a constant accounting for fluctuations in the content of a given substance in the environment. The use of the index of geo-accumulation is based on seven descriptive classes for increasing Igeo values (Table 3).

The enrichment factor allows distribution of the degree of contamination and to understand the distribution of anthropogenic elements in the elements [14].

$$EF = \frac{\left(C_m / C_{Fe} \right)}{\left(B_m / B_{Fe} \right)}$$

Where C_m is the metal content in the sediment; C_{Fe} is the content of iron in the sediments; B_m is the average grade of the metal in the earth's crust; B_{Fe} is the average content of iron in the Earth's crust.

Table 3. Igeo classes with respect to soil quality.

| I_{geo} Value	I_{geo} Class	Designation of soil 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

Table 4. Enrichment categories based on EF values.

EF Value	Enrichment levels
EF <2	Low enrichment
2≤ EF <5	Moderate enrichment
5≤ EF <20	Considerable enrichment
20 ≤ EF <40	Highly enriched
EF ≥ 40	Very highly enriched

Iron (Fe) is a major component of the phenomenon of acid

mine drainage, it is chosen as the normalizing factor for the determination of EF values. Iron is an element widely used reference for the calculation of the distribution of anthropogenic elements [15]. The different values of EF are divided into five (5) groups corresponding to five (5) categories of contamination [14] as indicated in table 4.

***Table 5.** Igeo and EF values of some elements in soil*

Element	Arsenic		Chromium		Cobalt		Copper		Lead		Nickel		Zinc	
Value	Igeo	EF	Igeo	EF	Igeo	EF	Igeo	EF	Igeo	EF	Igeo	EF	Igeo	EF
S1	-0.24	1.17	0.84	0.93	1.04	1.39	1.20	0.85	0.90	0.95	0.51	0.58	-0.03	0.48
S2	2.17	201.60	0.83	0.61	1.38	2.04	1.52	1.20	1.51	2.65	0.58	0.46	0.64	1.48
S3	0.64	7.70	1.04	1.29	1.03	1.19	1.29	0.90	0.47	0.31	0.69	0.75	-0.18	0.29
S4	0.51	4.96	1.27	1.92	1.24	1.66	1.26	0.74	0.57	0.34	1.00	1.34	0.05	0.44
S5	-0.65	0.96	0.52	0.96	0.51	0.87	0.70	0.58	0.66	1.17	-0.06	0.33	-0.63	0.25
S6	0.20	4.23	0.95	1.58	1.05	1.87	1.07	0.83	0.49	0.49	0.69	1.15	-0.27	0.36
S7	0.97	22.92	0.87	1.21	1.08	1.87	1.10	0.84	0.51	0.49	0.19	0.34	-0.44	0.23
S8	0.71	8.31	1.60	4.32	1.17	1.51	1.20	0.69	0.40	0.25	1.25	2.55	-0.15	0.29
S9	1.46	40.47	0.97	0.88	1.21	1.47	1.32	0.79	1.03	0.92	0.46	0.36	0.39	0.87
S10	1.18	25.25	0.82	0.74	1.13	1,43	1.20	0.71	0.49	0.31	0.53	0.50	0.07	0.49
S11	1.67	21.48	1.58	1.15	1.31	0.59	1.45	0.34	1.30	0.55	0.48	0.12	0.19	0.18
S12	0.30	4.63	1.14	2.12	1.04	1.62	1.08	0.74	0.51	0.44	0.61	0.84	-0.25	0.33
S13	0.93	22.96	0.74	0.99	1.09	2.12	1.10	0.91	0.51	0.53	0.30	0.47	-0.40	0.27
S14	0.36	4.67	0.88	1.02	0.97	1.20	0.89	0.42	0.57	0.45	0.21	0.29	-0.30	0.26
S15	0.30	4.42	0,76	0.84	0.91	1.14	0.98	0.56	0.44	0.36	0.35	0.43	-0.36	0.24

(a)

