

# Human Risk Assessment of Trace Metals in Surface Water from Bandama, Bia and Comoé Rivers, Southeast Côte d'Ivoire

## ABSTRACT

Water pollution is a global environmental problem. Trace metals present in polluted water can have harmful effects on human health. In Côte d'Ivoire, few data is available to assess human health risk associated with exposure to trace metals from rivers. This paper presents an assessment of the human health risk associated with exposure to trace metals from Bandama, Comoé and Bia Rivers, three mains rivers in Côte d'Ivoire.

The chronic daily intake (CDI), hazard quotient (HQ), hazard index (HI), non-carcinogenic risk and carcinogenic risk of metals by oral and dermal routes were determined to assess the human health risk.

The hazard quotient (HQ) values for arsenic are >1 in the Bia River and close to 1 in the other rivers during the dry and flood seasons. And the Hazard Index (HI) values are <1 at all stations during the dry and flood seasons, indicating that there is a likelihood of the local population contracting non-carcinogenic diseases from trace metals through ingestion of surface water. Arsenic represents a high cancer risk in rivers during the dry and wet seasons ( $1.00E-04 > C < 1.00E-03$ ).

Consequently, governmental environmental monitoring agencies should carry out continuous and increased monitoring of trace metals in rivers in order to make appropriate decisions for the safety of human health.

*Keywords: Rivers, Surface water, Trace metals, health risk assessment, Chronic daily intake, Hazard quotient, cancer risk*

## 1. INTRODUCTION

Trace metal contamination of surface waters is a major concern worldwide [1,2]. Trace metals in the environment originate from natural processes (such as atmospheric deposition, erosion and mineral weathering) and anthropogenic activities (such as urban and industrial development and agriculture) [3–6]. Trace metals such as copper (Cu) and zinc (Zn) are trace elements and are essential for the body to function properly, whereas arsenic (As), cadmium (Cd), and lead (Pb) are toxic metals that play no role. These metals can cause biological toxicity and pose a serious threat to aquatic ecosystems and human health at certain concentrations. A study of the total concentration of trace metals in surface water can provide information on the state of contamination of rivers, but not enough on the health risks.

In Côte d'Ivoire, most of the studies carried out have focused on metallic contamination of sediments and few studies have focused on contamination of river surface waters, given the

Commented [U1]: Little

Commented [U2]: risks

Commented [U3]: main

Commented [U4]: Remove 'and;

Commented [U5]: Remove in order

complexity of the fate of metals in water. In addition, most studies have focused on assessing river water quality, particularly in terms of physical, chemical and organic parameters. To our knowledge, there are no studies assessing the health risks of trace metals in rivers in the Côte d'Ivoire region to provide advice on environmental management [6–9].

The Bandama, Comoé and Bia rivers are among the main rivers in Côte d'Ivoire. The water from these rivers is used by the local population for their daily needs and above all as drinking and bathing water. Local people living near the rivers do not have access to tap water [2]. The use of this surface water contaminated by trace metals exposes the local population to illness and the risk of cancer. It is therefore important to assess the carcinogenic and non-carcinogenic risks in order to raise public awareness and attract the attention of governors.

The objective of this work is to assess the risks to human health in the surface waters of the Bandama, Bia and Comoé rivers by calculating the hazard quotient (HQ) and carcinogenic risk (CR), based on USEPA methods [5,10].

Commented [U6]: Remove 'inorder'

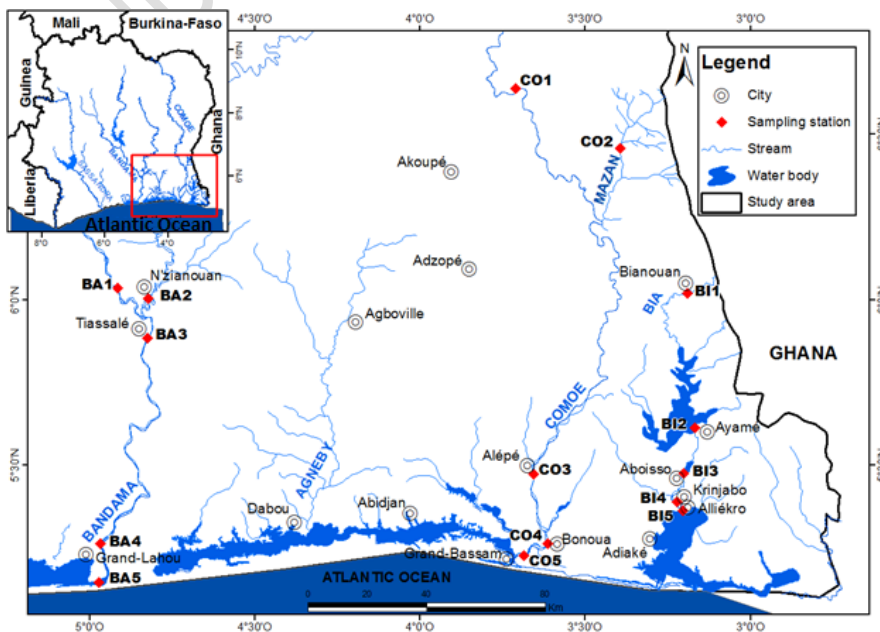
## 2. MATERIAL AND METHODS

### 2.1. Study Area and data collection

The study area is the lower part of the Bandama and Comoé rivers in the south and the coastal Bia River in the south-east of Côte d'Ivoire. Five stations were selected per river.

