Journal of Advanced Scientific Research

Available online through https://sciensage.info

ISSN
0976-9595
Research Article

Metal Contamination of the Sediments from the Area II of the Ébrié System Following the Reopening of the Grand-Bassam Inlet

DRIDA Bi Bénié Jean-Claude[1,2], YAO Marcel Konan[2]

[1]Doctoral School of Science, Technology and Sustainable Agriculture (ED-STAD), 01 BPV 34 Abidjan, Côte d'Ivoire.

[2]Laboratory of Reaction and Constitution of Matter (LCRM), UFR SSMT, Félix Houphouët-Boigny University, 22 BP 582 Abidjan 22, Côte d'Ivoire.

*Corresponding author: yaoamrcelkonan@gmail.com

Received: 12-12-2024; Accepted: 05-01-2025; Published: 30-01-2025

https://doi.org/10.55218/JASR.2025160101

ABSTRACT

This study aimed to assess the impact of the reopening of the Grand-Bassam inlet on the seasonal metal contamination of the superficial sediments of area II of the Ébrié system by thirteen trace metals (Al, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, and Zn) and the associated ecological and human health risks. This study was conducted from May 2023 to April 2024. US-EPA sediment quality guidelines and four metal contamination indices (Contamination Factor, Geoaccumulation Index, Contamination Degree, and Mean Contamination Degree) were used to assess the metal contamination of these substrates. Their ecological risks were assessed using two sediment quality guidelines (SEQ-Eau V2 and CB-SQGs) and four indices (mHQ, PERI, mPEC-Q, and mERM-Q). Human health risks, primarily through dermal contact, were assessed using the non-carcinogenic dermal hazard index and lifetime carcinogenic risks index. The findings indicated that metal seasonal contamination of these substrates by trace metals ranged from low to moderate. Overall, seasonal metal contamination of these sediments varied from moderate to considerable. Ecological risks were significant during some seasons. Generally, metal contamination and ecological risks were lower during the study period compared to before the reopening of this inlet. Short-term carcinogenic risks for humans were low, while lifetime carcinogenic risks were very high.

Keywords: Côte d'Ivoire, Metal Contamination Indexes, Grand-Bassam inlet, Metal Pollution, Ébrié System.

INTRODUCTION

Trace metals are naturally present in the terrestrial ecosystem. Since ancient times, they have been utilized in various anthropogenic activities due to their physical and chemical properties. Their usage has significantly increased since the Industrial Revolution. Currently, their demand is rising with the development of anthropogenic activities and population growth. Consequently, these metals are redistributed across all compartments of the terrestrial ecosystem at concentrations higher than their natural levels, leading to numerous ecological and health consequences.[1]

Trace metals are highly toxic to living organisms, although some, such as Al, Cu, Fe, Mn, Sb, and Zn, are essential for life. These ubiquitous compounds are persistent in the environment because they are non-biodegradable. They accumulate in living organisms and affect the entire trophic chain.[2,3] In aquatic environments, their relatively high presence poses severe ecological risks to biota. They are phytotoxic to many aquatic plants, inhibiting photosynthesis and limiting their growth, as is the case with As, Cd, Cu, and Hg.[3,4] They can also affect the physiological development of aquatic fauna, causing delayed embryo development, genital malformations, and poor growth.[3] Humans and terrestrial animals are exposed to trace metals from aquatic ecosystems through water ingestion and biota consumption. Trace metals can cause cancers, neurological disorders, respiratory issues, and dysfunctions of vital organs, among other pathologies[5]. This underscores the ongoing concern for trace metals in aquatic ecosystems, particularly in sediments, which act as their natural reservoir.[6,7]

Like the Ébrié system, area II has remarkable biodiversity. Unfortunately, this biodiversity is threatened by significant anthropogenic pressures on its watershed. For instance, Mahi et al.[8,9] demonstrated high ecological risks for its fauna and flora linked to substantial pollution of its waters and sediments during the closure of the Grand-Bassam channel. However, these studies did not highlight the human health risks related to this metallic pollution of the lagoon site. To evacuate pollutants from its watershed to the Atlantic Ocean and boost socio-economic development, the permanent reopening of the Grand-Bassam channel was implemented. This situation has consequently altered the hydrochemical evolution of this lagoon ecosystem, particularly its surface sediments. Drida and Yao [10] showed that this reopening impacted the dynamics of some trace metals. However, there is no scientific data on the impact of this hydromorphological change on the chemical pollution level of this estuary, particularly the metallic pollution of its surface sediments. In this context, the present study was conducted. Its primary objective was to evaluate the impacts of the channel reopening on the seasonal metallic contamination levels of surface sediments in this lagoon area by the total form of thirteen trace metals (Al, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, and Zn). The secondary objectives aimed to assess the associated seasonal ecological and health risks.

MATERIAL AND METHODS

Study Area

As mentioned by Mahi et al.,[8,9] the area II of the Ébrié system is located at its extreme eastern part. It is geolocated between longitudes West 3°40' and 3°50' and latitudes North 5°20' and 5°21'176471. This area is mainly composed of the Ébrié lagoon, as among the two lagoons that comprise it (Ébrié lagoon and Ouladine lagoon), the Ébrié lagoon has the larger surface area (87 km² for the Ébrié lagoon[11,12] compared to 4.5 km² for the Ouladine lagoon[13]). The Comoé River and the Mé River play key roles in the watershed of this area [8-10].

Similarly, the Atlantic Ocean influences this zone, especially with the reopening of the Grand-Bassam channel, which has significantly impacted its hydrology[10] (Figure 1). The watershed is dominated by intensive agriculture, industrial and mining activities, and illegal gold panning [8,9]. Currently, the water seasons are defined into four periods: the Hot Season (HS), the rainy season (RS), the Cold Season (CS), and the Flood Season (FS).[10]

Assessment of Metal Contamination Levels

The seasonal levels of metal contamination in the superficial sediments from this estuary were assessed based on the Sediment Quality Guidelines (SQGs) from the US-EPA[14]and four metal contamination indexes. The four indexes used are: Contamination Factor (CF), Geoaccumulation Index (Igeo), Contamination Degree (CD), and Mean Contamination Degree (MCD).

CF, defined by Hakanson[15], allows for the evaluation of the contamination level of a substrate by a metal i. It is expressed as follows:

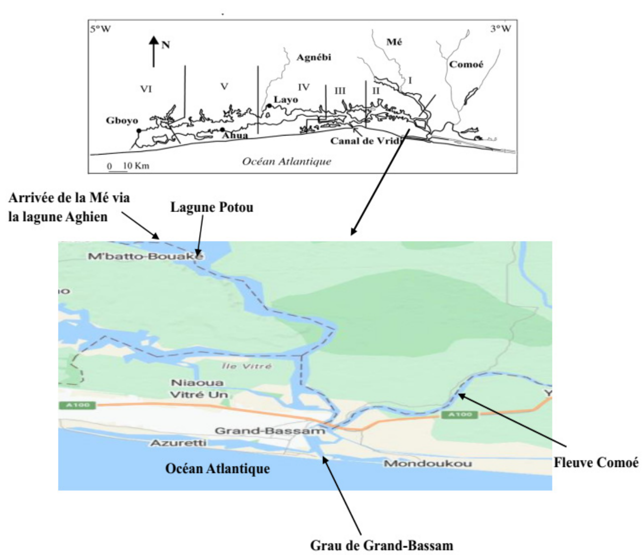

Figure 1: Geographic Location of Zone II in the Ébrié System.[10]

$$CF_i = \frac{[Me]_i}{[M} \quad (1)$$

where $[Me]_i$ represents the concentration of the trace metal i in substrate and

$[Me]_{ref}$ the geochemical reference concentration of this trace metal.

