

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

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Abstract

The objective of this work was to assess the impacts of the permanent reopening of the Grand-Bassam inlet on the seasonal dynamics of thirteen trace metals in the superficial sediments of the area II from the Ébrié system. In its implementation, the sediment samples were collected over a year (from May 2023 to April 2024). The concentrations of these trace metals were obtained by inductively coupled plasma mass spectrometry (ICP MS) according to ISO 17294-2 after dissolution according to NF X31-147. The results showed a significant input of these metals by meteorological inputs during the rainy, cold, and flood seasons, except for Cr, whose presence in these substrates was mainly related to the strong marine intrusion during the hot season. The modification of the geochemical and physical characteristics due to the reopening of this pass significantly influenced the presence of these trace metals in these substrates during the study period. A reduction in the use of inputs containing high concentrations of trace metals and the efficient treatment of anthropogenic discharges with high metal content in the watershed of this ecosystem should be considered to support the depollution initiated with the reopening of this inlet.

1. Introduction

The issue of metallic pollution in surface waters remains a global concern, as evidenced by numerous recent scientific studies. Trace metals can bioaccumulate significantly in the short and long term within the trophic chain of surface waters, leading to severe health consequences for aquatic life and, consequently, for humans [1,2]. This situation is due to extensive mining operations, industrial activities, and their intensive use in other anthropogenic fields, notably in agricultural [3,4].

Sediments are one of the most commonly used matrices for studying the level of metallic contamination in surface waters because they serve as their natural reservoir. Thus, they act as a memory indicator [5]. The dynamics of trace metals in sediments are influenced by several biogeochemical and physical factors. Among these factors are pH, redox potential, salinity, conductivity, moisture, and granulometric of the sediments, and the temperature of the overlying waters [6]. Increasing sediment acidity generally promotes trace metals desorption, while increasing alkalinity promotes their adsorption. The effect of pH on trace metal adsorption onto sediments can be interpreted in various ways, as mentioned by Serpaud et al. [7]. According to these

Received: November 15, 2024; Accepted: December 2, 2024; Published: December 8, 2024

Keywords and phrases: Côte d'Ivoire, metal contamination, Grand-Bassam inlet, Ébrié Lagoon, Atlantic Ocean.

authors, increasing the pH of the sediments decreases proton (H^+) competition with metallic cations on adsorption sites, increases the number of adsorption sites (carboxyl groups of organic matter, (oxy)hydroxides and clay minerals), and also favors the precipitation of oxides, hydroxides, or hydrocarbonates. They also note that the dissolution of aluminosilicates at acidic pH reduces adsorption sites. High salinities and conductivities of waters and sediments hinder their adsorption on various sites by competing with other cations, especially major ones [8,9]. Regarding temperature, the higher it is, the more significant the adsorption of trace metal on sediments [10,11]. The moisture of sediments also plays an important role in adsorption, as high moisture favors their adsorption on these substrates, just like a high organic matter content [12].

The Ébrié lagoon system is one of the aquatic ecosystems in Côte d'Ivoire subjected to significant metal pollution [13,14]. This is particularly the case for its area II, as first highlighted by Keumean et al. [15] and later by Mahi et al. [6,10]. This estuary, the largest from this lagoon system [16], has been long isolated from the Atlantic Ocean since the siltation of the Grand-Bassam inlet in the late 1990s [17]. To facilitate the evacuation of invasive aquatic plants to the Atlantic Ocean and the establishment of fishing harbours, the permanent reopening of this inlet was carried out. This event has resulted in significant oceanic water intrusion, which could have substantial impacts on its hydrochemistry. Therefore, this study was initiated to better understand this situation. The primary objective of this study was to monitor the seasonal dynamics of thirteen trace metal (Al, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, Zn) in the superficial sediments from this aquatic ecosystem following the reopening of the Grand-Bassam inlet. The secondary objectives were to determine some seasonal physical and chemical characteristics of these substrates (pH, redox potential, conductivity, salinity, relative humidity, organic matter content, and granulometric distribution) and their impacts on the seasonal dynamics of these trace metals.

2. Material and Methods

2.1. Study area description

The area II is one of the six area resulting from the stratification of the Ébrié system [18]. It is located at the extreme East of this lagoon system, precisely between longitudes $3^{\circ}40'W$ and $3^{\circ}50'W$ and latitudes $5^{\circ}20'N$ and $5^{\circ}21'176471N$. Its mean length, from East to West, is 17.143 km, while its mean width is 5.714 km [6,10]. This lagoon ecosystem is composed of the Ouladine lagoon and the Ébrié lagoon, with a total area of 87 km² [18,19]. However, the small area of the Ouladine lagoon, of 4.5 km² [15], compared to that of the Ébrié lagoon, of 82.5 km² [6], makes this ecosystem essentially that of the Ébrié lagoon. This ecosystem connects the Ébrié system to the Aby system via the Assinie canal [20].

The hydrology of this lagoon zone is primarily influenced by the Comoé River, the Mé River, and the Atlantic Ocean, whose impact on this area has significantly increased with the reopening of the Grand-Bassam inlet. Its watershed is therefore invaluable due to the Atlantic Ocean. Its continental watershed is dominated by that of the Comoé River, which covers 78,000 km² [21], while that of the Mé River covers 4,300 km² [5]. The Mé River drains its inputs into this lagoon site via the Aghien lagoon and the Potou lagoon. The watershed of the Mé River is sedimentary [22], and that of the Comoé River is sedimentary in the South and rests on a geological bedrock from the Center to the North [21]. The presence of the mouth of the Comoé River within this lagoon ecosystem makes it the most important estuary of this lagoon system [16]. The same is true with the reopening of the Grand-Bassam inlet. The elevation of the Ébrié system in general, and of this area in particular, relative to the Atlantic Ocean, favors permanent water and sediment inputs from the Comoé River to the

Atlantic Ocean. This has long been the cause of the siltation, then the closure of the Grand-Bassam inlet [19], unlike the Vridi canal, which, due to the presence of a canyon near its western jetty, cannot be silted up [23]. Irié et al. [24] noted that its sediments are mostly fluvial in origin. According to Adopo et al. [25], these sediments result from a long fluvial transport, with displacement mainly by saltation.