The study area has four seasons (a long rainy season, a short rainy season corresponding to the river flooding season, a long dry season and a short dry season). **Figure 1** shows the study area and the sampling sites.

Commented [U7]: southeast



**Fig. 1. Sampling locations of surface sediments collected from Bandama, Comoé and Bia River (Côte d'Ivoire) [2].**

The total concentrations of trace metal reported by Ouattara et al., [2] were used for human risk quantification. The methodologies used for sampling and metal analysis are detailed in the studies of Ouattara et al., [2].

**2.2. Health risk assessment**

Trace metals enter the human body by several routes, including direct ingestion, inhalation, skin absorption [11] and through the food chain. However, there are two main routes of exposure in water: ingestion of metals through water consumption and dermal absorption through swimming [12,13].

**2.3. Chronic daily intake (CDI)**

The chronic daily intake (CDI) (µg/kg/day) by water ingestion and skin absorption defines the quantity of trace metals ingested and absorbed by a human being per day through the use of water. It can be calculated using equations (1) and (2), respectively [5,14]. The definitions and values of the parameters and variables are presented in Table 1 [15–17].

$$CDI_i = \frac{C \times I \times R \times EF \times ED}{BW \times AT} \tag{1}$$

$$CDI_d = \frac{C \times SA \times K_p \times ET \times EF \times ED \times CF}{BW \times AT} \tag{2}$$

Where: CDI<sub>i</sub> is the chronic daily dose by ingestion (oral) and CDI<sub>d</sub>, the chronic daily dose by dermal route (skin).

**Table 1. Parameters characterising chronic daily intake (CDI) values.**

Parameters	Units	Values	Source
Concentration of trace metal in water (C)	µg/L	-	[2]
Ingestion rate (IR)	L/day	2	[15]
Exposure frequency (EF)	day/year	365	[5]
Exposure duration (ED)	year	51	[1]
Body weight (BW)	kg	60.7	[1]
Average time (AT)	day	18615	[1,15,18]
Skin-surface area (SA)	cm <sup>2</sup>	18	

Commented [U8]: to

Exposure time (ET)	h/day	0.6
Conversion factor (CF)	L/cm <sup>3</sup>	0.001
Permeability coefficient (Kp)		
Zn		0.0006
Cu	cm/h	0.001
As		0.001
Cd		0.001
Pb		0.004

#### 2.4. Non-carcinogenic risk

Non-carcinogenic risks are assessed by determining the hazard quotient (HQ). The contaminant hazard quotient is defined as the quotient of the chronic daily intake (CDI) by the toxicity threshold value or reference dose (RfD) for each chemical element according to each exposure route (ingestion of water and cutaneous absorption) as indicated by equation 3.

$$HQ = CDI / RfD \quad (3)$$

where CDI is the chronic daily dose ( $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$ ) and RfD is the reference dose of metals in a given condition ( $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$ ). The reference dose by ingestion of water (RfD in) was obtained from the [1]. RfD by dermal absorption (RfD dermal) was obtained from RfDin multiplied by a gastrointestinal absorption factor [19].

If the HQ value is close to or equal to unity, this indicates potentially harmful effects on human health or the need for further investigation. HQ values > 1 suggest even higher probabilities of adverse health effects [19–21].

#### 2.5. Hazardous Index (HI)

The hazardous index (HI) is used to assess the health risk due to the interaction of all trace metals present in water. Indeed, recent studies on the health risks due to metal contamination have shown that contamination by two or more metals could lead to an interaction between the latter and result in an addition of their toxicity [22,23]. In this way, the hazard quotient (HQ) of the various metals can be added together by the oral or dermal route (Hli and Hld, respectively) [22,24] to produce an even higher risk. The hazardous index generated by the daily use of water was calculated using the following equation:

$$HI = \sum_{i=1}^n HQ_i \quad (4)$$

HDi is the exposure quotient for element i. When HI < 1, it would have no adverse effects while for HI > 1 adverse effects could occur.

