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Stratigraphy of metal deposits in Quaternary sediment cores: The case of a transboundary lagoon in West Africa

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Abstract: The maintenance of the equilibrium of the Aby coastal lagoon during the Quaternary period prompted a vertical study (0-35 cm) of 09 sediment cores. The objectives of this study were to evaluate depth-dependent (0-35 cm) variations in texture, organic matter and trace elements Hg, As, Cd, Pb in the sediments, and to determine the stratigraphic environmental quality of the lagoon sediments. Texture results from sieving showed a sequence: muddy sand > sandy mud > slightly muddy sand. Total organic carbon (TOC) results showed an increase (0.3% - 19.1%) from the lower layers (25 - 35 cm) to the upper layers (0 - 15 cm). Similarly, the total concentrations of the trace elements Hg and As recorded using the atomic absorption spectrometer in the cores collected showed a decrease in content from the surface layers (0 - 15 cm) to the lower layers (20 - 35 cm). In contrast, the vertical distribution of Cd and Pb was sparse and independent of depth. The CF (Contamination Factor), PLI (Pollution Load Index) indice showed high Hg contamination of the sediment cores, which could be leading to deterioration of the Aby lagoon. EF (enrichment factor) and CHA (Hierarchical Cluster Analysis) revealed that this contamination came from anthropogenic sources, mainly mining activities. Evaluation by Effects-Range Low (ERL) and Effects-Range Median (ERM) indicated that 28% of the 63 samples could frequently cause Hg-related adverse effects.

1. Introduction

In aquatic ecosystems, sediment layers act as reservoirs and accumulation beds for trace metals. The impact and abundance of these trace metals in the environment have led us to describe recent decades as "techno-chemical". These trace metals, mainly mercury, arsenic, cadmium and lead, can be released into the environment through everyday activities such as mining, the use of agrochemicals in agriculture, the manufacture of industrial products, coal combustion, oil traffic and fishing using metal equipment (Ouattara et *al*., 2018, Li et *al*., 2020, Karaouzas et *al*., 2021). The contamination of these trace metals remains of prime importance for the aquatic ecosystem, as diagenetic sedimentation processes can amplify their toxicity (Sengör et *al*., 2007; Razzouki et *al*., 2015; Bazzi et *al*., 2020). Because of their persistence in nature, their non-biocompatibility and their long lifespan, trace metals can reach higher levels of toxicity with the burial conditions of lagoon sediment strata (Subba Rao et *al*., 2021, Ouaty et *al*., 2022). The impact of these trace metals directly affects humans, mainly their life expectancy and health due to their presences in the food cycle (Lei et *al*., 2019, Bełdowska et *al*., 2021). West African coastal lagoons show an altered equilibrium under the invasive action of these trace metal elements (Maanan et *al*., 2004, Dang et *al*., 2015). These ecosystems are exposed to heavy metal contamination due to their poor management.

The Aby lagoon represents an important ecological heritage for the states of Côte d'Ivoire and Ghana, and serves as a spawning area, nursery and habitat for the local benthic community (Ruiz et *al*., 2006). The Aby lagoon is home to sought-after species such as Anhinga rufa, Phalacrocorax africanus, Ardeola ibis, Ardeola ralloides, Milvus migrans, Sarotherodon melanotherodon, Trachinotus, Liza falcipinis, Arius africanus and Trichechus senegalensis. Moreover, the lagoon's metallic contamination is a source of recurrent conflict between these border states, and is of interest to UNESCO because of its Ramsar status.

The end of the 20th century and the current decade have seen studies on the metallic contamination of sediments in the Aby Lagoon (Kouadio and Trefry 1987, Miyittah et *al*., 2020). However, these studies are limited in time, incomplete, old and do not take into account core sediments, which are temporal markers. In order to better understand the vertical variation of trace elements as a function of successive sediment deposition in the Aby Lagoon, this study was carried out. The objectives of this study were to: (1) determine the texture and total organic carbon in the sediment cores; (2) assess the vertical distribution of the metallic trace elements Hg, As, Cd and Pb in the sediment cores from Lagune Aby; (3) examine the historical environmental quality of the sediment cores.

2. Methodology

2.1 Study area

The Aby Lagoon is a Pleistocene coastal depression of fluvial origin linking the states of Côte d'Ivoire and Ghana. The Aby Lagoon lies between longitudes West 2°51' - 3°21' and latitudes North 5°05' - 5°22' and extends over 424 km^2 (Durand and Skubich 1982). The Aby lagoon receives the contents of the coastal rivers Bia and Tanoé (Tano for Ghanaians), which drain catchment areas of around 10,000 km^2 and 16,000 km^2 respectively (Chantraine 1980). In addition to agricultural activities, Aby lagoon is exposed to effluent discharges from mining and industrial activities. Despite these degrading factors, Aby Lagoon records an average annual fish production estimated at around 2,000 tons (2018) and an average annual crab production estimated at around 100 tons of crustaceans. The sediments in this lagoon are a mixture of eroded ferralitic soils and zooplanktonic and phytoplanktonic debris (Kouadio and Trefry 1987, Koné et *al*., 2009, Karim et *al*., 2016). This lagoon is home to the UNESCO Ramsar project and is of significant ecological value (Miyittah et *al*., 2020).

2.2 Sediment collection

Nine (09) sediment cores were collected during 2020 at nine (09) stations selected on the basis of anthropogenic pressure and proximity to rivers and the Atlantic Ocean (**Figure 1**). These sampling stations are described in **Table 1**. Sediment core samples were taken using a manual corer following the modified method of Ekett et al. (2018). The corer was immersed in the water until it touched the bottom, and on contact with the bottom the corer was depressed as the sediment gradually moved up the corer tube.

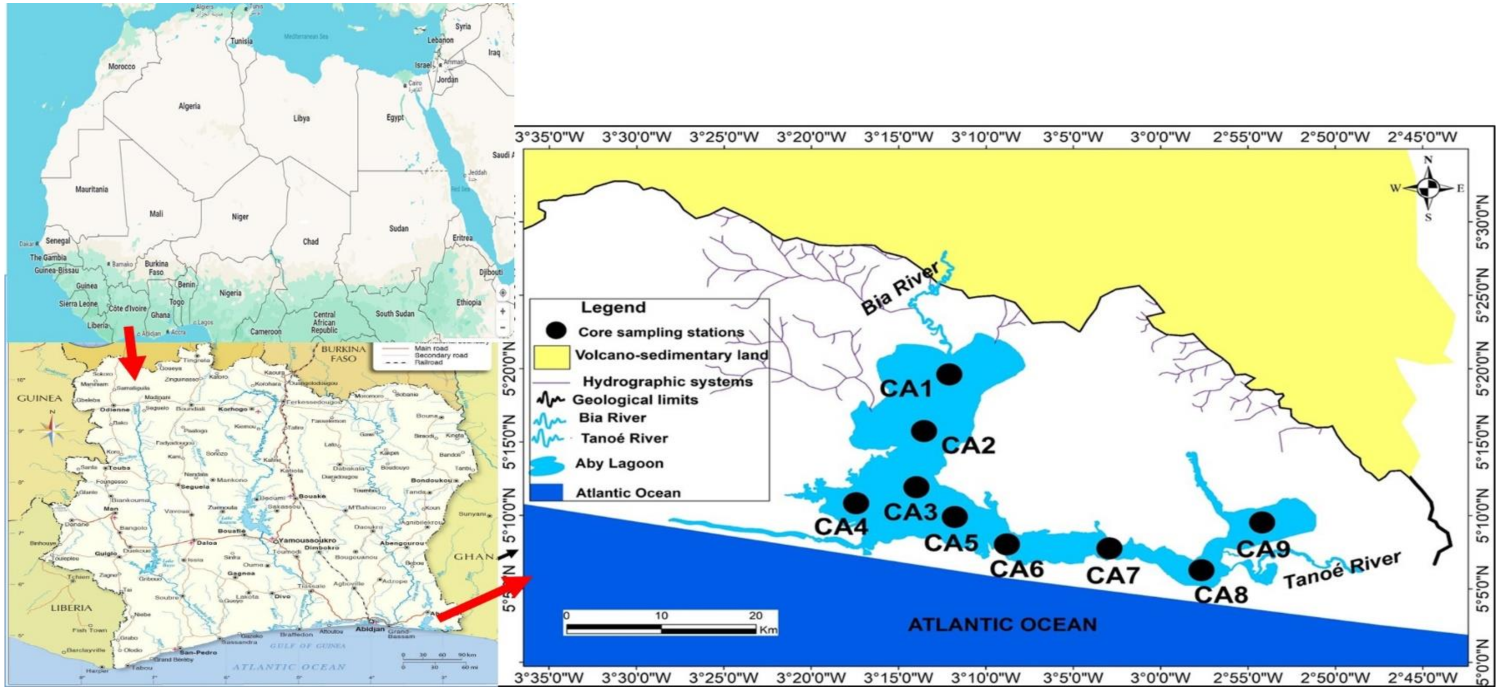


Figure 1. Locations of the core sediment sampling stations in the Aby Lagoon (West Africa – South Eastern Ivory Coast

A total of 63 sediment samples obtained from seven (07) sections were placed in polypropylene bags and graded as follows: 0-5cm (a), 5-10cm (b), 10-15cm (c), 15-20cm (d), 20-25cm (e), 25-30cm (f), 30-35cm (g). These samples were then stored in a cooler at 4°C and sent to the laboratory for analysis (Ekett *et al.* 2018).

Table 1. Longitude, latitude and characteristics of the sampling sites on the Aby Lagoon

Stations	Characteristics of the site	West longitude	North latitude
CA1	Close to the Bia river, bordered by cocoa crops	3°13'32"W	5°15'45"N
CA2	High urbanization, Close to the Bia river	3°12'05"W	5°19'37"N
CA3	Floral and faunal diversity and tourist activities	3°13'58"W	5°11'56"N
CA4	Close to the sea and bordered by banana crops	3°17'25"W	5°10'50"N
CA5	Close to the sea and fishing activities	3°11'46"W	5°09'54"N
CA6	Close to the sea and agricultural crops	3°08'47"W	5°08'02"N
CA7	Bordered by agricultural crops	3°03'29"W	5°07'35"N
CA8	Mining activities and Close to the Tanoé river	2°57'39"W	5°06'17"N
CA9	Mining activities and bordered by industrial crops	2°54'11"W	5°09'32"N

2.3 Laboratory analysis and quality assurance

The samples collected underwent three (03) separate analyses. The first analysis consisted in determining the granulometry and texture of sediment core sections using manual sieving on 63µm and 2µm mesh. The second analysis involved burning 5g of samples in an oven to determine total organic carbon (TOC). The final analysis involved the determination of trace elements Hg, As, Cd, Pb by hydride generation (HG-AAS) and graphite furnace atomic absorption spectroscopy (GFAAS) (SpectrAA100 spectrometer Varian, Japan) (Loring and Rantala 1992, Ouattara et *al*., 2018). The results of an analysis are not valid without verification of their reliability, as it is impossible to carry out a chemical analysis that is free from error or uncertainty. Blanks and duplicates were performed after each analysis of 10 samples. The calibration curve was established using standard solutions for each trace metal. **Table 2** gives the recovery rates and detection limits for the trace elements studied.