In order to facilitate the evacuation of macrophytes drained by continental inputs into the Atlantic Ocean and the installation of fishing ports, the permanent reopening of this inlet was carried out, with the works completed in 2023. This inlet is located at $3^{\circ}722048$ longitude West and $5^{\circ}190941$ latitude North (Figure 1). It currently constitutes the second communication route of the Ébrié system with the Atlantic Ocean. The current length of this pass is 245 m, while its current width is 122 m. The strong marine intrusion caused by the opening of this pass is likely to modify its functioning, particularly its hydrochemistry. Such a situation was observed by Albaret and Ecoutin [26], noting a modification of its floristic composition and the mortality of certain macrophytes, such as *Eichhornia crassipes*, during the penultimate reopening of this pass in 1987.

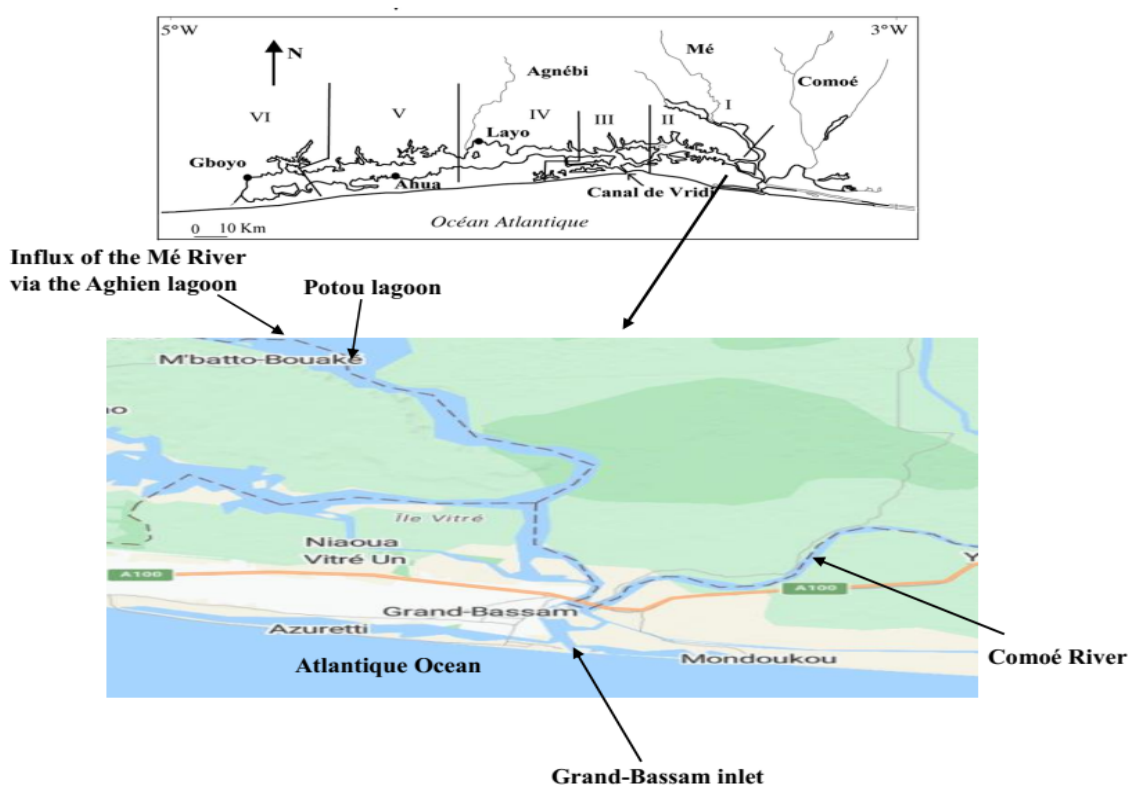


Figure 1. Geographic location of the area II of the Ébrié system.

Taking into account the hydrological regime of the Mé River, dependent on the subequatorial climate in the South, on the one hand, and the hydrological regime of the Comoé River, which varies from the subequatorial climate in the South to the humid tropical climate in the Center and the dry savanna tropical climate in the North [27], on the other hand, Mahi et al. [10] was defined the water seasons of this lagoon site as follows: the Hot Season (HS) from December to April, the Rainy Season (RS) from May to July, and the Flood Season (FS) from August to November. However, the reopening of the Grand-Bassam inlet, with the significant impacts of the Atlantic Ocean on this estuary, has modified its water seasons. Considering the water seasons of the Atlantic Ocean off Abidjan defined by Morlière [28], the current water seasons of this estuary are defined as follows: the Hot Season (HS) from December to April, the Rainy Season (RS) from May to July, the Cold Season (CS) from August to September, and the Flood Season (FS) from October to November.

As mentioned by Mahi et al. [10], the continental watershed of this lagoon area is dominated by intensive agricultural practices with chemical inputs, industrial and mining activities, as well as illegal gold panning.

2.2. Samples collection and conservation

This study was conducted over one year, from May 2023 to April 2024. The sample collection was carried out at five sampling sites, identical to those used by Mahi et al. [6,10] just before the reopening of this inlet (Figure 2). The objective was to better estimate the impacts of the reopening of this pass on the dynamics of these thirteen trace metals in the superficial sediments of this estuary during this period. The sediment samples were collected at these sites using a Van Veen grab sampler from 0 to -5 cm at the sediment surface, following ISO 5667-19 standard [29]. Once collected, the samples were stored in polyethylene flasks, as recommended by ISO 5667-15 standard [30]. Monthly sampling was conducted, resulting in a total collection of 60 sediment samples. Additionally, the seasonal depth of each sampling site was measured using a depth gauge.

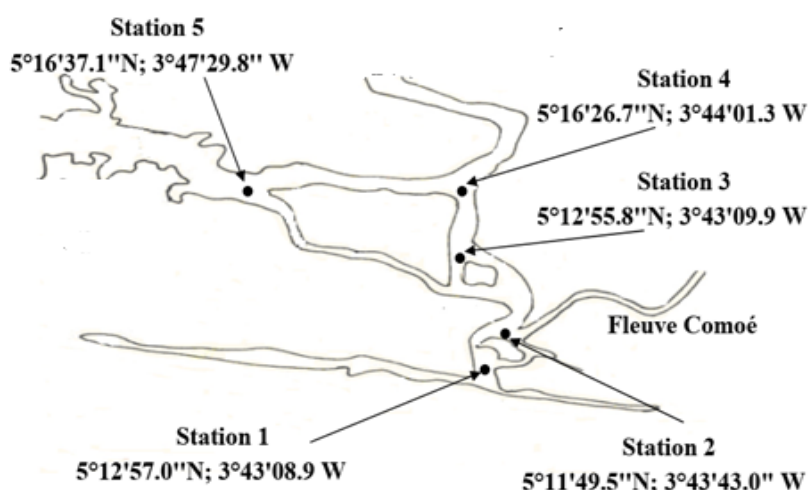


Figure 2. Geographic locations of the sampling sites used during the study period, the same as those used by Mahi et al. [6,10].