#### 2.6. Carcinogenic risk (CR)

Carcinogenic risks (CR) for metals have been estimated to assess the likelihood of an individual developing cancer during their lifetime following exposure to a potential carcinogen [25–27]. The CR is obtained using the Cancer Slope Factor (CSF) for the metal established by the US EPA [18] [5,10]. The carcinogenic risk is determined by the following relationship:

$$CR = CDI \times SF \quad (5)$$

where SF is the carcinogenic slope factor ( $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$ ); the SF by water ingestion (SF<sub>in</sub>) was provided by the US EPA [18] and SF by skin absorption was calculated by SF<sub>d</sub> = SF<sub>in</sub> / ABS<sub>g</sub>. The slope factor (SF) is a toxicity value that quantitatively defines the relationship between dose and response. The probabilities of potential carcinogenic effects that an individual will develop cancer over a lifetime of exposure are estimated from the projected intakes and the slope factor. **Table 2** gives the values of the slope factor and RfD.

**Table 2. Reference doses (RfD) and carcinogenicity factors (CSF) [1].**

Elements	As	Cd	Pb
----------	----	----	----

SF (mg/kg/j)	1.5	260	8.5
RfD (µg/kg/j)	0.3	0.5	1.4

The different levels of risk according to the values of carcinogenic risk are shown in **Table 3**

**Table 3. Risk according to cancer risk level [5].**

Cancer risk level	Risk
< 1.00E-06	Very low
1.00E-06 to 1.00E-05	Low
1.00E-05 to 1.00E-04	Medium
1.00E-04 to 1.00E-03	High
>1.00E-03	Very high

### 3. RESULTS AND DISCUSSION

#### Total concentration of trace metal

The total concentrations of trace metals in the surface water from Bandama, Bia and Comoé Rivers, are presented in [2]. The total concentration of the trace metals ranged between 0.02 and 360.49 µg/l.

#### Health risk assessment

##### The chronic daily intake (CDI)

**Table 4** presents the values of the chronic daily intake calculated for the metals studied. CDI values of arsenic, cadmium, copper, lead and zinc in the three rivers varied between 0.05 and 0.46 µg/kg.day, 0.001 and 0.033 µg/kg.day, 0.29 and 7.23 µg/kg.day, 0.04 and 0.53 µg/kg.day and 0.02 and 11.88 µg/kg.day respectively. The mean values of CDI of trace metals concentrations were found in the order of Zn > Cu > As > Pb > Cd in Bandama River and in the order of Zn > As > Cu > Pb > Cd in Comoé and Bia River. CDI values were higher in oral route compared to dermal route.

Commented [U9]: spelling 'River'

Commented [U10]: the oral

Commented [U11]: the dermal or a dermal

**Table 4. CDI values of trace metals in the river water.**

		As		Cd		Pb		Cu		Zn	
		CDI <sub>i</sub>	CDI <sub>d</sub>	CDI <sub>i</sub>	CDI <sub>d</sub>	CDI <sub>i</sub>	CDI <sub>d</sub>	CDI <sub>i</sub>	CDI <sub>d</sub>	CDI <sub>i</sub>	CDI <sub>d</sub>
Bandama	Min	0.161	8.42E-04	0.001	6.82E-06	0.097	2.03E-03	1.822	9.51E-03	1.907	5.97E-03
	Max	0.223	1.16E-03	0.003	1.59E-05	0.198	4.13E-03	4.117	2.15E-02	4.187	1.31E-02
	Moy	0.195	1.02E-03	0.002	1.22E-05	0.162	3.39E-03	2.942	1.54E-02	3.223	1.01E-02
	SD	0.025	0	0.001	0	0.042	0.001	0.938	0.005	1	0.003
Comoé	Min	0.217	1.13E-03	0.001	3.44E-06	0.115	2.41E-03	2.339	1.22E-02	2.188	6.85E-03
	Max	0.286	1.49E-03	0.002	1.29E-05	0.271	5.67E-03	2.585	1.35E-02	4.181	1.31E-02
	Moy	0.248	1.30E-03	0.001	7.71E-06	0.174	3.63E-03	2.44	1.27E-02	3.444	1.08E-02
	SD	0.026	0	0.001	0	0.066	0.001	0.099	0.001	0.791	0.002
Bia	Min	0.28	1.46E-03	0.001	3.44E-06	0.157	3.28E-03	2.007	1.05E-02	2.28	7.14E-03

<b>Max</b>	0.35	1.83E-03	0.013	6.53E-05	0.302	6.30E-03	3.588	1.87E-02	3.816	1.20E-02
<b>Moy</b>	0.325	1.70E-03	0.004	2.26E-05	0.208	4.33E-03	2.683	1.40E-02	3.089	9.68E-03
<b>SD</b>	0.028	0	0.005	0	0.061	0.001	0.67	0.003	0.583	0.002

The results showed that the local population using surface water from the River Bia absorbs more metals orally and dermally than the populations using water from the other two rivers. In fact, the average CDI values for the river Bia were higher than those for the other rivers for all metals. The CDI values show that the local population living near the river Bia is more exposed to the harmful effects of trace metals.

Commented [U12]: remove 'in fact'

**Hazard Quotient (HQ)**

Variations in the non-carcinogenic risk of trace metals by ingestion route (HQi) and by dermatological (HQd) in the waters of the Bandama, Comoé and Bia rivers are depicted in Table 5 and Table 6.