(b)
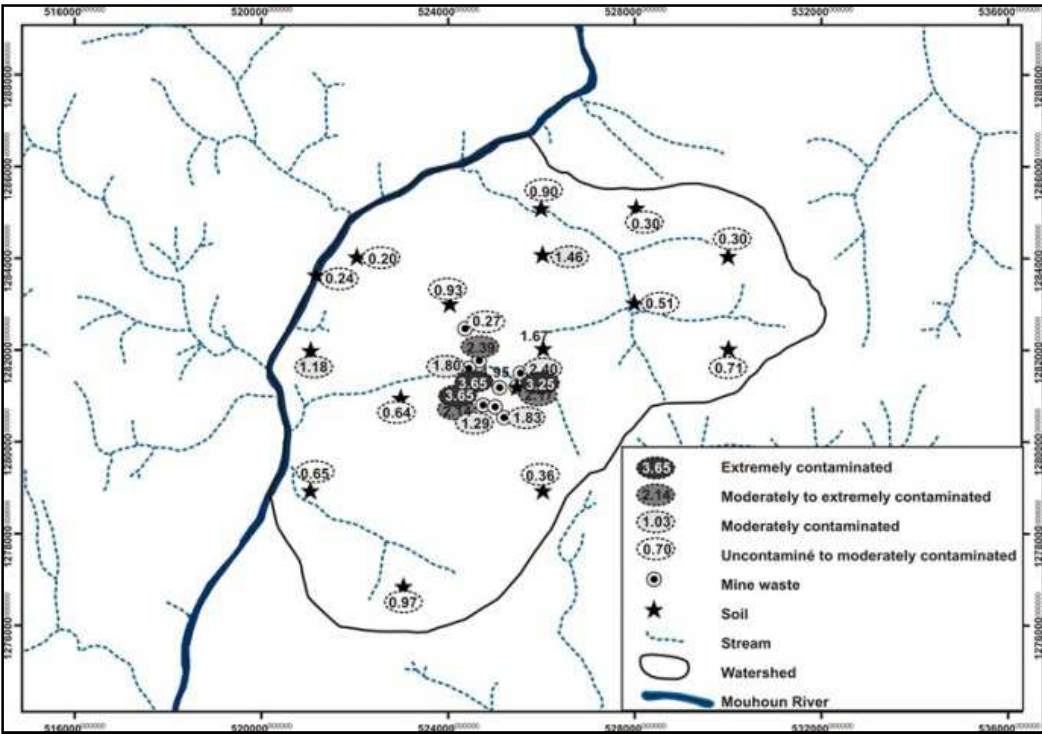
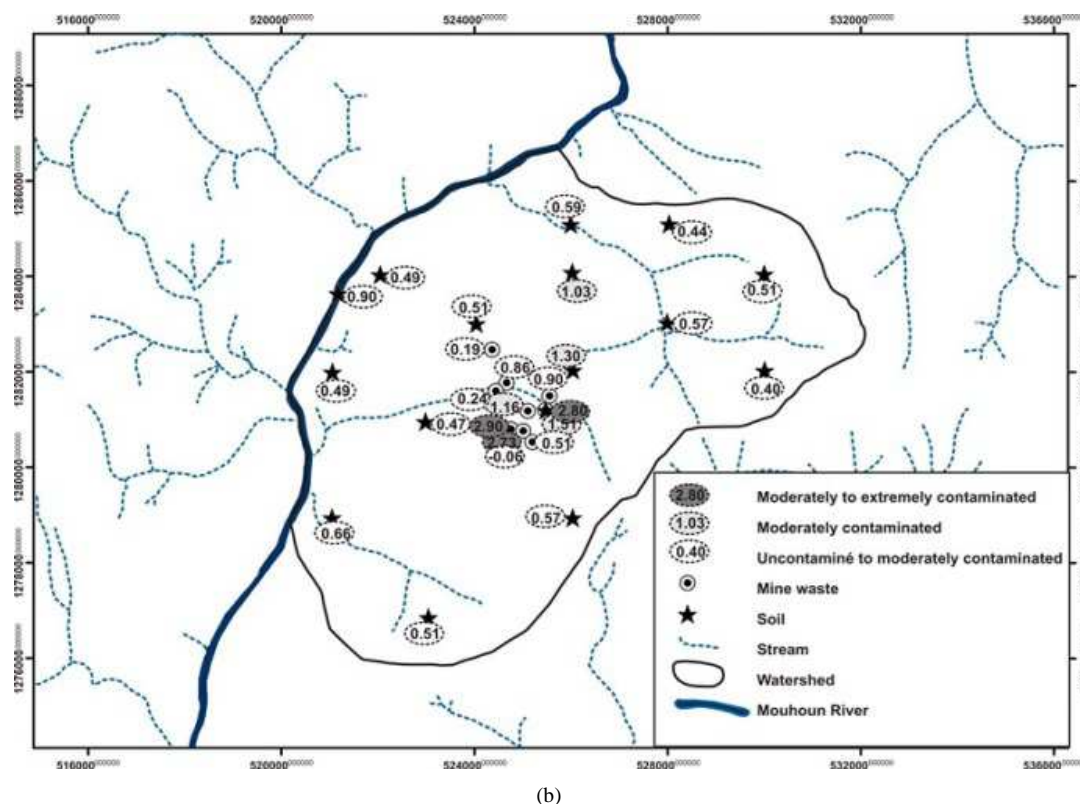*Figure 5. Distribution of geo-accumulation indexes (Igeo) values of arsenic (a) and lead (b).*