2.3. Treatment and conservation of the sediment samples in the laboratory

In the laboratory, the sediment samples were first cleaned of coarse elements (coarse plant materials, debris, shells, etc.). Then, they were homogenized and a small portion (approximately 10 mg) was taken and placed in polyethylene vials for the determination of their moisture. The other portion was immediately dried by lyophilization according to ISO 16720 standard [31], to minimize Hg losses. Finally, the dry sediment samples were stored in polyethylene flasks, hermetically sealed and kept in the dark to protect them from moisture, as recommended by ISO 5667-15 standard [30].

2.4. Physical and chemical parameters assessed in the laboratory

The pH, redox potential, conductivity, salinity, moisture, organic matter content, and granulometric distribution of the sediment samples were determined in the laboratory. For the determination of their pH, redox potential, conductivity, and salinity, the sediment samples were pre-ground in a mortar to reduce them to sizes

below 0.63 μm . The ground material of 0.63 μm was recovered after sieving on a 0.63 μm sieve. This operation aims to maximize the contact surface of these samples with the extracting solution (ultra-pure water).

The pH and redox potential of the sediment samples were assessed simultaneously, in accordance with ISO 10390 standard [32]. Their salinity and conductivity were determined according to ISO 11265 standard [33]. Their moisture was obtained in accordance with ISO 17892-1 [34]. Their organic matter content, specifically the volatile organic matter content, was determined by the loss on ignition method following NF 15935 standard [35]. Finally, the granulometric distribution of these sediments, including their contents of very coarse sand (rudites), coarse and medium sand, and fine sand, as well as silt and clay, was determined in accordance with ISO 17892-4 [36]. The experiments were performed in triplicate ($n = 3$).

2.5. Determination of trace metals concentrations in the sediment samples

The concentration of thirteen trace metals (Al, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, Zn) in the sediment samples was determined by successively implementing the NF X31-147 standard [37] and the ISO 17294-2 standard [38].

In practice, sediment samples were first reduced to sizes smaller than 0.63 μm . Following this operation, the trace metals were put into solution according to the NF X31-147 standard [37]. Thus, 0.3 g of sediments were contacted with 1 ml of pure perchloric acid at 72% and 2 ml of pure hydrofluoric acid at 48% in a Teflon container. The mixture was manually homogenized and allowed to rest for an hour to initiate the acid attack. The Teflon container was then heated to 120°C in a digester for 2 hours. The digestate was left to cool for an hour and then treated with boric acid at 135 g/L to potentially eliminate organic matter residues. The mixture was then transferred to a 50 ml flask. The Teflon container was rinsed several times with small amounts of ultra-pure water, and these rinses were added to the flask. The final volume of the extract was adjusted to 50 ml with ultra-pure water.

The obtained solution was analyzed by inductively coupled plasma mass spectrometry (ICP MS) according to the ISO 17294-2 standard [38] to determine trace metals concentrations, referring to calibration curves plotted from a Merck multi-element ICP standard solution. The spectrometer Agilent 7800 ICP-MS was used for purpose. The experiments were performed in triplicate ($n = 3$).

2.6. Data sources

The data on monthly temperature and monthly precipitation in the study area during the study period were provided by historique-meteo.net (2023; 2024) [39,40].

2.7. Statistical analysis of results

In addition to standard univariate statistical techniques, namely the mean (m), standard deviation (s), coefficient of variation (CV), minimum value (min), and maximum value (max), multivariate statistical techniques such as Principal Component Analysis (PCA), one-way ANOVA, and the Bravais-Pearson correlation matrix were used. PCA was employed to assess the seasonal influences of the evaluated physical and chemical parameters on the dynamics of these trace metals in surface sediments. The Bravais-Pearson correlation matrix was used to study the similarity or antagonism of the annual dynamics of these trace metals in these substrates, impacted by these physical and chemical parameters, to identify their general annual trend. The use of one-way ANOVA aimed to check whether there was a statistically significant difference between the

different seasonal means of the evaluated physical and chemical parameters. When a marked difference was found, three post-hoc tests (Fisher's LSD [41], Tukey's HSD [42], and Dunnett's test [43]) were implemented to determine the distinct seasonal means as well as the homogeneous subgroups that did not differ from each other. The results of the one-way ANOVA and post-hoc tests were considered statistically significant for $p < 0.05$.

The Student's t-test [44] was used to verify if the differences between the results obtained in this study and those determined by Mahi et al. [6] are statistically significant. Results were considered statistically significant for $p < 0.005$. All these statistical techniques were implemented using Statistica software version 7.

3. Results and discussion

3.1. Results

3.1.1. Seasonal dynamics of some physical and chemical characteristics and granulometric distribution of these sediments

The seasonal and annual pH, redox potential, salinity, conductivity, organic matter content, and moisture of these sediments over the study period are provided in Table 1.

These sediments were slightly acidic and oxidizing during the first three seasons, particularly in the FS. They became slightly basic and reducing in the HS. All seasonal variations in their mean pH were minor. As for the variations in their mean seasonal redox potentials, they were significant in all seasons except HS. One-way ANOVA revealed no statistically significant differences between their mean seasonal pH values ($p > 0.05$). The same was true for their mean seasonal redox potentials ($p > 0.05$).

The mean salinity and conductivity of these substrates were relatively high in HS compared to the other three seasons. The seasonal variations in their mean seasonal conductivities were significant in all seasons. This was also the case for their mean seasonal salinities, except in HS. One-way ANOVA showed overall significant differences between their mean seasonal salinities ($p < 0.05$) on one hand, and between their mean seasonal conductivities ($p < 0.05$), on the other hand. The various post-hoc tests used in this study revealed that only the mean salinity of these sediments in HS was statistically different from those of the other seasons ($p < 0.05$). They also showed that the difference between their mean conductivity in HS and that in the Rainy Season (SP) was statistically significant ($p < 0.05$). The same was true for the difference between their mean conductivity in HS and that in FS ($p < 0.05$).

