Ecological and human health risks assessment of Arsenic in sediments around gold mining areas in northern Côte d'Ivoire

Abstract

Arsenic contamination of sediments is a worldwide concern, both for the environment and for human health. However, few data are available on the state of arsenic pollution in sediments near artisanal and industrial gold mining areas in Côte d'Ivoire. The aim of this study is to assess the spatial distribution of arsenic and itsecological and human health risks in sediments around gold mining areas in northern Côte d'Ivoire. Sampling was carried out in artisanal and industrial mining areas inKorhogo and Tengrela, northern Côte d'Ivoire. Spatial differences were determined using analysis of variance. Pollution indices were studied using the contamination factor and the enrichment factor. Non-carcinogenic and carcinogenic risk indices were used to investigatehuman health risks. The study revealed total arsenic concentrations ranging from 1.64 ± 0.04 to 159.72 ± 51.91 µg/g.It found Arsenic concentrations in sediments variedconsiderably from station to station. The results of the contamination factor indicated that the sediments wereweakly to very strongly contaminate with arsenic.Non-carcinogenic risk index values ranged from 1.83E-04 to 1.78E-02, indicating low adverse effects on the surrounding habitats.In addition, the results of the potential risk (CRt) for human health revealed the existence of significant carcinogenic risks from arsenic for residents in the vicinity of the Tongon mining area.

Keywords: Arsenic, Gold mining, Sediment, Pollution Indices, Potential risk, Carcinogenic risk index

1. Introduction

Mining activities are widespread in many developing countries, such as Côte d'Ivoire [1, 2]. These various mining activities provide incomes around three to five times higher than other small-scale rural activities in agriculture, forestry, and fishing [3, 4]. However, gold mining is one of the main anthropogenic activities responsible for the release of arsenic (As) into the environment. This activity poses a potential threat to environmental resources and health problems for humans and animals [5, 6]. For example, chronic exposure to arsenic has been found to provoke humungousdiseases such as kidney and lung cancers, and reproductive organ dysfunction [7].For this reason, environmental studies of mining areas are important to protect the health of residents and the levels of arsenic contamination [8, 9]. High concentrations of arsenic in air, sediments, soils, fishery products, and water due to mining activities have been reported in many countries including China, Côte d'Ivoire, and Morocco. Excessive amounts of arsenic in aquatic systems are mainly linked to mining and other activities such as agriculture [10, 11]. In addition, in aquatic systems, sediments represent a sink for chemical pollutants [12]. They are therefore considered as a suitable indicator of aquatic arsenic pollution. Nevertheless, adsorbed pollutants in sediments can be released into the water column under varying physicochemical conditions [7].In Côte d'Ivoire, there has been significant development of agricultural and mining activities in the north of the country, especially in the Poro District. These activities have proved to be potential sources of arsenic in the environment [7]. Numerous research studies have documented arsenic contamination in sediments around mining areas in West Africa, with studies focusing on Nigeria [13, 14], Senegal [15], and Ghana [16, 17]. Recently, Kinimo et al. [18] showed that sediments from the gold mining area in southeastern Côte d'Ivoire were

contaminated with arsenic. Furthermore, in our study area, the use of chemical fertilizers in vegetable and fruit production in market garden crops around the Bandama and Bagoué riversin northern Côte d'Ivoire., can contain large amounts of arsenic [19]. Consequently, soil leaching by rainwater can lead to the presence of large quantities of arsenic in surface waters. Thus, arsenic must be taken into account when assessing the level of environmental pollution in this area.The objectives of the present study were (i) to determine total arsenic concentrations in surface sediments, (ii) to assess the level of contamination using pollution indices, (iii) to evaluate ecological and human health risks, and (iv) to explorearsenic mobility using the sequential extraction procedure.

2. Material and methods

2.1. Study Area

The study area covers the Bandama and Bagoué rivers in the Savannah District of northern Côte d'Ivoire (Figure 1). The Bandama River is in the Korhogo region, while the Bagoué River is in the Tengrela region. The Bandama River is the largest river in Côte d'Ivoire, with its source in northern Côte d'Ivoire, between Korhogo and Boundiali. [20-22]. The Bagoué river is a small river in northern Côte d'Ivoire. It rises in the Kokoum region, near the border between Côte d'Ivoire and Mali, passing through Tengrela (Côte d'Ivoire). In this study, two towns were selected in the Savannah District (Korhogo and Tengrela) to get an idea of the state of arsenic contamination in their environments. The sites selected were the Korhogo gold zone (stations R1 to R5, M1 to M5, and K1 to K10) and the Tengrela gold zone (stations T1 to T10). This was favored by the establishment of two gold industries, Ran Gold (Korhogo) and Perseus Mining (Tengrela) in these towns, as well as the existence of several artisanal and small-scale extractions.