The level of contamination of the substrate by the metal i is categorized as follows: low for CF < 1, moderate for 1 ≤ CF < 3, severe for 3 ≤ CF < 6, and very severe for CF ≥ 6.

Igeo is an empirical index used to evaluate the contamination level of a substrate by metal i while taking into account the geochemical background noise. Its expression is:

$$I_{geo} = log_2\left(\frac{[Me]_{sédiment}}{1{,}5\times[Me]_{ref}}\right) \quad (2)$$

with: $[Me]_{sediment}$, the concentration of trace metal i in substrate; $[Me]_{ref}$, the geochemical concentration of the race metal i; 1.5, the geochemical background exaggeration factor, which accounts for natural fluctuations in the geochemical background.

The contamination level of the substrate by the trace metal i is classified as follows: unpolluted for Igeo ≤ 0, unpolluted to moderate for 0 <Igeo ≤ 1, moderate for 1 <Igeo ≤ 2, moderate to severe for (2 <Igeo ≤ 3; severe for 3 <Igeo ≤ 4; severe to extreme for 4 <Igeo ≤ 5, and extreme for Igeo> 5[16].

CD and MCD assess the overall metal contamination level of the substrate relative to a set of n trace metals. The CD, defined by Hakanson[15], is expressed as:

$$CD = \sum \quad (3)$$

with: CF_i, the contamination factor of sediments obtained with trace metal i; n, the total number of trace metals considered.

According to this index, the degree of metal contamination of a substrate related to a set of n trace metals is low for CD < 6, moderate for 6 ≤ CD < 12, severe for 12 ≤ CD < 24, and very severe for CD ≥ 24.

As for MCD, it generally represents the mean value of the CD. It allows for defining intermediate contamination states mentioned by the CD[15]. This contamination index was defined by Abrahim and Parker[17]. It is expressed as follows:

$$MCD = \frac{CD}{n} = \frac{\sum_{i=1}^{n} CF_i}{n} \quad (4)$$

with: CD, the degree of contamination obtained with the set of n trace metals; CF_i, the contamination factor of the sediment obtained with the trace metal i; n, the number of trace metals considered.

The degree of metal contamination of a substrate by a set of trace metals is classified as follows: very low for MCD < 1.5, low for 1.5 ≤ MCD < 2, moderate for 2 ≤ MCD < 4, severe for 4 ≤ MCD < 8, very severe for 8 ≤ MCD< 16, extremely severe for 16 ≤ MCD < 32, ultra-severe for MCD ≥ 32.

For calculating these indices, the geochemical reference values of trace metals in the upper continental crust provided by Wedepohl[18] were used, namely (mg/kg): 2 for As, 77440 for Al, 0.102 for Cd, 11.6 for Co, 35 for Cr, 14 for Cu, 30890 for Fe, 0.056 for Hg, 527 for Mn, 19 for Ni, 17 for Pb, 0.31 for Sb, and 52 for Zn.

Assessment of Ecotoxicity Risks ofTrace Metals for Benthic Fauna and Flora

The ecotoxicity risks of trace metals considered in this study for the aquatic fauna and flora of this lagoon area were assessed using two SQGs and four indexes.

The two SQGs used for this purpose were the SEQ-Eau V2[19]and the Consensus-Based Sediment Quality Guidelines (CB-SQGs)[20].

The four indexes used in this study are the modified Hazard Quotient (mHQ), Potential Ecological Risk Index (PERI), mean Probable Effect Concentration-Quotient (mPEC-Q), the mean Effect Range Medium-Quotient (mERM-Q).

mHQ is an ecological risk index based on the SQGs by Smith et al.[21] (Threshold Effect Level (TEL)) and the SQGs by Persaud et al.[22](Probable Effect Level (PEL) and Severe Effect Level (SEL)). Its expression for a trace metal iis:

$$\mathrm{mHQ} = [C_i(\frac{1}{\mathrm{TEL_i}} + \frac{1}{\mathrm{PEL_i}} + \frac{1}{\mathrm{SEL_i}})]^{1/2} \qquad (5)$$

with: TEL_i, the Threshold Effect Level value of the trace metal; PEL_i, the Probable

Effect Level value of the trace metali; SEL_i, the Severe Effect Level value of the trace metal; C_i, the concentration of the trace metal.

The respective TEL values for the considered trace metals are (mg/kg): 5.9 for As, 0.596 for Cd, 35.7 for Cu, 37.3 for Cr, 0.174 for Hg, 18 for Ni, 35 for Pb, and 123 for Zn (123) [21]. Their PEL values are (mg/kg): 17 for As, 10 for Cd, 197 for Cu, 90 for Cr, 0.486 for Hg, 36 for Ni, 91.3 for Pb, and 315 for Zn. The different SEL values for these trace metals are: 33 for As, 3.53 for Cd, 110 for Cu, 110 for Cr, 2 for Hg, 75 for Ni, 250 for Pb, and 820 for Zn[22].

Classification ofmHQ is as follows: mHQ> 3.5 extreme severity of contamination, 3.0 <mHQ< 3.5 very high severity of contamination, 2.5 <mHQ< 3.0 high severity of contamination, 2.0 <mHQ< 2.5 considerable severity of contamination, 1.5 <mHQ< 2.0 moderate severity of contamination, 1.0 <mHQ< 1.5 low severity of contamination, 0.5 <mHQ< 1.0 very low severity of contamination, and mHQ< 0.5 nil to very low severity of contamination[23].

Defined by Hakanson,[15] PERI allows estimating the ecotoxicity risk level of a set of trace metals n. This index is based on the CF. PERI is obtained as the summation of individual potential ecological risks (E_r^i, as follows:

$$E_r^i = T_r^i \times CF_i \qquad (6)$$

$$PERI = \sum_{i=1}^{n} E_r^i \qquad (7)$$

with: E_r^i, the individual potential ecological risk for the trace metal i; T_r^i, the toxicity factor for the trace metal i; CF_i, the contamination factor for trace metal i.

The value of $T_r^i$is: 10 for As, 30 for Cd, 35 for Cr, 5 for Cu, 40 for Hg, 5 for Pb, and 1 for Zn.

The ecotoxicity risks for benthic fauna and flora are classified as follows: low for E_r^i< 40; moderate for 40 ≤ E_r^i< 80\); severe for 80 ≤ E_r^i< 160; very severe for 60 ≤ E_r^i< 320\; extremely severe for E_r^i ≥ 320\).

As for the ecotoxicity risks of a set of trace metals for this fauna, they are classified as: low for PERI < 150, moderate for 150 ≤ PERI < 300, severe for 300 ≤ PERI < 450, very severe for 450 ≤ PERI < 600, extremely severe for PERI ≥ 600.

mPEC-Q allows for the assessment of ecotoxicity risks of a set of n trace metals relative to their concentration in substrate and their PEC value in the CB-SQGs (MacDonald et al., 2000).[20] Its expression is:

$$mPEC - Q = \sum_{i=1}^{n} \frac{C_i}{PEC_i} \qquad (8)$$

with: C_i, the concentration of the trace metal i in the substrate; PEC_i, the PEC value of the trace metal i; n, the number of trace metals considered.

