Scientific Research Publishing

Open Journal of Geology, 2025, 15(11), 774-787
https://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Mapping and Descriptive Analysis of Surface Sediments at the Mouth of the Sassandra River (Southwest Côte d'Ivoire)

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How to cite this paper: N'dri, K.G.R., Donald, A.N., Nicolas, K.L., Natchia, A. and Sylvain, M. (2025) Mapping and Descriptive Analysis of Surface Sediments at the Mouth of the Sassandra River (Southwest Côte d'Ivoire). *Open Journal of Geology*, **15**, 774-787.
https://doi.org/10.4236/ojg.2025.1511040

Received: October 3, 2025
Accepted: November 24, 2025
Published: November 27, 2025

Abstract

The mouth of the Sassandra River (Southwestern Côte d'Ivoire) is a transitional zone influenced by both fluvial and tidal currents. Although previous studies have focused on sediment mapping, the geochemical characteristics of this area remain poorly documented. This study aims to characterize the textural and geochemical properties of surface sediments and to better understand their spatial variability. Twenty surface sediment samples were collected using a hand-operated Van Veen grab. Laboratory analyses included grain-size measurements following standard sedimentological procedures, X-ray fluorescence (XRF) for major and trace element composition, and scanning electron microscopy (SEM) for microstructural observations. The results reveal coarse sands upstream, coarse to medium sands within the main channel, predominantly medium to fine sands near the river mouth, muddy sediments around the island, and mixed sand-mud deposits in the northern estuarine branch. The sands are angular to sub-angular, displaying cracks and fractures, and are coated with chemical elements such as Si, Fe, Al, Na, P, Ca, K, and Mg. Carbonates and rare earth elements occur in very low concentrations. The integration of sedimentological and geochemical data provides essential insights into sediment provenance and depositional dynamics. Nevertheless, long-term monitoring of sediment fluxes is required to fully understand the sedimentary infill processes operating at the Sassandra River mouth.

Keywords

Estuary, Sassandra River, Sedimentology, Grain Size, Sand

1. Introduction

Transitional aquatic ecosystems, particularly estuaries, represent preferential sites for human settlement, industrial development, port construction, and various anthropogenic activities such as fishing, mariculture, tourism, and navigation. These ecosystems, which hold significant socio-economic importance, also serve as natural depocenters where various sediments accumulate.

The mapping and characterization of bottom sediments in aquatic environments, beyond their contribution to the understanding of hydrodynamic conditions [1], are of particular importance as they help establish correlations between the nature of the sedimentary environment and the distribution of exploitable species, such as fish.

In Côte d'Ivoire, river-sea interfaces are subject to silting, accelerated sediment infilling, and modifications of grain-size parameters [2] [3]. Sediment particles transported and deposited by fluvial and marine waters affect the morphostructure of estuarine environments by stabilizing riverbeds and promoting vegetation growth. However, these processes create challenges for navigation and the identification of fishery resources. Moreover, nutrients and pollutants such as heavy metals tend to adsorb onto these particles, thereby contributing to environmental pollution [4]. In this context, establishing a detailed map of the present-day sedimentary units of the estuarine floor is essential. The objective of this study is to highlight the morphology, evolution, and chemical composition of the unconsolidated materials.

2. Presentation of the Sassandra River Estuary

The Sassandra River, approximately 650 km long, drains a watershed of about 750,000 km^2 and terminates in an estuary that opens into the Atlantic Ocean (**Figure 1**). This estuary is located in the southwestern part of Côte d'Ivoire, within the Precambrian basement, between latitudes 5˚53' and 5˚49' N and longitudes 8˚25' and 8˚19' W. It is bordered to the extreme southeast by the town of Sassandra. The estuary extends over a length of about 7 km and a width of 2 km, covering an area of approximately 14 km^2. Its maximum depth reaches 8.5 m [5]. The estuary is divided into two unequal branches by an island situated near its central part.

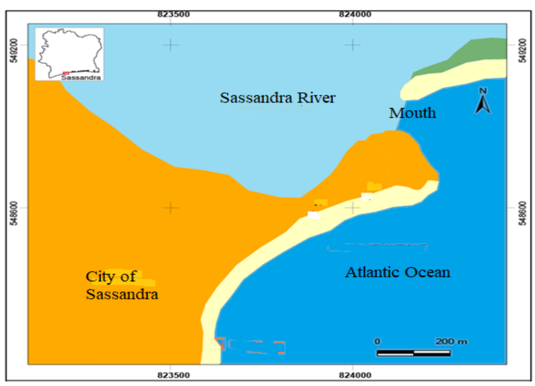

Figure 1. Location of the estuary of the Sassandra River [6].