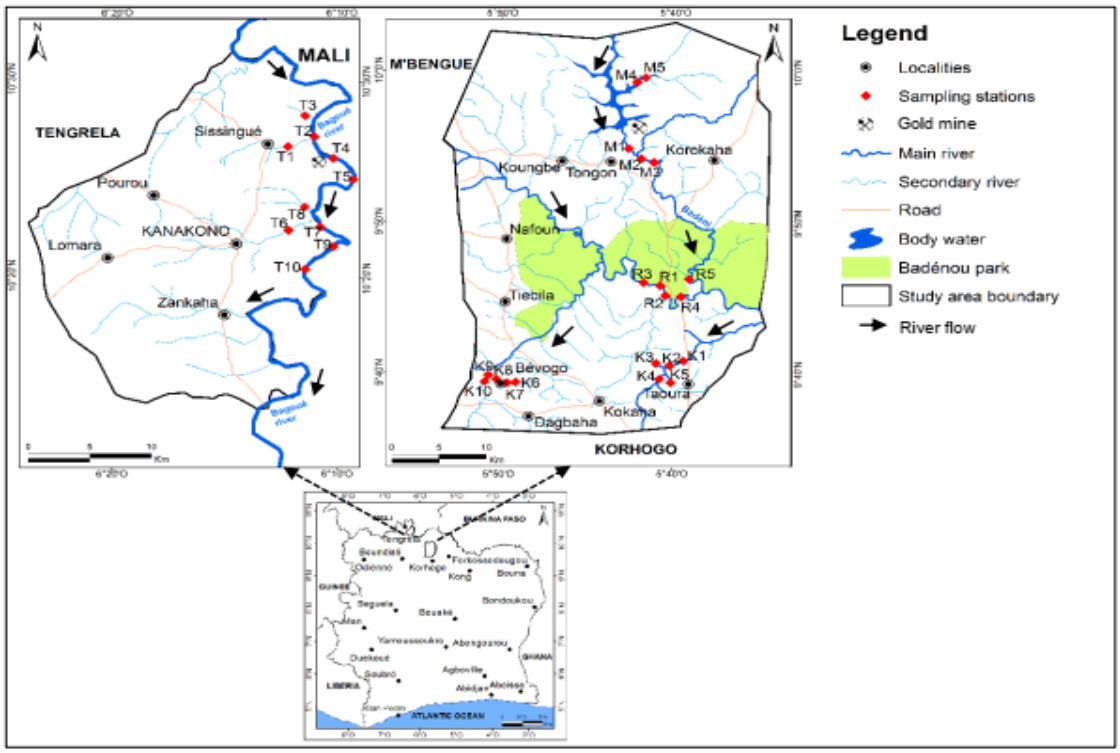

Figure1. Location of the SavannahDistrict and sediments sampling sites

Sissingue(T1, T2, T3, T4, T5**); Kanakono**(T6, T7, T8, T9, T10**); Tongon**(M1, M2, M3, M4, M5**);**

Badenou(R1, R2, R3, R4, R5**); Taoura**(K1, K2, K3, K4, K5**); Bevogo**(K6, K7, K8, K9, K10)

2.2. Sediment characterization and heavy metal analysis

Surface sediment sampling campaigns took place in 2016 during the dry season. Sediments were collected in accordance with USEPA (2001) using a Van Veen stainless steel grab sampler. Samples were sealed in plastic bags.Then, they were kept at 4°C and transported to the laboratory. Afterwards, they were oven-dried at 60°C, homogenized, and stored at 4°C until analysis [7]. After collection of the sediment samples, digestion and measurement of arsenic concentrations were described by N'goran et al. [23].

2.3. Sequential extraction of heavy metals

A modifiedBCR sequential extraction procedure [24] was performed on 1g of dried samples. Acid-soluble fraction (F1) was extracted by 40 mL of 0.11 M acetic acid at room temperature for 16h (step 1). The residue from step 1 was leached with 40 mL of 0.5 M hydroxylamine hydrochloride, pH = 1.5 at room temperature for 16h (step 2) to receive reducible fraction (F2). The residue from the second extraction step was treated twice with 5 mL of 8.8 M hydrogen peroxide (pH = 2) at room temperature for 1h.And then, it washeated at 80°C for1h. After cooling down, 20 mL of 1.0 M ammonium acetate (pH = 2) was added to the obtained sample at room temperature for 16h in order to extract oxidizable fraction (F3) (step 3). The residue from step 3 was digested using a mixture of HNO_3-HCl (1:3) at 180°C for 2h 30 min (residual fraction) [39,40]. Previous study upon river sediment showed recoveries (Recovery $= \frac{F1+F2+F3+R}{Pseudo\ -total} \times 100$) of this method in the range of 96–103% for As.