For mPEC-Q ≤ 0.5, the set of trace metals considered poses no toxicity effects for benthic fauna and flora; whereas for mPEC-Q > 0.5, this set of metals presents acute toxicity for this fauna[20].

Developed by Long et al.[24], m-ERM-Q allows for the estimation of the proportion of benthic fauna and flora exposed to the ecotoxicity of a set of n trace metals. m-ERM-Q is based on the ERM in the SQGs by Long et al. [25] Its expression is as follows:

$$m - ERM - Q = \frac{\sum_{i=1}^{n} \frac{C_i}{ERM_i}}{n} \qquad (9)$$

with: C_i, concentration of the trace metal i in substrate; ERM_i, the ERM value of the trace metal i; n, the number of trace metals.

ERM values are (mg/kg): 70 for As, 9.6 for Cd, 370 for Cu, 270 for Cr, 0.71 for Hg, 51.6 for Ni, 218 for Pb, and 410 for Zn[25].

The probability of benthic fauna and flora being subjected to the ecotoxicity of a set of trace metals is: 9% for m-ERM-Q < 0.1, 21% for 0.1 ≤ m-ERM-Q < 0.5, 49% for 0.5 ≤ m-ERM-Q < 1.5, 79% for 1.5 ≤ m-ERM-Q < 5.76, and 90% for m-ERM-Q ≥ 5.76.[24]

Assessment of Human Health Risks

The human health risks were primarily associated with dermal contact with the sediments. In this regard, non-carcinogenic dermal risks (HI_{derm}) and lifetime carcinogenic risks (RI) were assessed for two individuals: a child and an adult.

Non-carcinogenic dermal risks

Defined by the US-EPA[26], non-carcinogenic dermal risks (HQ_{derm}) related to a set of trace metals are obtained as the summation of the individual non-carcinogenic dermal risks of these trace metals. For a given trace metal i, the non-carcinogenic dermal risks (HQ_{derm}) are derived from $DJE_{derm,\,i,}$ which is expressed as:

$$DJE_{derm,i} = \frac{SA \times CF \times AF \times ABS \times EF \times ED}{m \times AT} \qquad (10)$$

with: SA, surface area of Adherence; CF, Conversion Factor; AF, Adherence Factor per unit area of the skin; ABS, dermal absorption rate; EF, Exposure Frequency; ED, Exposure Duration; m, body weight of the individual; AT, Average exposure Time.

$HQ_{derm,i}$ is obtained as follows:

$$HQ_{derm,i} = \frac{DJE_{derm,i}}{RfD_{derm,i}} \qquad (11)$$

with: $RfD_{derm,i}$ the dermal reference dose of the trace metal i.

The $RfD_{derm,i}$ for trace metals are derived from their oral reference dose (RfD_0) according to US-EPA [27] using the following relationship:

$$RfD_{derm,i} = RfD_{O,i} \times ABS_{GI,i} \qquad (12)$$

with: $ABS_{GI,i}$, the fraction of the contaminant absorbed in the gastrointestinal tract in critical toxicity studies (dimensionless).

The different $RfD_{derm,\,i}$ values (mg/kg/day) used are: 3x10^-4 for As, 1 for Al, 1.25x10^-5 for Cd, 7.5x10^-5 for Cr, 3x10^-4 for Co, 4x10^-2 for Cu, 0.7 for Fe, 3x10^-4 for Hg, 9.6x10^-4 for Mn, 4x10^-4 for Ni, 0.04 for Pb, 6x10^-5 for Sb, and 0.3 for Zn.

The HI_{derm} for individuals related to the entire set of these trace metals is given by:

$$HI_{derm} = \sum_{i=1}^{n} HQ_{derm,i} \qquad (13)$$

So, for ($HI_{derm} \leq 1$, the carcinogenic risks are very low. However, for $HI_{derm} > 1$, we cannot conclusively determine the carcinogenic risks, but the matrix appears to be dangerous[26].

Lifetime Carcinogenic Dermal Risks

Also defined by the US-EPA[26], the lifetime carcinogenic dermal risks (RI) of an individual associated with a set of n trace metals are obtained through the Incremental Lifetime Carcinogenic Risks related to a metal i ($ILCR_{derm,i}$). This index is derived from $LADD_{derm,\,i}$, which has the same expression as $DJE_{derm,\,i}$, except that AT is extended to the entire lifetime of the individual.

$$ILCR_{derm,i} = LADD_{derm,i} \times CSF_{derm,i} \qquad (14)$$

The lifetime dermal carcinogenic risks (RI) are finally expressed as follows:

$$RI_{derm} = \sum_{i=1}^{n} ILCR_{derm,i} \qquad (15)$$

As, Cd, Cr, Cu, and Pb are potentially carcinogenic to humans [26, 28]. Therefore, the RI_{derm} for the considered individuals was assessed using these trace metals. The value of $CSFd_{erm,\,i}$ (mg/kg/day) is: 3.66 for As, 20 for Cd, 20 for Cr, 42.5 for Cu, and 8.5x10^-6 for Pb.

The lifetime dermal carcinogenic risks for humans are classified as: negligible for $RI_{derm} \leq$ 10^-6, low for 10^-6< $RI_{derm} \leq$10^-4, moderate for 10^-4< $RI_{derm} \leq$ 10^-3, high for 10^-3 < $RI_{derm} \leq$ 10^-1, and very high for $RI_{derm} >$ 10^-1[26,28].

The parameters used for the calculation of all these indices for each individual are recorded in Table 1.

Data Source

The seasonal and annual mean values of the concentration of these trace metal in the sediments from this estuary in the study period were provided by Drida and Yao [10].

Statistical Treatment of Results

In addition to standard univariate statistical techniques, namely the mean (m) and the standard deviation (s), the Student's t-test[32]was used to determine whether the differences between the values of the various ecological and health standards defined by the SQGs and the indexes used, and the results obtained, are statistically significant or not. The results were considered statistically significant for $p < 0.05$. All these statistical techniques were implemented using Statistica software version 7.

Table 1: Parameter values used for the calculation of various human health risk indices in this study

Variables	*Individuals*	
	Child	*Adult*
$m_{individu}$ (kg)	42.6 [29]	70 [30]
SA (cm^2)	2,373 [31]	6,032 [31]
AF (mg/cm^2)	0.2 [31]	0.07 [31]
ABS	0.03 for As and 0.01 for the other trace metals [31]	
EF (once per day)	365	
ED (annual)	6	*40
AT (days) (non-carcinogenic index)	2,190	14,600
AT (day) Carcinogenic index (RI)	21,700	
FC (mg/kg))	10^-6 [31]	

*Considered from the age of 18 and the life expectancy in Côte d'Ivoire (58 years)

RESULTS AND DISCUSSION

Results

Metal contamination levels

These sediments were deemed polluted according to US-EPA[31] in RS due to their mean concentrations of As, Cd, and Zn; in CS due to their concentration of As; in FS due to their mean concentrations of As; and in CS due to their mean concentrations of Cd, Cr, and Mn. In other cases, this SQGs showed that they were either non-polluted or moderately polluted (Table 2). All these observations were confirmed by the Student's t-test ($p < 0.05$).

