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ORIGINAL ARTICLE

Impacts of Artisanal Gold Mining on Surface Water Quality and Sediment in Agbaou, Hire, Kokumbo And Angovia, Central-West Ivory Coast

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ABSTRACT

The assessment of the surface water quality located around the small-scale gold mining sites has been performed in four areas in Ivory Coast (Agbaou, Hiré, Kokoumbo and Angovia), where artisanal gold mining practices were increased significantly. In total, sixteen (16) water and sediments samples were collected along the streams draining those mining sites. The degree of metallic contamination of surface waters and sediments were assessed. Different physico-chemicals parameters such as pH, electrical conductivity (EC), turbidity, copper (Cu), zinc (Zn), total mercury (Hg) and arsenic (As) were analyzed. The results showed that abandoned and operating gold mining site have affected surface water and sediments. In general, the surface water from these localities have acidic to basic properties (6.59<pH<8.40), highly mineralized (110.03<EC< 831.34 µS/cm) with a high Turbidity (18.6 to >800 NTU). In general, high EC and turbidity values were observed at the sampling locality Hiré. The determination of heavy metals in surface waters samples shows that mercury, arsenic and zinc concentration are above the World Health Organization (WHO) for drinking water quality limits, this indicates pollution. However, in the sediments high concentrations of heavy metals as mercury, copper and zinc are observed. These concentrations exceed the threshold defined by GESAMP standards. Considering the localities, one notes that, it Hiré showed the highest concentrations of these metals in the surface waters and the sediment and Kokoumbo, Agbaou and Angovia showed the lowest concentrations.

***Keywords**: Small-scale mining, Gold mining, surface water, sediment, trace metal.*

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INTRODUCTION

The artisanal and small-scale gold mining, is an informal activity, exploiting mineral resources in an unplanned way, using mainly manual methods and rudimentary tools [15]. These practices have long been practiced in many countries of the West African sub-region [16]. Moreover, since the 1960s, the successions of African states' independence, the increase of gold cost and discoveries of exploitable deposits, has caused the intensification of mining activities [27]. Indeed, mining activities are lucrative for many households [27, 11]. However, although they are socio-economically profitable, they also have negative impacts on the environment and the health of living beings [5]. Consequently, several studies on the quality of the environment in the world, especially on the presence of metals in water resources were performed. In Ghana, the impact of artisanal and small-scall gold mining on the aquatic community of streams in tropical forest conducted by [22], revealed a high turbidity of these waters (424-2 874 NTU) and a significant mercury concentration of 0.64 mg/L. Leaching of mining residues and chemicals from gold activities in surface waters affects biodiversity and exposes populations to health risks [8, 7, 27]. Also, the accumulation of metallic contaminants in aquatic organisms has toxicological effects for species, ecosystems and health risks associated with bioaccumulation [10, 3]**.**

In Ivory Coast, after the 1960s, most of the mining activity was carried out by artisanal miners. Moreover, the fall in the costs of agricultural raw materials between 1980 and 1990 associated with the significant discoveries of mineral deposits in the country have allowed the Ivorian State to revitalize the mining sector by making the extractive industry the second base of its economy [17]. Today, after the post-election crisis, this sector is even more diversified, with the installation of several industrial mining companies (Mancha, Newcrest mining, Amara mining, Persus mining, etc.). Exploration and exploitation of gold carried out by these industrial companies were associated with the artisanal operations practiced on the companies' licenses. These artisanal miners, who exploited gold from alluvial and gold reef, are now using the ore deposits much deeper and richer in mineral [17, 34, 11]. In addition, these miners frequently use chemicals such as mercury, cyanide, zinc, sulfuric acid and nitric acid in their processes [33, 34]. As a result, their activities contribute to intensive soil degradation and the release of pollutants, including Traces Metallic (ETM), which can affect surface water quality. The work of [34] conducted on the gold mining sites of Hiré, have been used to evaluate metallic pollution of groundwater and surface water. The results showed high concentrations of arsenic (0.063-0.183 mg/L), mercury (0.017-0.665 mg/L) and zinc (0.092-0.75 mg/L) above the limit values set by the World Health Organization (WHO) (0.01 mg/L for arsenic, 0.001 mg/L for mercury and 3 mg/L for zinc). The intensification of artisanal mining activities in Côte d'Ivoire remains a concern for government authorities, given the magnitude of the environmental and health impacts that result. Indeed, these activities are increasingly developed in the central, northern and western areas of Côte d'Ivoire. This study proposes to evaluate the impacts of artisanal mining activities in the Agbaou, Hiré, Kokumbo and Angovia areas on the quality of surface water. More specifically, it involves (i) making an inventory of gold mining activities to show the sources of contamination of surface water; (ii) to analyze the physical parameters of the surface waters near the various gold mining sites studied and; (iii) determine the concentrations of metallic trace elements (mercury, arsenic, copper, and zinc) in the surface water and sediments of the study area.

MATERIAL AND METHODS

Study area description

The study area, Kokumbo, Hiré, Agbaou and Angovia are located within latitude **4°48' to 5°42**N and longitude **6°02' to 6°72' W** in Central-West Ivory Coast (figure 1). Dominant land-use is agriculture, especially cultivation of cocoa, plantain and oil palm and food crops including cassava. Many of farmland are characterized with holes that have been created during search for gold in the area. These localities were selected because of the importance of the practice of artisanal mining activities. The geology is characterized by Birimien rocks that is commonly borne by the Paleoproterozoic [21]. The climate is characterized by tropical wet and dry climate. Mean annual temperature varies between 25°C and 30°C, while relative humidity over the area varies from 80 to 90%. The Average annual precipitation is 1400-2500 mm [12]. The areas studied are mainly drained by Bandama River.