Table 2. Percentage recovery of errors and detection limits of trace element

TMEs	Recovery (%)	Detection Limits (µg/g)
Hg	102	0.05
As	98	0.03
Cd	99	0.002
Pb	101	0.09

2.4 Sample particle size and texture

The vertical grain size of sediment core samples was determined by sieving 100g of sediment over 63µm, 2µm sieve meshes. Sediments were classified into sandy (> 63µm), silty (63µm - 2µm) and clayey (< 2µm) fractions. The texture of each sediment core was determined using the Flemming model (**Figure 2**). This model is based on a ternary diagram (sand, silt, clay) and a subdivision into six (06) intervals (mud, slightly sandy silt, sandy silt, muddy sand, slightly muddy sand, sand). Flemming's model is important in determining the sediment deposition environment and also compensates for the approximations of visual sediment characterization (Flemming et *al.*, 2000).

2.5 Total organic carbon

Total organic carbon (TOC) of sediment core sections was determined by the adapted dry combustion method (Christensen 1987). 2.0 g of dry sediment samples deposited in porcelain crucibles were placed in a muffle furnace and heated to 550°C for 24 h to burn off the organic matter (Ouaty et *al.*, 2022). **Eqn. 1** was used to determine the % TOC.

$$\% \, TOC = \left(\frac{MAI - MAPI}{MAI}\right) \times 100 \qquad \textbf{Eqn. 1}$$

MAI: mass of sediment before heating; MAPI: mass of sediment after heating

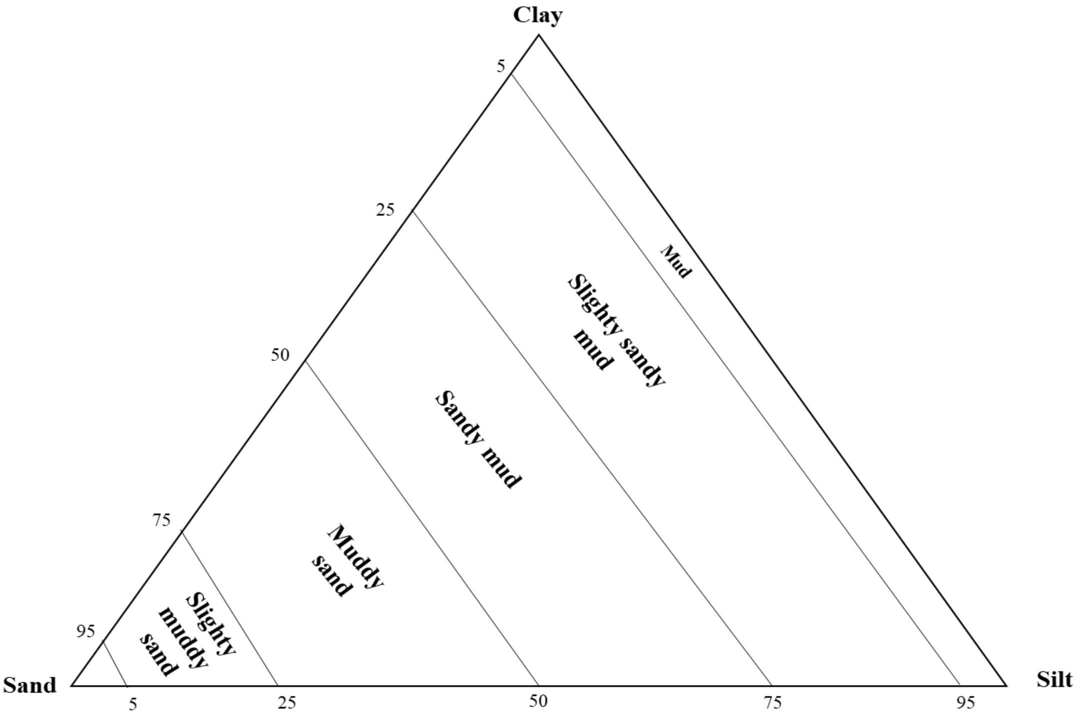


Figure 2. Textural ternary diagram of sediments according to Flemming

2.6 Contamination Factor (CF)

The contamination factor (CF) is a tool for determining the level of metallic contamination in sediments (Hakanson 1980). It is calculated from the following relationship (**Eqn. 2**):

$$CF = \frac{C_{metal}}{C_{background}} \qquad \textbf{Eqn. 2}$$

where C_{metal} is the concentration of the metal in the sediment and $C_{background}$ is the value of the geochemical background for a given metal. Concentrations recorded in the upper part of the earth's crust (29) were used as the geochemical background, to the detriment of direct measurements of concentrations recorded in the deepest zone of low anthropogenic activity, or of average concentrations recorded in sedimentary textures reported in the literature. The different levels of contamination according to CF values and geochemical background values are shown in **Table 3**.

Table 3. Standards for levels of contamination (**Hakanson 1980, Yang et *al.*, 2012**)

Contamination Factor (CF)	Contamination Level
CF < 1	Low Contamination
1 < CF < 3	Moderate contamination
3 < CF < 6	Considerable contamination
CF > 6	Very high contamination

2.7 Pollution Load Index (PLI) and Enrichment factor

The degree of overall pollution of sediments in a study area by selected trace elements can be estimated by the metal pollution index (PLI) (Ganugapenta et *al.*, 2018, Ajayi et *al.*, 2022). The method for calculating the PLI is described by **Eqn. 3** :

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \times \ldots\ldots \times CF_n} \qquad \textbf{Eqn. 3}$$

With: CF_i: contamination factor of metal i.

If PLI = 0, there is no deterioration; if PLI = 1, only reference levels of pollutants are present, and if the PLI value > 1, this indicates a progressive deterioration of the environment.

The enrichment factor (EF) is used to estimate the quantity of TMEs released into a given ecological environment and differentiate between these trace metals' anthropogenic and natural inputs (Karaouzas et *al.*, 2021). **Eqn. 4** defines the calculation of the enrichment factor. The reliability of this calculation requires a suitable choice of normalizing element and reference material. Iron (Fe) was chosen over Aluminum (Al) because Al is an abundant element in the structure of clay minerals that is present abundantly in the study area and is also associated with particle surfaces as an oxide coating (Daskalakis and O'Connor 1995). The reference material is UCC due to the lack of reliable local source rock data (Pekey 2006).

$$\boldsymbol{EF} = \frac{\left(\frac{M}{Fe}\right)\ sample}{\left(\frac{M}{Fe}\right) background} \qquad \textbf{Eqn. 4}$$

where EF, enrichment factor; M, metal concentration; Fe, iron concentration; sample; earth crust. Origins are defined as 0.5 ≤ FE ≤ 1.5, natural origin and FE > 1.5 anthropogenic origin (Zhang et *al.*, 2007).

2.8 Assessment of lagoon biota

To assess sediment quality, international bodies such as the Environmental Protection Agency (EPA) and researchers (Hakanson 1980, Long et *al.*, 1995) have proposed guideline values (SQGs). Metal quantification is based on pre-industrial time and post-industrial time or industrial civilization. Pre-industrial time made it possible to record pre-industrial reference values (PRVs) before the explosion of industry and trace elements in the earth's crust. In addition, the suggested margin established a threshold below which impacts on aquatic organisms rarely occur (ERL) and a threshold above which living organisms in sediments are likely to encounter adverse effects frequently (ERM) (Long et *al.*, 1995, Burton 2002) (**Table 4**).

Table 4. PRV-ERM/PEL guide values for assessment of the environmental quality of sediments (Hakanson 1980, Long et *al.*, 1995, Burton 2002)

ETMs (µg/g)	PRV (µg/g)	ERL (µg/g)	ERM (µg/g)
Hg	0.25	0.15	1.3
As	15	8.2	70
Cd	1.0	1.2	9.6
Pb	70	46.7	218

3. Results and Discussion

3.1 Total organic carbon (TOC) and sediment ternary diagram

Table 5 presents the total organic carbon (TOC) and vertical grain size results for sediment cores collected in Aby lagoon. **Figure 3** shows the vertical distribution of total organic carbon in sediment cores collected in Aby lagoon. TOC ranged from 0.3% (30-35cm) to 14.8% (0-5cm), from 1.1% (30-35cm) to 13.5% (0-5cm), from 0.9% (30-35cm) to 11% (0-5cm), from 1.4% (30-35cm) to 11.4% (0-5cm), from 1.9% (30-35cm) to 13.2% (0-5cm), from 0.6% (30-35cm) to 19.1% (0-5cm) and from 1.4% (30-35cm) to 17.4% for cores CA1, CA2, CA3, CA4, CA7, CA8 and CA9 respectively. The horizontal distribution of TOC by layer showed the following trend: (0-5cm) > (5-10cm) > (10-15cm) > (15-20cm) > (30-35cm) > (20-25cm) > (25-30cm) > (30-35cm). ANOVA results showed a significant difference ($p < 0.5$) between the different layers of cores CA1, CA2, CA3, CA7, CA8 and CA9.