2.4. Environmental assessment

2.4.1.Contamination factor (CF)

The contamination factor (CF) wascalculated to assess the level of arsenic contamination. The contamination factor was calculated as follows [25]:

$$CF=\frac{C_{arsenic\ \ (sediment\ \ )}}{C_{arsenic\ \ (background\ \ )}}(1)$$

Where $C_{arsenic}$ (sediment) is the concentration of arsenic in the sediment sample and $C_{arsenic}$ (background) is arsenic background value given by Wedepohl [26]. Four classes of CF have been distinguished by Hakanson [25]: class 1 (low contaminated) CF < 1; class 2 (moderately contaminated) 1 < CF < 3; class 3 (considerably contaminated) 3 < CF < 6; and, class 4 (very high contaminated) CF > 6.

2.4.2. Enrichment factor (EF)

Enrichment factor (EF) is a useful tool for determining the degree of anthropogenic heavy metal pollution. The EF is computed using the relationship below:

$$EF=\frac{(C_{Metal}\ /C_{Fe})\ Sample}{(C_{Metal}\ /C_{Fe})Backgroung}(2)$$

(C_{Metal}/C_{Fe}) sample is the ratio of each metal and iron concentration in the sample; (C_{Metal}/C_{Fe}) background is the ratio of each metal and iron concentration in the background.

In this study, iron (Fe) was used as a reference element for geochemical normalization because sequential extraction showed that Fe was relatively present in the residual fraction (89%) relative to Al (85%). Therefore, Fe has been chosen as the most appropriate reference element [23]. Local geochemical backgrounds calculated from the value at down-core were used as background data. EF values were interpreted as suggested by Maanan et al. [27], where: EF < 1 indicates no enrichment; 1 < EF < 3 is minor enrichment; 3 < EF < 5 is moderate enrichment; 5 < EF <10 showsmoderately severe enrichment; 10 < EF < 25 is severe enrichment; 25 < EF < 50 is very severe enrichment; and EF > 50 determinesextremely severe enrichment.

2.4.3.Risk assessment code (RAC)

The Risk Assessment Code (RAC) considers the ability of metals to be released and subsequently entered into the food chain and is based on the strength of the bond between metals and other components in sediments. Therefore, the RAC assesses the availability of metals by applying a scale to the percentage of metal in the carbonate and exchangeable fractions. When the percentage F_1 is less than 1% there is no risk (NR). For a range of 1–10%, there is low risk (LR), medium risk (MR) for a range of 11–30%, high risk (HR) for 31–50%, and very high risk (VHR) for 51–100% one [28].

2.4.4. Modified potential ecological risk index (MRI)

Although RAC evaluates the mobility of individual metals, the risk of heavy metal pollution depends not only on the total content of heavy metals but also on their chemical speciation [29, 30]. To assess the ecological risk of heavy metals in sediments considering these two aspects, the potential ecological risk index (MRI) proposed by Zhu et al. [30] was used in this study. MRI considers the toxicity of the metals and assumes that the metals are mostly in the mobile fraction (exchangeable):

$$MRI = \sum_{i=1}^{m} E_i^r = \sum_{i=1}^{m} T_i^r . \frac{\Omega . C_D^i}{C_R^i} \quad (3)$$

Wherever E_i^r is the potential risk of arsenic; T_i^r is the toxic-response factor of arsenic (As =10)[31, 32]; C_D^i is the present concentration of arsenic in sediments; Ω is the modified index of arsenic concentration calculating (is percentage of the F1 fraction, is the toxic index of the F1 fraction); C_R^i is the pre-industrial record of metal concentrations in sediments. The values vary depending on the RAC value: 1.0 (RAC ≤ 10), 1.2 (10 < RAC ≤ 30), 1.4 (30 < RAC ≤ 50), and 1.6 (RAC > 50) [30]. In this study, metal concentrations of the upper crust proposed by Hu and Gao [33], which is the revision of Gusiatin et al. [34], were used as the background level (Table 1). The classification of MRI is presented in Table 1 [29, 30].

Table 1: Classification of contamination and ecological risk.