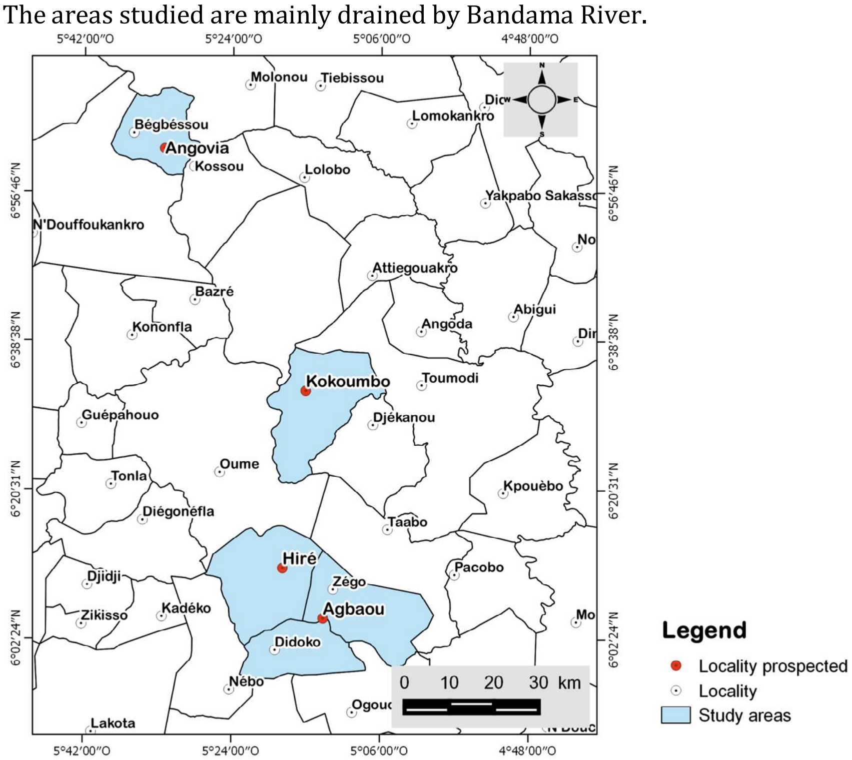


Figure 1: Location of artisanal and small-scale gold mining areas.

Description of the artisanal and small-scale gold mining activities sites

A field survey associated with the observation were used to describe the conditions of artisanal and small-scale gold mining areas, namely, the operating procedures, the use of chemicals and its immediate environment in order to appreciate the activities impacts. Likewise, this methodology made it possible to determine the location of the abandoned mining sites and the operating sites.

Selection of study area

The study area was selected based as the importance of the practice of artisanal mining activities; the presence of abandoned sites (SA) and operating sites (SE).

Water and sediment samples collection

After visits of several potential zones in each of the localities of study, several samples of water and sediment were collected. The samples points were selected based on criteria such as accessibility and their proximity of the mining sites. Thus, in the locality of Agbaou, four (4) sampling point were established on Assayé, Babo village and Gadama. Seven (7) other samples were taken in the locality of Hiré precisely on the sites of Agbalé, Léléblé, Doum and Tchébi.

Table 1: Geographical coordinates of the

Sampling locality	Samples	Sampling sites description		
Agbaou	4	 Assaye ;30N 0252531 / 0673774	 Babo; 30N 0253485 / 0672960	 Gadama ; 30N 0254600 / 0671340
Hiré	7	 Agbale SE; 30N 0248646 / 0683655	 Tchebi; 30N 0248681 / 0686459	 Doum ; 30N 0246166 / 0686001
		 Léléblé ; 30N 0248022 / 0686386		
Kokoumbo	3	 Kamissou; 30N 0251480 / 0722606		 Balo; 30N 0249041 / 0723303
Angovia	2	 N'gbando SE; 30N 0219853 / 0778918		 Cyanidation pond; 30N 0217470 / 0779314

As for the locality of Kokumbo, three (3) samples of surface water and sediments were taken on Kamissou and Balo sites. Also, in the village of Angovia, two (2) samples of water and sediments were taken on two sites (N'gbando SE and cyanidation pond) (Table1). In total, sixteen (16) samples of water and sediment were taken. All the sample were used for physicochemical analysis (EC, pH, turbidity, As, Hg, Cu and Zn). These sample points were identified using Global Positioning System (GPS). Water and sediment samples from rivers border abandoned sites (SA) and operating sites (SE) were taken in order to compare them. Figure 2 shows the sampling sites location. The collection of water was done facing the direction of flow of the stream. Water samples were collected in 1.5 L polyethylene bottles. After the sample collection, the water samples were transported to the laboratory in a cooler box with ice. Sediment samples were also collected from the same sites where the surface water was taken. Samples were taken with ECKMAN Benne and were collected in plastic bags which guarantee a closing insulating of the surrounding air and were kept with the shelter of the sun. After taking away, the sediments samples were transported, then dried in contact with the air in a closed room.