3. Materials and Methods

3.1. Material

In the field, a canoe was used as a means of transportation on the water surface, and a steel Van Veen grab equipped with a rope was employed for sediment sampling. A cooler was used to preserve the collected sediment samples (Figure 2).

(a) Embarkation (b) Van Veen grab

Figure 2. Photos showing the sampling equipment.

In the laboratory, grain-size analyses were conducted using a set of equipment that included a drying oven (Figure 3(a)) and a mechanical vibrating sieve (Figure 3(b)). The vibrating sieve consisted of sixteen (16) sieves from the AFNOR series. An X-ray fluorescence (XRF) spectrometer connected to a computer was used for geochemical analyses (Figure 3(c)).

(a) Oven for drying sediments (b) Sieve column and vibrating shaker (c) X-ray fluorescence spectrometer

Figure 3. Photos showing grain-size and geochemical analysis equipment.

3.2. Methods

3.2.1. Sediment Sampling

In the field, twenty (20) sediment sampling points were selected, taking into account the size of the study area and zones inaccessible by canoe. Sediments were collected at each station using a Van Veen grab. The grab was lowered in an open position through the water column until it reached the sediment surface (**Figure 4**). Upon contact with the bottom, the traction applied to the rope activated the grab arms, immediately enclosing the sediments. The collected sediments were then retrieved, transferred into pre-labeled plastic bags, and stored in a cooler at approximately 4˚C. All samples were subsequently transported to the laboratory for further analyses.

Figure 4. Photos showing the sampling technique.

3.2.2. Physical Treatment of Samples

In the laboratory, the samples were divided into two sets: one for grain-size analysis and the other for geochemical analysis and carbonate determination. Prior to grain-size analysis, the samples were washed with dichloromethane to remove metallic pollutants and organic matter. They were then placed in an oven at 50˚C for 12 hours to ensure complete moisture removal.

For the geochemical analysis, the sample preparation and X-ray fluorescence (XRF) analysis followed the protocol described below. After oven-drying at 70˚C for 24 hours, the samples were ground to obtain a very fine particle size (powdered samples). Five grams of powdered sample were mixed with 1 g of binder powder and thoroughly homogenized. The resulting mixture was then pressed into pellets using a hydraulic press.

3.2.3. Grain-Size Analysis

A 100 g sandy fraction of each treated sample was sieved using a stack of sixteen (16) sieves with decreasing mesh sizes ranging from 5 mm to 63 µm. The material retained on each sieve after agitation (20 minutes of vibration) was collected and weighed, allowing the determination of the weight percentage retained on each sieve.

3.2.4. Carbonate Determination

This analysis aims to quantify the carbonate ($CaCO_3$) content in each sediment sample. The carbonate percentage was determined by weight loss. One gram (1 g) of dry sediment was placed in an Erlenmeyer flask and treated with 10 ml of hydrochloric acid (HCl) diluted to 50%. This reaction released carbon dioxide (CO_2) gas. The calcium carbonate content was calculated based on the volume of gas evolved according to the following formula:

$$CaCO_3(\%) = \frac{(P_i - P_f) \times 100}{P_i}$$

(where P_i represents the initial weight of the dry sample, P_f represents the final weight of the sample after calcination).

3.2.5. X-Ray Fluorescence (XRF) Analysis

The pelletized sample was placed under the X-ray beam of the fluorescence spectrometer. Sample information was entered into the XRF analysis software. XRF is an elemental chemical analysis method that exploits a physical property of matter, namely X-ray fluorescence.

XRF analysis involves bombarding the sample with X-rays, causing it to emit energy in the form of X-ray photons. Each atom emits photons with specific energies and wavelengths, a phenomenon known as X-ray fluorescence or secondary X-ray emission, which is characteristic of the atoms present in the sample [7]. From the emitted secondary radiation, an X-ray spectrum is obtained, which is characteristic of the sample's chemical composition. Mass concentrations of the elements are then determined by analyzing this spectrum.

3.2.6. Preparation of Thin Sections and Observation of Polished Sections

The preparation of thin sections involved three main steps:

– Resin Impregnation: This initial step consolidated the sandy sediments with resin.
– Grinding and Mounting: The surface of the consolidated sediment was polished to render the grains observable under reflected light.
– Precision Cutting and Final Grinding: The section was cut using a precision saw, leaving approximately 500 µm of material on the slide.