Class	Degree	Ecologicalrisk
		MRI
I	Low	<150
II	Moderate	150-300
III	Considerable	300-600
IV	High	>600

2.4.5.Human exposure and health risk assessment

A human health risk assessment method applied to sediments has been presented in many studies [35; 36]. Generally, the three main pathways of trace metal transformation in ecological systems that are usually involved in human health risk assessment are ingestion, dermal contact, and respiration. This study examined the ingestion (CDI_{ing}) and dermal contact (CDI_{derm}) pathways of trace metal transport in sediment to evaluatehuman health risk. The following equations are used to calculate the different exposure values [36].

$$CDI_{ing} = \frac{C_{sed} \times IngR \times CF \times EF \times ED}{BW \times AT} \quad (4)$$

Where, CDI_{ing} is defined as the exposure risk by ingestion of sediment metals (mg/kg/day); C_{sed} is the determined content in the current sediment; IngR is defined as the daily ingestion amount; CF is the unit of measurement conversion factor; EF is defined as the frequency of exposure on the sediment; ED is the duration of exposure; BW is defined as the adult weight; AT is the number of days in 24 years [37].

$$CDI_{derm} = \frac{C_{sed} \times CF \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \quad (5)$$

Where, CDI_{derm} is defined as the dermal absorption risk; SA is considered as the exposed skin surface area on the sediment; AF is defined as the trace metal adhesion index on the unit skin surface; and ABS is considered as the dermal adsorption rate (Table 3) of the sediment [35]. Other exposure factors and values used in the risk assessment are presented in Table 2.

Hazardous quotients (HQ) were applied to determinethe health risks of trace metal exposure from surface sediments in accordance with health risk assessment guidelines [36]. The potential adverse health effects associated with such exposure with the quantification of carcinogenic or non-carcinogenic risk.

Table 2: Description of the parameters and the values used in the study

Factor	Definition	Unit	Value	Reference
Csediment	Heavy metal concentration in sediment	mg/kg	Adults	This Study
IngR	Ingestion rate	mg/day	100	[38;7]
ED	Exposure duration	years	24	[37,38]
EF	Exposurefrequency	days/year	350	[38,7]
BW	Average body weight	kg	70	[38,7]
SA	Exposure skin area	cm^2	5700	[36,7]
AF	Skin adherence factor	mg/cm^2h	0.07	[36,7]
AT	Average time	days	8760	[38,7]
CF	Unit conversion factor	$kg\ mg^{-1}$	10^{-6}	[38,7]

AT = ED x 365. For carcinogenic effects: LT × 365 [38]. In Côte d'Ivoire, LT (lifetime) is 58 [39]. For carcinogenic effects: AT = 21.17

2.4.6.Non-carcinogenic risk assessment

CDI for each element and route of exposure was then divided by the corresponding reference dose (RfD) to obtain a hazardous quotient (HQ, or non-carcinogenic risk; equations 4 and 5) for systemic toxicity. The HQ equations for the ingestion and dermal contact routes are as follows:

$$HQ_{ing} = \frac{CDI_{ing}}{RfD_{ing}} \quad (6)$$

$$HQ_{derm} = \frac{CDI_{derm}}{RfD_{derm}} \quad (7)$$

Where HQ is the hazardous quotient by an ingestion or dermal contact exposure route under the respective exposure concentration; RfD is the reference value for adverse health effect resulting from metal contaminations. The reference values by skin contact (RfDderm) and by the ingestion route (RfDing) are represented in Table 3.

Assuming that all metal risks were additive, we calculated the cumulative HQ expressed as a risk index (HI) using equations (8). If HQ and HI are less than 1, no adverse health effects will be found while if HQ and HI are greater than 1, indicate adverse human health effects [40].

$$HI = HQ_{ing} + HQ_{derm}$$ (8)

Table 3: The used relative toxicity values and dermal absorption factor (ABS) obtained from relevant studies

Metal	RfDing	RfDderm	ABSderm	ABSGI	SFing	SFderm
As	3.00E-04[ab]	1.23E-04[ab]	0.03[ae]	1[f]	1.5E+00[ad]	1.5E+00

a [38], b[41] ,c[35] ,d [42], e [43], f[44]

2.4.7. Carcinogenic risk assessment

For the carcinogenic risk, the various CDI for As were multiplied by the corresponding cancer slope factor (SF) to produce an excess lifetime cancer risk level induced by contaminated ingestion and skin contact. The oral cancer slope factor (SF_{ing}) values as well as the gastrointestinal ABS values are reported in Table 3. By account cancer slope factor (SF_{derm}) values for dermal exposure are not available, extrapolation can be found by dividing the oral cancer slope (Sf_{ing}) by the gastrointestinal absorption factor [45]. Commonly, the total CR is the sum of the CR_{ing} and CR_{derm} of the two exposure routes:

$$\mathrm{SF_{derm}} = \frac{\mathrm{SF_{ing}}}{\mathrm{ABS}_{GI}}$$ (9)

$$CR_{ing} = CDI_{ing} \times SF_{ing}$$ (10)

$$CR_{derm} = CDI_{derm} \times SF_{derm}$$ (11)

$$CR_{tot} = CR_{ing} + CR_{derm}$$ (12)

In this study, the CR due to the ingestion and dermal routes were calculated for all studied samples. The carcinogenic health risk can be ignored if CR $<10^{-6}$, while for CR $>10^{-4}$ the human cancer risk probably increases and values between 10^{-4} and 10^{-6} will lead to an acceptable human health risk [46].