The seasonal mean moisture and the seasonal mean organic matter content of these substrates were significant during all seasons. The highest organic matter content was observed in RS, while the lowest was recorded in HS. Regarding their moisture, the highest value was obtained in HS, and the lowest in CS. One-way ANOVA revealed no statistically significant differences between the seasonal mean moistures ($p < 0.05$) and between the seasonal mean organic matter contents ($p < 0.05$).

The superficial sediments of the study area revealed a granulometric texture dominated by medium and coarse sands throughout all seasons. Fine sands were very scarcely present, while silts and clays were absent. The intra-seasonal variations in their mean contents of very coarse sands, medium and coarse sands, as well as fine sands, were all very substantial (Table 2). One-way ANOVA did not highlight any significant difference between their mean seasonal contents in these sand fractions ($p > 0.05$).

Table 2. Seasonal mean contents (%) of different sand fractions in the superficial sediments of the area II from the Ébrié system during the study period.

Water seasons	Statistical parameters	Sand fractions			
		Very coarse sands ($\varnothing \geq 2$ mm)	Medium and coarse sands ($0.2 \leq \varnothing < 2$ mm)	Fine sands ($0.063 \leq \varnothing < 0.2$ mm)	Silt and clay ($\varnothing < 0.063$ mm)
RS	m±s	31.644±40.758	64.846±45.172	3.510±5.293	0.000±0.000
	CV (%)	128.803	69.661	150.794	
	Min-Max	0.710-86.110	8.250-99.290	0.000-11.910	0.000-0.000
CS	m±s	34.868±36.456	60.602±50.789	4.334±2.748	0.000±0.000
	CV (%)	104.554	90.408	63.409	
	Min-Max	1.830-88.650	1.350-91.870	0.000-6.800	0.000-0.000
FS	m±s	35.486±39.950	63.126±35.870	1.388±2.917	0.000±0.000
	CV (%)	104.124	56.822	210.181	
	Min-Max	10.060-100,00	0.000-83.340	0.000-6.600	0.000-0.000
HS	m±s	37.520±32.591	57.856±42.067	4.624±6.054	0.000±0.000
	CV (%)	102.855	72.710	130.925	
	Min-Max	0.000-87.750	0.000-100.000	0.000-11.250	0.000-0.000
Annual mean value	m±s	34.880±3.382	61.608±6.223	3.464±1.671	0.000±0.000
	CV (%)	9.696	10.102	48.234	
	Min-Max	0.000-100.000	0.000-100.000	0.000-11.910	0.000-0.000

3.1.2. Seasonal dynamics of these trace metals

Table 3 presents the mean seasonal concentrations of some trace metals in the superficial sediments of this lagoon area over the study period.

The substrates revealed the highest mean concentrations of As, Ni, and Pb in CS. Their lowest concentrations in all these trace metals were observed in the HS. The intra-seasonal variations in their mean concentrations of these trace metals were generally low. One-way ANOVA highlighted statistically significant differences in their mean seasonal concentrations of Ni ($p < 0.05$). However, no statistically significant differences were observed in their mean seasonal concentrations of As and Pb ($p > 0.05$). The different post-hoc tests indicated that the mean concentration of Ni determined in RS was not statistically different from those obtained in SF and in the Flood Season (SCr) ($p > 0.05$).

Regarding the mean concentrations of Al, Co, Cu, Fe, and Zn in these sediments, they were elevated in the RS. The lowest mean seasonal concentrations of Al and Zn were observed in FS. As for the lowest mean seasonal concentrations of Co, it was detected in CS, and those of Cu and Fe were in HS. All intra-seasonal variations in their concentrations of these four trace metals were low. One-way ANOVA highlighted significant differences in their mean seasonal concentrations of these trace metals ($p < 0.05$). The post-hoc tests used in this study showed that the mean seasonal concentrations of Al, Cu, and Zn obtained in RS were statistically distinct from the other three seasons ($p < 0.05$). They also indicated that only the mean concentrations of Co determined in CS and in FS were not statistically different ($p > 0.05$). For Fe, these tests highlighted statistical differences between its mean seasonal concentration in HS and those of the other three seasons ($p < 0.05$).

The highest mean concentrations of Cd, Cr, Hg, Mn, and Sb in these sediments were determined in HS. Their lowest concentrations of Cd and Sb were obtained in CS, while that of Cr was recorded in RS. As for their mean concentrations of Hg and Mn, the lowest were observed in FS. All intra-seasonal variations were also low. One-way ANOVA highlighted statistically significant differences in all their mean seasonal concentrations of these trace metals ($p < 0.05$). The different post-hoc tests used in this study showed that:

- Only their mean seasonal concentrations of Cr determined in SF and in SCr were not statistically different;
- their mean concentrations of Cd obtained in SC were statistically different from those determined in the other three seasons;
- their mean seasonal concentrations of Hg, Mn, and Sb obtained in SP were statistically different from those determined in SC, respectively;
- their mean seasonal concentrations of Hg, Mn, and Sb observed in SF were statistically different from those in SCr, respectively.

Table 3. Mean concentrations (mg/kg) of some trace metals in the superficial sediments from the area II of the Ébrié System during the study period.

