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Research Article

Physicochemical Characterisation of Water and Sediment of the Semimechanized Artisanal Gold Mining Environment of the Béké Locality

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This paper aims to investigate the level of pollution of water, sediment, and soil due to semimechanized artisanal gold mining in Béké, Adamawa region of Cameroon. For this purpose, water and sediment samples were collected and analyzed. In order to achieve this goal, several research studies and field observations were carried out. Questionnaires were also used to complement field investigations. All these enabled the identification of the potential sources of impacts on the human, physical, and biological environment. Three soil samples (S1, S5, and S7) were collected on the same spot with the water sample and analyzed to assess the intensity of soil contamination. The water samples (W1–S9) were characterized physically, chemically, and microbiologically to evaluate the water quality contamination. The results of the physicochemical analysis of the water samples showed that the rivers in this zone are moderately acidic (with pH values ranging from 5.11 to 6.37) and slightly mineralized (with sample W2 collected from the Béké river having an iron concentration of 6.7 g/L). The pattern of mean trace metal concentration in sediments was Fe > Mn > Cr > Pb > Cu > Zn. According to pollution indices, the contamination degree (CD) varied from 4.03 to 4.56 corresponding to low contamination. The index of ecological risk (E_r^i) for all the trace metals was low ($E_r^i \leq 40$) and the geo-accumulation index (I_{geo}) ranged between uncontaminated and moderately contaminated (I_{geo} 0-1). The result of our field investigations and analysis shows that the semimechanized artisanal gold mining in the locality of Béké has very significant environmental consequences such as land degradation, deforestation, water pollution, and landscape modification.

1. Introduction

The boom in the global demand for certain minerals since the end of the 20th century has led to the proliferation of mining projects, particularly concerning highly coveted and increasingly rare metals such as gold [1]. According to the World Bank, 80% of global sapphire comes from artisanal and small-scale production and 20% of gold mining. These farms are found in many developing countries across Africa, Asia, Oceania, and Central and South America and are an important source of economic development. However, it should be noted that mining is one of the most environmentally destructive industries in general and artisanal gold mining, in particular contributing significantly to the degradation of the natural environment and the socioeconomic conditions of the local populations [2, 3].

Several studies in various African countries have been conducted to assess the environmental and social impact of artisanal and semimechanized gold mining activity. In Southern Africa, the authors in [4] conducted studies on the impact of artisanal gold mining on water quality in Mozambique and Zimbabwe. They showed that artisanal-scale gold mining (ASGM) leads to deforestation and water depletion, siltation, turbidity and increased levels of heavy metals, and destruction of aquatic organisms and their habitats. In reference [5], aiming to assess the artisanal gold mining impact in Lolgorian (Kenya), they collected a sample of 250 questionnaires from surrounding populations. The exploitation of the answers obtained revealed that 94.3% of the operators did not carry out an environmental impact assessment of their mining operations. Several recommendations were made to this effect such as acceleration and centralization of formalized ASGM and establishing appropriate governance mechanisms to adopt for education and socioeconomic development and enhance the skills and knowledge of miners. In West Africa, the author in [6] studied the quality of water sources in the gold mining areas of Bibiani (Ghana) in terms of their physical and chemical properties. In the same localty, the authors in [7] ascertained the degree of contamination of the wastewater by characterizing the tailings dam effluent of Central Africa Gold Limited. The authors in [8] assessed the health and environmental impact of artisanal gold mining in Ijesha-land. They collected samples from surface, groundwater, bottom sediment, fish, and aquatic plant to analyze. The results obtained showed that higher concentrations of most major and trace element were found in the fish guts and they concluded that long-term environmental and human health risks may arise from artisanal gold mining activities in the study area. In addition, the authors in [9] analyzed the same type of sample as Obiri et al. Their results revealed that the concentration of some elements in surface water was higher than the acceptable limits in drinking water; these are aluminium ($305 \pm 950\,\mu$g/L) and iron ($0.35 \pm 0.56\,\mu$g/L). They concluded that the activities of artisanal gold mining are dangerous to human health. In addition, in [10], the Brong-Ahafo Region's Tano river catchment area near the Ahafo mine has been studied for its physical and chemical properties and heavy metal status. The authors in [11] highlighted the physicochemical characteristics of surface waters in Divo division (Côte d'Ivoire). Their analysis showed that waters near mining sites were the most mineralized.

In Cameroon, the authors in [12] assessed the impact of artisanal gold mining on water quality in the Betare-Oya locality in East Cameroon. In the same locality, the author in [13] evaluated the impact of artisanal mining wastewater on contaminated sites. In their article on the impacts of artisanal gold mining on human health and the environment, the authors in [14] noted these same observations with regard to the health problems suffered by the local populations. The authors in [15] obtained the correlation between different physicochemical parameters analyzed in the mining waste of Betare-Oya using a statistical analysis tool and carried out for heavy metals an absorption test on smectic clay to eliminate their concentration. The authors in [16] assessed soil by trace metals in Bindiba (East Cameroon) mining district.

However, several studies have been carried out globally to specifically assess sediment contamination in mining environments. In Brazil, the authors in [17] demonstrated the impact of mining activities on sediments downstream of the Currais Novos scheelite mine. In Turkey, the authors in [18] studied the physical and chemical properties of tailings and pond sediments in the Can Basin, as well as the heavy metal content and their morphology. In Mexico, the authors in [19] assessed the potential impact of runoff from abandoned artisanal mines and tailings in the Sonoran River Basin on river sediment quality. The risk and pollution levels of trace metals in the sediments on the river of the largest gold production base in China were assessed in the northwestern part of Shandong Peninsula, China [20]. In High Moulouya-Morocco, the authors in [21] studied the physical and chemical residences and whole content material of doubtlessly poisonous metals (Pb, Zn, As, Cd, and Cu) in sediments and floor waters from the pit lakes of the deserted Pb mine and assessed the pollution level. The authors in [22] investigated the distribution and stages of doubtlessly poisonous metals in water and sediments. They explored the pollution status and ecological risk levels of potentially toxic metals in sediments and determined the source apportionment of potentially toxic metals in Poyang Lake Basin. The authors in [23] studied spatiotemporal version and assessed hint steel illness in sediments alongside the Lom River in the gold mining website online of Gankombol (Adamawa Cameroon), and the end result printed that the degree of infection in sediments in the studied area globally led to widespread illness by way of hint metals. These research studies have often proven that human activities can have an effect on sediments in rivers. Trace metal concentrations above recommended standards were observed in these studies, indicating high levels of trace metal contamination. The sediments either absorb or release heavy metals found in rivers, leading to continuous and permanent degradation of water resources and the environment. Many studies about artisanal gold mining impacts on the environment in the East and Adamaoua regions have been carried out. To our knowledge, no study concerning the locality of Béké, municipality of Kétté (Eastern Region of Cameroon), has been done.

The Béké mining site was chosen because of the numerous negative impacts on gold panners, artisans, and the entire population observed from the semimechanized artisanal gold mining activity that takes place there and is also the main source of subsistence of the population [24]. The primary goals of this study are as follows:

(1) Assess the environmental and social impacts of semimechanized artisanal gold mining in the locality of Béké

(2) Evaluate the rate of contamination by determining the following pollution indices and ecological risk assessment: the contamination factor (CF), contamination

degree (CD), pollution load index (PLI), Nemerow index (NI), potential ecological risk index (RI), enrichment factor (EF), and geoaccumulation index (I_{geo})

(3) Determine the potential causes of pollution and proposed remedial measures

2. Materials and Methods

2.1. Presentation of the Study Area¶. The study area is located in Kétté subdivision, department of Kadey, East Region of Cameroon. Geographically, it is located between 14°40′ and 14°42′ latitude North and between −4°45′ and 4°47′ East longitude (Figure 1). It is characterized by a rugged and varied relief with an average altitude of −450 m. The mean temperature varies between 23.8° and 29°C, and the average annual rainfall is estimated at 1600 mm.