2.5. Statistical analysis

Multivariate statistical analysis including principal component and cluster analysis were performed to estimate geochemical factors controlling trace metals distribution in the sediments. The One Way Analysis of variance (ANOVA) was employedto examine differences among the sites and the activity types. The pairwise multiple comparison procedures were performed using the Tukey Test when the tests of normality and equal variance were positive. The Kruskal-Wallis One Way Analysis of Variance on Ranks was usedwhen the equal variance test failed. The difference was considered statistically significant at $p < 0.05$. Statistical analysis were carried outwith SigmaPlot 12.5, except cluster analysis that was performed with Statistica 7.1 Software.

3. Results and discussion

3.1. The content of arsenic in the organic and humus horizons

The total concentrations of arsenic measured in the sediment samples are shown in Figure1. These different arsenic concentrations will be compared with other concentrations in sediments from mining areas in several

countries.Arsenicconcentrations in Korhogo areas varied from 1.64 ± 0.04 inBadenou to 159.72 ± 51.91 µg/g inTongon to 1.36 ± 0.28 µg/g inTaoura to 8.72 ± 6.9 µg/g at Bevogo. In Tengrela areas, arsenic concentrations ranged from 26.40 ± 23.93 µg/g to 20.44 ± 4.83 µg/ginSissingue. The average of arsenicconcentrations in sediments were significantly higher ($p < 0.05$) in industrial mining areas of Tongon than in artisanal mining (Badenou, Taoura, and Bevogo). In contrast, data from artisanal sites showed that sediments collected fromTengrela sites were heavily contaminated with As compared to those inKorhogo.Nevertheless, industrial mining areas were significantly contaminated than artisanal areas when considering all the sites. Taking all into account regardless the activity, the average of arsenic concentration in sediments was the highest in Tongon and the lowest in Taoura. On the whole, the average of arsenic concentrations all over the study sites werelower than the concentration values obtained in China [46], Indonesia [47], and Côte d'Ivoire [18]. However, thearsenic values in the studywerehigher than those obtained in Australia [48] and Malaysia [35].