Observation of the polished sections using Scanning Electron Microscopy (SEM) provided lectron images. All particles present in the sample were automatically detected after image processing. Spectra of the polished sections were acquired using Energy-Dispersive Spectroscopy (EDS) coupled with SEM.

3.2.7. Spatial Distribution Mapping

The creation of spatial distribution maps for sediments and rare earth element concentrations required the input of geographic coordinates of the study area into the coordinate bar of ArcGIS software (version 10.2.2). The study area map was first georeferenced and then digitized. Georeferencing is the process of assigning real-world geographic coordinates to the study map image. For this work, the WGS 84-UTM-29N coordinate system was used. Digitizing the map creates a data layer.

Subsequently, the database was mapped using the Inverse Distance Weighting (IDW) method, which interpolates data within a grid of regularly spaced points. Each point in the grid was assigned a variable value calculated from the original data file values. This procedure allowed the generation of various maps representing the spatial distribution of the studied parameters.

4. Results

4.1. Nature and Spatial Distribution of Surface Sediments

The bottom of the Sassandra River estuary is covered by unconsolidated detrital sediment deposits. This superficial sedimentary layer is characterized by the presence of very coarse sands, coarse sands, medium sands, fine sands, and muds.

4.1.1. Coarse to Very Coarse Sands

These sands are composed of bioclastic fragments and exhibit minor color variations, ranging from yellow to reddish. They occupy the western (upstream) part of the estuary and extend along the southern channel until merging with medium sands. Small patches of coarse sediments are also observed near the large island and within areas of medium sands (**Figure 5**). The mean grain size (MZ) ranges from −0.49 to 0.90 Φ (**Table 1**). The sediments are very poorly to moderately sorted, with fine-skewed asymmetry for coarse sands and strongly fine-skewed asymmetry for very coarse sands.

4.1.2. Medium Sands

These sands, ranging in color from yellow to reddish-brown and brownish-yellow, constitute the largest part of the superficial sedimentary cover. They show maximum spatial extent (**Figure 5**), covering almost the entire estuary, including large portions of the channels, the river mouth area, and the eastern side. Around the large island and in the eastern channel, a mixture of medium and fine sands is observed. The mean grain size (MZ) varies from 1.07 to 1.92 Φ (**Table 1**). Standard deviation (Σ) values range between 0.37 and 0.79 Φ, indicating well-to moderately sorted sands. Skewness (Ski) ranges from 0.21 to 0.37 Φ, reflecting a fine-skewed distribution.

4.1.3. Fine Sands and Muds

Fine sands, ranging in color from yellow to brown, and dark to dark-greenish muds are concentrated around the large island. They form the dominant sedimentary cover in the northern branch of the estuary (**Figure 5**). Fine sands exhibit minor color variations.

4.2. Carbonate Content of Sediments

Carbonate contents range from 0.99% to 4.58%, with a mean value of 2.29% (**Table 1**), indicating undersaturated carbonate sedimentation. In coarse to very coarse sands, carbonate contents are higher compared to muds, medium sands, and fine sands.