2.2. Sampling Method. The sampling campaign was carried out on a sunny day, and the flow rate of the river was relatively average. Semirandom sampling was used. Nine water samples, i.e., W1–W9 were taken using plastic mineral water bottles at the format 1.5 liter, respectively, at the level of the mineralized gravel washing sluice, the current of the river where people do their laundry and where people drink. Three sediments, i.e., S1, S5, and S7 were taken. All these sampling points represented in Figure 2 were geolocated using an eTrex 30 single-frequency GPS receiver.

2.3. Analysis Methods. The water and sediment sample analyses were carried out on sites after sampling for certain physical parameters and at the physics-chemistry and microbiology laboratory of the Faculty of Sciences of the University of Yaoundé I. pH and conductivity were measured using a HACH HW-11d brand pH meter and a HACH HQ 14 d brand conductivity meter, respectively. Turbidity was measured using a HACH DR/2000-configured spectrophotometer to determine turbidity at a wavelength of 750 nm. The WikiHow method was used to measure suspended solids in water. The chemicals analysis were made on the major ions (SO_4^{2-}, K^+, Ca^{2+}, Na^+, NO_3^-, PO_4^{3-}, and Cl^-). Heavy metals (Pb, Fe, Hg, and Zn) were determined by atomic absorption spectrometry (AAS) using the Buck Scientific 205 spectrometer.

The preliminary work involved squeezing sediment samples to obtain sediments in the form of powder pellets before analyzing trace metal extracted from sediments. The trace metals (Fe, Mn, Cu, Zn, and Pb) were analyzed by X-ray fluorescence (XRF) spectrometry. The apparatus used was Skyray Instrument EDX Pocket III brand with the detection limit of 0.001–0.01%. Trace metals were analyzed at the laboratory of the Framework of Support for the Promotion of Mining Handicrafts (CAPAM) located in Yaounde (Cameroon). The concentrations of trace metals studied were compared with the WHO standard [25].

2.4. Contamination Evaluation Methods. Pollution indices are extensively regarded a beneficial device for the complete comparison of the degree of contamination. The environment has an effect on hint metals, and the degrees of illness in sediments have been chosen with the use of the following air pollution indices and ecological chance assessment: the contamination factor (CF), contamination degree (CD), pollution load index (PLI), Nemerow index (NI), potential ecological risk index (RI), enrichment factor (EF), and geoaccumulation index (I_{geo}). The CF, CD, PLI, and NI had been used to check the anthropogenic contribution of hint metals in sediments and to decide the stages or ranges of hint metallic contamination. The CF takes into account the infection of a single element. The CF was once calculated by evaluating the awareness of hint metals with the common shale attention given by [26], which is used as the world popular reference for unpolluted sediment. It is a ratio of the concentration of potentially toxic elements (PTEs) in a sample (C_i, mg/kg) to its background/reference concentration in sediment/roadside soil (C_b, mg/kg) [27, 28]. The calculation formula is as follows:

$$\mathrm{CF} = \frac{C_i\,[\text{sample}]}{C_b\,[\text{background}]}. \tag{1}$$

The integrated degree of pollution of the environment is represented by the CD, which is the sum of all the CFs [29]. The CD is expressed by the following equation:

$$\mathrm{CD} = \sum \mathrm{CF}. \tag{2}$$

The evaluation of PLI was done using the method proposed by [30]. It is expressed by the following equation:

$$\mathrm{PLI} = \left(\mathrm{CF}_1\; X\, \mathrm{CF}_2\; X\, \mathrm{CF}_3\; X \ldots X\, \mathrm{CF}_\mathrm{n}\right)^{1/n}, \tag{3}$$

where n is the number of heavy metal. PLI = 0 indicates no pollution; PLI = 1 indicates the baseline level of metals whereas PLI > 1 indicates that the site is polluted [31]. All analyzed trace metals' concentrations are included in the NI, which allows for the assessment of the overall degree of pollution of soil or sediment [32]. The calculation formula is as follows:

$$\mathrm{NI} = \sqrt{\frac{(\mathrm{CF}_{\mathrm{mean}})^2 + (\mathrm{CF}_{\mathrm{max}})^2}{2}}, \tag{4}$$

where CF is the pollution index of element, CF_{max} represents the maximum value of the hint steel air pollution index, and CF_{mean} represents the common price of the hint steel air pollution index. The CF and CD illness stages are given through the following [29]: low illness (CF < 1 and CD < 8); average illness (1 ≤ CF < 3 and 8 ≤ CD < 16); sizable infection (3 ≤ CF < 6 and 16 ≤ CD < 32); and very excessive illness (CF > 6 and CD > 32). Reference [33] gave the classes of NI air pollution as follows: no air pollution (NI ≤ 0.7); highly no air pollution (0.7 < NI ≤ 1); mild air pollution (1 < NI ≤ 2); reasonable air pollution (2 < NI ≤ 3); and excessive air pollution (NI < 3). The RI was once used to determine the unfavourable outcomes of trace metals in sediments [34]. The RI can be calculated by the following formula:

$$E_r^i = T_f^i + C_f^i, \tag{5}$$

where E_r^i is the ecological risk index of trace metal i in the sediment; C_f^i is the contamination factor of each metal; and T_f^i is the toxic biological factor of each metal [35]. We gave