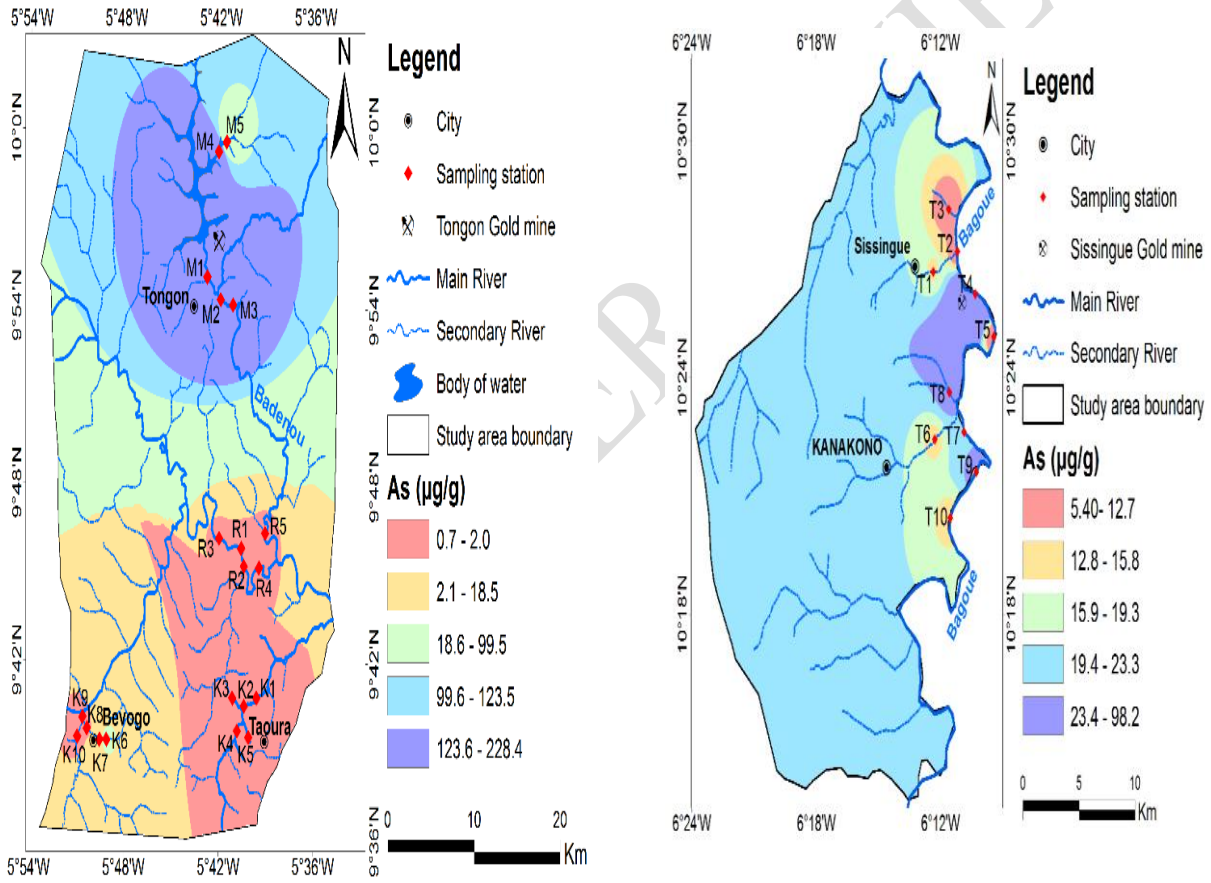

Figure2:The distribution patterns of concentrations of examinedarsenic in gold mining areas

3.2. The values of pollution indices

The mean values of the contamination factor (CF) and enrichment factor (EF) calculated to assess the level of arsenic contamination are shown in Table 4.

Table 4: Contamination factor (CF) and Enrichment Factors (EF) of arsenic in surface sediments collected from Korhogo and Tengrela gold mining areas

City	Stations		EF(As)	CF(As)
Korhogo	Badenou	mean	0.54	0.82
		SD	0.04	0.02
	Tongon	mean	45.1	79.86
		SD	61.5	5.95
	Taoura	mean	0.43	0.68
		SD	0.23	0.20
	Bevogo	mean	3.79	4.36
		SD	10.4	0.39
Tengrela	Sissingue	mean	13.2	13.75
		SD	34	1.94
	Kanakono	mean	10.7	10.22
		SD	9.01	2.41

3.2.1. Contamination factor (CF)

Table 2 shows the mean contamination factor (CF) values in sediments from Korhogo and Tengrela. Mean CF values were 0.82 ± 0.02 and 0.68 ± 0.2 at the Badenou and Taoura stations, respectively. These values showed that the sediments inBadenou and Taourawerelow in arsenic contamination. However, the mean value of the contamination factor for Bevogo sediments (4.36±0.39) presentedconsiderable contamination. On the other hand, there wasa very high level of contamination in the Tongon sediments, with a mean value of 79.86±5.95. Average arsenic contamination factor values in Tengrela sediments ranged from 10.22 ± 2.41 in Kanakono to 13.75 ± 1.94 inSissingue. These values indicated that the sediments werehighly contaminated with arsenic.

3.2.2.Enrichment Factor (EF)

The Enrichment Factor (EF) is used to evaluatethe possible impact of anthropogenic activities on the arsenic concentrations in the sediment. In order to identify the expected effect of anthropogenesis on heavy metal accumulation, the content of Fe was used, which is characterized by a low variability in its occurrence in sediment [49, 50]. The EF values are shown in table 3.On the Hakanson [25] scale, EF values calculated using mean arsenic concentrations in Korhogo(Badenou, Taoura, and Bevogo) showed sediments from naught to highly arsenic, except for the sediments of the Tongon mining area which were very severe contaminated.The high total arsenic concentration obtained may point to various anthropogenic activities such as agricultural practices and mining. On the other hand, all the sediments of Tengrela (Sissingue and Kanakona)werestronglycontaminated in arsenic.