Trace metals	Statistical parameters	Water seasons				Annual mean concentration
		RS	CS	FS	HS	
As	m±s	10.183±0.295	16.266±1.337	11.571±1.074	3.309±0.120	10.332±5.357
	CV (%)	2.898	8.217	9.284	3.636	51.850
	Min-Max	9.580-11.510	15.950-17.681	10.053-12.557	3.035-3.629	3.035-17.681
Al	m±s	357.236±10.589	126.530±3.918	102.083±3.360	160.709±7.396	186.639±116.245
	CV (%)	2.964	3.097	3.292	4.602	32.283
	Min-Max	78.427-494.574	115.500-129.952	98.550-105.232	151.550-164.404	78.427-494.574
Cd	m±s	11.003±0.235	0.323±0.009	0.968±0.125	21.797±1.004	8.523±10.111
	CV (%)	2.136	2.901	12.914	4.608	118.633
	Min-Max	10.370-12.560	0.316-0.360	0.955-0.977	21.005-22.629	0.316-22.629
Co	m±s	58.946±1.973	1.170±0.039	2.337±0.254	34.722±1.579	29.294±27.847
	CV (%)	3.348	3.318	10.868	4.549	114.623
	Min-Max	56.830-60.480	0.880-1.228	2.212-2.432	30.012-36.566	0.880-60.480
Cr	m±s	10.261±0.387	25.829±1.235	22.685±1.253	88.390±3.851	36.791±35.050
	CV (%)	3.776	4.738	5.525	4.357	95.266
	Min-Max	9.270-11.300	23.320-26.000	21.575-23.154	83.458-90.934	9.270-90.934
Cu	m±s	324.968±8.125	103.308±2.513	101.868±3.224	93.357±3.281	155.875±112.814
	CV (%)	2.500	2.433	3.165	3.515	72.375
	Min-Max	298.998-414.631	92.170-116.679	101.285-114.917	91.885-96.494	91.885-298.998
Fe	m±s	757.746±22.447	765.296±16.511	733.405±20.373	138.922±10.470	411.300±394.228
	CV (%)	2.962	2.157	2.778	7.536	95.849
	Min-Max	18.320-100.160	750.500-864.488	690.032-750.312	126.706-144.340	6.830-864.488
Hg	m±s	4.357±0.200	0.381±0.014	0.298±0.011	4.928±0.248	2.491±2.495
	CV (%)	4.580	3.554	3.802	5.023	100.174
	Min-Max	4.255-4.428	0.374-0.392	0.236-0.305	4.904-4.970	0.236-4.970
Mn	m±s	378.035±20.813	127.010±4.757	110.102±4.671	527.952±22.301	285.775±202.672
	CV (%)	5.506	3.746	4.243	4.224	70.920
	Min-Max	368.270-390.270	121.120-131.575	109.656-112.084	502.845-571.416	109.656-571.416
Ni	m±s	42.134±1.157	81.365±2.057	81.074±3.226	15.828±0.866	55.100±32.015
	CV (%)	2.746	2.528	3.979	5.470	58.104
	Min-Max	42.080-44.440	77.500-88,560	80.968-84.444	15.238-15.925	15.238-88.560
Pb	m±s	14.442±0.480	18.533±1.210	16.889±1.711	12.857±0.520	15.680±2.524
	CV (%)	3.325	6.529	10.128	4.046	16.094
	Min-Max	13.400-14.900	14.040-19.696	15.605-17.488	11.605-15.726	11.605-137.400
Sb	m±s	53.373±1.492	6.491±0.266	7.689±0.376	69.079±3.909	34.158±31.910
	CV (%)	2.795	4.092	4.893	5.658	93.418
	Min-Max	48.690-55.150	6.100-7.346	6.050-7.854	67.050-72.821	6.050-72.821
Zn	m±s	572.388±19.631	114.463±4.390	99.452±4.244	146.066±6.765	232.842±227.158
	CV (%)	3.430	3.835	4.268	4.664	97.559
	Min-Max	555.285-587.092	100.500-126.793	88.805-106.008	140.805-151.226	88.805-587.092

3.1.3. Impacts of physical and chemical parameters on the seasonal dynamics of these trace metals

The first two principal components (PC1 at 55.70% and PC2 at 34.80%) explain 89.50% of the information related to the 24 studied variables.

The mean pH, mean salinity, and mean conductivity of these sediments, as well as the mean ambient temperature, show strong positive correlations with PC1. The same applies to the mean concentrations of Cd, Cr, Hg, Mn, and Sb in these substrates. In contrast, the redox potential of these substrates, as well as the mean concentrations of As, Fe, Ni, and Pb within them, present strong negative correlations with this factor. The mean content of very coarse sands in these sediments shows a strong positive correlation with PC2. Their mean organic matter content and mean concentrations of Al, Co, Cu, and Zn show very strong negative correlations with PC2. The cumulative mean precipitation follows the same trend (Table 3). CS has a strong negative correlation with PC1, while HS presents a positive correlation with this principal component. RS shows a strong negative correlation with PC2 (Table 4).

These results indicate that relatively high ambient temperature, near-neutrality, low salinity, and conductivity of these sediments contributed to the relatively significant presence of Cd, Cr, Hg, Mn, and Sb in RS. The slightly oxidizing properties of these substrates favor relatively high mean concentrations of As, Fe, Ni, and Pb in these substrates in CS. The high precipitation and very high organic matter content of these sediments contributed to the relatively significant presence of Al, Co, Cu, and Zn in RS in these substrates.

Table 3. Factor coordinates of variables based on correlations.

Variables	Principal components			Variables	Principal components		
	PC1	PC2	PC3		PC1	PC2	PC3
Very coarse sands	0.542592	0.833493	0.104326	Al	0.086512	-0.990739	-0.104648
Medium and coarse sands	-0.679534	-0.648048	0.343901	Cd	0.965043	-0.262083	-0.001944
Fine sands	0.543089	-0.064085	-0.837226	Co	0.471955	-0.881574	-0.009229
Cumulate rain	-0.149698	-0.988721	0.004701	Cr	0.07852	0.416072	-0.051849
Ambient temperature	0.858111	-0.113510	0.500760	Cu	-0.39145	-0.990100	-0.018438
pH	0.790898	-0.203187	-0.577231	Fe	-0.968338	-0.248586	-0.022935
Redox potential	-0.983464	-0.173502	0.051924	Hg	0.811568	-0.582657	-0.043214
Salinity	0.913049	0.400455	-0.077312	Mn	0.915699	-0.396876	-0.063130
Conductivity	0.890429	0.435755	-0.131353	Ni	-0.930560	0.365274	0.025177
Organic matter	-0.523749	-0.842279	-0.127484	Pb	-0.875442	0.420883	-0.237612
Moisture	0.599199	-0.086320	0.795933	Sb	0.870762	-0.491499	-0.014213
As	-0.935460	0.118159	-0.333097	Zn	-0.020252	-0.998858	-0.043284

Table 4. Coordinates of individuals based on individuals (a) and contribution of individuals (Cos²) to the construction of principal components (b).