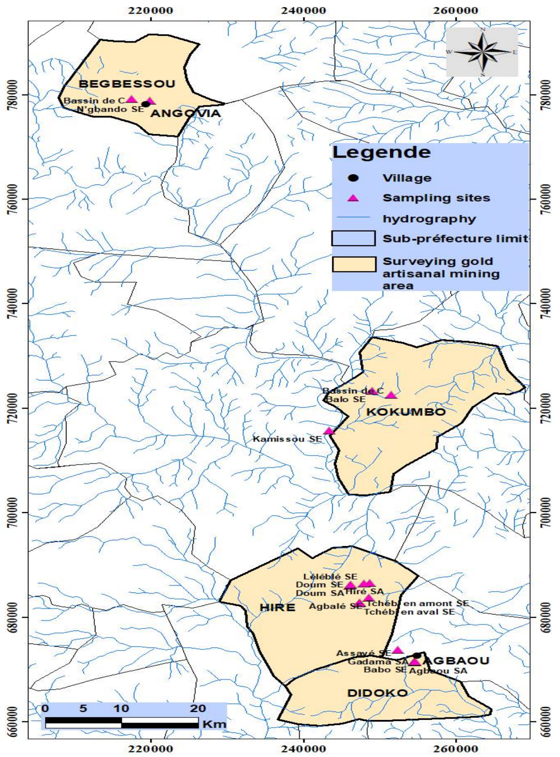


Figure 1 : Map of Study Area showing sampling points: SA= abandoned sites (SA), SE= active sites; C= Cyanuration

Water and sediment samples analysis

Physicochemical parameter of pH, conductivity, temperature and turbidity water were measured in-situ using a cobra 4 multimeter (PHYME) and the turbid meter AL250T-IR multimeter. The determination of the heavy metals in both water and sediment samples was determined using Atomic Absorption spectrophotometer (varian 240 FS model) (table 2 et table 3). The instrument setting and operational conditions were carried out in accordance to [6].

Sediment samples were air-dried to constant weight and sieved through a 2 mm AFNOR screen mesh size sieve and homogenized, before they were analyzed. Samples for analysis of Hg, As, Cu and Zn were also digested. A gram of dried fine sediment sample was weighed and transferred into an acid-washed, round bottom flask containing 10 cm^3 concentrated nitric acid. The mixture was slowly evaporated over a period of 1 hour on a hot plate.

Each of the sediment residue obtained was digested with a 9:4:1 ratio of concentrated HNO_3, HCL and HF. Hydrofluoricacid (HF) was used purposely for increasing the efficiency of oxidation of the samples and the rate of digestion of the samples. The digested mixture was placed on a hot plate and heated intermittently to ensure complete evaporation of the plate and heated intermittently to ensure complete evaporation of the fumes of HF. The mixture was allowed to cool at room temperature and filtered using Whatman paper into a 50 cm volumetric flask.

The results of water samples were compared to WHO standards for surface water quality. Moreover, the sediment samples analysis results were compared to GESAMP standards. Water and sediment quality parameters and the methods utilized in this study are presented in Table 2 and 3.

Table 2: Synthesis of methods and standards for the analysis of chemical parameters of water samples [6].

Parameter	Method	Standard
Mercury (Hg)	cold vapor Atomic Absorption Spectrophotometry	NF T90-113
Arsenic (As)	graphite furnace atomic absorption spectrophotometer	NF T90-119
Zinc (Zn)	Flame Atomic Absorption Spectrophotometer	NF T90-112
Copper (Cu)		

Table 3: Synthesis of methods and standards for the analysis of chemical parameters of sediment samples [6].

Parameter	Method	Standard
Mercury (Hg)	cold vapor Atomic Absorption Spectrophotometry	AOAC 974.14
Arsenic (As)	graphite furnace atomic absorption spectrophotometer	AOAC 999.10
Zinc (Zn)	Flame Atomic Absorption Spectrophotometer	AOAC 999.10
Copper (Cu)		

Data analysis

Data were analyzed for differences under locality, abandoned mine site, operating site and cyanidation pond using the analysis of variance (ANOVA). The statistical program used for both tests was R software 3.1.1. The significance level was $p < 0.05$.

RESULTS AND DISCUSSIONS

Impacts of mining activities on water resources

Artisanal and small-scale gold mining activities generate negative impact on water resources. Those impacts were generated by the discharging of sludge obtained after washing the ore into the surrounding watercourse (Figure 3). This introduces large amounts of suspended solids and contaminants directly into aquatic habitats [29] that causes siltation of these streams (Figure 4a and 4b). That disturbance of surface water can cause the loss of the biodiversity and damage the water quality. [2] and [19] reported similar results for types of Pollution generated by gold mining respectively in Burkina Faso and Brezil.

Figure 2 : Discharging of mining bud into the Bandama river near the locality of Kokoumbo (Central West of Côte d'Ivoire).

Gold mining operation utilize large volumes of water during ore washing by using a sluice box, mercury and cyanide treatment, diverting local water resources away from other uses. Indeed, for sluice box (figure 4a), the artisans move a large volume of water to the washing point which contributes to a depletion of these water resources. In the same way, the mining craftsmen located not far from the watercourse get their water from the banks using a motor pump installed in the water. This constant pumping of water leads to the depletion and modification of the surface water basins (Figure 3) and reflects the high risk of contamination of water by hydrocarbons and other petroleum products. In addition, small-scale miners use mercury in processing their ore. The waste products in most cases are dumped into water bodies which cause bioaccumulation in the bodies of aquatic animals and can enter the food chain of human beings [7]. After the mercury treatment, mercury in the air may settle into water bodies and affect water quality. Also, water pollution is caused using toxic chemical products, such as cyanide which is widely used in post-processing to extract residual gold after mercury processing, the artisanal miners discharge the wastewater resulting from the washing in the watercourses.