All seasonal mean values of the CF of As, Al, Co, Cr, Fe, Mn, Ni, Pb, and Zn were below 1, showing the weakly contamination of these sediments by these trace metals. They were severely contaminated in RS and in HS by Cd and Sb. However, they were weakly contaminated by these two trace metals in CS and in FS. They were moderately contaminated by Cu and severely contaminated by Hg in RS and in HS. However, they were weakly contaminated during the other three seasons by these two trace metals. These observations were highlighted by the Student's t-test ($p < 0.05$)). These same findings were practically identical with Igeo. This index was indicated unpolluted state of these sediments by As, Al, Co, Cr, Fe, Mn, Ni, Pb, and Zn. The same was true for their contamination by Cu. They were moderately to severely contaminated in RS and moderately contaminated in HS by Cd and Sb. However, they were unpolluted by these two trace metals during the other two seasons. They were moderately contaminated in RS and from unpolluted to moderately polluted in HS by Hg. They were unpolluted by this trace metal during the other two seasons (Table 3). These results were corroborated by the Student's t-test ($p < 0.05$). The seasonal mean

Table 2: Metal contamination levels of the superficial sediments from the area II of the Ébrié system during the study period according to the US-EPA[31].

Trace metals	*Level pollution according US-EPA (2004) (Concentration in mg/kg)*			*Seasonal and annual mean concentration obtained in this study (mg/kg)*		*Pollution level*
	Unpollued	*Moderately polluted*	*Highly polluted*			
As	<3	3-8	> 8	RS	10.183 ± 0.295	Highly polluted
				CS	16.266 ± 1.337	
				FS	11.571 ± 1.074	
				HS	3.309 ± 0.120	Moderately polluted
				Annual	10.332 ± 5.357	Highly polluted
Cd	-	-	> 6	RS	11.003 ± 0.235	Highly polluted
				CS	0.323 ± 0.009	Unpolluted
				FS	0.968 ± 0.125	
				HS	21.797 ± 1.004	Highly polluted
				Annual	8.523 ± 10.111	
Cr	< 25	25-75	> 75	RS	10.261 ± 0.387	Unpolluted
				CS	25.829 ± 1.235	Moderately polluted
				FS	22.685 ± 1.253	Non pollué
				HS	88.390 ± 3.851	Highly polluted
				Annual	36.791 ± 35.050	Moderately polluted
Fe	< 17,000	17,000-25,000	> 25,000	RS	757.746 ± 22.447	Unpolluted
				CS	765.296 ± 16.511	
				FS	733.405 ± 20.373	
				HS	138.922 ± 10.470	
				Annual	411.300 ± 394.228	
Mn	< 300	300-500	> 500	RS	378.035±20.813	Moderately polluted
				CS	127.010±4.757	Unpolluted
				FS	110.102±4.671	
				HS	527.952±22.301	Highly polluted
				Annual	285.775±202.672	Unpolluted
Pb	< 40	40-60	> 60	RS	14.442±0.480	Unpolluted
				CS	18.533±1.210	
				FS	16.889±1.711	
				HS	12.857±0.520	
				Annual	15.680±2.524	
Zn	< 90	90-200	> 200	RS	572.388±19.631	Highly polluted
				CS	114.463±4.390	Moderately polluted
				FS	99.452±4.244	
				HS	146.066±6.765	
				Annual	232.842±227.158	Highly polluted

values of CF and Igeo for As, Cd, Cr, Hg, Ni, and Pb determined in this study were lower than those determined by Mahi et al. [9]. The opposite was true for Cu and Zn.

The seasonal mean values of CD obtained over the study period highlighted the weak contamination of these substrates in CS and FS by all these trace metals. This was highlighted by the Student's t-test ($p< 0.05$). However, the Student's t-test was highlighted the considerable contamination of these sediments by all these trace metals in RS and CS, showing by their mean values of DCin these two seasons ranged between 12 and 24 ($p< 0.05$). As for the seasonal mean values of MCD, they confirmed the weak contamination of these substrates by all these trace metals; as confirmed by the Student's

Table 3: Seasonal and annual meanvalues of CF and Igeofor these trace metals in the superficial sediments from the areaII of the Ébrié system during the study period.

Trace metals	*Seasons*	*FC*	*Igeo*	*Trace metals*	*Seasons*	*CF*	*Igeo*
	RS	0.318±0.418	-2.273±0.648		RS	4.863±3.563	1.274±1.240
As	CS	0.407±0.668	-3.318±2.033	Hg	CS	0.340±0.241	-2.541±1.286
	FS	0.305±0.537	-3.627±1.856		FS	0.280±0.203	-2.796±1.179
	HS	0.097±0.060	-4.231±0.964		HS	5.176±4.420	0.450±2.672
	Annual	0.264±0.237	-3.066±1.333		Annual	2.242±1.750	-0.123±1.754
	RS	2.884x10^-4±1.367x10^-4	-12.493±0.687		RS	0.045±0.039	-5.451±1.022
Al	CS	8.170x10^-5±5.060x10^-5	-14.400±0.862	Mn	CS	0.012±0.009	-7.248±0.896
	FS	6.940x10^-5±4.340.10^-5	-14.638±0.850		FS	0.011±0.009	-7.391±0.879
	HS	1.221x10^-4±9.551.10^-5	-14.060±1.269		HS	0.059±0.042	-5.371±1.768
	Annual	1.240x10^-4±6.140.10^-5	-13.779±0.894		Annual	0.028±0.018	-6.148±1.198
	RS	6.742±2.304	2.099±0.448		RS	0.139±0.061	-2.962±0.566
Cd	CS	0.158±0.092	-3.560±1.101	Ni	CS	0.214±0.108	-2.419±0.811
	FS	0.499±1.225	-3.062±1.752		FS	0.224±0.169	-2.498±1.029
	HS	12.571±9.846	1.208±3.663		HS	0.049±0.046	-4.849±1.192
	Annual	4.190±3.314	0.482±2.291		Annual	0.159±0.048	-2.719±0.477
	RS	0.318±0.170	-2.489±0.964		RS	0.053±0.028	-5.021±0.810
Co	CS	0.005±0.003	-8.551±1.079	Pb	CS	0.055±0.071	-5.440±1.380
	FS	0.011±0.022	-8.274±1.588		FS	0.052±0.101	-6.184±1.845
	HS	0.176±0.136	-4.618±3.140		HS	0.044±0.031	-5.605±1.477
	Annual	0.105±0.078	-4.779±2.248		Annual	0.048±0.037	-5.308±1.024
	RS	0.018±0.011	-6.606±0.914		RS	10.761±4.812	2.733±0.558
Cr	CS	0.037±0.035	-5.728±0.975	Sb	CS	1.047±0.857	-1.046±1.331
	FS	0.034±0.036	-5.791±0.848		FS	1.306±1.214	-0.972±1.642
	HS	0.149±0.110	-4.041±1.762		HS	13.108±12.609	1.661±2.904
	Annual	0.054±0.033	-5.157±1.137		Annual	5.552±4.240	1.183±1.787

Cu	RS	1.451±0.580	-0.145±0.539
	CS	0.369±0.180	-2.178±0.683
	FS	0.383±0.230	-2.171±0.683
	HS	0.392±0.234	-2.168±0.843
	Annual	0.575±0.264	-1.574±0.826
Fe	RS	1.533x10^5±7.267.10^-5	-16.723±0.667
	CS	0.001±5.350.10^-4	-10.454±0.929
	FS	0.001±6.600.10^-4	-10.442±0.857
	HS	2.645.10^-4±3.389.10^-4	-13.708±1.916
	Annual	7.510.10^-4±1.740.10^-4	-11.005±0.370
Zn	RS	0.688±0.378	-0.748±0.818
	CS	0.110±0.084	-3.617±1.245
	FS	0.101±0.082	-3.737±1.186
	HS	0.164±0.136	-3.183±1.499
	Annual	0.229±0.134	-2.494±1.235

Table 4: Seasonal and annual mean values of CD and MCDfor all these trace metals in the superficial sediments from the area II of the Ébrié system during the study period.