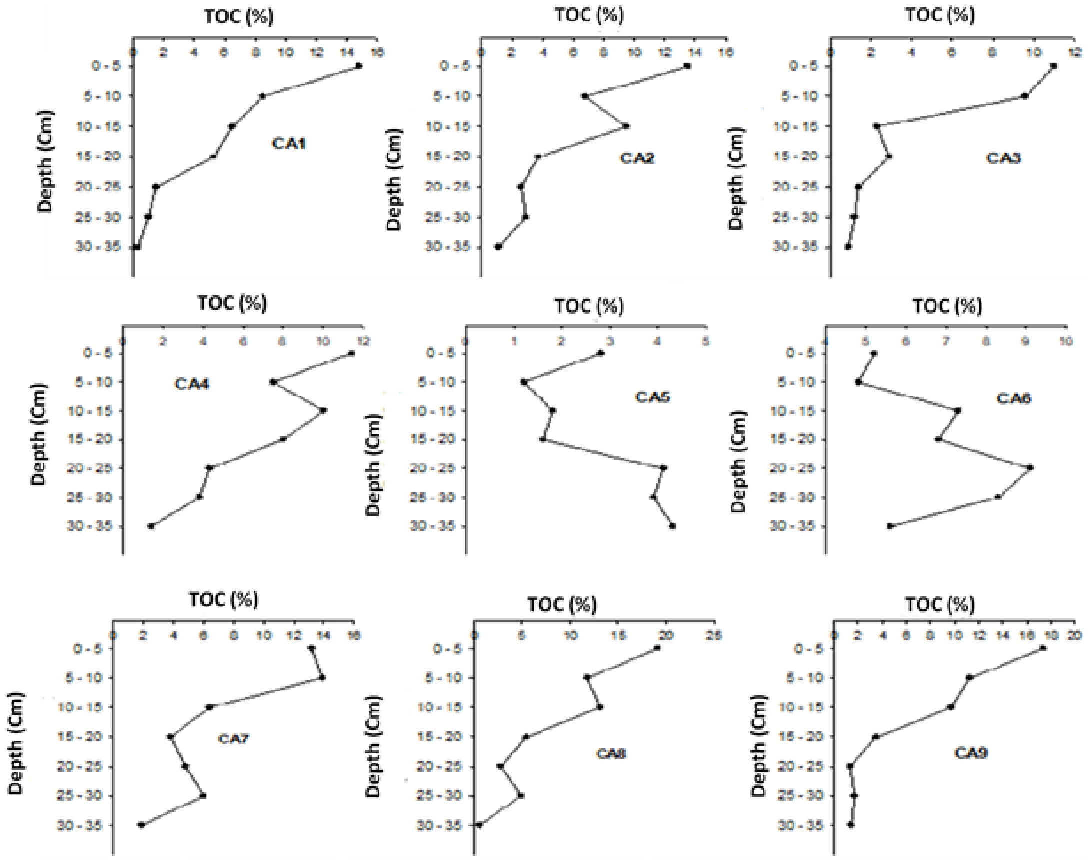


Figure 3. Depth profiles of total organic carbon (%TOC) in sediments cores collected in Aby Lagoon

The results of the grain size percentages recorded (**Table 5**) in the sediment cores generally ranked in the order: (30-35cm) > (20-25cm) > (0-5cm) > (5-10cm) > (15-20cm) > (25-30cm) > (10-15cm) for sand. Silt percentages also followed the order: (25-30cm) > (20-25cm) > (30-35cm) > (0-5cm) > (15-20cm) > (10-15cm) > (5-10cm). Clay evolved according to: (10-15cm) > (5-10cm) > (15-20cm) > (0-5cm) > (25-30cm) > (20-25cm) > (30-35cm).

Table 5. Particle size and total organic carbon (TOC) percentages of sediments cores of Aby Lagoon

Stations	**Depth (cm)**	**% TOC**	**% Sand**	**% Silt**	**% Clay**
CA1	A (0-5)	14.8	59	17	24
	B (5-10)	8.5	62.5	10.5	26
	C (10-15)	6.5	63	5.4	30.2
	D (15-20)	5.3	60.3	3	35.8
	E (20-25)	1.5	79	5.4	14.8
	F (25-30)	1.02	80	8.5	9.9
	G (30-35)	0.3	82	9.1	8.2
	Mean ± SD	5.42 ± 5.2	69.4 ± 10.4	8.4 ± 4.6	21.3 ± 10.5
CA2	A (0-5)	13.5	66.3	11	22.6
	B (5-10)	6.8	61.5	18.2	20
	C (10-15)	9.5	65.9	14.5	19
	D (15-20)	3.7	55.2	13.3	30.9
	E (20-25)	2.6	56	23	19.4
	F (25-30)	2.9	52.7	31	15
	G (30-35)	1.1	91.3	2.7	4.8
	Mean ± SD	5.7 ± 4.5	64.1 ± 13.1	16.2 ± 9	18.8 ± 7.90
CA3	A (0-5)	11	66.4	25.5	7.2
	B (5-10)	9.6	65.2	10.5	23.8
	C (10-15)	2.3	54.6	12.6	30.6
	D (15-20)	2.9	74.8	18	7.1
	E (20-25)	1.4	82	9.4	8
	F (25-30)	1.2	77	10.5	11.8
	G (30-35)	0.9	79.1	4.2	16.4
	Mean ± SD	4.2 ± 4.3	71.3 ± 9.7	13.0 ± 6.9	15.0 ± 9.2
CA4	A (0-5)	11.4	67	8.4	23.7
	B (5-10)	7.5	39.5	6.2	53.7
	C (10-15)	10	36.2	2.6	59.8
	D (15-20)	8	26.2	7.8	65.4

	E (20-25)	4.3	26	5.2	68.1
	F (25-30)	3.8	35.4	3.8	60.2
	G (30-35)	1.4	37.6	3.2	58.8
	Mean ± SD	6.6 ± 3.6	38.3 ± 13.8	5.3 ± 2.3	55.7 ± 14.8
CA5	A (0-5)	2.8	81.3	4.8	13.4
	B (5-10)	1.2	76	13	10.1
	C (10-15)	1.8	69	19.7	10.9
	D (15-20)	1.6	72	18.4	9.3
	E (20-25)	4.1	78	17.8	3.8
	F (25-30)	3.9	77	4.7	17.9
	G (30-35)	4.3	72.8	13.1	13.8
	Mean ± SD	2.8 ± 1.3	75.2 ± 4.2	13.1 ± 6.2	11.3 ± 4.4
CA6	A (0-5)	5.2	78.5	8	12.7
	B (5-10)	4.8	72.1	6.5	20.8
	C (10-15)	7.3	61	9.1	30
	D (15-20)	6.8	80.1	4.6	14.6
	E (20-25)	9.1	77.5	5.6	16.1
	F (25-30)	8.3	24.1	31.5	43
	G (30-35)	5.6	49	31	18.9
	Mean ± SD	6.7 ± 1.6	63.2 ± 20.6	13.8 ± 12.0	22.3 ± 10.7
CA7	A (0-5)	13.2	71	15.8	13.1
	B (5-10)	13.9	69	10.4	19
	C (10-15)	6.4	66.1	11.4	22
	D (15-20)	3.8	74	9.4	16.3
	E (20-25)	4.8	83	6.8	9.7
	F (25-30)	6	75	14.2	8.9
	G (30-35)	1.9	77	10.8	11.9
	Mean ± SD	7.1 ± 4.6	73.6 ± 5.6	11.3 ± 3.0	14.4 ± 4.9
CA8	A (0-5)	19.1	64.4	18.4	17
	B (5-10)	11.8	69	8.9	21.6
	C (10-15)	13.1	85	5.4	8.9
	D (15-20)	5.5	79.5	10.8	9.3
	E (20-25)	2.8	49.9	33.8	15.8
	F (25-30)	4.9	58	22.8	18.6

	G (30-35)	0.6	56	31.4	12.2
	Mean ± SD	8.3 ± 6.6	66.0 ± 12.8	18.8 ± 11.1	14.8 ± 4.8
CA9	A (0-5)	17.4	40.7	6	52.8
	B (5-10)	11.3	49.7	6.2	43.4
	C (10-15)	9.7	33.5	16.7	48.8
	D (15-20)	3.5	42.1	7.5	49.7
	E (20-25)	1.3	79.2	6.5	13.9
	F (25-30)	1.7	76	8.2	14.7
	G (30-35)	1.4	68	17.2	13.7
	Mean ± SD	6.6 ± 6.3	55.6 ± 18.5	9.8 ± 5.0	33.9 ± 18.7

TOC results showed an increase in organic matter towards the surface and superficial layers. This trend could be explained by an increasing input of detrital material and decomposition of animal and plant matter in the upper layers (BadrElDin et *al.*, 2022). It could also suggest a low burial rate at depth, which would favor microbial degradation in the lower layers (Zhang et *al.*, 2007, Badr and Hussein 2010, Khalil et *al.*, 2013). In contrast, the trend observed in cores CA5 and CA6 would indicate a zonal phenomenon, probably a low sedimentation rate with depth (Amir et *al.*, 2020). These high percentages of organic matter on the surface would probably constitute a trap for trace metal elements. The trend of sand growth with depth indicates diagenesis. This trend would confirm the very low quantity of organic matter recorded in the lower layers. Indeed, organic matter is generally associated with fine particles (clays, silt) (Chen et *al.*, 2010). The ternary sediment diagram was represented by the average recorded from the results of each core sampled (**Figure 4**). Texture provides an understanding of trace element adsorption and desorption phenomena due to their close binding (Chen et *al.*, 2016, Zonta et *al.*, 2018).

The results showed three (03) texture types according to Flemming's diagram: The textures, of muddy sand, sandy mud and slightly muddy sand. The results of the statistical Analysis of Variance revealed no significant differences ($p > 0.05$). The high level of muddy sands (07 cores) is thought to derive from the weathering of Pleistocene geological formations (sandstones, granites) (Allersma and Tilmans 1993). The sandy-clay texture recorded in core CA4 is probably due to the nature of the deposits and altered diagenetic conditions (Ouaty et *al.*, 2022). Core CA5, taken from an island consisting mainly of sand, would explain the sandy texture recorded.

3.2 Mapping the vertical distribution of trace elements Hg, As, Cd and Pb in sediment cores

The total concentrations of the trace elements Hg, As, Cd, Pb are recorded in **Table 6**, and the vertical distribution profiles are shown in **Figure 5**. The mean total concentrations of Hg (**Figure 5a**) recorded ranged from 1.32 ± 0.92 µg/g (CA1), 0.93 ± 0.49 µg/g (CA2), 0.72 ± 0.55 µg/g (CA3), 0.50 ± 0.45µg/g (CA4), 1.20 ± 0.83 µg/g (CA5), 0.55 ± 0.40 µg/g (CA6), 0.90 ± 0.53 µg/g (CA7), 1.28 ± 1.23 µg/g (CA8), 1.46 ± 0.7 µg/g (CA9). Mean total As concentrations (**Figure 5b**) ranged from 1.70 ± 1.03 µg/g (CA1), 1.73 ± 1.04 µg/g (CA2), 0.99 ± 0.79 µg/g (CA3), 0.64 ± 0.37 µg/g (CA4), 0.74 ± 0.65 µg/g (CA5), 0.90 ± 0.75 µg/g (CA6), 1.87 ± 1.13 µg/g (CA7), 1.83 ± 0.91 µg/g (CA8), 1.16 ± 0.75 µg/g (CA9). Mean total Cd concentrations (**Figure 5c**) ranged from 0.09 ± 0.05 µg/g (CA1), 0.07 ± 0.04 µg/g (CA2), 0.11 ± 0.07 µg/g (CA3), 0.07 ± 0.07 µg/g (CA4), 0.05 ± 0.03 µg/g (CA5), 0.13 ± 0.12 µg/g (CA6), 0.22 ± 0.21 µg/g (CA7), 0.21 ± 0.19 µg/g (CA8), 0.19 ± 0.09 µg/g (CA9). Mean total Pb concentrations (**Figure 5d**) ranged from 1.25 ± 0.67 µg/g (CA1), 0.8 ± 0.5 µg/g (CA2), 1.08 ± 1.05 µg/g (CA3), 0.51 ± 0.25 µg/g (CA4), 0.46 ± 0.21 µg/g (CA5), 1.10 ± 0.83 µg/g (CA6),1.15 ± 0.77 µg/g (CA7), 1.49 ± 0.74 µg/g (CA8), 2.19 ± 1.49 µg/g (CA9).