Figure 4: Illustration of the physical impacts on the surrounding waters of the mining sites in Hiré: clean gold sluice box (a), discharge of wastewater from washing (b).

Physical quality of surface waters

The summary statistics of the physical parameters obtained from water in the study area are given in Table 4.

The pH values of study area varied from 6.59 to 8.40. The pH values recorded in all localities were not significantly different (Kruskal-wallis: $p > 0.05$). These results show that water samples have acidic to basic properties. In general, high pH values were observed at the sampling sites Agbalé SE (8,4), N'gbando SE (8,16), Agbaou SE (7,73), Tchébi aval (7,7) and léleblé (7,61). These basic pH values could be linked to the high gold mining activities which is carried out in these sites. [34], who assessed the metal pollution of surface water in the city of Hiré, obtained the same results. Indeed, pH could be controlled by biological activities (photosynthesis and respiration) but also by the buffering capacity of water, especially carbonate (CO_3^{2-}), bicarbonate ion (HCO^-_3) and carbon dioxide (CO_2) [30, 20, 32]. Similarly, pH obtained remains weakly acidic at Babo (6.91), at the abandoned Doum site (6.59) and in the cyanidation pond of Angovia (6.95). This acid pH is due to a high concentration of nitric and sulfuric acid used during the chemical treatment of gold. As for the low acidity observed on the abandoned sites of Doum and Babo, it could be explained by the exposure to the open air of the mining waste on the one hand and on the other hand by the presence of the cyanidation basins. Indeed, exposure of these wastes to the environment generates a large change in the stability conditions of these chemicals [1].

The electrical conductivity (EC) of the water samples was in the range of 110.03- 462.43 µS/cm in Agbaou, 187.67- 831.3367 µS/cm in Hiré, 168.3- 210 67 µS/cm in Kokumbo and 154.57- 289. 67 µS/cm in Angovia. The comparison test (Kruskal wallis test: $p > 0.05$) between the mean values of electrical conductivities did not show any significant difference in the localities studied. The maximum EC values were determined at Hiré locality (mean value obtained 429.29 ± 237.47 µS / cm) and this is due to the presence of some dissolved minerals in the water. Indeed, the runoff of ore tailings into streams over time has favored a release of metals resulting in significant mineralization. According to [26], higher value of EC is a good indicator of the presence of contaminants**.** It is also important to note that EC varies from one point to another. The abandoned Doum-Hiré site has the highest EC (831.33 µS/cm) while the Assayé (Agbaou site) has the lowest EC (110.03 µS/cm). This spatial variation is due to the importance and the intensity of mining activities around each sampling point.

The turbidity values of the studied water are ranged respectively from 79.17 to > 800, from 28.03 to > 800, from 18.6 to 27.6 and from 76.6 to 637.33 NTU in Agbaou, Hiré, Kokumbo and Angovia as indicated in table 4. The highest turbitdity (>800 NTU) mainly observed around mining sites such as Agbaou locality, Doum and Léléblé sampling points. Water turbidity at different stations were not significantly different (Kruskal Wallis: $p > 0.05$). Around these sample points, the activities of gold miners carried out in these rivers, which also generates a strong presence of suspended matter in these rivers. Indeed, liquid waste resulting from gold washing has a very high content of MES that causes the turbidity of the water [24]. These high suspended matters generated by abandoned gold mining site, which have deposited in the bottoms and clogging the beds of these rivers, could also influence the temperature of these waters (high values in all the study areas between 21.77 and 29.07 °C). Indeed, the presence of suspended matter in a watercourse causes it to warm up [13].

Table 4: Physical parameter on the abandoned sites (SA) and operating sites (SE)**.**

Localities	Sampling point	pH	Temperature (C)	Conductivity (µS/cm)	Turbidity (NTU)
Agbaou	Assayé SE	7.46	22.93	110 .03	403.33
	Agbaou SA	7.73	23.63	312.33	>800
	Babo SE	6.91	26.2	462.43	15.23
	Gadama SA	7.56	22.1	261.53	79.17
Hiré	Agbalé SE	8.4	25.47	241	186
	Hiré SA	7.31	21.77	677.67	36.03
	Doum SE	7.41	28.53	322.67	>800
	Doum SA	6.59	26.9	831.33	28.03
	Léléblé SE	7.61	26.97	500.67	>800
	Tchébi en amont SE	7.1	28.37	187.67	45.87
	Tchébi en aval SE	7.7	28.6	246.17	616
Kokumbo	Balo SE	7.37	22.8	210	18.6
	Cyanuration pond	7.64	26.23	186.33	22.87
	Kamissou SE	7.57	26.4	168.3	27.6
Angovia	Bassin de cyanuration	6.95	29.07	154.57	76.6
	N'gbando SE	8.16	25.07	289.67	637.33

Chemical quality of surface waters and sediments in study areas

Total Hg, As, Cu and Zn concentration in both water and sediments samples collected in four artisanal mining localities (Agbaou, Hiré, Kokumbo and Angovia) are shown in following figures.