Seasons	*CD*	*MCD*
RS	*25.395±7.306	***1,953±0,562
CS	2.755±1.942	0,212±0,149
FS	3.207±2.584	0,247±0,199
HS	**31.986±24.229	2,460±1,864
Annual	13.446±8.895	1,034±0,684

* Student's t-test for CD > 24 has p = 0.364, o 12 ≤ CD < 24;
** Student's t-test for CD > 24 has p = 0.244, so 12 ≤ DC < 24;
*** Student's t-test for MCD> 2 has p = 0.912, so 2 ≤ MDC < 4.

t-test ($p< 0.05$). Regarding their contamination by these trace metals, it was moderate in RS and HS according to the Student's t-test, showing the mean values of DCM in these seasons ranged between 2 and 4 (Table 4). All mean seasonal values of CD and MCD related to these trace metals were lower than those obtained by Mahi et al.[9].

Ecological risk levels

These sediments exhibited poor ecological quality in RS due to their mean concentrations of Cd, Cu, Hg, and Zn; in CS and FS due to their mean concentration of Ni; and in HS due to their mean concentrations of Cd and Hg. In other cases, they displayed ecological qualities ranging from moderate to good according to SEQ-Eau V2 [19] (Table 5). These observations were highlighted by the Student's t-test ($p< 0.05$).

According to CB-SQGs,[20] the ecotoxicity risks of Cd for the benthic fauna of this ecosystem were significantly high in RS and HS. Similarly, the risks associated with Cu for this fauna were particularly high in RS, while those for Hg were high in RS and HS for these living organisms. Regarding the ecotoxicity risks of Ni for the benthic fauna of this lagoon area, they were marked in CS and FS, and those of Zn were significant in RS. The ecotoxicity risks due to As, Cd, Cr, Hg, Ni, Pb, and Zn were low respectively in HS, CS and FS,CSF and FS, HS, all seasons, and CS and FS. In other cases, the risks associated with these trace metals for the benthic fauna of this ecosystem were undefined, as the mean concentrations of these trace metals were between TEC and PEC (Table 6). All these observations were highlighted by the Student's t-test ($p< 0.05$).

The seasonal mean values of m-HQ for Cd in RS and FS indicate its low severity ecotoxicity for the benthic fauna of this lagoon site during these seasons. However, in the other two seasons, its ecotoxicity for this fauna is considered very low. As for the ecotoxicities of As, Ni, and Pb for this fauna, they were very low in all seasons. All these observations were highlighted by the Student's t-test ($p< 0.05$). Regarding Cr, its ecotoxicity for organisms living in these substrates in the first three seasons was very low, as highlightded by the Student's t-test ($p< 0.05$). However, its ecotoxicity for these organisms in HS was of low severity according to the Student's t-test. The same was true for Cu for this fauna in the last three seasons according to the Student's t-test. In contrast, it was very low in RS for these organisms, as confirmed by the Student's t-test ($p < 0.05$)). Hgwas presented very low ecotoxicities for thesebenthic fauna in CSF and FS, as highlighted by the Student's t-test ($p< 0.05$); while

Table 5: Ecological qualities of the superficial sediments of this estuary in relation to Their concentrations in some trace metals according to SEQ-Eau V2[19] over the Study Period.

Trace metals	*Threshold values (mg/kg)*				*Seasonal and annual mean concentrations obtained in this study (mg/kg)*		*Ecological quality level*
	Excellent quality	*Good quality*	*Moderate quality*	*Poor quality*			
As	1	9,8	33	> 33	RS	10.183 ± 0.295	Moderate
					CS	16.266 ± 1.337	
					FS	11.571 ± 1.074	
					HS	3.309 ± 0.120	Good
					Annual	10.332 ± 5.357	Moderate
Cd	0.1	1	5	> 5	RS	11.003 ± 0.235	Poor
					CS	0.323 ± 0.009	Good
					FS	0.968 ± 0.125	
					HS	21.797 ± 1.004	Poor
					Annual	8.523 ± 10.111	
Cr	4.3	43	110	> 110	RS	10.261 ± 0.387	Good
					CS	25.829 ± 1.235	
					FS	22.685 ± 1.253	
					HS	88.390 ± 3.851	Moderate
					Annual	36.791 ± 35.050	Good
Cu	3.1	31	140	> 140	RS	324.968 ± 8.125	Poor
					CS	103.308 ± 2.513	Moderate
					FS	101.868 ± 3.224	
					HS	93.357 ± 3.281	
					Annual	155.875 ± 112.814	Poor
Hg	0.02	0.2	1	> 1	RS	4.357 ± 0.200	Poor
					CS	0.381 ± 0.014	Moderate
					FS	0.298 ± 0.011	
					HS	4.928 ± 0.248	Poor
					Annual	2.491 ± 2.495	
Ni	2.2	22	48	> 48	RS	42.134 ± 1.157	Moderate
					CS	81.365 ± 2.057	Poor
					FS	81.074 ± 3.226	
					HS	15.828 ± 0.866	Good
					Annual	55.100 ± 32.015	Poor
Pb	3.5	35	120	> 120	RS	14.442 ± 0.480	Bonne
					CS	18.533 ± 1.210	
					FS	16.889 ± 1.711	
					HS	12.857 ± 0.520	
					Annual	15.680 ± 2.524	
Zn	12	120	460	> 460	RS	572.388 ± 19.631	Poor
					CS	114.463 ± 4.390	Moderate
					FS	99.452 ± 4.244	Good
					HS	146.066 ± 6.765	Moderate
					Annual	232.842 ± 227.158	

Table 6: Seasonal and annual ecotoxicity risks of some trace metals for the benthic fauna of these sediments according to CB-SQGs[20]aver the study period.