3.3. Chemical fractionation of arsenic

The percentages of the arsenic fractions in the sediments (F1-R), as previously described, are shown in Figure3. The predominant residual fraction (R) was very high for arsenic, ranging from 53.04% (Tongon) to 67.42% (Badenou). The concentration ranged from 80.83±39.42 µg/g to 1.10±0.08 µg/g out of a total of 161.42 µg/g to 1.64 µg/g. These results suggested that an important part of arsenicwasrelated to the crystalline structure of the sediment [7]. The proportion obtained in the sediments fromthe Tongon industrial extraction zone resulted in significantly higher concentrations without any remarkabledifference according to ANOVA analysis ($p<0.05$). This observation corresponded to a concentration of 80.83±39.42 µg/g out of a total of 161.42 µg/g. These concentration values show that the R fraction wasincorporated into the silicate crystal structures of the sediments. Andthearsenic fraction wasvery stable and wasunlikely to be released into the sediment water [51, 52]. Therefore, these resultsdenotethat the area presents a low environmental risk for arsenic. The results of this study weresimilar to those of Rodrigues et al. [53] who reported that arsenic was predominantly associated with the residual fraction of sediments collected around the Caveira mine in Portugal. The percentage fraction (F3) of arsenic bound to organic matter and sulphides variedbetween 21.04 (Badenou) and 30.92% (Tongon). The ANOVA analysis ($p<0.05$) showed that there wasno noticeabledifference between the stations. Indeed, thefraction (F3) representedthe second most important reactive fraction for these different sediments. That fraction marked distribution for the organic phase reflectedthe affinity of arsenic with organic matter. The proportions of the arsenic fraction (F2) bound to iron and manganese oxides variedbetween 10.37 (Badenou) and 18.35% (Taoura). There wasno significant difference (ANOVA, $p<0.05$) between the stations. The percentages of the F1 fraction corresponding to the fraction of exchangeable and carbonate-bound arsenic ranged from 1.23% (Badenou) to 2.12% (Tongon). Thatfraction representedthe most important reactive fraction for the different sediments. Sediments from the industrial extraction area of Tongon recorded the highest percentage without any considerabledifference ($p<0.05$). Thatpercentage in the Tongon industrial extraction zone gave3.55 µg/g out of a total of 161.42 µg/g. The distribution of arsenic in the different phases of the sediments of the studyareas is ordered as follows: Badenou, Tongon, Taoura, Bevogo, Kanakono, and Sissingue **(i.e.,** $R> F_3> F_2> F_1$).

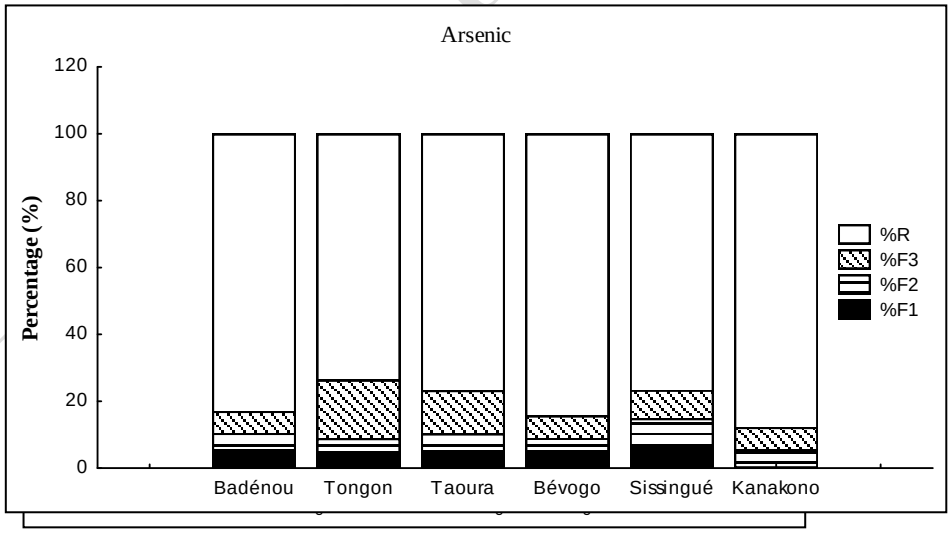

Figure3. Mean percentages of arsenic distributed in the acid soluble, reducible, oxidizable, and residual fractions in sediment from the studyarea

3.4. Risk assessment code (RAC) and modified potential ecological risk index (MRI)

Risk assessment codepercentages of arsenic in studiedsedimentsare shown in table 5. It can be observed thearsenic can cause a low risk in all the studied stations ($0.87 \leq RAC\ (\%) \leq 2.91$).The MRI values of arsenic ranged from 6.80 to 798.60(Table 5) all over the studied sites.Overall, the MRI values of As (MRI<150) showed a low environmental risk over the studied mining areas, except the industrial mining area of Tongon (MRI>600), whichdepicteda very high environmental risk.