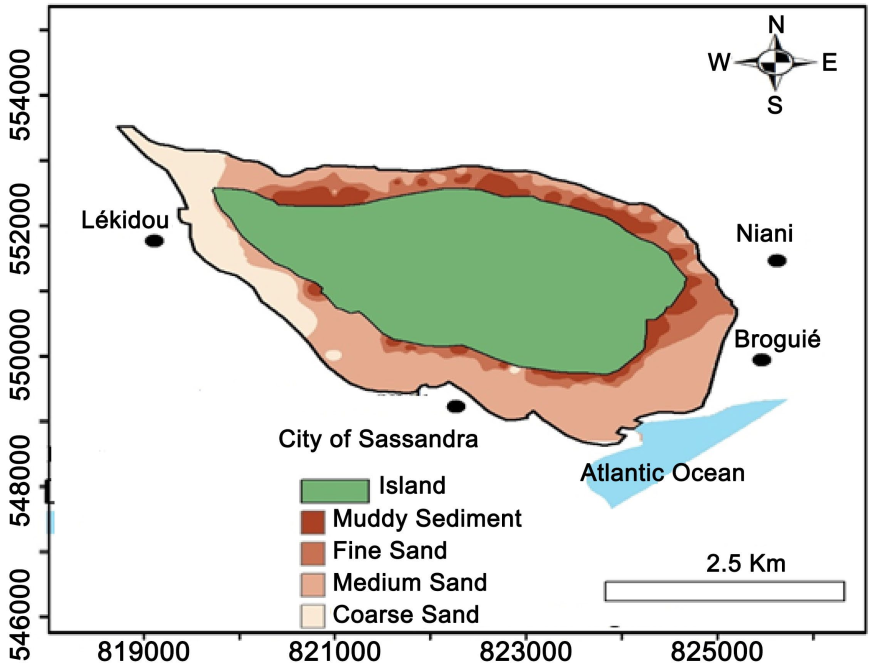

Figure 5. Map of the distribution of surface sediments on the seabed.

Table 1. Description of the sands and silts of the Sassandra River estuary.

N° Ech	Long X	Lat Y	Sedimentary description
E1	823,300	549,100	Medium sand, moderately sorted, skewed toward fine particles, yellow-brown, very weakly carbonated (0.99%)
E2	822,800	549,400	Medium sand, moderately sorted, skewed toward fine particles, yellow-brown, very weakly carbonated (1.08%)
E3	821,700	549,500	Medium sand, moderately sorted, skewed toward fine particles, reddish-yellow, very weakly carbonated (1.24%)
E4	821,000	550,100	Medium sand, moderately sorted, skewed toward fine particles, reddish-yellow, very weakly carbonated (1.28%)
E5	820,300	551,000	Coarse sand, moderately sorted, skewed toward fine particles, reddish-yellow, very weakly carbonated (1.36%)
E6	819,700	552,100	Coarse sand, moderately sorted, skewed toward fine particles, reddish-yellow, weakly carbonated, with gravel and pebbles
E7	823,300	549,400	Medium sand, moderately sorted, skewed toward fine particles, yellow-brown, very weakly carbonated (1.26%)
E8	823,800	548,300	Well-sorted medium sand, strongly skewed toward fine particles, yellow-brown, very weakly carbonated (3.68%)
E9	824,500	549,500	Medium sand, moderately sorted, skewed toward fine particles, yellow-brown, very weakly carbonated (3.21%)
E10	824,800	551,000	Poorly sorted fine sand, skewed toward fine particles, reddish-yellow, very weakly carbonated (2.23%)

Continued

E11	823,000	552,500	Poorly sorted fine sand, skewed toward fine particles, reddish-yellow, very weakly carbonated (2.21%)
E12	821,000	552,500	Medium sand, moderately sorted, skewed toward fine particles, reddish-yellow, very weakly carbonated (2.56%)
E13	819,500	552,960	Coarse sand, moderately sorted, skewed toward fine particles, reddish-yellow, very weakly carbonated (4.46%)
E14	819,430	553,000	Very coarse sand, very poorly sorted, strongly skewed toward fine particles, reddish-yellow, weakly carbonated, with gravel and pebbles
E1*	820,800	550,900	Dark silt, very weakly carbonated (1.22%)
E2*	821,605	550,200	Dark silt, very weakly carbonated (1.27%)
E3*	824,100	549,760	Dark silt, very weakly carbonated (3.19%)
E4*	824,700	550,400	Olive-green silt, very weakly carbonated (3.38%)
E5*	823,050	552,000	Olive-green silt, very weakly carbonated (3.04%)
E6*	821,000	552,350	Dark silt, very weakly carbonated (2.16%)

Ech: Echantillon. Long: longitude. Lat: latitude.

4.3. Surface Condition and Chemical Composition of Sandy Sediments

Figure 6 shows sand grains with angular to sub-angular shapes. Many of these grains exhibit numerous cracks and fractures with black coatings. Spectral analysis of these coatings reveals the presence of chemical elements such as iron, magnesium, phosphorus, silicon, aluminum, sodium, calcium, and potassium (Spectrum 3, Spectrum 1, Figure 7). Semi-quantitative compositions of the black coatings observed on the grain surfaces and within the cracks are presented in Table 2 and Table 3. Iron, potassium, and phosphorus are the most dominant chemical elements.