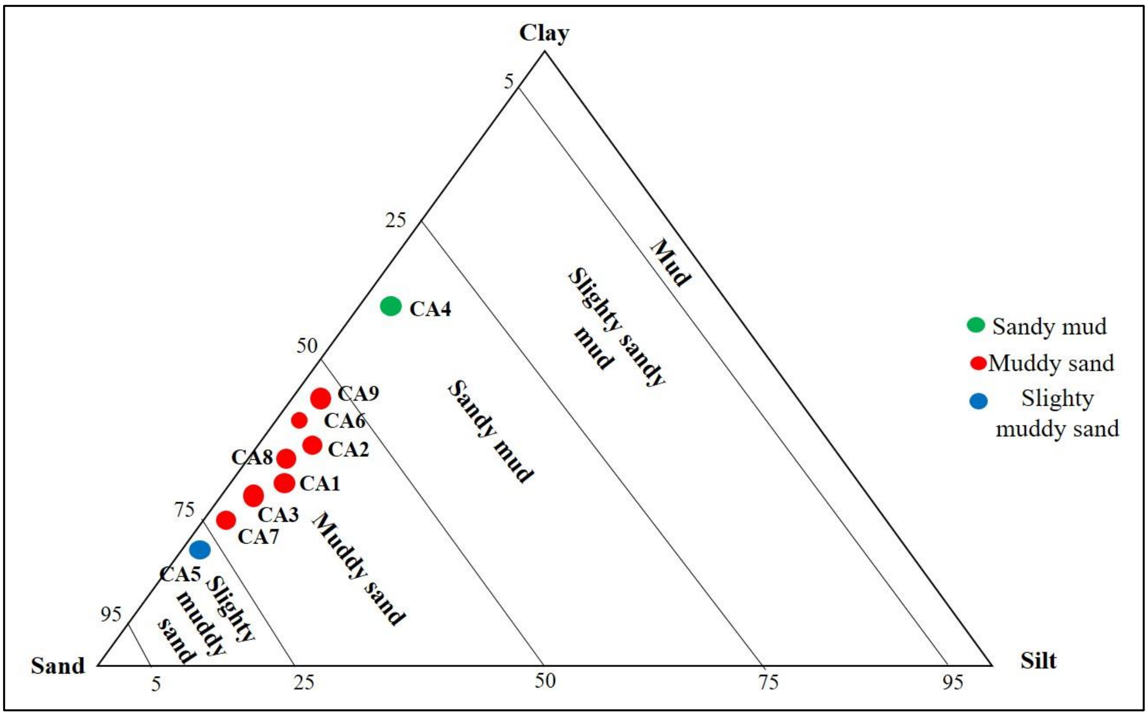


Figure 4. Sediments cores texture of the Aby Lagoon

With regard to the distribution of levels (µg/g) by stratum, Hg varied in the order: (0-5cm) > (10-15cm) > (5-10cm) >(15-20cm) > (20-25cm) > (25-30cm) > (30-35cm); As followed the trend: (5-10cm) > (0-5cm) > (10-15cm) > (15-20cm) > (25-30cm) > (20-25cm) > (30-35cm); Cd, (0-5cm) > (10-15cm) > (20-25cm) > (30-35cm) > (15-20cm) > (25-30cm) > (5-10cm) and Pb was as follows: (10-15cm) > (15-20cm) > (25-30cm) > (5-10cm) > (0-5cm) > (20-25cm) > (30-35cm).

The ANOVA results showed a significant difference ($p < 0.05$) in the total concentrations of Hg and As in the different sections of the cores collected in Aby Lagoon. The vertical distribution may reflect historical trace element content (Wang et *al.*, 2015). The trend towards higher total Hg concentrations in the upper sections of the sediment cores could be explained by the intensity of mining activities in the study area over the decades. Indeed, locals are increasingly neglecting fishing and sacred local activities in favor of mining activities. These mining activities, which are less well controlled by local people, release large quantities of Hg into the sediment deposits in Aby lagoon (Fitzgerald and Lamborg 2014; Kouassi et *al.*, 2022). Anthropogenic activities such as oil traffic, which is highly accentuated in the area, and domestic discharges evolving in the anthropogen could also suggest these high levels of Hg in the upper layers (0-15cm) (Wilhelm 2000; Rahman and Singh 2019).

As with Hg, the disposition observed in As concentrations would testify to the increasingly growing influence of anthropogenic activities such as agrochemicals over the long term (Smedley and Kinniburgh 2002*;* BadrElDin et *al.*, 2022). In addition, the continuous inflow of water from the Bia and Tanoé rivers into the Aby lagoon basin will likely increase the distribution of trace elements in the sediments.

Table 6. Total concentrations (µg/g) of traces elements Hg, As, Cd and Pb in the sediment cores of Aby lagoon

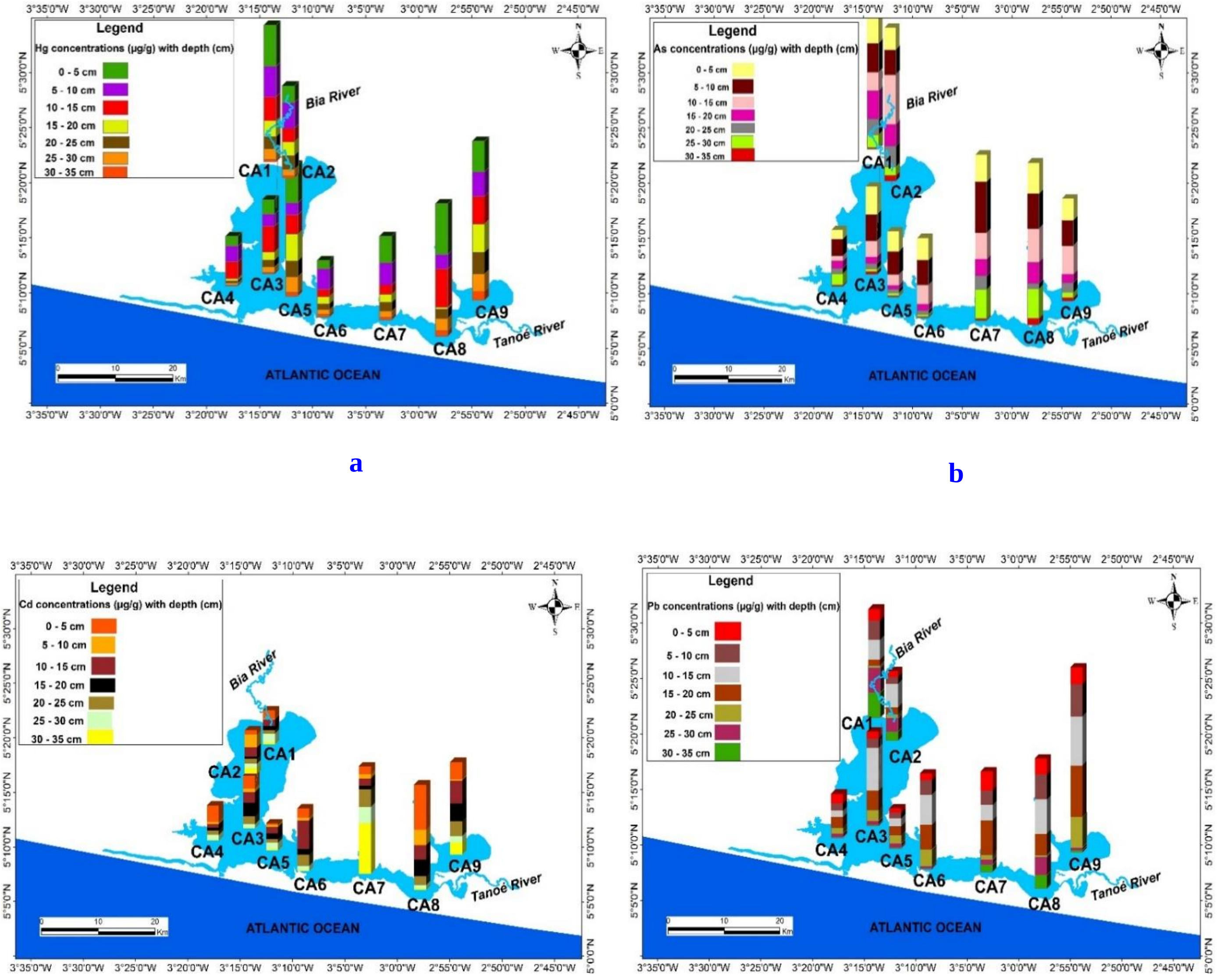
Stations	Depth (cm)	Hg (µg/g)	As (µg/g)	Cd (µg/g)	Pb (µg/g)
CA1	A (0-5)	2.92	3.56	0.06	0.94
	B (5-10)	2.16	2.3	0.18	1.55
	C (10-15)	1.67	1.45	0.13	1.56
	D (15-20)	1.13	2.25	0.03	0.49
	E (20-25)	0.86	1.26	0.07	0.19
	F (25-30)	0.33	1.01	0.06	1.98
	G (30-35)	0.18	0.09	0.08	2.03
	Mean ± SD	1.32 ± 0.92	1.70 ± 1.03	0.09 ± 0.05	1.25 ± 0.67
CA2	A (0-5)	1.19	1.75	0.12	0,48
	B (5-10)	1.81	1.97	0.01	0.54
	C (10-15)	0.96	3.91	0.09	1.88
	D (15-20)	0.95	1.74	0.06	0.57
	E (20-25)	0.98	1.66	0.05	0.29
	F (25-30)	0.42	0.67	0.12	1.11
	G (30-35)	0.19	0.44	0.03	0.71
	Mean ± SD	0.93 ± 0.49	1.73 ± 1.04	0.07 ± 0.04	0.8 ± 0.5
CA3	A (0-5)	1.03	2.19	0.18	0.55
	B (5-10)	0.85	2.09	0.05	0.73
	C (10-15)	1.83	1.25	0.15	3.43
	D (15-20)	0.54	0.55	0.19	1.55
	E (20-25)	0.5	0.41	0.11	0.89
	F (25-30)	0.18	0.22	0.05	0.3
	G (30-35)	0.11	0.23	0.01	0.09
	Mean ± SD	0.72 ± 0.55	0.99 ± 0.79	0.11 ± 0.07	1.08 ± 1.05
CA4	A (0-5)	0.68	0.69	0.23	0.78
	B (5-10)	1.12	1.34	0.03	0.58
	C (10-15)	1.18	0.4	0.05	0.5
	D (15-20)	0.16	0.6	0.04	0.85
	E (20-25)	0.15	0.41	0.06	0.49
	F (25-30)	0.13	0.91	0.07	0.27
	G (30-35)	0.09	0.12	0.01	0.07
	Mean ± SD	0.50 ± 0.45	0.64 ± 0.37	0.07 ± 0.07	0.51 ± 0.25
CA5	A (0-5)	2.7	1.58	0.02	0.34
	B (5-10)	0.83	1.83	0.03	0.48
	C (10-15)	1.35	0.83	0.09	0.63
	D (15-20)	1.89	0.33	0.08	0.71
	E (20-25)	1.14	0.31	0.05	0.64
	F (25-30)	0.27	0.21	0.09	0.33
	G (30-35)	0.19	0.09	0.02	0.08
	Mean ± SD	1.20 ± 0.83	0.74 ± 0.65	0.05 ± 0.03	0.46 ± 0.21