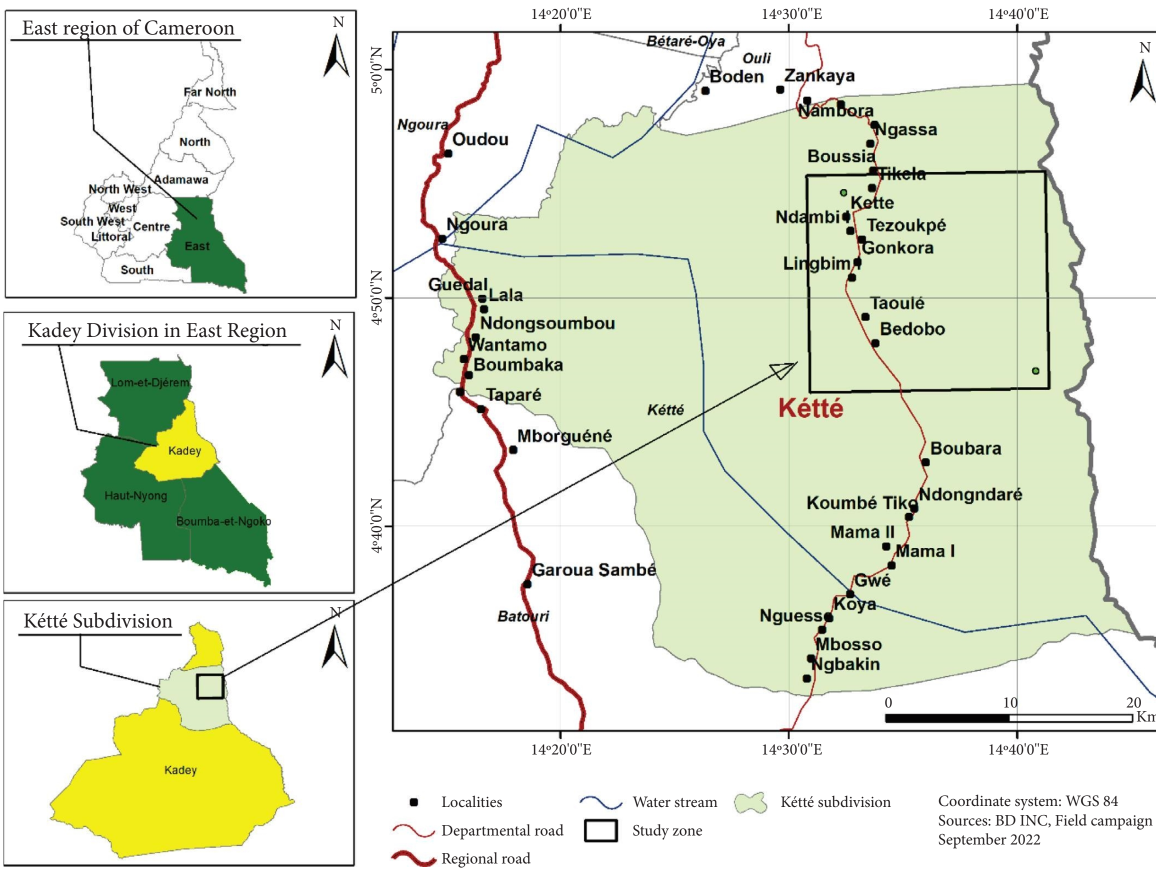

Figure 1: Location map.

the toxic response factors on each of the trace metals as follows: Fe = 1; Mn = 1; Cu = 5; Zn = 1; Cr = 2; and Pb = 5. The RI is the sum of E_r^i of all the heavy metals:

$$\mathrm{RI} = \sum_{i=1}^{n} E_r^i. \tag{6}$$

The pollution stages of E_r^i and RI are classified as follows: low risk ($E_r^i \le 40$ and $\mathrm{RI} \le 150$); moderate risk ($40 < E_r^i \le 80$ and $150 < \mathrm{RI} \le 300$); considerable risk ($80 < E_r^i \le 160$ and $300 < \mathrm{RI} \le 600$); high risk ($160 < E_r^i \le 320$ and $\mathrm{RI} \ge 600$); and very high risk ($E_r^i \ge 320$). Evaluating the degree of enrichment and contamination of different environmental media is easily made using the EF's regular formula [36]. The EF measures the potential impact of human activities on the concentration of trace metals in sediment. In the existing study, iron (Fe) is used to be chosen as the reference stationary issue to operate the calculations. The following equation is the expression of EF:

$$\mathrm{EF} = \frac{[M]/[\mathrm{Fe}]\mathrm{samp}}{[M]/[\mathrm{Fe}]\mathrm{RM}}, \tag{7}$$

where EF is the enrichment factor; $[M]$ is the concentration of the studied trace metal; [Fe] is the iron concentration; samp indicates the sample; and RM is the reference material. The five categories of EF are deficiency to minimal enrichment ($\mathrm{EF} \le 2$); moderate enrichment ($2 < \mathrm{EF} \le 5$); significant enrichment ($5 < \mathrm{EF} \le 20$); very high enrichment ($20 < \mathrm{EF} \le 40$); and extremely high enrichment ($\mathrm{EF} > 40$). A final criterion for evaluating the intensity of metallic contamination is the I_{geo} [37]. This index is used to assess the anthropogenic impact. This empirical index compares a given concentration versus a value considered as a geochemical background.

$$I_{\mathrm{geo}} = \log 2\left[\frac{C_n}{1.5B_n}\right], \tag{8}$$

where I_{geo} is the geoaccumulation index; log2 is the logarithm to base 2; n is the issue considered; C is the awareness measured in the sample; B is the background content material of the common shale as described by [26]; and 1.5 is the factor compensating background data (correction factor) due to the lithogenic effect [38], the feature which takes into account the natural functions of the geochemical background. Based on I_{geo}, soil contamination levels can be categorised into seven classes, i.e., uncontaminated ($I_{\mathrm{geo}} \le 0$), uncontaminated to somehow contaminated ($0 \le I_{\mathrm{geo}} \le 1$), moderately contaminated ($1 \le I_{\mathrm{geo}} \le 2$), rather to closely contaminated ($2 \le I_{\mathrm{geo}} \le 3$), closely contaminated ($3 \le I_{\mathrm{geo}} \le 4$), closely to very heavily/extraordinarily contaminated ($4 \le I_{\mathrm{geo}} \le 5$), and very heavily/extremely contaminated ($I_{\mathrm{geo}} > 5$) [39].

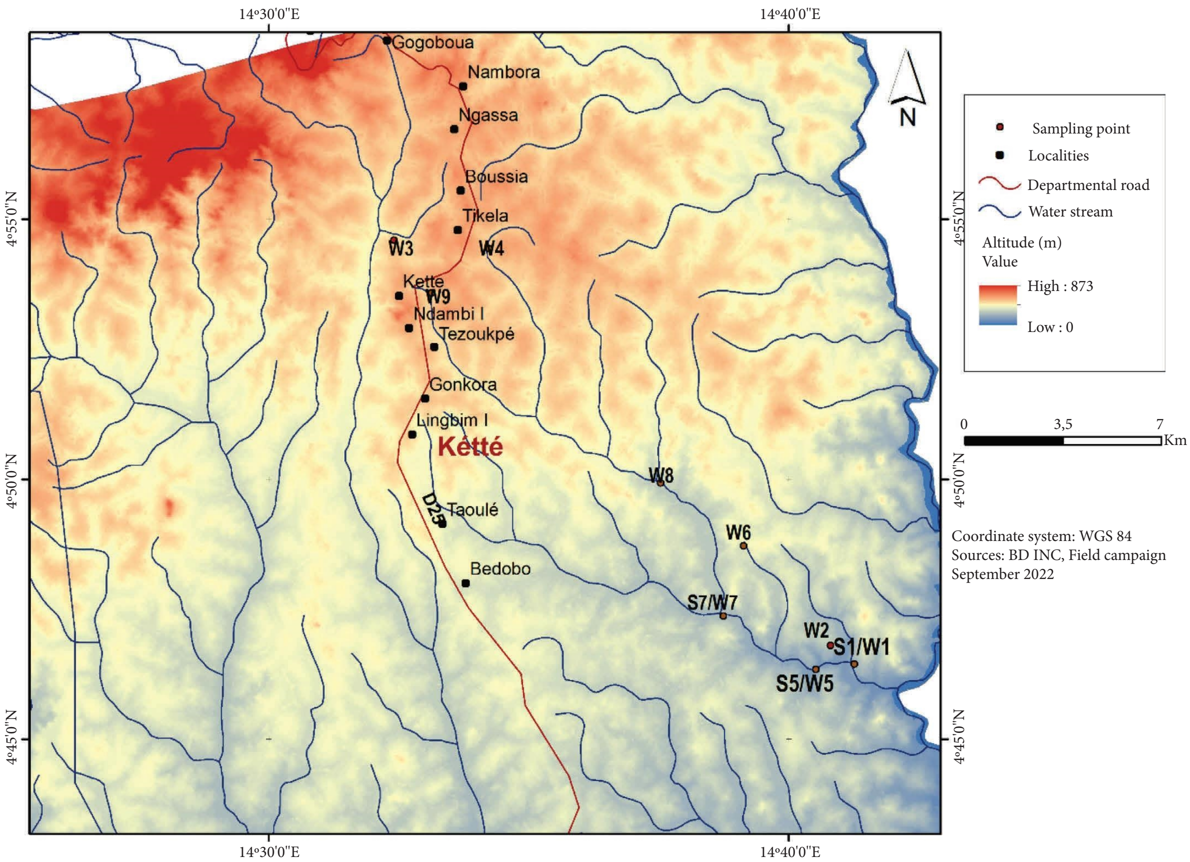

Figure 2: Sampling map.