Trace metals	*mg/kg dry weight*		*Mean concentration (mg/kg dry weight)*		*Ecotoxicity risksfor benthic fauna*
	TEC	*PEC*			
As	9.79	33	RS	10.183 ± 0.295	Undefined
			CS	16.266 ± 1.337	
			FS	11.571 ± 1.074	
			HS	3.309 ± 0.120	Low
			Annual	10.332 ± 5.357	Undefined
Cd	0.99	4.98	RS	11.003 ± 0.235	High
			CS	0.323 ± 0.009	Low
			FS	0.968 ± 0.125	
			HS	21.797 ± 1.004	High
			Annual	8.523 ± 10.111	
Cr	43.4	111	RS	10.261 ± 0.387	Low
			CS	25.829 ± 1.235	
			FS	22.685 ± 1.253	
			HS	88.390 ± 3.851	Undefined
			Annual	36.791 ± 35.050	Low
Cu	31.6	149	RS	324.968 ± 8.125	High
			CS	103.308 ± 2.513	Undefined
			FS	101.868 ± 3.224	
			HS	93.357 ± 3.281	
			Annual	155.875 ± 112.814	High
Hg	0.18	1.06	RS	4.357 ± 0.200	High
			CS	0.381 ± 0.014	Low
			FS	0.298 ± 0.011	
			HS	4.928 ± 0.248	High
			Annual	2.491 ± 2.495	
Ni	22.7	48.6	RS	42.134 ± 1.157	Undefined
			CS	81.365 ± 2.057	High
			FS	81.074 ± 3.226	
			HS	15.828 ± 0.866	Low
			Annual	55.100 ± 32.015	High
Pb	35.8	128	RS	14.442 ± 0.480	Low
			CS	18.533 ± 1.210	
			FS	16.889 ± 1.711	
			HS	12.857 ± 0.520	
			Annual	15.680 ± 2.524	
Zn	121	459	RS	572.388 ± 19.631	High
			CS	114.463 ± 4.390	Low
			FS	99.452 ± 4.244	
			HS	146.066 ± 6.765	Undefined
			Annual	232.842 ± 227.158	

Table 7: m ± s of mHQ of some trace metals in the superficial sediments from the area II of the Ébrié system over the study period

Trace metals	*RS*	*CS*	*FS*	*HS*	*Annual*
As	0.396 ± 0.090	0.360 ± 0.291	0.313 ± 0.251	0.214 ± 0.070	0.321 ± 0.112
Cd	1.176 ± 0.192	0.174 ± 0.056	0.242 ± 0.222	1.381 ± 0.884	0.743 ± 0.371
Cr	0.167 ± 0.051	0.229 ± 0.093	0.222 ± 0.086	*0.419 ± 0.213	0.267 ± 0.071
Cu	0.910 ± 0.175	**0.454 ± 0.110	***0.459 ± 0.128	****0.462 ± 0.138	0.571 ± 0.028
Hg	*****1.407 ± 0.549	0.374 ± 0.138	0.340 ± 0.124	******1.328 ± 0.827	0.862 ± 0.341
Ni	0.244 ± 0.076	0.305 ± 0.160	0.301 ± 0.147	0.132 ± 0.056	0.245 ± 0.051
Pb	0.192 ± 0.052	0.179 ± 0.094	0.154 ± 0.126	0.168 ± 0.070	0.173 ± 0.032
Zn	0.646 ± 0.180	0.250 ± 0.099	0.239 ± 0.095	0.300 ± 0.134	0.359 ± 0.040

* For mHQ< 0.5, p = 0.386, therefore 0.5 <mHQ< 1.5;
** For mHQ< 0.5, p = 0.06, therefore 0.5 <mHQ< 1.5;
*** For mHQ< 0.5, p = 0.197, therefore 0.5 <mHQ< 1.5;
**** For mHQ< 0.5, p = 0.353, therefore 0.5 <mHQ< 1.5;
***** For mHQ< 1.5, p = 0.543, therefore 1.5 <mHQ< 2;
****** For mHQ< 1.5, p = 0.357, therefore 1.5 <mHQ< 2.

this test showed that its ecotoxicity was moderately severe in RS and HS. The ecotoxicity of Zn for this fauna was of low severity in RS and very low severities in the last three seasons, also highlighted by the Student's t-test (p< 0.05) (Table 7).

The analysis of the mean values of PERI of these substrates for CS and FS indicates the low ecological risks related to As, Cd, Cr, Cu, Hg, Pb, and Zn in these two seasons. However, they were very high in HS and RS, as demonstrated by the mean value of PERI for these trace metals in these seasons during the study period. This was highlighted by the Student's t-test (p < 0.05). Regarding the ecological risks according to the mean value of PERI of these sediments in RS related to these trace metals, the Student's t-test revealed that they were not severe (p> 0.05), but rather very high (p< 0.05). The low ecological risks in CS and FS were also confirmed by the low values of m-PEC-Q related to the ecotoxicity risks of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn for the benthic fauna of this ecosystem. In contrast, in the other two seasons, these risks related to these trace metals were acute over the study period. These results were highlighted by the Student's t-test (p< 0.05). Similar observations were also made by m-ERM-Q, which indicates that 9% of the benthic fauna of this lagoon area were exposed to the ecotoxicity risks of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn in CS and FS. However, 49% of this fauna was exposed to the ecotoxicity risks of these trace metals in the other two seasons during this period. These remarks were also highlighted by the Student's t-test (p< 0.05) (Table 8).

Table 8: Seasonal and annual mean values of PERI, mPEC-Q, and mERM-Q of the superficial sediments from this lagoon site over the study period.

Seasons	*PERI	**mPEC-Q	**mERM-Q
RS	***408.813±126.560	0.696±0.199	0.952±0.613
CS	25.934±16.712	0.196±0.112	0.073±0.045
FS	32.714±38.993	0.196±0.148	0.067±0.042
HS	592.694±420.119	0.664±0.418	1.078±0.851
Annual	265.039±150.833	0.438±0.194	0.525±0.332

* obtained with the seasonal concentrations of As, Cd, Cr, Cu, Hg, Pb, and Zn in these sediments;
** obtained with the seasonal concentrations of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn in these sediments;
*** Student's t-test for PERI < 450 has p = 0.292 in HS, thus 450 < PERI < 600 (p = 6.832x10^-5).

Human health risk levels

All seasonal mean values of HI_{derm} for child and adult were below 1, as highlighted by the Student's t-test (p < 0.05). So, the daily carcinogenic risks for these individuals at these life stages are negligible. As for the lifetime carcinogenic risks, they were very high in all seasons for these individuals, as highlighted by the seasonal mean values of theirRI_{derm} ranging between 0.001 and 0.1 (Table 9). These observations were confirmed by the Student's t-test (p< 0.05).

DISCUSSION

The reopening of the Grand-Bassam inlet immediately facilitated the partial metal depollution of this estuary by enabling their transport into the Atlantic Ocean through meteoric waters, along with invasive aquatic plants[33]. This metal depollution of these sediments was significant during the study period, especially for elements As, Cd, Cr, Hg, Ni, and Pb, as indicated by the seasonal mean values of their CF and Igeo, which were much lower than those determined by Mahi et al.[9]just before the reopening of this pass. This was also highlighted by the seasonal mean values of CD and MCD related to all trace metal for these sediments, which were lower than those determined by these authors. This biogeochemical and physical process was favoured by the position of this estuary, located at a higher altitude relative to the Atlantic Ocean in front of the inlet, similar to the Ébrié system. The contamination levels of Cu and Zn in these sediments, compared to those noted by Mahi et al.[9]based on CF and Igeo, can be partly explained by the modification of the floristic and faunal composition of this aquatic ecosystem, induced by the strong intrusion of ocean waters[33]. Indeed, some floristic species, such as *Eichhorniacrassipes*, are very sensitive to salinity, which, for values above 24 g/l, leads to their mortality[34].

The seasonal contamination levels of these sediments by these trace metals, according to the US-EPA[31], differ for some trace metals across seasons compared to those determined using CF and Igeo. Indeed, this SQG was showed, like these two contamination

Table 9: Seasonal and annual mean values of HI_{derm} and RI_{derm} for Child and adult over the study period.