**Table 5. Hazard quotient ingestion of trace metals in water from the rivers.**

		Bandama			Comoé			Bia		
		Dry	Wet	Flood	Dry	Wet	Flood	Dry	Wet	Flood
As	Min	0.60	0.25	0.67	0.55	0.15	1.03	1.00	0.39	1.38
	Max	0.77	0.54	0.98	1.19	0.59	1.35	1.25	0.88	1.53
	<b>Mean</b>	0.72	0.40	0.83	0.90	0.41	1.18	1.12	0.65	1.48
	SD	0.08	0.12	0.13	0.23	0.18	0.12	0.11	0.18	0.06
Cd	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Max	0.01	0.01	0.01	0.01	0.00	0.00	0.02	0.00	0.07
	<b>Mean</b>	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.02
Cu	SD	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03
	Min	0.09	0.01	0.02	0.13	0.01	0.01	0.09	0.02	0.04
	Max	0.18	0.04	0.12	0.16	0.02	0.03	0.17	0.04	0.07
	<b>Mean</b>	0.13	0.02	0.07	0.14	0.02	0.02	0.12	0.03	0.05
Pb	SD	0.04	0.02	0.04	0.01	0.00	0.01	0.04	0.01	0.01
	Min	0.04	0.04	0.13	0.07	0.04	0.12	0.08	0.03	0.20
	Max	0.19	0.08	0.23	0.26	0.11	0.22	0.24	0.06	0.38
	<b>Mean</b>	0.11	0.06	0.18	0.15	0.06	0.16	0.13	0.04	0.27
Zn	SD	0.07	0.02	0.04	0.07	0.03	0.04	0.07	0.02	0.07
	Min	0.02	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.00
	Max	0.04	0.00	0.00	0.04	0.00	0.00	0.04	0.00	0.00
	<b>Mean</b>	0.03	0.00	0.00	0.03	0.00	0.00	0.03	0.00	0.00
	SD	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00

**Table 6. Hazard quotient dermal of trace metals in water from the rivers.**

		Bandama	Comoé	Bia
--	--	---------	-------	-----

		Dry	Wet	Flood	Dry	Wet	Flood	Dry	Wet	Flood	
As	Min	3.12E-03	1.33E-03	3.49E-03	2.87E-03	7.98E-04	5.37E-03	5.22E-03	2.04E-03	7.20E-03	
	Max	4.04E-03	2.84E-03	5.11E-03	6.20E-03	3.08E-03	7.06E-03	6.52E-03	4.61E-03	7.98E-03	
	Mean	3.75E-03	2.11E-03	4.34E-03	4.68E-03	2.14E-03	6.14E-03	5.83E-03	3.40E-03	7.75E-03	
	SD	3.92E-04	6.32E-04	6.76E-04	1.21E-03	9.63E-04	6.41E-04	5.53E-04	9.23E-04	3.17E-04	
		Min	1.38E-04	1.38E-04	1.38E-04	1.38E-04	1.38E-04	1.38E-04	1.38E-04	1.38E-04	1.38E-04
Cd	Max	1.05E-03	7.84E-04	1.06E-03	1.05E-03	3.65E-04	1.38E-04	2.59E-03	4.06E-04	6.92E-03	
	Mean	7.19E-04	4.21E-04	3.21E-04	6.05E-04	1.83E-04	1.38E-04	7.94E-04	1.91E-04	1.72E-03	
	SD	3.49E-04	2.80E-04	4.11E-04	4.37E-04	1.02E-04	0.00E+00	1.03E-03	1.20E-04	2.92E-03	
		Min	2.36E-03	1.89E-04	5.14E-04	3.35E-03	3.31E-04	2.57E-04	2.29E-03	5.43E-04	1.03E-03
	Max	4.72E-03	1.11E-03	3.00E-03	4.08E-03	5.70E-04	8.58E-04	4.46E-03	1.00E-03	1.74E-03	
Cu	Mean	3.44E-03	6.19E-04	1.70E-03	3.68E-03	4.78E-04	6.17E-04	3.17E-03	7.00E-04	1.38E-03	
	SD	9.24E-04	4.15E-04	1.10E-03	2.66E-04	9.02E-05	2.53E-04	1.08E-03	2.03E-04	2.55E-04	
		Min	8.47E-04	7.41E-04	2.76E-03	1.38E-03	7.78E-04	2.46E-03	1.66E-03	5.37E-04	4.22E-03
	Max	3.91E-03	1.74E-03	4.80E-03	5.33E-03	2.29E-03	4.52E-03	5.06E-03	1.34E-03	7.90E-03	
	Mean	2.25E-03	1.16E-03	3.85E-03	3.11E-03	1.30E-03	3.36E-03	2.72E-03	8.44E-04	5.72E-03	
Pb	SD	1.43E-03	4.18E-04	7.55E-04	1.56E-03	6.26E-04	8.70E-04	1.49E-03	3.49E-04	1.48E-03	
		Min	2.76E-04	2.06E-05	1.12E-06	3.04E-04	1.86E-05	1.07E-06	3.37E-04	1.85E-05	1.48E-06
	Max	6.20E-04	4.00E-05	1.62E-06	6.13E-04	4.02E-05	1.32E-06	5.55E-04	4.06E-05	1.67E-06	
	Mean	4.72E-04	3.10E-05	1.30E-06	5.07E-04	3.12E-05	1.19E-06	4.50E-04	3.18E-05	1.56E-06	
	SD	1.50E-04	8.40E-06	2.00E-07	1.23E-04	9.48E-06	9.49E-08	8.48E-05	9.95E-06	7.02E-08	