According to Igeo values, soil inside the watershed is uncontaminated to moderately contaminated by all the elements reported in Table 5 (i.e. arsenic, chromium, cobalt, copper, lead, nickel, zinc); moderately contaminated by arsenic, chromium, cobalt, copper lead and to a lesser extent by nickel; moderately to strongly contaminated by only arsenic. These results show that contamination levels vary from one element to another and from one point to another within the watershed (Fig. 5). This situation can be attributed to the fact that the mine wastes have not undergone the same degree of oxidation in the watershed.

Concerning the enrichment factor, as out showed the index of geo-accumulation, the soil is considerably to very highly enriched in arsenic. However, it is low enriched in arsenic, chromium, cobalt, copper, lead, nickel and zinc on one hand, and moderately in arsenic, chromium, cobalt and lead in the other hand.

Contamination depends largely on the availability of elements. Arsenic, chromium, cobalt and lead are the most available elements; nevertheless arsenic appears to be the most polluting element which is known carcinogen. EF shows that their contents in soil are due to a supply. Several authors have reported arsenic contamination of soils and sediments related to mining operations (e.g. [15 - 17]. Reference [18] show that strong arsenic enrichments in sediments from Elqui watershed in Chile is not only industrial derived (mining operations), but also a major geological process, related to long-lived erosion of the As-rich epithermal ores and alteration zones.

Arsenic enrichment in Sambayourou watershed can be attributed to the mine wastes from Poura old gold mine. Ore zones and mainly those bearing sulfide minerals are often enriched in arsenic [19]. In fact gold exists in two forms at Poura: the first form is related to free gold or disseminated in quartz, and the second form concerns the association of gold and sulfide minerals: pyrite (FeS), chalcopyrite (CuFeS$_2$) and arsenopyrite (FeAsS). So, arsenic can result from arsenopyrite which composes mine wastes with others minerals. In addition, the soil derives from the bedrock through erosion and pedogenesis processes. But according to the contamination levels i.e. Igeo indexes and enrichment factors values, sources of arsenic related to erosion and pedogenesis processes are assumed to be lower than those related to mine wastes stored during several years.

4. Conclusions

In Sambayourou watershed, a portion of mine wastes is oxidized and as result acid mine drainage with a red-brick color concerning surface water can be observed. In addition, acidification of surface water leads to high contents of heavy metals and arsenic. Ground-water which consists of hand-pumped boreholes and wells presents in some area high levels of arsenic and lead above accepted standards. In surface water and ground-water, arsenic appears as the most polluting element. Arsenic is assumed to derive from oxidation and acidification of mine wastes and from host rocks of ground-water.

Soil is also contaminated by heavy metals and arsenic. As in the case of water pollution (surface water and ground-water), the soil is strongly contaminated by arsenic and the enrichment factor indicates a very high enrichment. Even if, erosion and pedogenesis processes can apply soil in arsenic, enrichment factor and oxidation/acidification of several tons of mine wastes are assumed to be the main source of arsenic contamination.

Acknowledgements

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