Pollution indices and ecological risk assessment had been calculated primarily based on the common concentrations of studied trace metals. No research has been carried out on the location to determine the geochemical background concentrations. Therefore, the common shale concentration (ASC) defined by [26] can be used as the geochemical background value as it is regarded as the world standard reference for contaminated sediments.

3. Results and Discussion

3.1. Water Analysis. The results of the physical parameters studied here including the pH, electrical conductivity, turbidity, suspended solids (MESs), salinity, and colour are listed in Table 1. These chemical parameters were carried out on the major ions (cations and anions) and on heavy metals (iron, lead, mercury, and zinc). The obtained results showed that the pH value ranged from 5.11 to 6.07 which were moderately acidic. These results are similar to those obtained by the author [40] in the Mari bassin (Bétaré Oya, Cameroon) and by the authors in [41] in Kettara (Morocco). This pH is slightly below the WHO pH requirement for drinking water. These pH values can be attributed to the hydrolysis due to the presence of sulphates, notably pyrite which mostly accompanies gold. The different turbidity values for the samples range from 4 NTU to 1770.02 NTU, respectively, which is very high compared to the WHO standard (5 NTU). Only the S3 sample shows a turbidity value equal to 4 NTU, which is acceptable according to the WHO standards. The high turbidity value of the water collected from the mining site is due to the presence of organic particles from the soil and the washing, while the low value from the drinking borehole sample is because this bore is found very far from the mining site. Turbidity values are far higher than those obtained in previous studies [12, 42, 43]. The conductivity values for the water are lower than the maximum value recommended by the WHO norm (1055 μs/cm). This water is very mineralized, and these values are justified by the possibility of the presence of heavy metals at a high level in these sampling points. The suspended solids represent all the mineral and organic particles contained in the waters.

Figure 3 represents the results of the analysis of the physical parameters of the water samples with respect to the WHO standards for drinking water.

3.1.1. Major Ions. Table 2 represents the major ions concentrations for samples W3, W4, and W5 collected from the drinking borehole compared to the WHO standards. This is to enable a correlation between the health issues in this locality with the drinking water quality. The major ion concentrations in the Béké drinking borehole site were in the following order: $Ca^{2+} > Cl^{-} > Na^{+} > NO_3^{-} > SO_4^{2}$.

It is noted that the values of these chemical elements do not exceed the recommendation of the WHO standards. This is an indication that the drinking borehole in this

Table 1: Results of the physical parameters of the analyzed water samples.

Parameters	Samples									WHO standards
	W1	W2	W3	W4	W5	W6	W7	W8	W9	
pH	6.07	5.38	5.34	5.07	6.34	5.65	5.58	5.11	5.56	$6.5 < pH < 8.5$
Conductivity (μs/cm)	35	32.5	17.35	35.87	43.52	41.02	26.48	23.98	8.83	1055 μs/cm
Turbidity (NTU)	1710	1020	4	64.02	1770.0	1080.02	1649.98	959.98	124.02	5 NTU

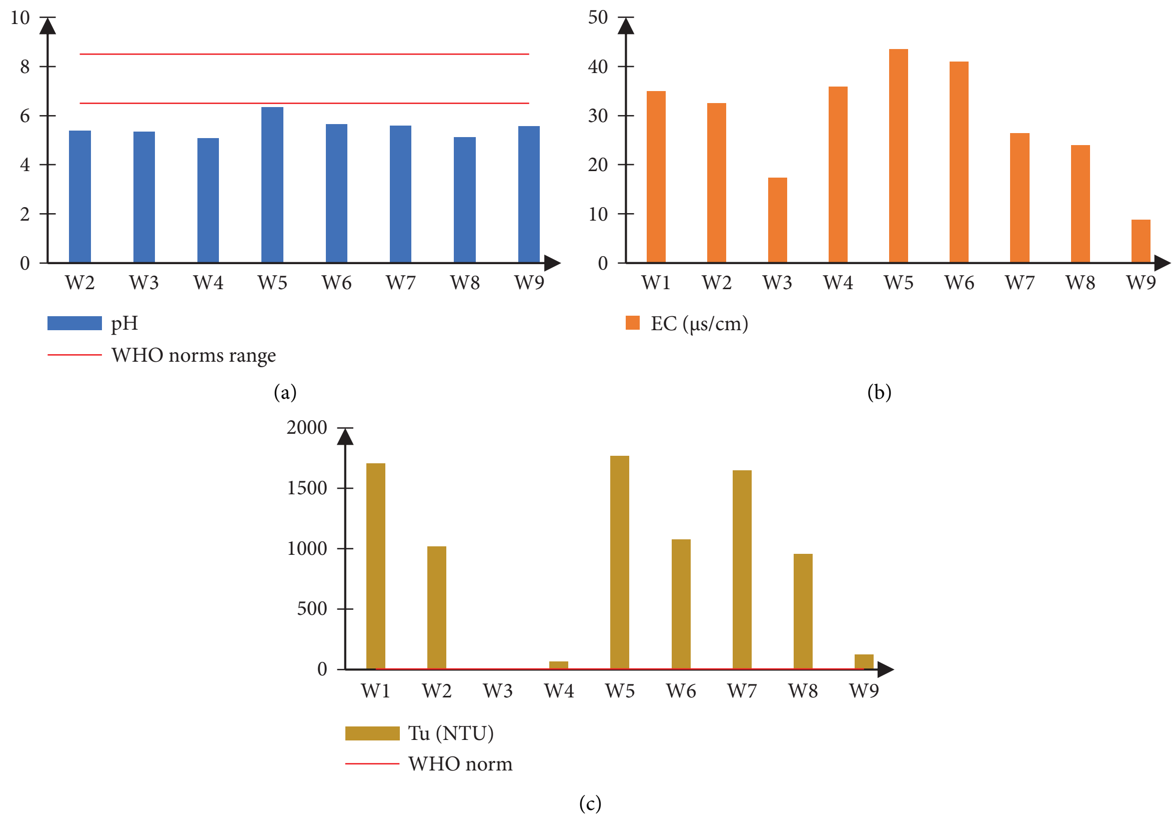

Figure 3: Spatial variation of the physical parameters in water: (a) pH; (b) EC; (c) Tu.

Table 2: Major ions concentrations in water samples.

Analyzed parameters	Samples			WHO norm
	W3	W4	W5	
Phosphate PO_4^{3-} (mg/l)	0	0	0	5 mg/l
Sulphates SO_4^{2-} (mg/l)	0	0.81	1.62	250 mg/l
Nitrates NO_3^- (mg/l)	0.045	0.4	0.75	50 mg/l
Chlorides Cl^- (mg/l)	45	45.45	44.55	250 mg/l
Sodium Na^+ (mg/l)	0.56	2.24	3.92	200 mg/l
Calcium Ca^{2+} (mg/l)	65	67.43	62.57	100 mg/l

locality is fit for consumption in terms of its chemical ions content. Figure 4 illustrates a comparison of the results of the major ions in samples W3, W4, and W5.

3.1.2. Result of Heavy Metal Analysis. Heavy metals are naturally redistributed in the surroundings by way of geological procedures and biological cycles. In general, the tailings from gold extraction are a significant source of heavy metals in water, as well as chemicals used during the separation of gold and excavation. Their concentrations can fluctuate widely, depending on the extent of exposure of these minerals [44, 45]. However, above certain limits, they come to be toxic to humans. The heavy metal concentrations in the analyzed samples are introduced in Table 3. The order of abundance was $Fe > Pb > Zn > Hg$.