CA6	A (0-5)	0.6	1.73	0.13	0.55
	B (5-10)	1.45	1.97	0.04	1.15
	C (10-15)	0.51	1.52	0.4	2.43
	D (15-20)	0.5	0.52	0.08	1.95
	E (20-25)	0.41	0.28	0.16	1.36
	F (25-30)	0.28	0.19	0.06	0.17
	G (30-35)	0.1	0.08	0.01	0.06
	Mean ± SD	0.55 ± 0.40	0.90 ± 0.75	0.13 ± 0.12	1.10 ± 0.83
CA7	A (0-5)	1.88	2.14	0.11	1.52
	B (5-10)	1.55	4.04	0.06	1.17
	C (10-15)	0.66	2.07	0.1	1.25
	D (15-20)	0.58	1.35	0.05	2.74
	E (20-25)	0.62	1.07	0.25	0.37
	F (25-30)	0.59	2.31	0.23	0.43
	G (30-35)	0.41	0.14	0.71	0.58
	Mean ± SD	0.90 ± 0.53	1.87 ± 1.13	0.22 ± 0.21	1.15 ± 0.77
CA8	A (0-5)	3.59	2.44	0.63	1.28
	B (5-10)	1.02	2.77	0.22	2
	C (10-15)	2.71	2.66	0.2	2.75
	D (15-20)	0.11	1.69	0.24	1.71
	E (20-25)	0.66	0.43	0.12	0.16
	F (25-30)	0.55	2.31	0.05	1.44
	G (30-35)	0.31	0.53	0.02	1.08
	Mean ± SD	1.28 ± 1.23	1,83 ± 0.91	0.21 ± 0.19	1.49 ± 0.74
CA9	A (0-5)	2.18	1.71	0.24	1.35
	B (5-10)	1.71	2.01	0.02	2.58
	C (10-15)	1.95	2.25	0.32	3.94
	D (15-20)	1.99	0.69	0.25	4.11
	E (20-25)	1.54	0.77	0.21	2.47
	F (25-30)	0.69	0.39	0.09	0.21
	G (30-35)	0.13	0.28	0.17	0.18
	Mean ± SD	1.46 ± 0.7	1.16 ± 0.75	0.19 ± 0.09	2.12 ± 1.49

In order to situate the vertical variation of trace elements in the sediment cores, total concentrations were compared with standard values recorded in UCC and SQGs (Sediments Quality Guidelines) (Wedepohl 1995, Karaouzas et *al*., 2021). Total Hg concentrations in the sections (0-35cm) of all cores collected for this study were higher than those recorded in UCC (0.056 µg/g). Similarly, these recorded concentrations were higher than the SQGs values (0.486 µg/g) for the sections (0-25cm) of all cores collected. Total As concentrations in sections (0-15cm) of cores CA1, CA7, CA8, CA9 were higher than those of UCC (2.0 µg/g). In contrast, total Cd and Pb concentrations in all sections (0-35cm) of the cores collected (CA1 - CA9) in this study were lower than UCC (0.102 µg/g; 17 µg/g) and SQGs (3.53 µg/g; 91.3 µg/g) respectively.

3.3 Contamination Factor (CF) and Pollution Load Index (PLI)

The level of trace element contamination accumulated in the sediment cores was determined and shown in **Table 7**. Mean CF values for Hg ranged from 8.95 ± 8.05 (CA4) to 23.60 ± 16.42 (CA1), for CF As from 0.32 ± 0.18 (CA4) to 0.94 ± 0.56 (CA7), CF Cd ranged from 0.53 ± 0.29 (CA5) to 2.11 ± 2.10 (CA7) and CF Pb from 0.03 ± 0.01 (CA4, CA5) to 0.07 ± 0.04 (CA1). Metallic assessment of the ecological balance of the sediment cores was carried out using the metallic pollution index (PLI).



a

b

c

d

Figure 5. Spatial distribution of trace elements Hg, As, Cd and Pb in the cores of sediments of the Aby Lagoon

The PLI results shown in **Figure 6** ranged from 0.49 ± 0.35 (CA4) to 1.40 ± 0.95 (CA8). The level of contamination assessed by the contamination factor and the PLI pollution index showed that all the sediment cores collected were highly contaminated (CF > 6) with Hg. In contrast, the sediment cores collected showed no contamination (CF < 1) in As and Pb. Furthermore, Cd contamination in the sediment cores ranged from non-contamination (1 < CF < 3) to moderate contamination. This finding would confirm the major impact of mining effluent discharges into the Aby lagoon basin, which would not fade over time. Hg contamination of the various sediment core layers could indicate a permanent release of this trace element into the Aby lagoon basin. With regard to the PLI results, 02 trends were observed, with sediment cores from stations CA1, CA7, CA8 and CA9 being deteriorated (PLI > 1) while the other stations were not deteriorated (PLI < 1). The results would indicate that sediment cores located near the Bia and Tanoé rivers are deteriorated.

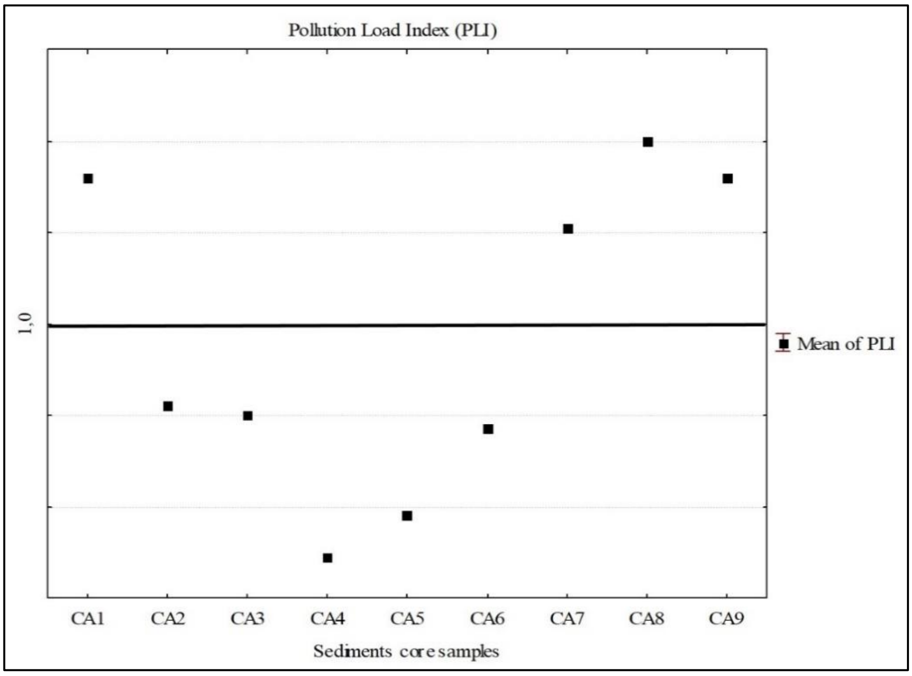


Figure 6. Pollution Load Index (PLI) of metals on the sediment cores from the Aby Lagoon

Table 7. Contamination Factor for each metal and Pollution Load Index (PLI) of total metals in sediment cores of Aby lagoon

Stations	Depth (cm)	CF Hg (µg/g)	CF As (µg/g)	CF Cd (µg/g)	CF Pb (µg/g)	PLI
CA1	A (0-5)	52.14	1.78	0.59	0.06	1.32
	B (5-10)	38.57	1.15	1.76	0.09	1.63
	C (10-15)	29.82	0.73	1.27	0.09	1.26
	D (15-20)	20.18	1.13	0.29	0.03	0.66
	E (20-25)	15.36	0.63	0.69	0.01	0.52
	F (25-30)	5.89	0.51	0.59	0.12	0.67
	G (30-35)	3.21	0.05	0.78	0.12	0.34
	Mean ± SD	23.60 ± 16.42	0.85 ± 0.52	0.85 ± 0.46	0.07 ± 0.04	1.06 ± 0.63
CA2	A (0-5)	21.25	0.88	1.18	0.03	0.89
	B (5-10)	32.32	0.99	0.1	0.03	0.56
	C (10-15)	17.14	1.96	0.88	0.11	1.34
	D (15-20)	16.96	0.87	0.59	0.03	0.73
	E (20-25)	17.5	0.83	0.49	0.02	0.59
	F (25-30)	7.50	0.34	1.18	0.07	0.66
	G (30-35)	3.39	0.22	0.29	0.04	0.31
	Mean ± SD	16.58 ± 8.68	0.87 ± 0.52	0.67 ± 0.39	0.05 ± 0.03	0.82 ± 0.48
CA3	A (0-5)	18.39	1.10	1.76	0.03	1.04
	B (5-10)	15.18	1.05	0.49	0.04	0.76
	C (10-15)	32.68	0.63	1.47	0.20	1.57
	D (15-20)	9.64	0.28	1.86	0.09	0.82
	E (20-25)	8.93	0.21	1.08	0.05	0.57
	F (25-30)	3.21	0.11	0.49	0.02	0.24
	G (30-35)	1.96	0.12	0.10	0.01	0.10
	Mean ± SD	12.86 ± 9.76	0.50 ± 0.40	1.04 ± 0.64	0.06 ± 0.06	0.80 ± 0.63