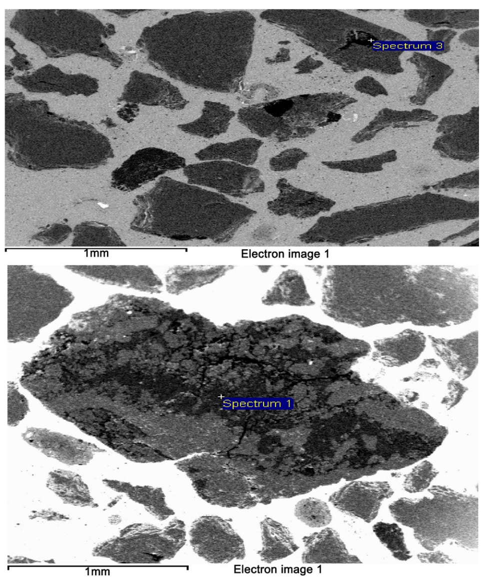

Figure 6. SEM image of sand grains with numerous cracks and black coatings.

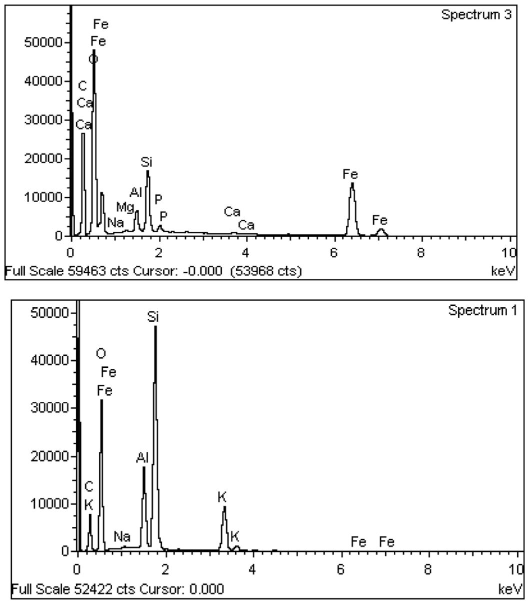

Figure 7. Spectra of black coatings observed on the surface of sand grains.

Table 2. Representative chemical composition of the black coatings on the surface of sand grains (Spectrum 3).

Eléments	Poids (%)	Atomique (%)	Composition (%)	Formule
C	17.86	26.47	65.44	CO_2
Na	0.04	0.08	0.06	Na2O
Mg	0.07	0.05	0.11	MgO
Al	0.92	0.61	1.74	Al_2O_3
Si	2.83	1.79	6.06	SiO_2
P	0.38	0.22	0.86	P_2O_5
Ca	0.15	0.07	0.21	CaO
Fe	19.84	6.32	25.52	FeO
O	57,91	64.44		
total	100			

Table 3. Representative chemical composition of the black coatings on the surface of sand grains (Spectrum 4).

Eléments	Poids (%)	Atomique (%)	Composition (%)	Formule
C	14.50	20.84	53.49	CO_2
Na	0.13	0.10	0.18	Na_2O
Al	4.52	2.87	8.53	Al_2O_3
Si	14.36	8.77	30.73	SiO_2
K	5.67	2.48	6.83	KO_2
Fe	0.20	0.06	0.25	FeO
O	60.53	64.88		
total	100			

4.4. Rare Earth Element (REE) Concentrations in Surface Sediments

The rare earth elements (REEs) present in the sediments, along with their concentrations, are listed in Table 4. The analyzed REEs include lanthanum (La), cerium (Ce), thulium (Tm), and yttrium (Y). Their concentrations range from 0.0 to 39.90 ppm for La, 0.0 to 20.50 ppm for Ce, 2.40 to 10.50 ppm for Tm, and 2.50 to 9.00 ppm for Y.

Table 4. Rare earth elements (REE) concentrations (ppm) in surface sediments.

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14
Y	6	3.2	4.2	2.5	3.5	2.7	9	5.5	5.3	2.5	2.6	3.3	7.2	7.1
La	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.9	0.0	0,0	0.0	0.0	39.3	39.9
Ce	0.0	0.0	11.5	0.0	0.0	20.5	0.0	0.0	0.0	0.0	0.0	0.0	19.3	19.4
Th	6.8	4.3	3.1	2.6	2.6	2.4	6.8	3.6	3.1	2.4	2.7	2.6	10.4	10.7

Their spatial distributions in the surface sediments generally indicate higher concentrations upstream. Lanthanum and yttrium exhibit elevated concentrations both upstream and at the river mouth (Figure 8 and Figure 9). Thulium and cerium are more concentrated upstream and in the extreme southwestern part of the estuary (Figure 10 and Figure 11). In contrast, the remainder of the estuary is characterized by very low concentrations.