Individuals	Principale components			Principale components		
	CP1	CP2	CP3	CP1	CP2	CP3
RS	-0.55244	-4.31228	-0.03226	0.016146	0.983799	0.000055
CS	-2.49677	1.70187	-1.81012	0.502456	0.233450	0.264094
FS	-2.27786	1.58305	1.88717	0.460963	0.222638	0.316398
HS	5.32707	1.02736	-0.04478	0.964074	0.035858	0.000068
		a			b	

The Bravais-Pearson correlation matrix revealed that the low content of very coarse sands in these sediments was favored their very high organic matter content (r' (Very Coarse Sands, Organic Matter Content) = -1.00). The increase in cumulative precipitation, and consequently the inputs from the Mé River, the Aghien and Potou lagoons, and the Comoé River, contributed to the high relative presence of Al (r' (Cumulative Precipitation; Al) = 0.97), Cu (r' (Cumulative Precipitation; Cu) = 1.00), and Zn (r' (Cumulative Precipitation; Zn) = 0.99) in these substrates. Additionally, the decrease in redox potential, simultaneously with the increases in salinity and conductivity of these sediments, contributed to their Cr concentrations (r' (Redox Potential; Cr) = -0.97; r' (Salinity; Al) = 1.00; and r' (Conductivity; Al) = 1.00)). Conversely, an increase in ambient temperature, and therefore the waters of this estuary, contributes to a decrease in the concentration of As (r' (Ambient Temperature; As) = -0.98) in these substrates.

3.1.4. Comparison of trace metal concentrations in surface sediments during the study period to those determined by Mahi et al. [10]

The concentrations of As in these substrates obtained in RS, FS and HS during the study period were lower than those determined by Mahi et al. [6] for the same seasons. This trend was also observed for their concentrations of Cr, Fe, and Ni, except for those obtained in HS for Cr, in RS for Fe, and in FS for Ni. In contrast, their concentrations of Cd, Cu, Mn, and Zn observed during these seasons over the study period were higher than those reported by Mahi et al. [6] for the same seasons. The same was true for their concentrations of Hg and Pb, except for those in FS for Hg and in HS for Pb. All these observations were confirmed by the Student's t-test ($p < 0.05$) (Table 5).

Table 5. Comparison between the concentrations of some trace metals in the superficial sediments from the area II of the Ébrié system and those obtained by Mahi et al. [6].

Trace metals	Seasons and annual	Mean concentration (mg/kg) obtained in this study	Mean concentration (mg/kg) obtained par Mahi et al. [6]
As	RS	10.183±0.295	41.11±0.001
	FS	11.571±1.074	41.39±1.18
	HS	3.309±0.120	40.85±6.40
	Annual	10.332±5.357	41.15±3.29
Cd	RS	11.003±0.235	0.82±0.08
	FS	0.968±0.125	0.85±0.11
	HS	21.797±1.004	1.05±0.19
	Annual	8.523±10.111	0.91±0.16
Cr	RS	10.261±0.387	47.81±1.14
	FS	22.685±1.253	46.20±3.64
	HS	88.390±3.851	46.77±1.92
	Annual	36.791±35.050	46.75±2.55
Cu	RS	324.968±8.125	0.84±0.03
	FS	101.868±3.224	0.90±0.10
	HS	93.357±3.281	0.99±0.07
	Annual	155.875±112.814	0.92±0.10
Fe	RS	757.746±22.447	1549.50±105.08
	FS	733.405±20.373	1632.05±121.86
	HS	138.922±10.470	1619.07±6.55
	Annual	411.300±394.228	1609.38±104.63

Hg	RS	4.357±0.200	0.73±0.04
	FS	0.298±0.011	0.73±0.04
	HS	4.928±0.248	0.79±0.07
	Annual	2.491±2.495	0.75±0.06
Mn	RS	378.035±20.813	3.37±0.19
	FS	110.102±4.671	3.31±0.10
	HS	527.952±22.301	3.44±0.27
	Annual	285.775±202.672	3.37±0.18
Ni	RS	42.134±1.157	57.58±0.39
	FS	81.074±3.226	57.41±1.14
	HS	15.828±0.866	58.31±1.78
	Annual	55.100±32.015	57.75±1.22
Pb	RS	14.442±0.480	11.44±0.17
	FS	16.889±1.711	12.42±0.79
	HS	12.857±0.520	13.41±0.24
	Annual	15.680±2.524	12.53±0.92
Zn	RS	572.388±19.631	5.66±0.08
	FS	99.452±4.244	6.08±0.76
	HS	146.066±6.765	5.82±0.34
	Annual	232.842±227.158	5.90±0.53

3.2. Discussion

Although the Grand-Bassam Inlet has been reopened, the influence of meteorological inputs, particularly those from the Comoé River, remains significant on this estuary in all seasons, as it was during the closure of this pass [24]. Meteorological inputs increase from the RS to the FS. Indeed, they are marked in RS by the inputs of runoff meteorological waters, the inputs from the Mé River during its first and most significant flood, and the inputs from the Comoé River from its watershed in the South of the country. In the CS, meteorological inputs are mainly marked by those from the Comoé River with the beginning of its true flood. In SF, the inputs from the Comoé River reach their maximum as its flow peaks, to which are added the inputs from the Mé River from its minor flood, and the meteorological runoff waters following the short terrestrial rainy season [6,10]. In HS, the influences of runoff meteorological water inputs and the Mé River are negligible. This is not the case for those from the Comoé River, which, although its flow is significantly reduced, still significantly impacts this lagoon area due to its mouth within it [16]. The elevation of the Ébrié system in general, and its area II in particular, compared to the Atlantic Ocean, favors permanent inputs of water and sediments from the Comoé River towards the Atlantic Ocean. This has long been the cause of the silting up and subsequent closure of the Grand-Bassam Inlet [19], unlike the Vridi Canal, which, due to the presence of a canyon near its west jetty, cannot be silted up [23].

The reopening of the inlet and the intensive sand dredging it caused, particularly in the area from this inlet to the mouth of the Comoé River, led to a predominance of these sediments by coarse and medium sands, with a total absence of silts and clays. This contrasts with the observations of Mahi et al. [6], who, just before the reopening of this pass, noted a strong presence of very coarse sands and coarse and medium sands in similar proportions. However, the reopening of this pass had little effect on the fine sand contents, which remained comparable to those determined by these authors. These results also agree with those of Adopo et al. [25], who observed before the reopening of the inlet that coarse and medium sands were concentrated around the Bouet

and Morin islands, representing 65% of the sediments. These two locations include the first three sampling sites. Additionally, they noted that the bed of the Comoé River concentrated coarse and medium sands, thus confirming the predominant origin of the coarse and medium sands observed in these sediments, particularly in the area of the mouth of this river at the Grand-Bassam inlet. The same applies to the Mé River, which, in addition to these sand fractions, transports those from the Aghien Lagoon [45] and the Potou Lagoon [46] from this lagoon area to the Atlantic Ocean. The new orientation of the Grand-Bassam inlet and the construction of jetties and breakwaters led to the retention of larger sand fractions in this estuary and the evacuation of its fine fractions into the Atlantic Ocean to avoid its rapid silting. This operating mode of this pass is identical to that of the Vridi canal in its old configuration [47]. These inputs of coarse and medium sands are very important in seasons of high meteorite inputs into this estuary, particularly in RS where their presence in these substrates was the most significant. Conversely, the circulation of waters in this estuary induced by the relatively strong marine influence in RS tends to favor the sedimentation of this sand fraction, but also its partial evacuation into the Atlantic Ocean. They remain predominant even though their content in these sediments was the lowest observed in this season during the study period. However, this marine influence favored a clear growth of very coarse sands and fine sands in these substrates, the highest noted during the period. The non-significance of differences between their mean contents of these fractions revealed by one-way ANOVA also confirms the presence of these sediments mainly of continental origin.