CA4	A (0-5)	12.14	0.35	2.25	0.05	0.81
	B (5-10)	20	0.67	0.29	0.03	0.61
	C (10-15)	21.07	0.20	0.49	0.03	0.5
	D (15-20)	2.86	0.30	0.39	0.05	0.36
	E (20-25)	2.68	0.21	0.59	0.03	0.31
	F (25-30)	2.32	0.46	0.69	0.02	0.33
	G (30-35)	1.61	0.06	0.10	0.00	0.08
	Mean ± SD	8.95 ± 8.05	0.32 ± 0.18	0.69 ± 0.66	0.03 ± 0.01	0.49 ± 0.35
CA5	A (0-5)	48.21	0.79	0.20	0.02	0.62
	B (5-10)	14.82	0.92	0.29	0.03	0.58
	C (10-15)	24.11	0.42	0.88	0.04	0.76
	D (15-20)	33.75	0.17	0.78	0.04	0.65
	E (20-25)	20.36	0.16	0.49	0.04	0.49
	F (25-30)	4.82	0.11	0.88	0.02	0.31
	G (30-35)	3.39	0.05	0.20	0.00	0.11
	Mean ± SD	21.35 ± 14.75	0.37 ± 0.33	0.53 ± 0.29	0.03 ± 0.01	0.58 ± 0.36
CA6	A (0-5)	10.71	0.87	1.27	0.03	0.79
	B (5-10)	25.89	0.99	0.39	0.07	0.91
	C (10-15)	9.11	0.76	3.92	0.14	1.40
	D (15-20)	8.93	0.26	0.78	0.11	0.68
	E (20-25)	7.32	0.14	1.57	0.08	0.60
	F (25-30)	5	0.10	0.59	0.01	0.23
	G (30-35)	1.79	0.04	0.10	0.00	0.07
	Mean ± SD	9.82 ± 7.12	0.45 ± 0.37	1.23 ± 1.19	0.06 ± 0.05	0.77 ± 0.63
CA7	A (0-5)	33.57	1.07	1.08	0.09	1.36
	B (5-10)	27.68	2.02	0.59	0.07	1.23
	C (10-15)	11.79	1.04	0.98	0.07	0.97
	D (15-20)	10.36	0.68	0.49	0.16	0.86
	E (20-25)	11.07	0.54	2.45	0.02	0.75
	F (25-30)	10.54	1.16	2.25	0.03	0.91
	G (30-35)	7.32	0.07	6.96	0.03	0.59
	Mean ± SD	16.05 ± 9.44	0.94 ± 0.56	2.11 ± 2.10	0.07± 0.05	1.21 ± 0.84
CA8	A (0-5)	64.11	1.22	6.18	0.08	2.46
	B (5-10)	18.21	1.39	2.16	0.12	1.59
	C (10-15)	48.39	1.33	1.96	0.16	2.13
	D (15-20)	1.96	0.85	2.35	0.10	0.79
	E (20-25)	11.79	0.22	1.18	0.01	0.41
	F (25-30)	9.82	1.16	0.49	0.08	0.83
	G (30-35)	5.54	0.27	0.20	0.06	0.37
	Mean ± SD	22.83 ± 22.05	0.92 ± 0.46	2.07 ± 1.84	0.09 ± 0.04	1.40 ± 0.95
CA9	A (0-5)	38.93	0.86	2.35	0.08	1.58
	B (5-10)	30.54	1.01	0.20	0.15	0.98
	C (10-15)	20.54	1.13	3.14	0.23	2.02
	D (15-20)	35.54	0.35	2.45	0.24	1.64
	E (20-25)	20.36	0.39	2.06	0.15	1.24
	F (25-30)	12.32	0.20	0.88	0.01	0.40
	G (30-35)	2.32	0.14	1.67	0.01	0.28
	Mean ± SD	22.93 ± 12.08	0.58 ± 0.38	1.82 ± 0.93	0.12 ± 0.09	1.32 ± 0.78

3.4 Sources and classification of trace elements in lagoon sediment cores

Trace element sources were evaluated through the enrichment factor (EF). The enrichment factor shown in **Table 8** showed that values ranged from EF (Hg), 2.05 ± 1.59 (CA5) to 28.81 ± 33.7 (CA1), EF (As), 0.22 ± 0.15 (CA4) and 1.87 ± 1.13 (CA7), EF (Cd), 0.05 ± 0.03 (CA5) and 1.39 ± 1.04 (CA3) and EF (Pb), 0.04 ± 0.02 (CA2) and 2.12 ± 1.49 (CA9). These results suggest that the presence of Hg in the collected sediment cores is from anthropogenic sources (EF > 1.5). Similarly, cores CA7 and CA9 would indicate anthropogenic inputs of trace elements As and Pb respectively. In addition, the upper layers (0-10cm) of sediment cores CA5, CA6, CA7, CA8 and CA9 would be strongly impacted by anthropogenic activities generating As.

Table 8. Enrichment factor (EF) in the sediment cores of Aby Lagoon

Stations	Depth (cm)	EF Hg	EF As	EF Cd	EF Pb
CA1	A (0-5)	22.6	0.77	0.25	0.02
	B (5-10)	22.59	0.67	1.03	0.05
	C (10-15)	17.16	0.42	0.73	0.05
	D (15-20)	108.95	6.07	1.59	0.16
	E (20-25)	23.37	0.96	1.04	0.02
	F (25-30)	4.99	0.43	0.50	0.10
	G (30-35)	2.01	0.03	0.49	0.07
	Mean ± SD	28.81 ± 33.7	1.34 ± 1.95	0.81 ± 0.42	0.07 ± 0.04
CA2	A (0-5)	11.25	0.46	0.62	0.01
	B (5-10)	13.76	0.42	0.04	0.01
	C (10-15)	9.92	1.13	0.51	0.06
	D (15-20)	25.75	1.32	0.89	0.05
	E (20-25)	1.13	0.05	0.03	0.00
	F (25-30)	7.24	0.32	1.14	0.06
	G (30-35)	3.83	0.25	0.33	0.05
	Mean ± SD	10.41 ± 7.43	0.57 ± 0.44	0.51 ± 0.38	0.04 ± 0.02
CA3	A (0-5)	22.76	1.35	2.18	0.04
	B (5-10)	8.26	0.57	0.27	0.02
	C (10-15)	21.73	0.42	0.98	0.13
	D (15-20)	14.68	0.42	2.83	0.14
	E (20-25)	21.27	0.49	2.57	0.12
	F (25-30)	4.88	0.17	0.74	0.03
	G (30-35)	2.77	0.16	0.14	0.01
	Mean ± SD	13.76 ± 7.85	0.51 ± 0.37	1.39 ± 1.04	0.07 ± 0.05
CA4	A (0-5)	3.52	0.19	1.21	0.78
	B (5-10)	8.63	0.46	0.20	0.58
	C (10-15)	2.15	0.1	0.25	0.5
	D (15-20)	1.13	0.12	0.15	0.85
	E (20-25)	2.86	0.22	0.63	0.49
	F (25-30)	2.09	0.41	0.62	0.27
	G (30-35)	0.24	0.04	0.07	0.07
	Mean ± SD	2.94 ± 2.53	0.22 ± 0.15	0.45 ± 0.37	0.51 ± 0.25

CA5	A (0-5)	4.7	1.58	0.02	0.34
	B (5-10)	3.83	1.83	0.03	0.48
	C (10-15)	2.35	0.83	0.09	0.63
	D (15-20)	1.89	0.33	0.08	0.71
	E (20-25)	1.14	0.31	0.05	0.64
	F (25-30)	0.27	0.21	0.09	0.33
	G (30-35)	0.19	0.09	0.02	0.08
	Mean ± SD	2.05 ± 1.59	0.74 ± 0.65	0.05 ± 0.03	0.46 ± 0.21
CA6	A (0-5)	7.6	1.73	0.13	0.55
	B (5-10)	3.45	1.97	0.04	1.15
	C (10-15)	2.51	1.52	0.4	2.43
	D (15-20)	0.75	0.52	0.08	1.95
	E (20-25)	0.41	0.28	0.16	1.36
	F (25-30)	0.28	0.19	0.06	0.17
	G (30-35)	0.1	0.08	0.01	0.06
	Mean ± SD	2.07 ± 2.51	0.90 ± 0.75	0.13 ± 0.12	1.10 ± 0.83
CA7	A (0-5)	7.88	2.14	0.11	1.52
	B (5-10)	4.55	4.04	0.06	1.17
	C (10-15)	0.66	2.07	0.1	1.25
	D (15-20)	0.58	1.35	0.05	2.74
	E (20-25)	0.62	1.07	0.25	0.37
	F (25-30)	0.59	2.31	0.23	0.43
	G (30-35)	0.41	0.14	0.71	0.58
	Mean ± SD	2.18 ± 2.70	1.87 ± 1.13	0.22 ± 0.21	1.15 ± 0.77
CA8	A (0-5)	3.59	2.44	0.63	1.28
	B (5-10)	3.02	2.77	0.22	2
	C (10-15)	2.71	2.66	0.2	2.75
	D (15-20)	2.11	1.69	0.24	1.71
	E (20-25)	0.66	0.43	0.12	0.16
	F (25-30)	1.55	2.31	0.05	1.44
	G (30-35)	0.81	0.53	0.02	1.08
	Mean ± SD	2.06 ± 1.03	1,83 ± 0.91	0.21 ± 0.19	1.49 ± 0.74
CA9	A (0-5)	6.18	1.71	0.24	1.35
	B (5-10)	3.71	2.01	0.02	2.58
	C (10-15)	5.95	2.25	0.32	3.94
	D (15-20)	2.99	0.69	0.25	4.11
	E (20-25)	2.54	0.77	0.21	2.47
	F (25-30)	0.69	0.39	0.09	0.21
	G (30-35)	0.13	0.28	0.17	0.18
	Mean ± SD	3.17 ± 2.17	1.16 ± 0.75	0.19 ± 0.09	2.12 ± 1.49

Indeed, anthropogenic activities such as open-pit mining and also the misuse of agrochemicals, would strongly contribute to the distribution of Hg and As in lagoon sediments (Ruiz-Fernández et *al.*, 2019). In addition, accidental oil spills and washing by motorized pirogues are relatively important in the south of Aby lagoon (part associated with the Tanoé River), facilitating the release of Pb into sedimentation (BadrElDin et *al.*, 2022). In addition, the timeless inflow of the Bia and Tanoé rivers into the lagoon basin could increase the trace element content of the sediments.

Hierarchical clustering (HCA) was used to assess similarities/differences in the metal content of sediment cores. The results of the HCA, shown in **Figure 7**, revealed two (02) major groups. Group I, which includes all the cores collected (CA1 - CA9), but excludes some core sections. This large group of sediment samples characterized by identical trace element sources could demonstrate the homogeneity of anthropogenic activities or domestic discharges carried out in the Aby lagoon basin. This trend confirms the FE results which showed that mining activities and agrochemical drainage would predominantly control the distribution of trace metal elements in sediments (Mandal and Suzuki 2002, Wang et *al.*, 2004, Xu et *al.*, 2015). In addition, this could also suggest that the parameters controlling trace element mobility in sediment sample layers are hitherto unknown. Group II includes sections (layers) of sediment cores located mainly downstream of the Aby lagoon. These samples show the particular influence of the Tanoé River (Kouassi et *al.*, 2022). As shown in the vertical distribution of metal concentrations, the Tanoé River drains its contents (approx. 4.5 10^9 m3/year) into the lagoon basin, mainly in its southern part (Chantraine 1980). This could probably influence some levels of sedimentary layers in the Aby lagoon.