Table 5: Environmental risk assessment of sediment (RAC) andmodified potential risk index (MRI)

City	stations	RAC (%)	MRI
Korhogo	Badenou	1.23	8.20
	Tongon	2.12	798.60
	Taoura	1.36	6.80
	Bevogo	1.65	43.60
Tengrela	Sissingue	1.60	132.00
	Kanakono	1.49	102.20

3.5.Human health risk assessment

The HQ, HI, and CR values for each element for adults were calculated using the mean values of bioavailable arsenic concentrations from Table 6.

Table 6: The results of health risk assessment (non-carcinogenic and carcinogenic risks) of arsenic in sediments

		Non-carcinogenic Risks			Carcinogenic Risks		
Metal	Stations	HQ_{ing}	HQ_{derm}	HI	CR_{ing}	CR_{derm}	CR_{tot}
As	Badenou	1.82E-04	5.58E-07	1.83E-04	1.63E-06	1.63E-06	3.26E-06
	Tongon	1.77E-02	5.43E-05	1.78E-02	1.59E-04	1.59E-04	3.17E-04
	Taoura	1.51E-04	4.62E-07	1.51E-04	1.35E-06	1.35E-06	2.70E-06
	Bevogo	9.68E-04	2.96E-06	9.71E-04	8.66E-06	8.66E-06	1.73E-05
	Sissingue	2.93E-03	8.98E-06	2.94E-03	2.62E-05	2.62E-05	5.24E-05
	Kanakono	2.27E-03	6.95E-06	2.27E-03	2.03E-05	2.03E-05	4.06E-05

3.5.1. Non-carcinogenic health risk assessment

HQ and HI values greater than 1 suggest adverse health effects of arsenic in sediment. In the present study, HQ and HI values for arsenic in sediments from all studied sites were below 1 (Table 6), a reference threshold suggested by USEPA [54]. These values suggestedthat a non-carcinogenic health risk was present, and the risks from both ingestion and dermal contact routes of arsenic were low.However, the sequence of distinctive exposure ranfor non-carcinogenic doses wasHQ_{ing}>HQ_{derm} of adults for arsenic in all studied stations.Therefore, we can conclude that arsenic may have potential adverse effects through ingestion due to an HQ_{ing} value higher

than the HQ_{derm} value.The highest value of HQ_{ing}=1.77E-2 wasdetermined in the sediments of Tongon, which is located in an industrial gold mining area. In this region, arsenic concentrations were found to be the highest ones. Taking account of the aforementioned observations, we can say that industrial gold mining represented the main contaminant of the sediments and had a great impact on arsenic exposure in this study area.

3.5.2.Carcinogenic health risk assessment

The values for CR_{ing}, CR_{derm},and total risk (CRt) are shown in Table 6.The carcinogenic risk assessment (CRt) showed that the potential risk values for arsenic at all the studied stations ranged from 10^{-6} to $10^{-4}$with the exception of the CRt value in the Tongon sediments, which wasgreater than 10^{-4}. Based on the these results, the arsenic levels in the sediments of Badenou, Taoura, Bevogo, Sissingue, and Kanakono indicated an acceptable carcinogenic risk to human health. However, the CRt value for arsenic related to carcinogenic risk in Tongon sediments wasvery high and causeda serious threat to human health. Thus, Tongon populations could be prone to a risk of developing skin, lung, prostate, liver, kidney, and bladder cancer [55]. In this study, CR_{ing} averages were virtually identical to CR_{derm} averages. Therefore, ingestion and skin contact may be the routes of exposure to arsenic from sediments.

4. Conclusion

The CF, EF, MRI, and RAC methods applied to the analysis of ecological arsenic pollution risks in the sediments of the studied mining areas and the obtained results provided the following information. The high arsenic content in some of the studied stations revealed that the highest level of pollution was distributed in the research area where mining activities were concentrated. Furthermore, this study suggestedthat most of the arsenic was caused by anthropogenic factors such as mining activities. The chemical speciation of arsenic was determined using a BCR sequential extraction procedure to assess mobility potential. The result showedthat arsenic was mainly bound to the residual fraction. This impliedthat the R fraction wasembedded into the silicate crystalline structures of the sediments and that this arsenic fraction washighly stable.According to the RAC, arsenicpresenteda low risk to the ecosystem due to their percentages in marketable fractions. Overall, arsenicwasweakly to very highly contaminate in the studied sediments.However, MRI values showed a low environmental risk in the studied mining areas, with the exception of the Tongon industrial mining zone, which presenteda very high environmental risk. The potential human health risk results indicated that there wasno significant non-carcinogenic risk from arsenic for residents at any of the study sites. On the other hand, the results of the potential risk (CRt) to human health revealed that there were significant carcinogenic risks for residents living in the vicinity of the Tongon mining areas for arsenic.

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