The results of our analysis show that the Pb, Fe, and Hg concentrations for samples W1–W9 except W3 are higher than the values given by the WHO guideline. This indicates the contamination of the water table by gold

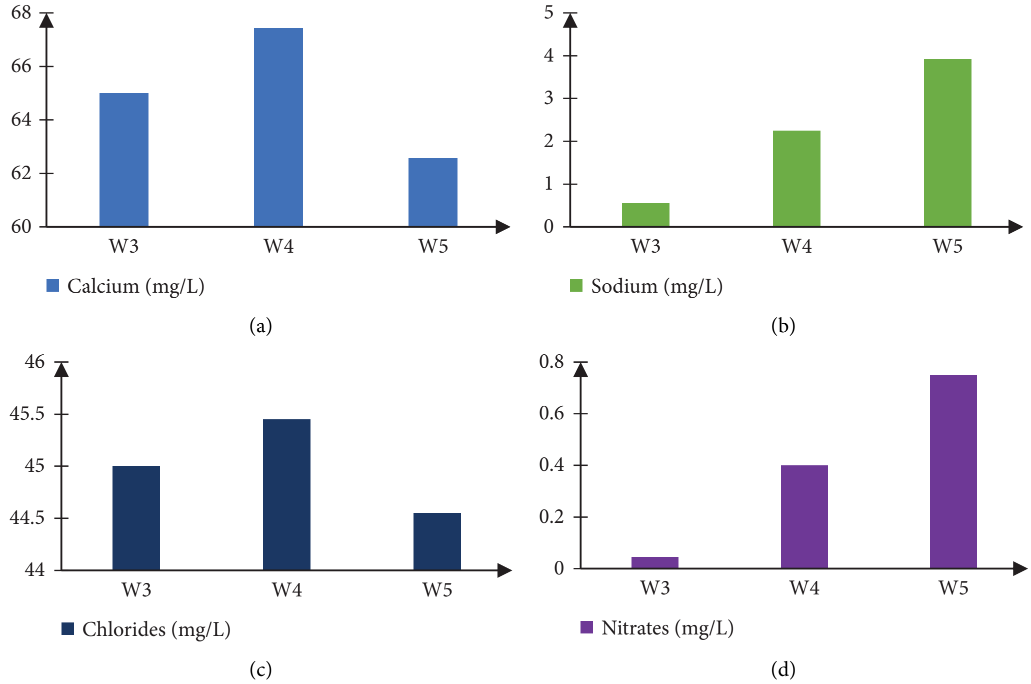

Figure 4: Spatial variation of ions concentration: (a) calcium; (b) sodium; (c) chlorides; (d) nitrates.

Table 3: Results of heavy metal concentrations in water samples.

Parameters (mg/L)	Samples									WHO standards (mg/L)
	W1	W2	W3	W4	W5	W6	W7	W8	W9	
Lead (Pb)	0.31	1.52	0.01	1.19	1.49	2.27	2.67	0.34	2.37	0.01
Iron (Fe)	8.1	6.7	0	2.36	9.28	7.88	6.92	5.52	1.18	0.3
Mercury (Hg)	0.02	0.31	0	0.63	0.65	0.94	1.28	1.57	1.26	0.001
Zinc (Zn)	—	—	0.2	0.76	—	—	—	—	1.32	3 mg/L

washing waste water. The gold washing waste water from the mining site is channeled to the river course which implies that the surface water in this locality is contaminated by heavy metals. The Pb, Fe, Hg, and Zn concentration values for sample W3 are below those of the WHO guideline for drinking water. This indicates that the water from the borehole is suitable for consumptions. This can be explained by the position and distance between the sampling point and the mining site. These heavy metals are presented in Figure 5.

3.2. Result of Sediment Sample Analysis. The results of the sediment sample analysis are represented in Table 4.

From the results of the sediment sample analysis, we notice that Fe has the highest concentration amongst the heavy metals found in the sediment sample. This can be attributed to ferralitic soil type found in the Kétte-Béké mining zone. This could also be as a result of the weathering and erosion of Fe-rich rocks during the raining season. The weathered and eroded materials from Fe-rich rocks which are transported and deposited at the river banks could be responsible for this high concentration. The average Fe concentration (46118.43 mg/kg) was higher than that reported for the sediments of Metaloui stream in the food phosphate mud mining area [46] and also higher than the value (35886.71 mg/kg) obtained by [47].

3.3. Impacts on Soil and Water. Gold mining in the site where our studies was carried out has led to landscape destruction due to the displacement of large quantities of rocks and sterility which has created large artificial lakes (Figure 6) and pits with stagnant water. It has also led to the destruction of the vegetation cover and soil degradation. The cutting down of trees has led to the loss of some key forest objects leaving it sterile and poor in vegetation. The noise from the installation and manipulation of machines has chased away wildlife. The effluent from the washing of gold is deposited in to the river (Figure 7). This effluent contains chemicals and heavy metal vectors which can lead to water and soil pollution. Sulphide mining residue when exposed to air or water can generate acidic effluent, thereby causing water and soil pollution.

Gold mining in the Béké mining site makes use of a very large surface area which is the principal cause of landscape modification (Figures 8(a) and 8(b)). This is also the case in Ghana at Central African Gold Bibiani Limited, where we

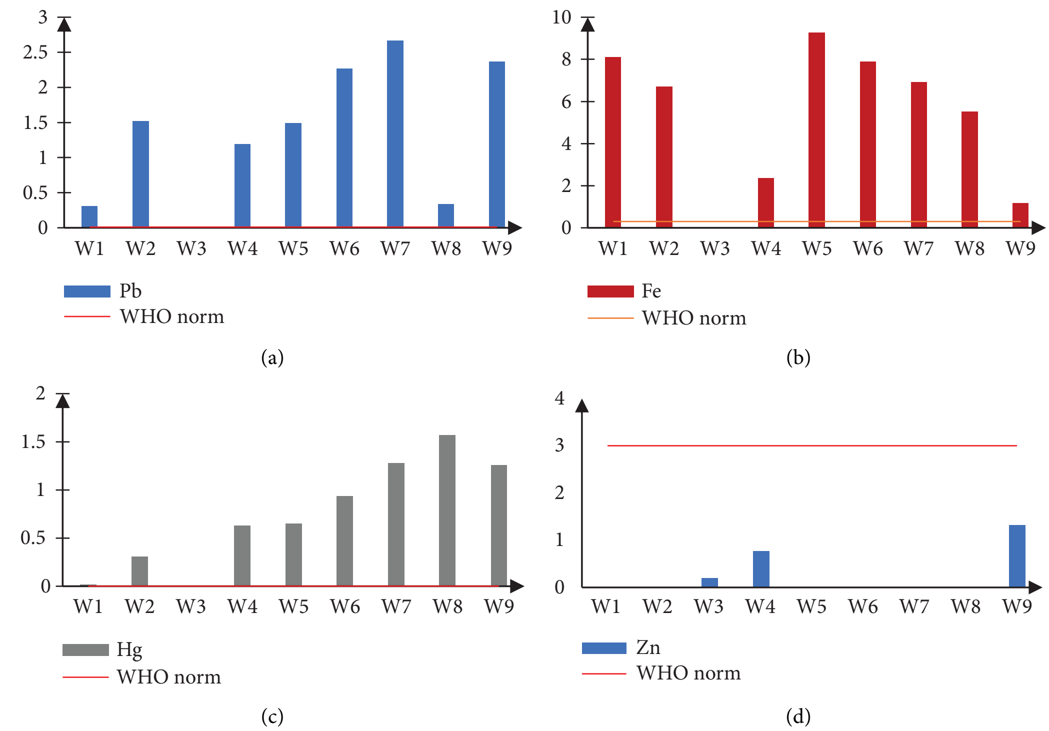

Figure 5: Special variation of lead, iron, mercury, and zinc in water samples: (a) Pb; (b) Fe; (c) Hg; (d) Zn.