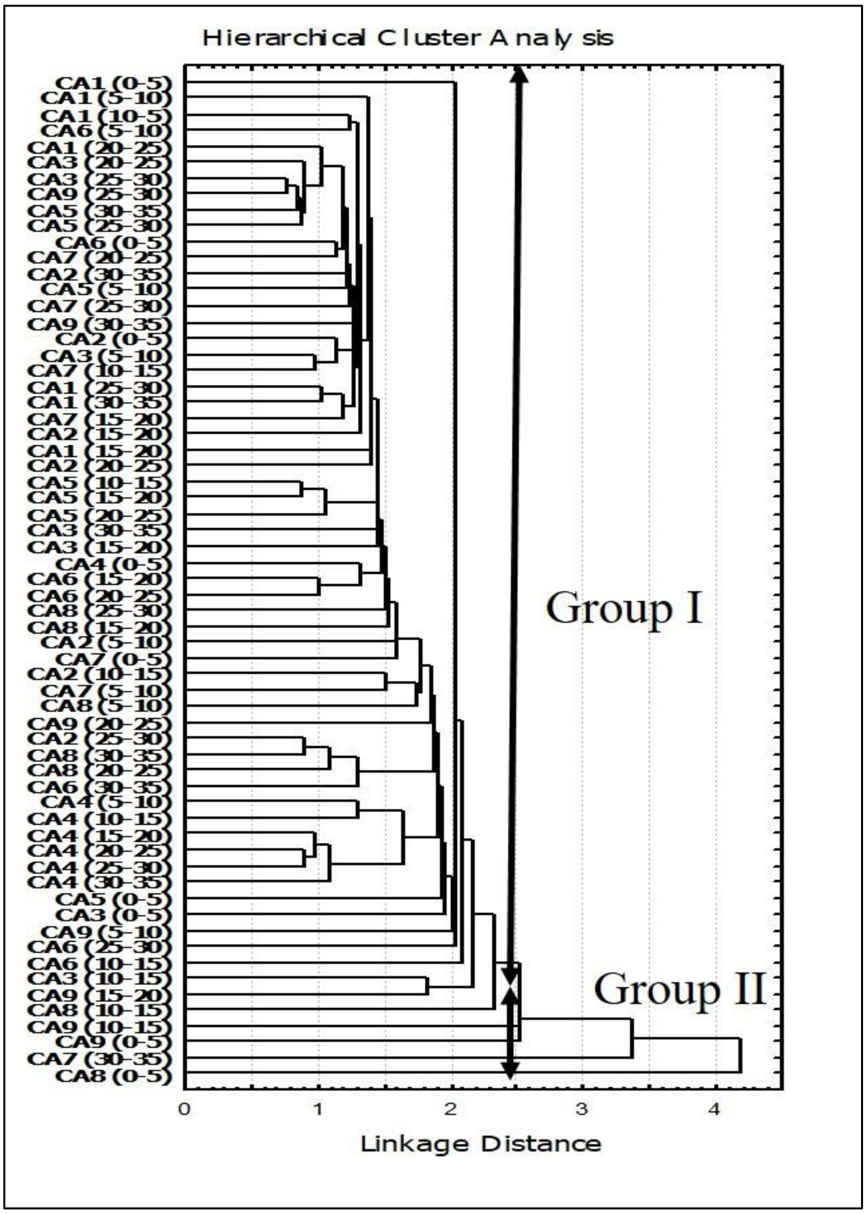


Figure 7. Dendogram using average linkage between groups showing the separation of the core samples into two major groups

3.5 PRV and ERL - ERM

PRV (Pre-Industrial Reference Values), ERL and ERM indices were established (Hakanson 1980, Long et *al.*, 1995) to characterize the toxicity of sediment cores. **Table 9** shows the results of the comparison of trace element concentrations (Hg, As, Cd, Pb) recorded in all sediment layers (63 sections) and standard PRV, ERL and ERM values. The results showed that Hg concentrations in forty-nine (49) sediment sections exceeded the PRV standard value (0.25 µg/g). In addition, the concentrations of As, Cd and Pb in the cores were lower than the standard GRP values respectively (15 µg/g; 1.0 µg/g; 70 µg/g). These results could suggest a significant increase in Hg with industrial civilization. Indeed, these GRP values would be those recorded before the explosion of industrial civilization, which released many trace element pollutants into the earth's crust. This would confirm the increased Hg contamination in the lagoon basin and the alarming state observed through the contamination index (CF Hg). On the other hand, the results for trace elements As, Cd and Pb, in agreement with those of the PRV, would indicate a natural and non-alarming state of the Aby lagoon sediments.

Comparisons of metal concentrations in this study with those of ERL and ERM showed similar trends to those of GRP. Only Hg presented different aspects in terms of potential toxic effects on sediment sections. The Hg results showed that five (05) core section samples were below the ERL value (0.15 µg/g), forty (40) samples were between ERL - ERM and eighteen (18) samples were above ERM (1.3 µg/g). This could mean that over 28% of samples could frequently cause Hg-related adverse effects. On the other hand, the results for As, Cd and Pb showed that all samples (63) were below the ERL guide values. These results would mean that sediment samples could not occasionally cause adverse effects related to these trace elements.

Table 9. Number of samples from all cores that had metal concentrations above the PRV (the preindustrial reference values), Effects-Range Low (ERL) and Effects-Range Median (ERM)

Total numbers of samples	PRV (µg/g)	> PRV	ERL	ERM	< ERL	ERL - ERM	> ERM
63	Hg (0.25)	49	0.15	1.3	5	40	18
	As (15)	00	8.2	70	63	00	00
	Cd (1.0)	00	1.2	9.6	63	00	00
	Pb (70)	00	46.7	218	63	00	00

Conclusion

The historical assessment of Aby lagoon sediments was carried out through the study of 09 sediment cores collected during the year 2020. Total organic carbon (TOC) results showed that organic matter was moving from the lower layers (25-35cm) to the upper layers (0-10cm), due to domestic effluent discharges and phytoplankton and zooplankton debris. Sediments grain size analysis showed three (03) texture types: sandy-muddy, vaso-sandy and sandy. Mapping profiles of total trace element concentrations showed an overall decrease with depth for Hg, As, Cd and Pb. In addition, cores CA1 and CA2 for Cd and Pb showed total concentrations evolving with depth. The growth in sediment concentrations over time could be associated with increasing anthropogenic pressure on the lagoon basin. Total Hg concentrations in the sections (0-35cm) of all cores collected were higher than the guide values (UCC and SQGs) respectively (0.056 µg/g; 0.486 µg/g). On the other hand, total concentrations of the trace elements As, Cd and Pb aligned with these. Contamination factor (CF) results showed that all sediment cores were highly contaminated with Hg. However, the cores showed no contamination in As and Pb. The PLI values suggested that the sediment cores near the Bia and Tanoé rivers deteriorated and unbalanced. If the enrichment factor (EF) results are considered, the presence of Hg and As in the upper layers (0-15cm) of the sediment layers would be from anthropogenic sources. With regard to the common sources of the sampling sites, hierarchical ascending classification (HAC) showed that the stations were practically related to each other. This reflected an identical source of trace element supply. These results would confirm the major role played by mining activities and agricultural effluent discharges in releasing trace elements in sediment core sections. Environmental quality assessment through ERL and ERM revealed that more than 28% of the sediment core samples could frequently cause Hg-related adverse effects.

The results obtained in this study can provide numerical support for monitoring coastal ecosystems. However, the depths considered in this study can be improved and dated for greater understanding. This work is part of a collective commitment to sustainable development worldwide.

Credit authorship contribution statement

Eudes Assy Armel Yapi: Conceptualization, Methodology, Data curation, Formal analysis, Funding acquisition, Resources, Writing - original draft. **Dehoule N’guessan Fulgence Kouassi:** Formal analysis, investigation. **N'guessan Louis Berenger Kouassi:** Methodology, supervision, Data curation, Writing - review & editing, project administration, Validation. **Aoua Sougo Coulibaly:** Project administration, Supervision.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval *Not applicable.*

Consent to Participate *Not applicable.*

Consent to publish *All authors read and approved the final manuscript.*

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References

Ajayi F.F., Olatunji A.S. (2022) *Assessment of the spatial distribution and chemical speciation of potential toxic elements in Ikeja Wetland Sediments, Lagos, Southwest, Nigeria*. Chemistry Africa. https://doi.org/10.1007/s42250-022-00371-y

Allersma E. and Tilmans W.M.K. (1993) *Coastal conditions in West Africa-a review*. Ocean Coast Manag 19:199-240. https://doi.org/10.1016/0964-5691(93)90043-X

Amir M., Debajyoti P., Malik J.N. (2020) *Geochemistry of Holocene sediments from Chilika Lagoon, India: inferences on the sources of organic matter and variability of the Indian summer monsoon*. Quaternary International. https://doi.org/10.1016/j.quaint.2020.08.050

Badr N.B.E., and Hussein M.M.A. (2010) *An input/ output flux model of total phosphorous in Lake Edku, a northern Eutrophic Nile Delta lake*. Glob. J. Environ. Res. 4, 64-75. ISSN 1990-925X.

BadrElDin A.M., Badr N.B.E, Hallock P.M. (2022) *Evaluation of trace-metal pollution in sediment cores from lake Edku, Egypt.* Regional Studies in Marine Science 53, 102454. https://doi.org/10.1016/j.rsma.2022.102454

Karim S., Aouniti A., El hajjaji F., Taleb M., Belbachir C., Hammouti B. and Zarrouk A. (2016), Bioaccumulation of heavy metals in commercially important marine fishes (Palaemon Serratus and Solea Vulgaris) caught in the Mediterranean coast from the North East of Morocco, *Der Pharma Chemica*, 8(19), 515-523

Bazzi, I. El Mouaden K., Chaouay A., Ait Addi A., Hamdani M., El Issami S., et al. (2020), Monitoring heavy metal contamination levels and microbiological pollution in seawater of Agadir coastal zones, *Indonesian Journal of Science & Technology*, 5 (3), 463-469

Bełdowska M., Jędruch A., Sieńska D., Chwiałkowski W., Magnuszewski A., Kornijów R. (2021) *The impact of sediment, fresh and marine water on the concentration of chemical elements in water of the ice-covered lagoon.* Environmental Science and Pollution Research 28:61189-61200. https://doi.org/10.1007/s11356-021-14936-w

Burton G.A. (2002) *Sediment quality criteria in use around the world*. Limnology 3, 65e75. https://doi.org/10.1007/s102010200008

Chantraine J.M. (1980) *Lagune Aby (Ivory Coast) Morphology, Hydrology, physico-chemical parameters*. Doc Sci, Centre Rech Océanogr, Abidjan 2: 39-70 (In French). https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers10-10/02785.pdf [Chantraine JM (1980) *The Aby lagoon (Cote d'Ivoire) Morphology, Hydrology, physico-chemical parameters*. Doc Sci, Centre Rech Océanogr, Abidjan 2,39-70. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers10-10/02785.pdf]