For mercury (Hg), it has an average concentration of 0,0043 ± 0,0004 mg/l in the surface water (figure 7a). when compared with World Health Organization guidelines for drinking water, it is slightly higher than the acceptable limit for drinking water (0,001 mg/l). Hg concentrations measured in Cyanide pond at kokumbo (0.0065 mg/L) are much higher than in upstream Chebi (Hiré) (0.0055 mg/L) and N'gbando at Angovia (0.0053 mg/L). However, Hg concentrations were not significantly different between sampling locations (Kruskal Wallis test: p> 0.05).

In addition, concentrations of Hg recorded in sediment (figure 7b) are much higher than in surface water and are several orders of magnitude above the GESAMP sediments quality standards (0.3 mg/kg). It has an averages concentration of 1.01 ± 0.79 mg / kg in sediment at Angovia, 0.957 ± 0.54 mg / kg in sediment at Agbaou, 0.74 ± 0.5 mg / kg in sediment at Kokumbo, and 0.65 ± 0.38 mg/kg to Hiré. However, the concentration of Hg in the Hiré SA and Balo SE sediment were lower than the maximum acceptable level in river sediments (Figure 7b). The comparison test (Kruskal Wallis test: p> 0.05) of the mercury concentration in the sediments did not show any significant difference in the localities studied. The high mean concentration of Hg in both water and sediments samples recorded in all the rivers studied could be attributed to the numerous artisanal mining activities located along these rivers; with frequent use of Hg to extract gold from the ore [4, 23].

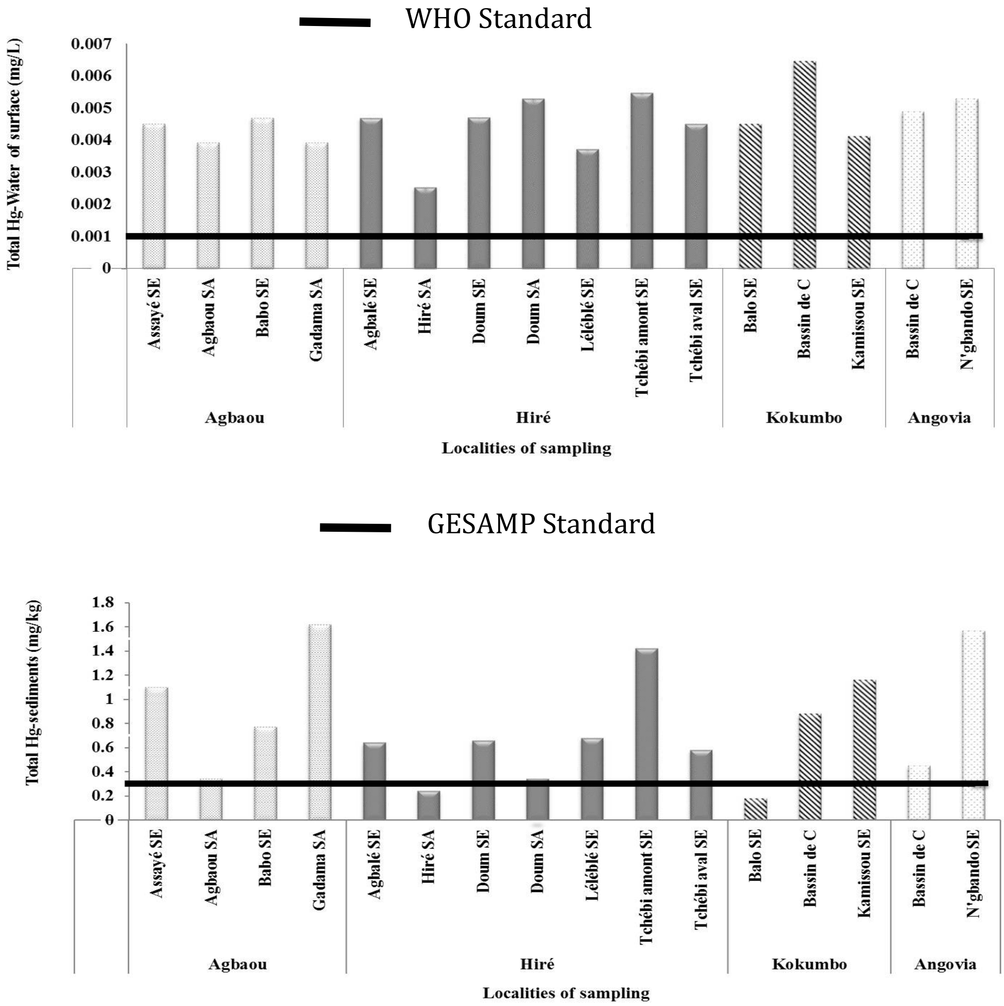
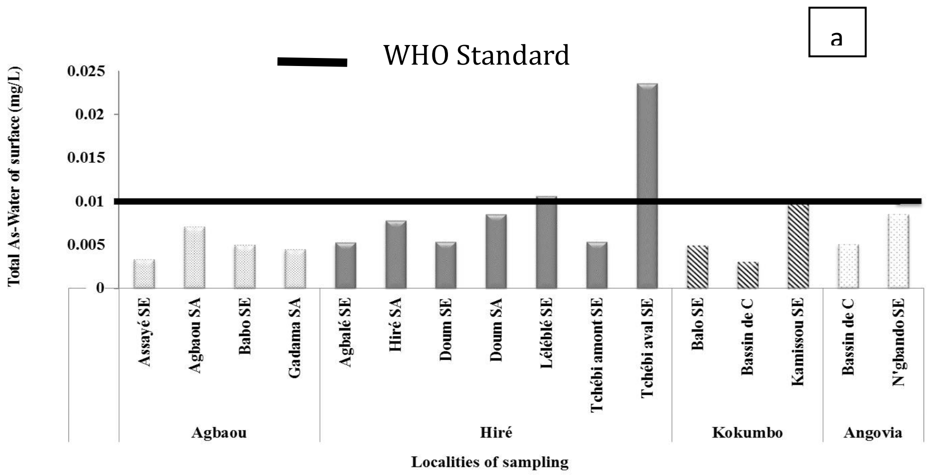