The mean seasonal values of moisture of these sediments, higher than those obtained by Mahi et al. [6], reveal that their density, texture, and porosity favor water retention within them. This is particularly true for the coarse and medium sands, which are predominant in all seasons in these substrates and characterized by high porosity in the watershed of this lagoon area [48]. This observation explains the non-statistically significant differences between the mean seasonal values of their moisture, as highlighted by one-way ANOVA in this study. These high relative moistures contribute to the high organic matter content observed during the study period, through water-sediment exchanges. The inputs from the Mé River and the Aghien and Potou Lagoons appear to be richer in organic matter [49] than those from the Comoé River [50] and the Atlantic Ocean coastline in front of this inlet [51]. This is manifested by a progressive decrease in the mean organic matter content of these sediments from RS to HS. However, the non-statistically significant differences between their mean seasonal organic matter contents indicate a constant presence of organic matter in these substrates from these waters, in addition to complex autotrophic processes [52] on one hand, and their pH and redox potential on the other hand, favoring the presence of organic matter within them [53].

The essentially continental origins of these sediments, the presence of the Comoé River mouth in this estuary, and its proximity to the Mé River also explain their slight acidity and oxidizing nature, as well as their low salinity and conductivity observed during the study period. This situation contrasts with the Vridi Canal, which is distant from these two watercourses and the Agnéby River, which plays an important role in the hydrochemistry of the area III [23]. Aside from the mean seasonal pH values, the redox potentials, salinity, and conductivity of these substrates during the study period were significantly higher than those obtained by Mahi et al. [6]. This is due to the greater marine intrusion during the study period compared to when the pass was closed. The strong impacts of continental inputs, particularly from the Comoé River, explain the low acidity, oxidizing nature, salinity, and conductivity of these substrates from RS to FS. Conversely, the strong marine water intrusion led to their near-neutrality and slight reducing nature, as well as a notable increase in their salinity and conductivity, although they remained relatively low, in HS. The permanent influences of continental inputs on the sediments from this estuary resulted in the near-stability of their pH and redox potential over the study period, as highlighted by one-way ANOVA. The effects of the relatively significant

marine intrusion in HS were illustrated by significant differences between their mean conductivity and mean salinity in HS and those obtained in RS, two consecutive seasons shown by the post-hoc tests used in this study.

The reopening of this inlet has altered several physical and biogeochemical characteristics of the superficial sediments from this estuary. This particularly affected their granulometry, salinity, conductivity, organic matter content, and relative humidity, as observed in this study. These changes influenced the concentrations of these trace metal in these sediments during the study period. For instance, the concentrations of As, Cr, Fe, and Zn in these substrates were lower than those reported by Mahi et al. [6] for most corresponding seasons. In contrast, the concentrations of Cd, Cu, Hg, and Mn during this period were higher than those determined by these authors for most corresponding seasons. Most of these trace metals originated from meteorological inputs, especially Al, Cu, and Zn, as highlighted by the Bravais-Pearson matrix in this study. The significant marine intrusion into this estuary contributed to a relatively high presence of Cr, while the relatively high water temperatures of this estuary (around 30°C [10]) contributed to the solubilization and volatilization of As throughout the study period, as also illustrated by the Bravais-Pearson matrix. In general, the high organic matter content and relative humidity of these sediments contributed to the presence trace metals within sediments [12]. The same applies to the low salinity and conductivity of these substrates [9].

The pH of these substrates, varying from slightly acidic to neutral, favored the solubilization of Fe in these sediments. The release of this trace metal from the sediments was accentuated by strong bioturbation due to various water inputs and hydroclimatic conditions [54]. These phenomena were particularly marked in the presence of a strong marine intrusion during HS, where these sediments are weakly reducing [55], as highlighted by PCA in this study. In contrast, these physical and chemical processes were less pronounced during seasons of high continental inputs, where they were oxidizing [56], especially during meteorological inputs in SP. This led to statistically significant differences in Fe concentrations in these sediments between seasons of high continental inputs (from RS to FS) and the season with significant marine intrusion (HS), as revealed by the post-hoc tests used in this study.

Cd, Hg, Mn, and Sb in these substrates were primarily of meteorological origin, especially during RS, where the Mé River, the Aghien lagoon and the Potou Lagoon, and the Comoé River from its southern watershed, contributed more significantly to their transport. This resulted in the observation of their relatively high concentrations in these substrates during this season over this period. In contrast, meteorological inputs during CS and FS, particularly fluvial inputs from the Comoé River, transported them less. It is during these seasons that their relatively low presence in these substrates was noted. In the case of Hg, strong bioturbations contributed to its solubilization and volatilization during these seasons. The strong intrusion of marine waters in HS, favoring the insoluble precipitates of these trace metals on these substrates and/or their deposition [57-59], led to their relatively high concentrations in these sediments during this season. In the particular case of Mn, the neutrality and slightly reducing nature of these substrates limited its solubilization during this season, which under more acidic and oxidizing conditions is six to seven times greater than that of Fe. The same applies to the low salinity and conductivity of these substrates, as well as the relatively high temperature of this estuary favoring the adsorption of this trace metal on these substrates in HS [10]. These physical and chemical characteristics of these substrates and the high temperature of this estuary waters also favored the presence of Hg, Cd, and Sb [12,59] during this season. This was highlighted by PCA in the present study. The effects of marine waters during HS on the concentrations of Hg, Mn, and Sb were similar to the meteorological inputs during RS, but more pronounced in the case of Cd. This explains the statistically significant differences between the mean concentration of Cd in these sediments in HS and those of the other three seasons, as well as

the non-statistically significant differences between the mean concentrations of Hg, Mn, and Sb in these substrates during HS and those during RS.