Chen Z., Salem A., Xu Z., Zhang W. (2010) *Ecological implications of heavy metal concen trations in the sediments of Burullus Lagoon of Nile Delta, Egypt*. Estuarine, Coastal and Shelf Science 86, 491-498. doi:10.1016/j.ecss.2009.09.018

Chen Y.M., Gao J.b., Yuan Y.Q., Ma J., Yu S. (2016) *Relationship between heavy metal contents and clay mineral properties in surface sediments: Implications for metal pollution assessment*. Cont. Shelf Res. 124, 125-133. https://doi.org/10.1016/j.csr.2016.06.002

Christensen B.T. (1987) *Decomposability of organic matter in particle size fractions from feld soils with straw incorporation.* Soil Biol Biochem 19(4):429-435. https://doi.org/10.1016/0038-0717(87)90034-4

Dang H.D., Lenoble V., Durrieu G., Omanovic D., Mullot J.U., Mounier S., Garnier C. (2015) *Seasonal variations of coastal sedimentary trace metals cycling: insight on the effect of manganese and iron (oxy) hydroxides, sulphide and organic matter*. Mar. Pollut. Bull. https://dx.doi.org/10.1016/j.marpollbul.2014.12.048

Daskalakis K.D. and O'Connor T.P. (1995) *Normalization and elemental sediment contamination in the coastal United States*. Environmental science and technology 29 (2), 470-477. https://doi.org/10.1021/es00002a024

Durand J.R., Skubich M. (1982) *Les lagunes ivoiriennes*. Aquatique culture, 27:211-250. doi: 10.1029/2005GB002515

Ekett S.I., Fred-Ahmadu O.H., Benson A.N.U. (2018) *Trace and major elements distribution in coastal sediment cores from Lagos Lagoon, Nigeria*. Data in Brief 19, 93-100. https://doi.org/10.1016/j.dib.2018.05.030

Fitzgerald W.F., Lamborg C.H. (2014) *Geochemistry of mercury in the environment*. In: Treatise on geochemistry 2nd Edition.. http://dx.doi.org/10-1016/B978-0-08-095975-7,00904-4

Flemming B.W. (2000) *A revised textural classification of gravel-free muddy sediments on the basis of ternary diagrams*. Continental shelf research 20 (10-11), 1125-1137. https://doi.org/10.1016/S0278-4343(00)00015-7

Ganugapenta S., Nadimikeri J., Chinnapolla S.R.R.B. et al. (2018) *Assessment of heavy metal pollution from the sediment of Tupilipalem Coast, southeast coast of India*. Int J Sedim Res 33(3):294-302. https://doi.org/10.1016/j.ijsrc.2018.02.004

Hakanson L. (1980) *An Ecological Risk Index for Aquatic Pollution Control: A Sedimentological Approach*. Water Res. 14, 975-1001. https://doi.org/10.1016/0043-1354(80)90143-8

Karaouzas I., Kapetanaki N., Mentzafou A., Kanellopoulos T.D., Skoulikidis N. (2021) *Heavy metal contamination status in Greek surface waters: A review with application and evaluation of pollution indices*. chemosphere, *263*, 128192. https://doi.org/10.1016/j.chemosphere.2020.128192

Khalil M.K., ElZokm G.M., Fahmy M.A., Said T.O., Shreadah M.A. (2013) *Geochemistry of some major and trace elements in sediments of Edku and Mariut Lakes, North Egypt*. World Appl. Sci. J. 24, 282-294. https://doi.org/10.1016/j.gexplo.2012.11.018

Koné Y.J.M., Abril G., Kouadio K.N., Delille B., & Borges A.V. (2009) *Seasonal variability of carbon dioxide in the rivers and lagoons of Ivory Coast (West Africa)*. Estuaries and Coasts, 32(2), 246-260. https://doi.org/10.1007/s12237-008-9121-0

Kouadio I. and Trefry J.H. (1987) *Sediment trace metal contamination in the ivory coast, west africa. Water, Air, and Soil*. Pollution 32, 145-154. https://doi.org/10.1007/BF00227690

Kouassi D.N.F., Yao K.M., Coulibaly A.S., Irié Bi T.J.G. (2022) *Trace metal concentrations, fluxes, and potential human health risks in West Africa rivers: a case study on the Bia, Tanoé, and Comoé rivers (Cote d'Ivoire)*. Environ Monit Assess 194, 475. https://doi.org/10.1007/s10661-022-09810-2

Lei P., Zhong H., Duan D., Pan K. (2019) *A review on mercury biogeochemistry in mangrove sediments: Hotspots of methylmercury production*? Science of the Total Environment 680, 140 -150. https://doi.org/10.1016/j.scitotenv.2019.04.451

Li Y., Chen H., Teng Y. (2020) *Source apportionment and source-oriented risk assessment of heavy metals in the sediments of an urban river-lake system*. Science of the Total Environment 737 :140310. https://doi.org/10.1016/j.scitotenv.2020.140310

Long E.R., Macdonald D.D., Smith S.L., Calder F.D. (1995) *Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments*. J. Environ. Manag. 19 (1), 81-97. https://doi.org/10.1007/bf02472006

Loring D.H., Rantala R.T.T. (1992) *Manual for the geochemical analyses of marine sediments and suspended particulate matter*. Earth-science reviews 32 (4), 235-283. https://doi.org/10.1016/0012-8252(92)90001-A

Maanan M., Zourarah B., Carruesco C., Aajjane A., Naud J. (2004) *The distribution of heavy metals in the Sidi Moussa lagoon sediments (Atlantic Moroccan Coast)*. Journal of African Earth Sciences 39, 473-483. doi:10.1016/j.jafrearsci.2004.07.017

Mandal B.K. and Suzuki K.T. (2002) *Arsenic round the world: a review*. Talanta 58:201–235. https://doi.org/10.1016/S0039-9140(02)00268-0

Miyittah M.K., Tulashie S.K., Tsyawo F.W., Sarfo J.K., Archibald A.D. (2020) *Assessment of surface water quality status of the Aby Lagoon System in the Western Region of Ghana*. Heliyon 6 e04466. https://doi.org/10.1016/j.heliyon.2020.e04466

Ouattara A.O., Yao K.M., Soro M.P., Diaco T., Trokourey A. (2018) *Arsenic and Trace Metals in Three West African rivers: Concentrations, Partitioning, and Distribution in Particle-Size Fractions*. Archives of Environmental Contamination and Toxicology. https://doi.org/10.1007/s00244-018-0543-9

Ouaty E.O., M'rini E.A., Nachite D., Marrocchino E., Marin E., Rodella I. (2022) *Assessment of the heavy metal sources and concentrations in the Nador Lagoon sediment, Northeast-Morocco*. Ocean and Coastal Management 216105900. https://doi.org/10.1016/j.ocecoaman.2021.105900

Pekey H. (2006) *Heavy metal pollution assessment in sediments of the Izmit Bay, Turkey*. Environ Monit Assess 123, 219-231. https://doi.org/10.1007/s10661-006-9192-y

Rahman Z. and Singh V.P. (2019) *The relative impact of toxic heavy metals (THMs) (arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg) and lead (Pb)) on the total environment: an overview*. Environ Monit Assess 191:419. https://doi.org/10.1007/s10661-019-7528-7

Razzouki B, El Hajjaji S, Azzaoui K, Errich A, A Lamhamdi, M Berrabah, et al., (2015) *Physicochemical study of arsenic removal using iron hydroxide*, J Mater Environ Sci 6 (5), 144-1450

Ruiz M.F., Abad M., Galan E., Gonzalez I. (2006) *The present environmental scenario of el Melah lagoon (NE Tunisia) and its evolution to a future sabkha*. Journal of African earth sciences 44(3): 289-302. https://doi.org/10.1016/j.jafrearsci.2005.11.023

Ruiz-Fernández A.C., Rangel-García M., Pérez-Bernal L.H., et al. (2019) *Mercury in sediment cores from the southern Gulf of Mexico: Preindustrial levels and temporal enrichment trends*. Marine Pollution Bulletin 149, 110498. https://doi.org/10.1016/j.marpolbul.2019.110498

Sengör S., Spycher S., Ginn T.R., Sani R.K., Peyton B. (2007) *Biogeochemical reactive-diffuse transport of heavy metals in Lake cœur d'Alene sediments*. Applied Geochemistry, 22 (12), 2569-2594. Doi :10.1016/j.apgeochem.2007.06.011

Smedley P.L., and Kinniburgh D.G. (2002) *A review of the source, behaviour and distribution of arsenic in natural waters*. Appl Geochem 17:517-568. https://doi.org/10.1016/j.apgeochem.2017.05.008

Subba Rao N., Dinakar A., Kumari B.K, Karunanidhi D., Kamalesh T. (2021) *seasonal and spatial variation of groundwater quality vulnerable zones of Yellareddygudem Watershed, Nalgonda District, Telangana*. Archives of Environmental Contamination and Toxicology. https://doi.org/10.1007/s00244-020-00783-2

Wang H., Wang J., Yu L.R.W., Shen Z. (2015) *Spatial variation, environmental risk, and biological hazard assessment of heavy metals in surface sediments of the Yangtze River estuary*. Mar. Pollut. Bull. 93, 250-258. https://doi.org/10.1016/j.marpolbul.2015.01.026

Wang Q., Kim D., Dionysiou D.D., Sorial G.A., Timberlake D. (2004) *Sources and remediation for mercury contamination in aquatic systems - a literature review*. Environmental Pollution, 131, 323-336. https://doi.org/10.1016/j.envpol.2004.01.010

Wedepohl K.H. (1995) *The composition of continental crust*. Goechim Cosmochim Acta 59(7):1227-1232. https://doi.org/10.1016/0016-7037(95)00038-2

Wilhelm S.M., Bloom N. (2000) *Mercury in petroleum*. Fuel Process. Technol. 63, 1-27. https://doi.org/10.1016/S0378-3820(99)00068-5

Xu J., Bravo A.G., Lagerkvist A., Bertilsson S., Sjöblom R., Kumpiene J. (2015) *Sources and remediation techniques for mercury contaminated soil*. Environment International, 74, 42-53. https://doi.org/10.1016/j.envint.2014.09.007

Zhang L., Ye X., Feng H., Jing Y., Ouyang T., Yu X., Liang R., Gao C., Chen W. (2007) Heavy metal contamination in western Xiamen Bay sediments and its vicinity, China. *Marine pollution bulletin* 54 (7), 974-982. doi:10.1016/j.marpolbul.2007.02.010

Zonta R., Botter M., Cassin D., Bellucci L.G., Pini R., Dominik J. (2018) Sediment texture and metal contamination in the Venice Lagoon (Italy): A snapshot before the installation of the MOSE system, estuarine. *Coastal and Shelf Science*, 205, 131-151. doi:10.1016/j.ecss.2018.03.007