Figure 7: Variation of the mercury concentration in the different localities: Surface water (a); Sediment (b); SE = sites in operation, SA = abandoned sites; C = cyanidation.

For arsenic it has an average concentration of 0.0074 ± 0.0049 in the surface waters (Figure 8 a); comparing the results with World Health Organization guidelines (WHO) for drinking water the value is lower than the acceptable limit of 0.01 mg/L with the exception of Tchébi aval SE in Hiré where arsenic has the highest concentration. Arsenic concentrations recorded at the different stations of the visited localities were not significantly different (Kruskal Wallis test: p> 0.05).
Arsenic concentration from sediment were lower and ranged from 0.70 to 1.65 in Agbaou, 0.97 to 1.92 in Hiré, 1.14 to 2.47 in Kokumbo, and 1.14 and 1.79 mg/kg in Angovia with mean concentration of 1.08 ± 0.45 mg/L, 1.26 ± 0.31 mg/L, 1.59 ± 0.76 mg and 1.46 ± 0.46 mg/kg respectively (Figure 8b). when compared with GESAMP guidelines for sediment, the value obtained for sediment sample is lower than the maximum allowable concentration of As in soil i.e (15mg/kg). The concentrations of arsenic from sediment samples collected in localities were not significantly different (Kruskal-wallis test, p> 0.05). Concentration of arsenic recorded in the surface waters draining the Hire gold site could be related to the mineral complex of the study area. In addition, the pH of these waters is basic. However, according to [9], in the waters surrounding the alkaline pH mine sites, the adsorption of an oxyanion such as arsenic is minimal, and the solubility is high. This would better explain the high arsenic concentrations recorded in the Léléblé sample (0.01065 mg/L) and the one taken downstream of Chebi (0.0236 mg/L). However, comparing arsenic levels from abandoned sites to operating sites as a whole, those from operating sites remain high compared to abandoned sites. This could be explained by the fact that, despite the persistence of metals produced as a result of previous work on abandoned sites, the activities of gold miners on certain sites in operation produce more.