Seasons	HI_{derm}		RI_{derm}	
	Child	Adult	Child	Adult
RS	0.019 ± 0.007	0.010 ± 0.004	0.0012 ± 0.0006	0.0043 ± 0.0023
CS	0.005 ± 0.004	0.003 ± 0.002	0.0012 ± 0.002	0.0044 ± 0.0058
FS	0.006 ± 0.005	0.003 ± 0.003	0.0012 ± 0.002	0.0042 ± 0.0082
HS	0.032 ± 0.024	0.017 ± 0.013	0.0009 ± 0.0006	0.0036 ± 0.0025
Annual	0.015 ± 0.009	0.008 ± 0.005	0.0011 ± 0.0008	0.0041 ± 0.0028

indexes, the lower contamination of these substrates by Fe and Pb in all seasons, nor by Cd and Mn in CS and FS, nor by Cr in RS and FS during the study period. In some cases, the contamination levels of these entities defined by this SQG differ from those obtained by FC and Igeo. These divergences are explained by the fact that CF and Igeo are based on geochemical references of trace metals in the upper continental crust [15,16], while the US-EPA[31]considers the empirical ecotoxic effects of trace metals on benthic fauna. This empirical consideration of SQGs also led to divergences with SEQ-Eau V2 [19] and CB-SQGs[20], both of which are also empirical, concerning the seasonal contamination levels of these substrates and their potential toxicity risks for benthic fauna in most cases.

According to SEQ-Eau V2[19]and CB-SQGs[20], the ecotoxicity risks of Cd, Cu, Hg, Ni, and Zn for aquatic fauna were significant on mean over the study period. This was particularly the case for Cd and Hg during RS and HS, Cu during RS, Ni during CS and FS, and Zn during RS. These findings were confirmed by the seasonal mean values of mHQ for these trace metals during these seasons. Thus, the meteoric water inputs in SP and the strong intrusion of ocean waters favored relatively very significant ecological risks for aquatic fauna related to Cd, Cu, Hg, and Ni during the study period. The impacts of these inputs also explain the high ecological risks for benthic fauna related to As, Cd, Cr, Cu, Hg, Pb, and Zn during these seasons, as highlighted byPERI, mPEC-Q, and mERM-Q. In contrast, the significant leaching of these trace metals in these sediments by the Comoé River during its flood towards the Atlantic Ocean led to low ecotoxicity risks of these trace metals for benthic fauna during CS and FS, as also highlightedby these metal pollution indexes. The high bioaccumulation of these trace metals by the benthic fauna of this ecosystem can induce numerous pathologies in these organisms, including oxidative and DNA damage[35]. This situation illustrates the strong anthropogenic pressures on the basin of the area II of the Ébrié system, as already mentioned by Mahi et al.[8,9].

The severe health risks associated with these trace metals for this fauna have serious ecological implications, as this benthic fauna plays an important role in recycling these substrates and consequently in the resources of this estuary. They also have serious socio-economic implications, particularly on human health[36]. The health risks for humans are all the more significant as the products of this estuary are highly appreciated by the populations, especially the local population. Moreover, these risks are also significant through dermal contact, as trace metals can cross the dermal barrier in humans[37]. This is especially true as this aquatic ecosystem is used daily for swimming, bathing, laundry, and dishwashing by the local population, as well as all populations living along the shores of the Ébrié system[38]. If the daily dermal contact risks were not significant for children and adults for all thirteen trace metals, this is not the case for lifetime carcinogenic risks, which are very high and related to As, Cd, Cr, Cu, and Pb, especially to Cd, Cr, and Cu, which are potentially carcinogenic for humans through dermal contact[26,28].

CONCLUSION

This work has highlighted the partial self-purification of this lagoon site with respect to metal pollution, facilitated by the reopening of the Grand-Bassam pass. However, ecological risks remain significant during certain seasons, as do long-term health risks. Additional studies are necessary to better understand the behaviour of trace metals in the surface sediments of this lagoon site, particularly their mobility in these substrates.

AUTHOR'S CONTRIBUTION

Drida Bi Benie Jean-Claude: Conceptualization; Funding acquisition; Methodology; Roles/Writing – original draft; Writing – review & editing; Resources

YAO Marcel Konan: Project administration; Validation; Supervision; Visualization; Resources; Roles/Writing – original draft; Writing – review & editing; Resources.

CONFLICTS INTEREST

The authors declare there is not conflict of interest.

REFERENCES

1. Miller H, Dikau S, Svartzman R, Dees S. The Stumbling Block in 'the Race of our Lives': Transition-Critical Materials, Financial Risks and the NGFS Climate Scenarios. Working paper, Banque de France ed. paper no 907; 2023.http://dx.doi.org/10.2139/ssrn.4356692
2. Zergui A, Boudalia S, Joseph ML. Heavy metals in honey and poultry eggs as indicators of environmental pollution and potential risks to human health. J Food Compos Anal. 2023; 119: 105255. https://doi.org/10.1016/j.jfca.2023.105255
3. Saravanan P, Saravanan V, Rajeshkannan R, Arnica G, Rajasimman M., Baskar G et al.Comprehensive review on toxic heavy metals in the aquatic system: sources, identification, treatment strategies, and health risk assessment. Environ Res. 2024 ; 258 : 119440. https://doi.org/10.1016/j.envres.2024.119440
4. El Zrelli RB, Yacoubi L, Castet S, Grégoire M, Lin Y-J, Attia F et al.Compartmentation of trace metals in Cymodoceanodosa from a heavily polluted area (Central Gulf of Gabes; Southern Mediterranean Sea): Potential use of the seagrass as environmental monitoring and bioremediation tool. Reg Stud Mar Sci. 2023 ; 65 :103056. https://doi.org/10.1016/j.rsma.2023.103056