Assessing the non-carcinogenic risks of heavy metals involves evaluating the potential adverse health consequences, other than cancer, of exposure to these metals. According to Karki et al., (2024), its main objective is to understand the hazards that heavy metals pose to different organs and systems in the human body, such as the nervous system, liver, kidneys and respiratory system.

The QDI values for Cd, Cu, Pb and Zn trace metals are less than 1 in all samples for the three rivers. For arsenic, the QDI values obtained are greater than 1 during the dry and flood seasons in all samples from the Bia, while in the Comoé river only 20% of samples have QDI values greater than 1.

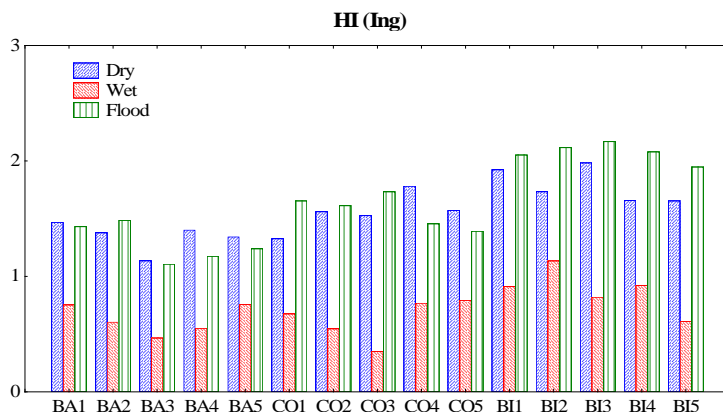
These results show that arsenic can cause adverse effects through ingestion of contaminated water and that there is no health risk from dermatological exposure of the population for all the trace metals studied [28–30].

In addition, the QDI in the study area were found in the following order: As> Pb> Cu> Zn> Cd. The QDD values calculated are all well below 1 for all elements.

Commented [U13]: river,

### Hazard Index (HI)

Figure 2 and 3 shows the HI values for oral intake and dermal route of trace metals through use of river water.



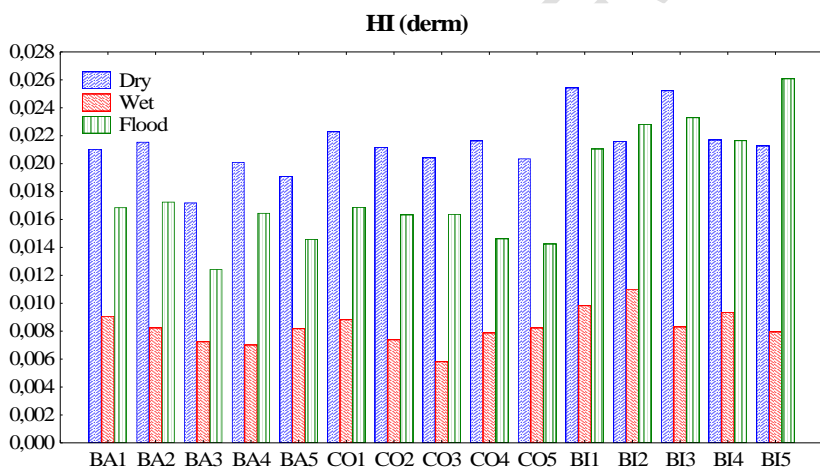
Commented [U14]: Figures

Commented [U15]: show

Commented [U16]: the dermal

Commented [U17]: the use

**Fig. 2. Hazard index ingestion (H<sub>ing</sub>) in the Bandama, Comoé and Bia rivers.**



**Fig 3. Hazard index dermal route (HI<sub>d</sub>) in the Bandama, Comoé and Bia rivers.**

The HI values by ingestion are higher than the limit suggested by USEPA (HI = 1) for all samples during the dry season, the flood season and for 6.67% of samples during the rainy season. This suggests a risk of chronic contamination, and hence health problems for the population. Arsenic is the major contributor to the non-carcinogenic risk of water ingestion by residents, with percentages ranging from 41.39% to 77.94%.