Most of Al and Co in these sediments mainly originate from bauxite, cobalt ore, and clay minerals, resulting from the alteration and erosion of rocks, as well as anthropogenic activities in the watershed of this ecosystem. These trace metals were easily transported by the inputs from the Mé River, the Aghien lagoon and the Potou Lagoon, and the Comoé River from its sedimentary watershed in the South. This is not the case for the inputs from this river originating from its watershed in the Central and Northern regions, which rest on a geological basement [60]. Thus, the significant meteorological inputs of these trace metals in RS, combined with their complexation and/or precipitation with the high organic matter content in these sediments, particularly in their coarse and medium sand fraction [58], led to their highest concentrations in these entities during this season. The strong affinities of these trace metals with organic matter in the coarse and medium sands of these substrates were highlighted during this season by PCA. This biogeochemical process was also intense in the presence of marine waters in HS [61], but with less amplitude than during RS. Generally, the high organic matter content, near-neutrality, and low redox potentials of these sediments contributed to the presence of these trace metals within them during the study period [62]. The high meteorological inputs of Al during RS resulted in statistically significant differences between its concentration during this season and those of the other three seasons, as highlighted by the post-hoc tests used in this study. For Co, the low inputs from the Comoé River during its flood resulted in a non-significant difference between its concentration during CS and FS, as also highlighted again by the post-hoc tests used in this study.

The presence of As in sediments, as in soil, is regulated by pH and the amount of clay, Fe, Al, Ca, and P [63]. In the context of this study area, the concentrations of As in these sediments of this estuary seem more correlated with Fe concentrations than with Mn. Indeed, Mahi et al. [10] observed a relatively high presence of As in these substrates, concomitant with Fe. This observation is corroborated by the present study, where the concentrations of As in these entities decreased parallel to those of Fe, despite an increase in Mn concentrations, referring to the works of these authors. Such an observation was also made by Wang et al. [59]. The slight acidities and oxidizing nature, as well as the high organic matter content of these sediments, were favored the presence of As by limiting the transfer of the As/Fe pair to open waters [63]. This phenomenon was particularly marked during CS with the beginning of the flood of the Comoé River. It is also the case in HS, where the reducing nature of these substrates contributed to its presence by reducing its oxidized forms into more stable oxidized forms and metallic As, thus limiting its volatilization, favored by the temperatures of the open water near these sediments [64]. The impact of these different processes, in addition to microbiological ones [63], led to the quasi-stationary presence of As throughout the study period, given the non-statistically significant differences in its seasonal concentrations revealed by one-way ANOVA.

The high concentrations of Ni and Pb in these sediments were favored by their high organic matter content throughout the study period [66]. The same applies to their low salinity and conductivity during this period [9,65]. During seasons of high meteorological inputs (from RS to FS), the concentrations of Pb and Ni in these sediments, mainly of continental origin, were also favored by very slight acidity and oxidizing characteristics, especially during the flood of the Comoé River. The reducing nature of these substrates in HS favored the presence of these trace metals in them by reducing the most oxidized forms to less oxidized forms and their metallic form, in addition to their precipitation on these substrates [66]. All these inputs and biogeochemical processes contributed to the observation of non-statistically significant differences between the seasonal concentrations of Ni and Pb in these sediments over the study period, as highlighted by one way ANOVA.

Cu and Zn in these sediments were mainly brought by continental inputs, especially during RS, where these

inputs came from the sedimentary watershed of this ecosystem. This situation is demonstrated by their highest concentrations observed in this season. This was not the case for the inputs from the Comoé River originating from the Central and Northern regions of its watershed. The high presence of these two trace metals in these substrates coincides with the decrease in their Fe concentration and the increase in their Mn concentration, relative to the observations of Mahi et al. [6]. This suggests a significant contribution of Mn in the presence of precipitates of these two trace metals in these sediments [62]. Furthermore, the near-neutrality and low redox potentials of these sediments contributed to their presence in complexed forms throughout the study period [67]. The same applies to their high organic matter content, especially in the coarse and medium sand fraction in RS, as highlighted by PCA. This also applies to their low salinity and conductivity [9]. However, the near-absence of silts and clays in these substrates partially inhibited their presence, due to the high affinity of these trace metals with the fine sediment fraction [12,67]. Their very high inputs in RS, relative to the other three seasons, resulted in non-statistically significant differences between their concentrations in RS and those of the other three seasons, as highlighted by the post-hoc tests used in this study.

The dynamics of Cr in these substrates, unlike the majority of other trace metals, tend to show that its presence is mainly in the form of CrO_4^{2-} complexes. This ion is stable at pH levels above 6.5, especially in reducing environments [68]. This explains its high concentration in these sediments during HS compared to other seasons. During this period, the high temperature of this estuary also contributed to its high presence in these substrates [69]. The impacts of the temperature of this aquatic ecosystem and the near-neutrality of these sediments on the high presence of this trace metal were highlighted by PCA. Generally, meteorological inputs transported this trace metal mainly in dissolved form due to their oxidizing nature [68]. This was particularly observed with the inputs from the Comoé River during its flood over the study period. This fact was highlighted by the post-hoc tests used in this study, showing a non-statistically significant difference between its concentration in SF and that in SCr.

4. Conclusion

This study has highlighted a significant influence of the permanent reopening of the Grand-Bassam inlet, through its orientation and the installation of jetties and breakwaters, on the hydrochemistry of this area of the Ébrié system; and this, despite the strong influence of continental inputs, especially from the Comoé River with its mouth in this area. This has resulted in a modification of the hydrochemistry of these sediments. This modification has had consequences on the seasonal dynamics of trace metals within them. A general decrease in the concentrations of As, Cr, Fe, Ni, and a general increase in the concentrations of Cd, Cu, Hg, Mn, and Zn in these substrates were observed during the study period. The self-purification of the sediments in this ecosystem with respect to certain metals, facilitated by the reopening of this inlet, should be supported by robust managerial actions aimed at limiting metallic pollution in its watershed. This approach will contribute to the conservation, the growth of its biodiversity, and the reduction of associated health risks for humans. The reopening of the Grand-Bassam inlet is likely to modify the fluxes of these trace metals at the water-sediment interface, their mobility, and the resulting ecological and health risks. These aspects deserve to be studied for a better understanding of the impact of this pass's reopening on the metallic contamination of this lagoon area.

5. 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.

6. Conflicts of Interest

The authors declare there is not conflict of interest.

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