Table 4: Results of soil sample analysis.

Analyzed parameters	Samples		
	S1	S5	S7
Fe (mg/kg)	46118.76	43258.54	48978
Mn (mg/kg)	864.54	854.26	874.82
Cu (mg/kg)	6.98	31.26	19.12
Zn (mg/kg)	2.2	0.3	4.11
Pb (mg/kg)	25.06	24.62	25.5
Cr (mg/kg)	54.17	63.66	44.68

Figure 6: Artificial lake.

Figure 7: Effluent from gold washing.

observed small-scale gold mining responsible for the removal of large quantities of plant cover and massive deforestation [48]. In order to access, gold excavation is done up to 15 meters deep which also causes the displacement of large volume of rocks and sterility. Gold mining in this zone also involved the cutting down of trees, soil excavation, and deviation of the river course. It has also led to the destruction of the vegetation cover and soil degradation. This activity also leads to the displacement of some animal and plant species. These can be mitigated by taking suitable measures to preserve some rare species.

The solid and liquid wastes such as waste oil from machines are a source of soil pollution. The use of chemical products such as mercury is also a potential source of soil pollution. The erosion of hips of soil during the raining season increases the amount of suspended solids and the turbidity in the Béké river. This can be seen from the results of the water sample analysis. These impacts can be corrected or mitigated by the recycling or treatment of mining effluents before final deposition and also by the restoration or rehabilitation of the site.


(a)


(b)

Figure 8: Degradation of landscape.

Table 5: Contamination factor.

Samples	CF (Fe)	CF (Mn)	CF (Cu)	CF (Zn)	CF (Pb)	CF (Cr)
S1	0.98	1.01	0.15	0.02	1.25	0.60
S5	0.92	1.00	0.69	0.003	1.23	0.70
S7	1.04	1.02	0.42	0.04	1.27	0.49

3.4. Evaluation of Contamination Intensity. Anthropogenic effects of investigated trace metals on sediment quality were previously reported by CF in Table 5.

The CF of Fe ranged from 0.92 to 1.04 and was low at all the sampling points except the sampling point S7 with a moderate contamination (1.04), corresponding to the maximum value of the study area but lower than those obtained by [47] (2.66) and [23] (1.31). The CF of Mn ranged from 1 to 1.02, corresponding to a moderate contamination. For Cu, Zn, and Cr, the CF values indicated no contamination. A moderate contamination was identified at all points according to the CF of Pb which ranged from 1.23 to 1.25. Overall concentration of trace elements follows the following order: Pb > Mn > Fe > Cr > Cu > Zn.

Figure 9 represents the results of CD, PLI, and NI calculated from CF data.

The PLI was below 1 at all the sampling points. This showed a perfect state of pollution of sediments according to the PLI. The CD values of all samples showed a moderate contamination (CD < 6). These results show that the development of the mining industry progressively increased the inputs of trace metal concentrations into the environment. Despite the natural input of trace metals, they are exposed during excavation operations on the mining site, increasing their concentration and consequently the contamination degree on the site. To assess the pollution risk from several trace metals in the sediments of the Béke mining site, the NI was used. The NI ranged from 1 to 1.03, showing a light pollution.

The harm of studied trace metals in sediments was evaluated by E_r^i and RI. The results of E_r^i and RI assessments are reported in Table 6. The I_{geo} was applied to certify the geochemical figures of the trace metals in sediments.

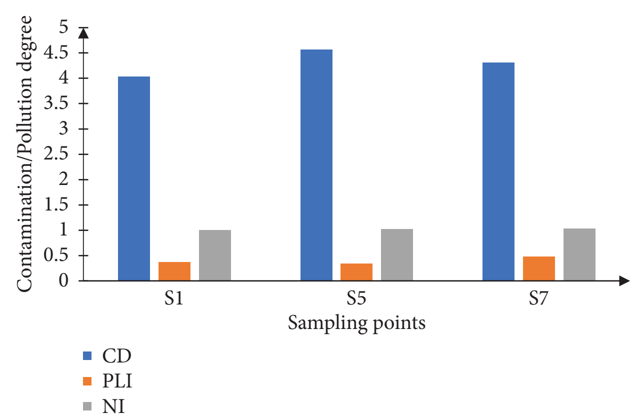

Figure 9: Contamination degree, pollution load index, and Nemerow index.

E_r^i for all trace metals shows the decreasing order of Pb > Cu > Cr > Mn > Fe > Zn. E_r^i was low ($E_r^i \leq 40$) for all the studied trace metals, and the maximum value of RI (12.95) obtained was also classified to low risk (RI ≤ 150). According to the RI, the concentrations of trace metals in sediments along the studied section of Lom River were not alarming.

The results of EF assessment of studied trace metals in sediments are presented in Table 7.

An EF between 0.5 and 1.5 indicates that the concentration of a given metal is mainly the result of weathering of the geological material, while values above 1.5 indicate the presence of anthropogenic inputs or from other sources (Tang et al., 2010). The EF for all trace metals showed the decreasing order of Mn > Cr > Pb > Fe > Cu > Zn (Table 8). The EF of all trace metals in the tree samples corresponds to a minimal enrichment (EF < 2). For Cu, the EF value of sample S5 exceeded 1.5 and revealed the presence of anthropogenic inputs.

Table 6: Ecological risk index.

Sample	E_r^i (Fe)	E_r^i (Mn)	E_r^i (Cu)	E_r^i (Zn)	E_r^i (Pb)	E_r^i (Cr)	RI
S1	0.98	1.01	0.77	0.023	6.26	1.2	10.25
S5	0.92	1	3.47	0.003	6.15	1.41	12.95
S7	1.04	1.02	2.12	0.04	6.37	0.99	11.58

Table 7: Enrichment factor.

Samples	EF (Fe)	EF (Mn)	EF (Cu)	EF (Zn)	EF (Pb)	EF (Cr)
S1	1	1.09	0.33	0.02	0.98	1.03
S5	1	1.15	1.59	0.004	1.03	1.29
S7	1	1.04	0.86	0.04	0.94	0.8

Table 8: Geoaccumulation index.

Samples	I_{geo} (Fe)	I_{geo} (Mn)	I_{geo} (Cu)	I_{geo} (Zn)	I_{geo} (Pb)	I_{geo} (Cr)
S1	0.19	0.18	0.03	0.004	0.25	0.12
S5	0.18	0.18	0.15	0.0006	0.24	0.14
S7	0.21	0.18	0.09	0.008	0.25	0.09

Table 8 summarizes the results of I_{geo} in sediments of the study area.

The I_{geo} values of trace metals in sediments of the Béké mining site are in the range of 0 to 1, corresponding to uncontaminated to moderately almost equal to those obtained by [23].