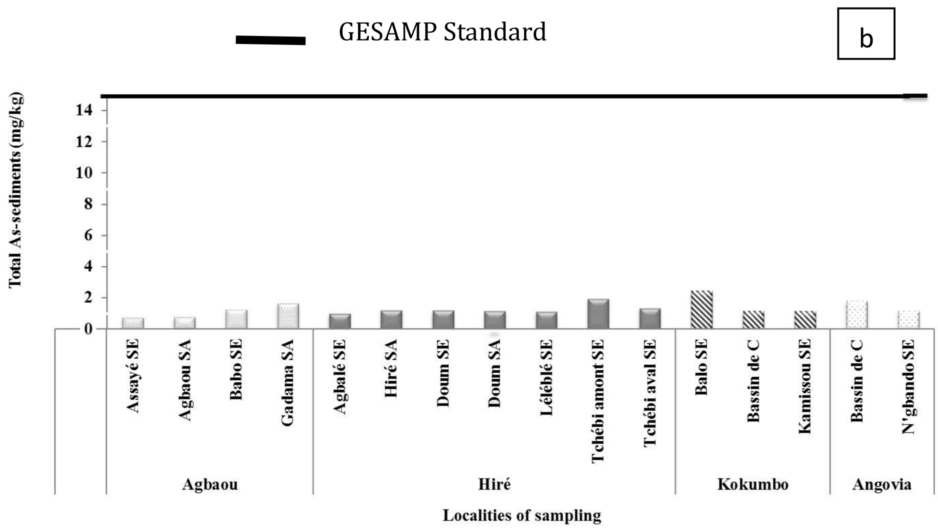


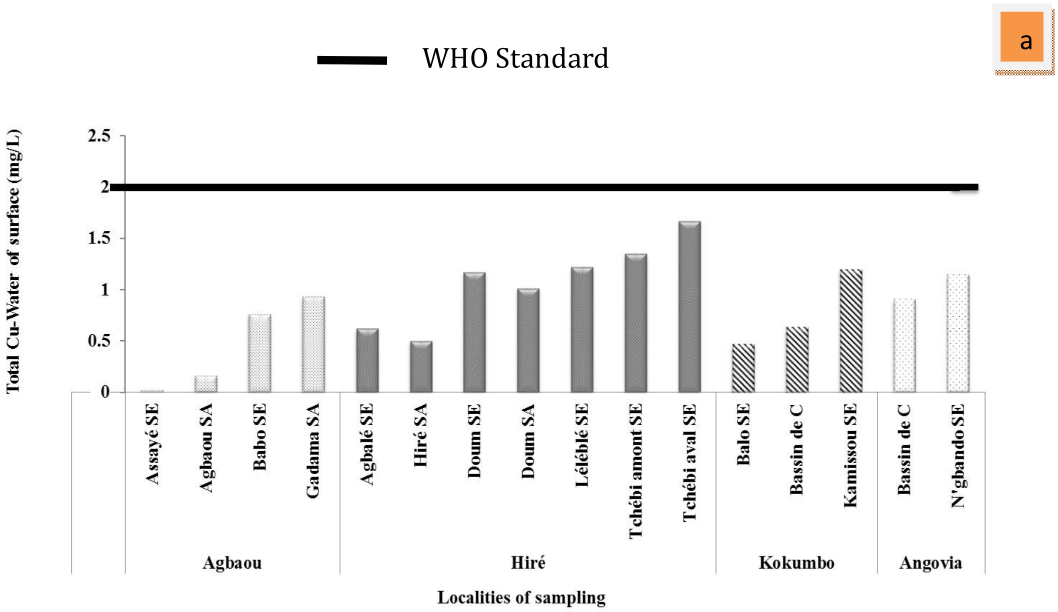
Figure 8: Variation of the concentration of arsenic in the different localities: Surface water (a); Sediment (b); SE = Exploitation Site, SA = Abandoned Site, C = Cyanidation.

Copper concentration in sediment and water samples from the rivers Agbaou, Hiré, Kokumbo and Angovia are reported in figure 9.

Copper concentrations in surface water ranged from 0.02 to 0.93 mg / L, 0.50 to 1.67 mg/L, 0.47 to 1.20 mg/L, 0,91 to 1.15 mg/L, respectively in the localities of Agbaou, Hiré, Kokumbo and Angovia (Figure 9a). These values are lower than the WHO standard level for drinking water (2 mg/L). However, Chebi amont SE and Chebi Aval SE have the highest Cu concentration. The mean concentration of copper in each locality ranged from 0.47 ± 0.44 mg/L (Agbaou) to 1.07 ± 0.38 mg/L (Kokumbo). Copper concentration recorded from all localities were not significantly different (Kruskal Wallis test: $p > 0.05$).

In the sediment, the mean concentration of copper is in the order of 103.59 ± 39.65 mg / kg at Hire, 164.91 ± 39.64 mg / kg at Agbaou, 179.56 ± 38.11 mg/kg at Angovia and 195.61 ± 47.19 mg/kg at Kokumbo (Figure 9b). However, the maximum concentration was measured at Balo (245.28 mg/kg), followed by that of N'gbando (206.51 mg/kg), Gandama (198.12 mg/kg) and that taken in the cyanidation basin at Kokumbo (190.21 mg/kg) and then at the abandoned Angovia site (185.52 mg/kg). The comparison of sediment concentrations showed a significant difference between the copper concentration from Hiré locality samples and those of the other localities (Kruskal Wallis test: $p < 0.05$).

The copper concentration remains very high in all the stations and largely exceeds the GESAMP guidelines value (33 mg/kg). Only Agbalé SE sample in Hiré showed lower values (22.67 mg/kg). The high concentrations of copper in the water and sediments are likely to be related to the drainage of waste rock piles from the quarry operated by the industrial mining company in the Hire area. Copper concentration obtained at the sites in operation are still high. However, the strong presence of copper in water and sediments can be explained by the natural presence of copper in the rocks. Indeed, according to [25], copper is an abundant element in the earth's crust. The leaching of these formations and deposits containing it leads to an increase in its concentration in water and sediments. Similarly, according to [14] copper is one of the few metals that exists in the native state. Thus, even with a low occurrence, this native copper could be added to the copper produced in an anthropic way on the mining sites.



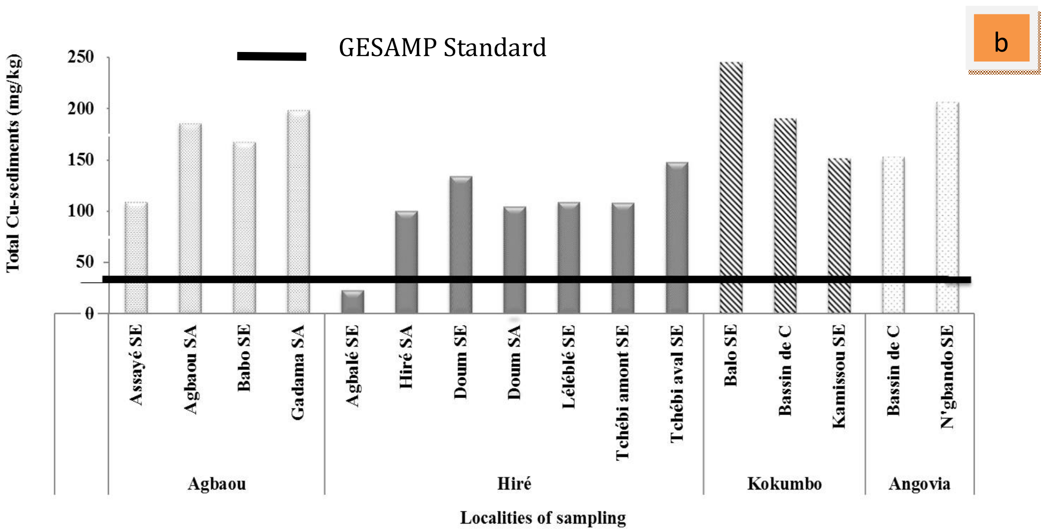


Figure 9: Variation of copper concentration in the different localities: Surface water (a); Sediment (b); SE = operating site, SA = abandoned site, C = cyanidation.