The dermatological HI values for all the trace metals are less than 1 for all the samples (Figure 3). This result indicates that there is no health risk to the population from prolonged skin contact with river water.

As arsenic, cadmium and lead are carcinogenic, we assessed the carcinogenic risk associated with these elements by oral route.

### Carcinogenic risk assessment (CR)

Carcinogenic substances are substances or elements that have a high probability of causing cancer, particularly in humans, in the event of prolonged or significant exposure [15]. The CR results are given in **Table 7**.

**Table 7. Carcinogenic risk of trace metals in the Bandama, Comoé and Bia rivers.**

	As			Cd			Pb		
	DRY	WET	FLOOD	DRY	WET	FLOOD	DRY	WET	FLOOD
BA1	1.5E-04	1.0E-04	1.9E-04	1.0E-10	4.0E-10	1.0E-10	2.9E-05	1.0E-05	2.8E-05
BA2	1.4E-04	7.2E-05	2.0E-04	7.7E-10	3.7E-10	1.0E-10	1.2E-05	1.4E-05	3.8E-05
BA3	1.2E-04	5.1E-05	1.5E-04	5.8E-10	5.8E-10	1.0E-10	6.7E-06	5.8E-06	2.2E-05
BA4	1.5E-04	7.0E-05	1.3E-04	5.2E-10	1.0E-10	7.8E-10	3.1E-05	6.0E-06	3.3E-05
BA5	1.5E-04	1.1E-04	1.6E-04	6.7E-10	1.0E-10	1.0E-10	1.0E-05	1.0E-05	3.1E-05
CO1	1.1E-04	8.1E-05	2.4E-04	7.7E-10	2.7E-10	1.0E-10	4.2E-05	1.8E-05	3.6E-05
CO2	1.8E-04	6.3E-05	2.4E-04	1.0E-10	1.0E-10	1.0E-10	2.9E-05	1.2E-05	3.2E-05
CO3	1.8E-04	3.1E-05	2.7E-04	1.0E-10	1.0E-10	1.0E-10	2.6E-05	7.1E-06	2.4E-05
CO4	2.4E-04	1.2E-04	2.2E-04	5.8E-10	1.0E-10	1.0E-10	1.5E-05	6.1E-06	1.9E-05
CO5	2.0E-04	1.2E-04	2.1E-04	6.8E-10	1.0E-10	1.0E-10	1.1E-05	7.8E-06	2.2E-05
BI1	2.5E-04	1.3E-04	3.1E-04	1.9E-09	1.0E-10	4.5E-10	1.3E-05	1.1E-05	3.3E-05
BI2	2.2E-04	1.8E-04	3.0E-04	1.0E-10	1.0E-10	6.0E-10	1.3E-05	8.6E-06	4.3E-05
BI3	2.4E-04	1.3E-04	3.0E-04	1.0E-10	1.0E-10	1.0E-10	4.0E-05	4.2E-06	6.2E-05
BI4	2.0E-04	1.4E-04	3.0E-04	4.4E-10	1.0E-10	1.0E-10	2.7E-05	5.1E-06	5.1E-05
BI5	2.1E-04	7.8E-05	2.8E-04	3.8E-10	3.0E-10	5.1E-09	1.4E-05	4.9E-06	3.6E-05

The CR values calculated for cadmium ( $CR < 1.00E-06$ ) showed that there is no carcinogenic risk in all surface water samples. For lead, the values ( $10^{-6} < CR < 10^{-4}$ ) found show average risks of contracting cancer in all seasons. Whereas the values observed for arsenic are higher than  $10^{-4}$  during the dry season and the flood season in the three rivers, and in general are lower than  $10^{-4}$  during the rainy season in the Bandama and Comoé rivers and higher than  $10^{-4}$  for the Bia river. There is therefore a high probability that an individual will develop cancer by ingesting water after a certain length of time at these stations.

## 4. CONCLUSION

In the present study, the hazard quotient (HQ) and carcinogenic risk (CR), based on USEPA methods were used in order to assess the non-cancer and cancer risks of arsenic, copper, cadmium, lead and zinc in surface water from Bandama, Bia and Comoé River. The results of the risk assessment showed that, among the trace metals studied, As could cause harmful effects by oral ingestion and long-term cancer through consumption of river water, particularly from the Bia. Indeed, the high values of hazard quotient and cancer risk were observed in Bia River for arsenic. The health risks are higher during dry and flood seasons. The results showed that concentrations of As and Pb in the Comoé and Bia rivers posed a threat to the local population. Monitoring of trace metal pollution in these rivers should therefore be put in place by decision-makers. It is also recommended that the water from these rivers be treated and a remedy established to eliminate trace metals in order to guarantee the health of the local population.