4. Conclusion

The main objective of this work was to carry out a physicochemical characterisation of water and sediment of semimechanized and artisanal gold mining activity in the locality of Béké. A field work was carried out, and three soils samples were collected and analyzed to assess the intensity of soil contamination. The water samples (W1–W9) were characterized physically and chemically to evaluate the water quality contamination. The results of the physicochemical analysis of the water samples showed that the rivers in this zone are moderately acidic (with pH values ranging from 5.11 to 6.37) and slightly mineralized (with samples W2, W6, and W8 collected from the Béké river having an iron concentration of 6.7 g/L, 7.88 g/L, and 5.2 g/L, respectively). All the physical parameters (pH, conductivity, turbidity, total dissolve solids, suspended solids, salinity, and colour) and chemical parameters (phosphate ion, calcium ion, and potassium ion) of samples W1, W2, W4, W5, W6, W7, W8, and W9 has significantly exceeded the limits prescribed by the World Health Organization (WHO) guidelines for drinking water. All the physical and the major ions (sodium ion, phosphate ion, calcium ion, potassium ion, nitrate ion, sulphate ion, and chloride ions) of sample W3 (collected from the drinking borehole) on the other hand complies with the WHO standards. Pollution indices and an ecological risk assessment were used to evaluate levels of metal contamination. Based on pollution indices and ecological risk assessment, the level of metallic contamination in the sediment was overall low to moderate. All of the abovementioned results provide ample evidence of the role of mining in the deterioration of water quality. The identification and evaluation of impacts reveal that the semimechanized and artisanal gold mining in Béké though very economically profitable has very significant environmental consequences such as land degradation, deforestation, soil pollution, water pollution, and landscape modification.

Data Availability

The data used to support the findings of this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Mambou Nguepep Luc Leroy conceptualized the study and proposed the methodology. Mefomdjo Fotie Blanche, Kapta Momegni Christian, and Ebua Eta Manyi Audrey performed formal analysis and investigated the study. Kapta Momegni Christian, Ebua Eta Manyi Audrey, Mefomdjo Fotie Blanche, Boukari Harouna, and Elhadji Daou Ibrahim wrote the draft paper. Tchuikoua Louis Bernard and Mambou Nguepep Luc Leroy supervised the works and read the final version. All the authors have reviewed the manuscript.

References

[1] M. Deshaies, "Grands projets d'exploitation minière et stratégie des firmes pour se rendre environnementalement acceptables," *L'Espace Politique*, vol. 15, 2011.

[2] I. Butaré et and S. Kéita, *Aspects environnementaux liés au développement du secteur minier en Afrique de l'Ouest (Rapport technique)*, Centre de recherches pour le développement international (CRDI), Dakar, Sénégal, 2010.

[3] C. Mestanza, J. Cuenca-Cumbicus, G. D'Orio et al., "Gold mining in the Amazon region of Ecuador. History and review of its socio-environmental impacts," *Land*, vol. 11, 2022.

[4] N. Mujere and M. Isidro, “Impacts of artisanal and small-scale gold mining on water quality in Mozambique and Zimbabwe,” *IGI Global Book Series Practice, Progress, and Proficiency in Sustainability (PPPS)*, IGI Global, Hershey, PA, USA, 2015.

[5] L. L. Tampushi, J M. Onyari, and N. Muthama, “Assessing Assessing Social and Environmental Impacts of Artisanal and Small-Scale Gold Mining Practices in Lolgorian, Kenya,” *European Journal of Sustainable Development Research*, vol. 6, no. 3, 2022.

[6] F. Nana Gyawu-Asante, “Physico-chemical quality of water sources in the gold mining areas of bibiani,” Master of science thesis the Department of Theoretical and Applied Biology, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, 2012.

[7] P. Anane-Acheampong-Osisiadam, L. Darkwah, and G. Owusu-Boatenng, “Mine water and environment: a case study at ceentral African Gold Bibiani Limited, Ghana,” *Global Advanced Research Journal of Physics Applied Physics*, vol. 2, 2013.

[8] S. Obiri, P. Mattah, M. Mattah et al., “Assessing the environmental and socio-economic impacts of artisanal gold mining on the livelihoods of communities in the tarkwa nsuaem municipality in Ghana,” *International Journal of Environmental Research and Public Health*, vol. 13, 2016.

[9] J. A. Awomeso, A. M. Taiwo, E. O. Dada, and O. O. Ayantobo, “Human health and environmental assessments of small-scale and artisanal mining activities in the Gold City of Ijeshaland, Southwestern Nigeria,” *Environmental Systems Research*, vol. 6, no. 1, p. 18, 2017.

[10] A. Banunle, B. Fei-Baffoe, and K. G. Otchere, “Determination of the physico-chemical properties and heavy metal status of the Tano River along the catchment of the Ahafo mine in the BrongAhafo region of Ghana,” *Journal of Environmental and Analytical Toxicology*, vol. 3, 2018.

[11] S. A. Yao Kouassi et and E. Ahoussi Kouassi, *Caractérisation physico-chimique des eaux de surface sans un environnement minier du Centre-Ouest de la Côte d’Ivoire: Cas du département de Divo*, European scientific, Strasbourg, France, 2020.

[12] F. Rakotondrabe, J. Ngoupayou, Z. Mfonka et al., “Assessment of surface water quality of bétaré-oya gold mining area (East-Cameroon),” *Journal of Water Resource and Protection*, vol. 9, no. 8, pp. 960–984, 2017.

[13] A. Talla and C. Moandjim-Me-Bock, “The impact of wastewater from artisanal mining on the pollution of contaminated sites: a case study of betare-oya in EastEast Cameroon,” *Advances in Research*, vol. 16, no. 2, pp. 1–12, 2018.

[14] R. Obase, G. Ngoran, F. Nde, H. Luma, and G. Ngwane, “Impact of artisanal gold mining on human health and the environment in the batouri gold district, East Cameroon,” *Academic journal of interdisciplinary journal*, vol. 7, no. 1.

[15] L. L. Mambou, J. R. Mache, M. Ayiwouw, S. Takougang, R. Y. Abende, and S. Roukayatou, “Physicochemical characterization of mining waste from the betare-oya gold area (East Cameroon) and an adsorption test by sabga smectite (North-West Cameroon),” *Hindawi, Scientifica*, vol. 2020, Article ID 6293819, 12 pages, 2020.

[16] M. M. Njayou, M. Ngounouno Ayiwouo, and I. Ngounouno, “Trace metal contamination status in soils of the abandoned gold mining district of Bindiba (East Cameroon): pollution indices assessment, multivariate analysis and; geostatistical approach,” *J Environ Health Sci Engineer*, vol. 21, no. 1, pp. 143–155, 2023.

[17] R. A. Petta, S. Sindern, R. F. Souza, and T. F. C. Campos, “Influence of mining activity on the downstream sediments of scheelite mines in Currais Novos (NE Brazil),” *Environmental Earth Sciences*, vol. 72, no. 6, pp. 1843–1852, 2014.

[18] O. Karaca, C. Cameselle, and K. Reddy, “Acid pond sediment and mine tailings contaminated with metals: physicochemical characterization and electrokinetic remediation,” *Environmental Earth Sciences*, vol. 76, no. 12, pp. 408–412, 2017.

[19] H. Guzmán, A. Gómez-Álvarez, J. Valenzuela-García, M. A. Encinas-Romero, A. I. Villalba-Atondo, and K. Encinas-Soto, “Assessment of the impact on sediment quality from abandoned artisanal mine runoffs in a semi-arid environment (the Sonora River basin—northwestern Mexico),” *Environmental Earth Sciences*, vol. 78, no. 5, pp. 145–214, 2019.

[20] J. Song, Q. Liu, and Y. Sheng, “Distribution and risk assessment of trace metals in riverine surface sediments in gold mining area,” *Environmental Monitoring and Assessment*, vol. 191, no. 3, pp. 191–213, 2019.