5. Génard-Walton M, Warembourg C, Duros S, Ropert-Bouchet M, Lefebvre T, Guivarc'h-Levêque A et al.Heavy metals and diminished ovarian reserve: single-exposure and mixture analyses amongst women consulting in French fertility centres. ReprodBioMed Online. 2023;47(3): 103241. https://doi.org/10.1016/j.rbmo.2023.05.013
6. Zhu R, Zeng YY, Liu LM, Yin L, Xu KP, Chen WF et al. Pollution status and assessment of seven heavy metals in the seawater and sediments of Hangzhou Bay, China. Mar Pollut Bull. 2024; 209 (Part B):117261. https://doi.org/10.1016/j.marpolbul.2024.117261
7. Ma X, Song Z, Wang YP, Wang S, Zhan ZX, He D. Heavy metal dynamics in riverine mangrove systems: A case study on content, migration, and enrichment in surface sediments, pore water, and plants in Zhanjiang, China. Mar Environ Res. 2025; 203: 106832. https://doi.org/10.1016/j.marenvres.2024.106832
8. Mahi AMA, Yao MK, Claon JS, Trokourey A. Metal Pollution, Ecological and Health Risks Status of the Open Waters from the Lagoon Area II of Ébrié System (Côte d'Ivoire). Asian J Chem Sci. 2022a; 11(3): 1-15.DOI: 10.9734/ajocs/2022/v11i319121
9. Mahi AMA., Yao MK, Claon JS, Trokourey A.Seasonal metal pollution level and ecological risks of the superficial sediments from a tropical lagoon area. Inter J Adv Res. 2022b; 10(10): 1036-1049.DOI: 10.21474/IJAR01/15579
10. Drida B. J.C., Yao M. K. Effects of the reopening of the Grand-Bassam inlet on the seasonal dynamics of some trace metals in the superficial sediments from the area II of the Ébrié system. Earth J ChemSci, 2025; 12(1) :
11. Durand JR, GuiralD.Hydroclimat et hydrochimie. In Les milieux lagunaires, Tome 2 : Environnement et ressources aquatiques de Côte d'Ivoire. ORSTOM edition; 1994. pp. 59-90.
12. Bamba SB, Ouffoué S, Blé MC, Métongo BS, Bakayoko S. État de l'environnement lagunaire de l'Ile Vitré (Grand-Bassam, Côte d'Ivoire) : Aspects physiques, chimiques et biologiques. RevIvoirSciTechnol. 2008 ; 12 : 77–92.
13. Keumean KN, Bamba SB, Soro G, Soro N, Métongo BS, Biémi, J. Concentration en métaux lourds des sédiments de l'estuaire du fleuve Comoé à Grand-Bassam(Sud-Est de la Côte d'Ivoire). J ApplBiosci. 2013; 6: 4530–9.
14. US-EPA. United States Environmental Protection Agency; Washington, DC: 2004. Risk Assessment Guidance for Superfund, Volume □: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment)https://www.epa.gov/sites/production/files/201509/documents/part_e_final_revision_10-03-07.pdf EPA/540/R/99/005. Office of Superfund Remediation and Technology Innovation; 2004a.
15. Hakanson L. An ecological risk index for aquatic pollution control, a sedimentological approach. Water res. 1980; 14: 975-1001. https://doi.org/10.1016/0043-1354(80)90143-8
16. Secu CV, Lesenciuc DC. Copper concentration in the vineyard and forest topsoils. A comparative study with individual pollution indices. Environ Sustain Ind. 2024; 24: 100508. https://doi.org/10.1016/j.indic.2024.100508
17. Abrahim GMS, Parker RJ. Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki Estuary, Auckland, New Zealand. Environ Monit Assess. 2007; 136: 227–238.DOI: 10.1007/s10661-007-9678-2
18. Wedepohl HK, The composition of the continental crust. GeochimCosmochimActa. 1995 ; 59 : 1217–32.https://doi.org/10.1016/0016-7037(95)00038-2
19. MEDD et Agence de l'eau. Système d'Évaluation de la Qualité des Eaux (SEQ-Eaux), grilles d'évaluation, France, 2003.
20. MacDonald DD, Ingersoll CG, Berger TA.Development and evaluation of consensus based sediment quality guidelines for freshwater ecosystems. Arch Environ ContamToxicol. 2000; 39: 20–31.https://doi.org/10.1007/s002440010075
21. Smith SL, MacDonald DD, Keenleyside KA, Ingersoll CG, Field J. A preliminary evaluation of sediment quality assessment values for freshwater ecosystems. J Great Lakes Res. 1996; 22: 624–38. https://doi.org/10.1016/S0380-1330(96)70985-1
22. Persaud D, Jaagumagi R, Hayton A. Guidelines for the protection and management of aquatic sediment quality in Ontario. Water Resources Branch, Ontario Ministry of the Environment, Toronto; 1993.
23. El-Alfy MA, El-Amier YA, El-Eraky TE. Land use/cover and ecotoxicity indices for identifying metal contamination in sediments of drains, Manzala Lake, Egypt. Heliyon. 2020; 6(1): e03177. https://doi.org/10.1016/j.heliyon.2020.e03177
24. Long ER, Ingersoll CG, MacDonald DD. Calculation and uses of mean sediment quality guideline quotients: a critical review. Environ Sci Technol. 2006; 40(6):1726-36. doi: 10.1021/es058012d.
25. Long ER, Macdonald DD, Smith SL, Calder FD. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. Environ Manage. 1995;19: 81–97. https://doi.org/10.1007/BF02472006
26. US-EPA. Risk-based Concentration Table. Philadelphia PA : United States Environmental Protection Agency, Washington D.C., USA ; 2009: 34.
27. US-EPA. Guidelines for human exposure assessment. (EPA/100/B-19/001). U.S. Environmental Protection Agency; Washington, D.C., USA: 2020. https://cfpub.epa.gov/ncea/risk/recentadd.cfm Risk Assessment Forum, U.S. EPA.
28. US-EPA Integrated risk information system (IRIS). United States Environmental Protection Agency, Washington D.C., USA; 2010.
29. Kramoh KE, N'goran YNK, Aké-Traboulsi E, Boka BC, Harding DE, Koffi DBJ et al. Prévalence de l'obésité en milieu scolaire en Côte d'Ivoire. Ann CardiolAngeiol.2012 ; 61(3): 145-9. https://doi.org/10.1016/j.ancard.2012.04.020
30. https://www.donneesmondiales.com/taille-moyenne.php#by-country. Consulté, le 27/04/2024
31. US-EPA. The Incidence and Severity of Sediment Contamination in Surface Waters of the United States. Contaminated Sediment Report to Congress, National Sediment Quality Survey: Second ed., EPA 823-R-04-007; 2004b.
32. Gosset WS. The probable error of a mean. Biometrika. 1908 ;6(1): 1–25. https://doi.org/10.2307/2331554
33. Albaret J.J, Ecoutin J-M (1991). Communication mer-lagune : Impact d'une réouverture sur l'ichtyofaune de la lagune Ébrié (Côte d'Ivoire*).* J IvoirOcéanolLimnol. 1991 ; I(2) : 99-109.
34. Guezo NC, Flogbe ED, Azon MTC, Kouamelan EP, Ouattara A.Évaluation des effets du chlorure de sodium (NaCl) sur le développement de la jacinthe d'eau *Eichhorniacrassipes*: Résultats préliminaires. Environ Water Sci. Public Health &Territorial Intelligence.2017 ;1(4) : 34-40.
35. Luo B, Li J, Wang M, Zhang X, Mi Y, Xiang J et al., Gong S., Zhou Y., Ma T. Chronic toxicity effects of sediment-associated polystyrene nanoplastics alone and in combination with cadmium on a keystone benthic species*Bellamya aeruginosa*. J Hazard Mat. 2022; 433: 128800. https://doi.org/10.1016/j.jhazmat.2022.128800
36. Lipi JA, Hossain MB, Jolly YN, Paray BA, Arai T, Yu J. Response of benthic assemblages to heavy metal contamination from shipbreaking operations in a tropical coastal area. Reg Stud Mar Sci.2024;78: 103766. https://doi.org/10.1016/j.rsma.2024.103766

37. Gelaye Y. Public health and economic burden of heavy metals in Ethiopia: Review. Heliyon.2024 ; 10(19) : e39022.https://doi.org/10.1016/j.heliyon.2024.e39022

38. Kouassi PA. Stratégies comparées de l'exploitation des plans d'eau lagunaire de Côte-d'Ivoire. *Les Cahiers d'Outre-Mer*, 2010 ; 251 : 347-363. https://doi.org/10.4000/com.6038

HOW TO CITE THIS ARTICLE: Jean-Claude DBB, Konan YM. Metal Contamination of the Sediments from the Area II of the Ébrié System Following the Reopening of the Grand-Bassam Inlet. *J Adv Sci Res*. 2025;16(1): 1-13 **DOI:** 10.55218/JASR.2025160101