Commented [U18]: remove in order

Commented [U19]: from

Commented [U20]: the Bia

Commented [U21]: remove in order

## REFERENCES

- [1] A.A. Ouattara, K.M. Yao, K.C. Kinimo, A. Trokourey, Assessment and bioaccumulation of arsenic and trace metals in two commercial fish species collected from three rivers of Côte d'Ivoire and health risks, *Microchemical Journal* 154 (2020) 104604. <https://doi.org/10.1016/j.microc.2020.104604>.
- [2] A.A. Ouattara, K.M. Yao, M.P. Soro, T. Diaco, A. Trokourey, Arsenic and Trace Metals in Three West African rivers: Concentrations, Partitioning, and Distribution in Particle-Size Fractions, *Arch Environ Contam Toxicol* 75 (2018) 449–463. <https://doi.org/10.1007/s00244-018-0543-9>.
- [3] S.J. Cobbina, Y. Chen, Z. Zhou, X. Wu, T. Zhao, Z. Zhang, W. Feng, W. Wang, Q. Li, X. Wu, L. Yang, Toxicity assessment due to sub-chronic exposure to individual and mixtures of four toxic heavy metals, *Journal of Hazardous Materials* 294 (2015) 109–120. <https://doi.org/10.1016/j.jhazmat.2015.03.057>.
- [4] T. Dippong, M.-A. Resz, Heavy metal contamination assessment and potential human health risk of water quality of lakes situated in the protected area of Tisa, Romania, *Heliyon* 10 (2024) e28860. <https://doi.org/10.1016/j.heliyon.2024.e28860>.
- [5] B.K. Karki, K. Lamichhane, L. Joshi, R. Kc, M.K. Sah, M. Pathak, K.R. Karki, Risk assessment of heavy metals in the major surface water system of Nepal with potential remediation technologies, *Environmental Challenges* 14 (2024) 100865. <https://doi.org/10.1016/j.envc.2024.100865>.
- [6] K.C. Kinimo, K.M. Yao, S. Marcotte, N. Guessan L.B. Kouassi, A. Trokourey, Preliminary data on arsenic and trace metals concentrations in wetlands around artisanal and industrial mining areas (Cote d'Ivoire, West Africa), *Data Brief* 18 (2018) 1987–1994. <https://doi.org/10.1016/j.dib.2018.04.105>.
- [7] N.L.B. Kouassi, K.M. Yao, N. Sangare, A. Trokourey, B.S. Metongo, The mobility of the trace metals copper, zinc, lead, cobalt, and nickel in tropical estuarine sediments, *Ebrie Lagoon, Côte d'Ivoire, J Soils Sediments* 19 (2019) 929–944. <https://doi.org/10.1007/s11368-018-2062-8>.
- [8] N.L.B. Kouassi, K.M. Yao, A. Trokourey, M.B. Soro, Distribution, Sources, and Possible Adverse Biological Effects of Trace Metals in Surface Sediments of a Tropical Estuary, *Environmental Forensics* 16 (2015) 96–108. <https://doi.org/10.1080/15275922.2014.991433>.
- [9] M.-P. Soro, K.M. N'goran, A.A. Ouattara, K.M. Yao, N.L.B. Kouassi, T. Diaco, Nitrogen and phosphorus spatio-temporal distribution and fluxes intensifying eutrophication in three tropical rivers of Côte d'Ivoire (West Africa), *Marine Pollution Bulletin* 186 (2023) 114391. <https://doi.org/10.1016/j.marpolbul.2022.114391>.
- [10] B. Mekassa, E. Etana, L.B. Merga, Proximate analysis, levels of trace heavy metals and associated human health risk assessments of Ethiopian white sugars, *Journal of Agriculture and Food Research* 16 (2024) 101086. <https://doi.org/10.1016/j.jafr.2024.101086>.
- [11] J. Lee, A.B. Pedersen, M. Thomsen, Framework for combining REACH and national regulations to obtain equal protection levels of human health and the environment in different countries – Comparative study of Denmark and Korea, *Journal of Environmental Management* 125 (2013) 105–116. <https://doi.org/10.1016/j.jenvman.2013.02.015>.
- [12] E. De Miguel, I. Iribarren, E. Chacón, A. Ordoñez, S. Charlesworth, Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain), *Chemosphere* 66 (2007) 505–513. <https://doi.org/10.1016/j.chemosphere.2006.05.065>.