[21] S. Bouzekri, H. E. El Fadili, M. L. El Hachimi, M. El Mahi, and E. M. Lotfi, “Assessment of trace metals contamination in sediment and surface water of quarry lakes from the abandoned Pb mine Zaida, High Moulouya-Morocco,” *Environment, Development and Sustainability*, vol. 22, no. 7, pp. 7013–7031, 2019.

[22] L. Yi, B. Gao, H. Liu, Y. Zhang, C. Du, and Y. Li, “Characteristics and assessment of toxic metal contamination in surface water and sediments near a uranium mining area,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 2, p. 548, 2020.

[23] M. Ngounouno Ayiwouo, L. L. Ngueyep Mambou, S. T. Kingni, I. Ngounouno, and I. Ngounouno, “Spatio temporal variation and assessment of trace metal contamination in sediments along the Lom River in the gold mining site of Gankombol (Adamawa Cameroon),” *Environmental Earth Sciences*, vol. 81, no. 14, p. 379, 2022.

[24] Pcd Commune de Kétté, “Reseau D’APPUI au developpement communautaire (radec),” 2011, https://www.oyili.org/home-12-association-inner-3-detail-2449.html.

[25] World Health Organization, *Guidelines for Drinking-Water Quality. Recommendations*, World Health Organization, Geneva, Switzerland, 2011.

[26] K. Turekian and K. Wedepohl, “Distribution of the elements in some major units of the earths crust,” *Geological Society of America Bulletin*, vol. 72, no. 2, pp. 175–192, 1961.

[27] Z. Ali, R. N. Malik, Z. K. Shinwari, and A. Qadir, “Enrichment, risk assessment, and statistical apportionment of heavy metals in tannery-affected areas,” *International journal of Environmental Science and Technology*, vol. 12, no. 2, pp. 537–550, 2015.

[28] M. Nouri and A. E. M. Haddioui, “Assessment of metals contamination and ecological risk in ait Ammar abandoned iron mine soil, Morocco,” *Ekologia*, vol. 35, no. 1, pp. 32–49, 2016.

[29] H. Ahdy and A. Khaled, “Heavy metals contamination in sediments of the western part of the Egyptian Mediterranean Sea,” *Australian Journal of Basic and Applied Sciences*, vol. 3, pp. 3330–3336, 2009.

[30] D. Tomlinson, J. G. Wilson, C. R. Harris, and D. W. Jeffrey, “Problems in the assessment of heavy metal levels in estuaries and the formation of a pollution index,” *Helgolaender Meeresuntersuchungen*, vol. 33, no. 1–4, pp. 566–575, 1980.

[31] K. Mohiuddin, H. Zakir, K. Otomo, S. Sharmin, and N. Shikazono, “Geochemical distribution of trace metal pollutants in water and sediments of downstream of an urban

river," *International journal of Environmental Science and Technology*, vol. 7, no. 1, pp. 17–28, 2010.

[32] G. Qingjie, D. Jun, X. Yunchuan, W. Qingfei, and Y. Liqiang, "Calculating pollution indices by heavy metals in ecological geochemistry assessment and a case study in parks of Beijing," *Journal of China University of Geosciences*, vol. 19, no. 3, pp. 230–241, 2008.

[33] A. A. Yari, J. Varvani, and R. Zare, "Assessment and zoning of environmental hazard of heavy metals using the Nemerow integrated pollution index in the vineyards of Malayer city," *Acta Geophysica*, vol. 64, 2020.

[34] W. Guo, X. Liu, Z. Liu, and G. Li, "Pollution and potential ecological risk evaluation of heavy metals in the sediments around dongjiang harbor, tianjin," *Procedia Environmental Sciences*, vol. 2, pp. 729–736, 2010.

[35] X. Luo, B. Ren, A. S. Hursthouse, J. R. M. Thacker, and Z. Wang, "Soil from an abandoned manganese mining area (hunan, China): significance of health risk from potentially toxic element pollution and its spatial context," *International Journal of Environmental Research and Public Health*, vol. 17, no. 18, p. 6554, 2020.

[36] J. F. Chifoleau, D. Claisse, D. Cossa et al., "La Contamination Métallique. Programme scientifque Seine Aval," 2001, https://www.eyrolles.com/BTP/Livre/la-contamination-metallique-9782844330659/.

[37] G. Müller, "Index of geoaccumulation in sediments of the rhine river," *Geojournal*, vol. 2, pp. 108–118, 1969.

[38] S. R. Taylor, "Abundance of chemical elements in the continental crust: a new table," *Geochimica et Cosmochimica Acta*, vol. 28, no. 8, pp. 1273–1285, 1964.

[39] S. K. Sarkar, *Trace Metals in a Tropical Mangrove Wet Land*, Springer Nature Singapore Pte Ltd, Singapore, 2018.

[40] P. Simo, *Impact de l'exploitation minière sur la qualité des eaux du bassin de Mari à Bétaré-Oya*, Mémoire de maîtrise, Université de Yaoundé I, Cameroun, 2014.

[41] R. Hakkou and M. Benzaazoua et Bussière Bruno, "Évaluation de la qualité des eaux de ruissellement dans la mine abandonnée de Kettara (Maroc)," 2006, https://www.researchgate.net/publication/239579338_Evaluation_de_la_qualite_des_eaux_de_ruissellement_dans_la_mine_abandonnee_de_Kettara_Maroc.

[42] M. Ayiwouo, L. L. Mambou Ngueyep, J. R. Mache, S. Takougang Kingni, and I. Ngounouno, "Waters of the Djouzami gold mining site Adamawa Cameroon Physico-chemical characterization and treatment test by Bana smectite (West Cameroon)," *Case Studies in Chemical and Environmental Engineering*, vol. 2, Article ID 100016, 2020.

[43] M. Ayiwouo, L. L. Mambou, J. R. Mache, S. Kingni, S. Nforsoh, and I. Ngounouno, "Evaluation of the impact of gold mining activities on the waters and sediments of Lom River, Wakasso, Cameroon and the restorative efect of Moringa Oleifera seeds," *Applied Water Science*, vol. 11, 2021.

[44] J. Li, F. Li, Q. Liu, and Y. Zhang, "Trace metal in surface water and groundwater and its transfer in a yellow river alluvial fan: evidence from isotopes and hydrochemistry," *Science of the Total Environment*, vol. 472, pp. 979–988, 2014.

[45] H. Pahimi, C. R. Panda, M. B. Ngassoum, and R. Tchameni, "Environmental impacts of mining in the volcano-sedimentary basins of Cameroon: case study of artisanal gold mine tailings (Betare Oya, East-Cameroon)," *International Journal of Energy, Sustainability and Environmental Engineering*, vol. 2, pp. 5–15, 2015.

[46] F. Srarf, R. Rachdi, R. Bol, M. L. Gocke, N. Brahim, and S. N. Shimi, "Stream sediments geochemistry and the infuence of food phosphate mud in mining area, Metlaoui, Western south of Tunisia," *Environmental Earth Sciences*, vol. 78, no. 211, pp. 1–13, 2019.

[47] K. Manoj and P. Padhy, "Distribution, enrichment and ecological risk assessment of six elements in bed sediments of a tropical river, chottanagpur plateau: a spatial and temporal appraisal," *Journal of Environmental Protection*, vol. 5, no. 14, pp. 1419–1434, 2014.

[48] G. Hilson, "The environmental impact of small-scale gold mining in Ghana: identifying problems and possible solutions," *The Geographical Journal*, vol. 168, no. 1, pp. 57–72, 2002.