Figure 10 shows zinc concentration recorded in the surface water and sediment of the study areas. Regarding surface water, it is between 0 and 0.15 mg/L, between 0.01 and 11.11 mg/L and between 0.01 and 0.28 mg/L respectively in the localities of Agbaou, Hiré and Kokumbo (Figure 10a). Only Doum SA has the highest zinc concentration (11.11 mg/L) when compared with WHO guideline for drinking water it is slightly higher than acceptable limit for drinking water (2 mg/L). The mean concentration of zinc measured at each locality is 0.075 ± 0.08 mg / L, 0.103 ± 0.15 mg/L, 0.13 ± 0 mg/L, and 1.72 ± 4.14. mg/L respectively to Agbaou, Kokumbo, Angovia and Hiré. The comparison test with that of kruskal wallis did not show a significant difference (P> 0.05) between the different concentrations of zinc.

As for sediment, the average zinc concentration obtained is 48.23 ± 30.91 mg/kg at Agbaou, 81.095 ± 15.40 mg/kg at Angovia, 92.14 ± 42.34 mg/kg at Kokumbo and from 130.04 ± 138.80 mg/kg to Hire (Figure 10b). The abandoned site in Doum has the highest concentration (344.29 mg/kg), followed by the abandoned site located near the town of Hiré (313.67 mg/kg). These results could be explained by the high quantities of solid waste discharged by gold miners. These are batteries, accumulators, paperboard rubbers and ferrous products. Indeed, according to [28], zinc forms 44 to 47% of batteries and accumulators, 12 to 13% of ferrous products, 11 to 13% of rubbers and 8 to 9% of paperboard. The high levels of Zn recorded in water and sediment are consistent with those obtained by [24]. According [18], this concentration of zinc could also be explained by the tailing from gold extraction and chemical products used during the separation of gold in cyanide tanks and excavating machine. However, sometimes this element can be derived from geological units. Indeed, Zinc occurs in gold ore bodies in the form of sphalerite (ZnS) which is often associated with galena [35]. The excessive presence of zinc on abandoned sites could be attributed to the unique site geology as highlighted previously [31]. Indeed, zinc is a moderately reactive metal, so it persists constantly in a medium.

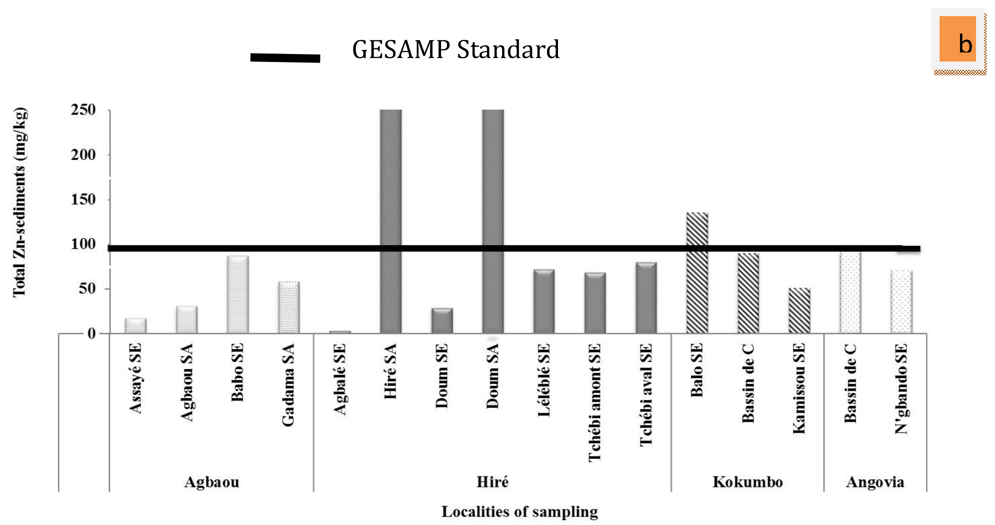


Figure 10: Variation of the zinc concentration in the different localities: Surface water (a); Sediment (b); SE = operating site, SA = abandoned site, C = cyanidation.

CONCLUSION

This work has assessed the impact of artisanal mining activities in the Agbaou, Hiré, Kokumbo and Angovia areas on the quality of surface water and sediment. Observations and the physicochemical quality of surface water and sediments near the various gold mining sites were evaluated. Abandoned golf mining sites that have not been rehabilitated lead to stagnation of surface water, which causes a high mineralization of these waters. However, the results show that abandoned and operating gold mining site have affected water resource and sediments. In fact, surface waters are contaminated by mercury, arsenic and zinc. The levels measured exceeded WHO drinking water guideline value. In addition, in the sediments there is contamination by mercury, copper and zinc whose concentrations far exceed the threshold set by the GESAMP. Considering the localities, we note that the locality of Hiré showed the highest conductivity, temperature, turbidity and concentrations of trace metals in surface water and sediments.

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