- [13] E. Kim, J.C. Little, N. Chiu, Estimating Exposure to Chemical Contaminants in Drinking Water, *Environ. Sci. Technol.* 38 (2004) 1799–1806. <https://doi.org/10.1021/es026300t>.
- [14] E.N. Munene, N.O. Hashim, W.N. Ambusso, Human health risk assessment of heavy metal concentration in surface water of Sosian river, Eldoret town, Uasin-Gishu County Kenya, *MethodsX* 11 (2023) 102298. <https://doi.org/10.1016/j.mex.2023.102298>.
- [15] T.L. Jolaosho, I.O. Elegbede, P.E. Ndimele, G.O. Mekuleyi, I.O. Oladipupo, A.A. Mustapha, Comprehensive geochemical assessment, probable ecological and human health risks of heavy metals in water and sediments from dredged and non-dredged Rivers in Lagos, Nigeria, *Journal of Hazardous Materials Advances* 12 (2023) 100379. <https://doi.org/10.1016/j.hazadv.2023.100379>.
- [16] S. Muhammad, M.T. Shah, S. Khan, Health risk assessment of heavy metals and their source apportionment in drinking water of Kohistan region, northern Pakistan, *Microchemical Journal* 98 (2011) 334–343. <https://doi.org/10.1016/j.microc.2011.03.003>.
- [17] S. Selvam, K. Jesuraja, P.D. Roy, S. Venkatramanan, R. Khan, S. Shukla, D. Manimaran, P. Muthukumar, Human health risk assessment of heavy metal and pathogenic contamination in surface water of the Punnakayal estuary, South India, *Chemosphere* 298 (2022) 134027. <https://doi.org/10.1016/j.chemosphere.2022.134027>.
- [18] I. Usepa, US Environmental Protection Agency's integrated risk information system Environmental protection agency region I, Washington DC 20460 (2011).
- [19] U.C. Emmanuel, M.I. Chukwudi, S.S. Monday, A.I. Anthony, Human health risk assessment of heavy metals in drinking water sources in three senatorial districts of Anambra State, Nigeria, *Toxicology Reports* 9 (2022) 869–875. <https://doi.org/10.1016/j.toxrep.2022.04.011>.
- [20] L. Chen, B. Ren, X. Deng, W. Yin, Q. Xie, Z. Cai, Potential toxic heavy metals in village rainwater runoff of antimony mining area, China: Distribution, pollution sources, and risk assessment, *Science of The Total Environment* 920 (2024) 170702. <https://doi.org/10.1016/j.scitotenv.2024.170702>.
- [21] A. Sarkar, S.D. Karri, Human health risk assessment of selected heavy metals in tanker water: A study from Kudlu, Bengaluru, *Chinese Journal of Analytical Chemistry* 51 (2023) 100337. <https://doi.org/10.1016/j.cjac.2023.100337>.
- [22] N. Mirzaei, S. Kalteh, H. Zamani-Badi, H. Moradpour, Z. Parmoozeh, M. Baziar, Estimating human health risks associated with heavy metal exposure from bottled water using Monte Carlo simulation, *Heliyon* 9 (2023) e20647. <https://doi.org/10.1016/j.heliyon.2023.e20647>.
- [23] A.M. Taiwo, J.A. Awomeso, Assessment of trace metal concentration and health risk of artisanal gold mining activities in Ijeshaland, Osun State Nigeria— Part 1, *Journal of Geochemical Exploration* 177 (2017) 1–10. <https://doi.org/10.1016/j.gexplo.2017.01.009>.
- [24] Y. Abebe, T. Alamirew, P. Whitehead, K. Charles, E. Alemayehu, Spatio-temporal variability and potential health risks assessment of heavy metals in the surface water of Awash basin, Ethiopia, *Heliyon* 9 (2023) e15832. <https://doi.org/10.1016/j.heliyon.2023.e15832>.
- [25] S. Li, Q. Zhang, Risk assessment and seasonal variations of dissolved trace elements and heavy metals in the Upper Han River, China, *Journal of Hazardous Materials* 181 (2010) 1051–1058. <https://doi.org/10.1016/j.jhazmat.2010.05.120>.
- [26] Z. Li, Z. Ma, T.J. van der Kuijp, Z. Yuan, L. Huang, A review of soil heavy metal pollution from mines in China: pollution and health risk assessment, *Science of the Total Environment* 468 (2014) 843–853.

- [27] X. Yang, J. Duan, L. Wang, W. Li, J. Guan, S. Beecham, D. Mulcahy, Heavy metal pollution and health risk assessment in the Wei River in China, *Environ Monit Assess* 187 (2015) 111. <https://doi.org/10.1007/s10661-014-4202-y>.
- [28] B.K. Isa, S.B. Amina, U. Aminu, Y. Sabo, Health risk assessment of heavy metals in water, air, soil and fish, *Afr. J. Pure Appl. Chem.* 9 (2015) 204–210. <https://doi.org/10.5897/AJPAC2015.0654>.
- [29] E. Moses, B. Etuk, Human Health Risk Assessment of Trace metals in Water from Qua Iboe River Estuary, Ibeno, Nigeria, *J Environ Occup Sci* 4 (2015) 150. <https://doi.org/10.5455/jeos.20150714122504>.
- [30] P. Wongsasuluk, S. Chotpantarat, W. Siriwong, M. Robson, Heavy metal contamination and human health risk assessment in drinking water from shallow groundwater wells in an agricultural area in Ubon Ratchathani province, Thailand, *Environ Geochem Health* 36 (2014) 169–182. <https://doi.org/10.1007/s10653-013-9537-8>.

UNDER PEER REVIEW