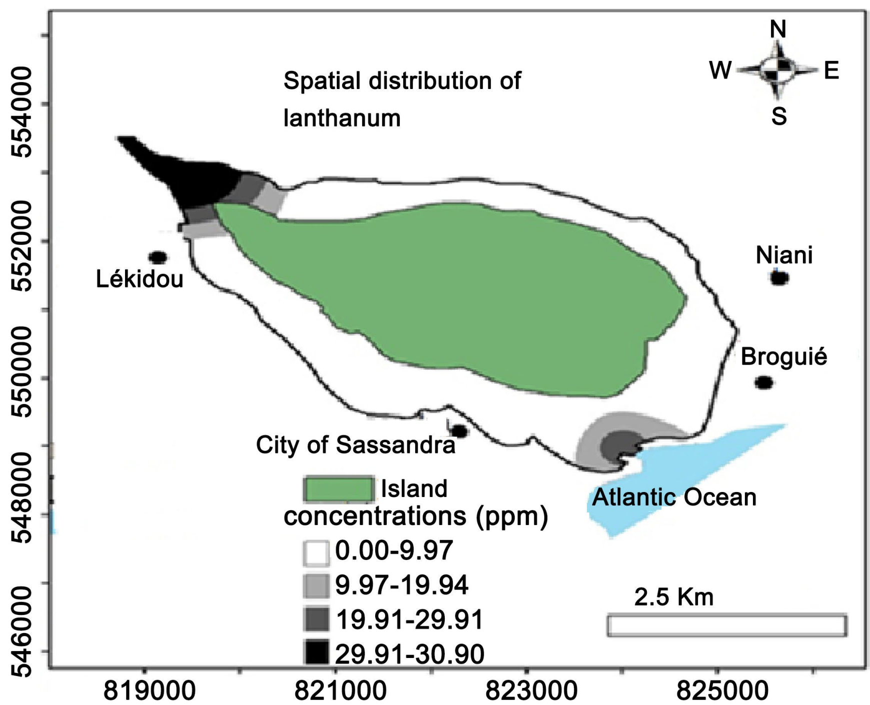

Figure 8. Distribution of lanthanum in surface sediments.

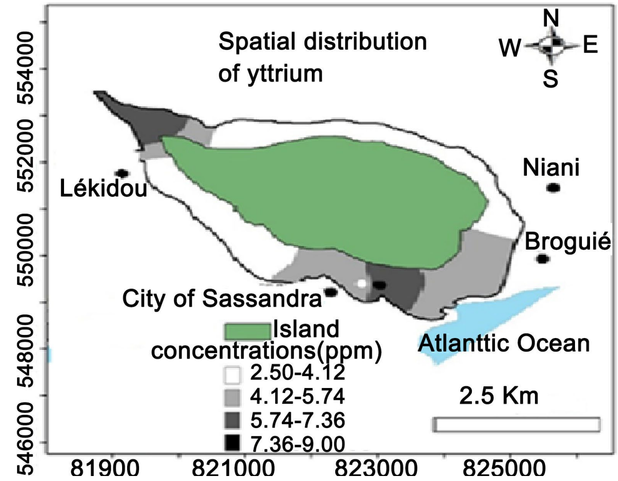

Figure 9. Distribution of yttrium in surface sediments.

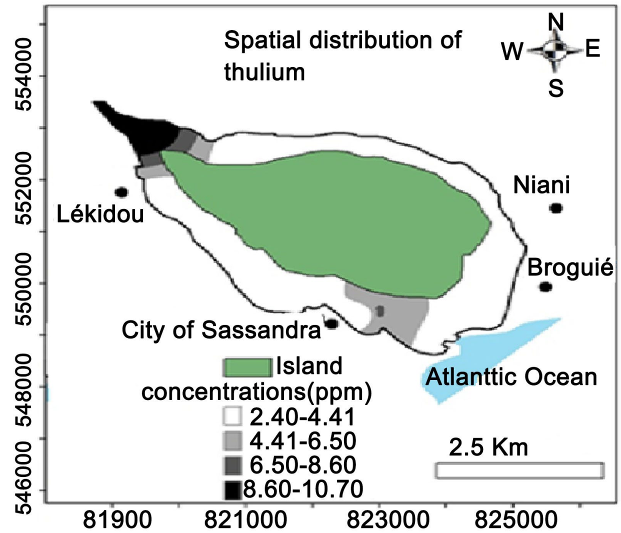

Figure 10. Distribution of thulium in surface sediments.

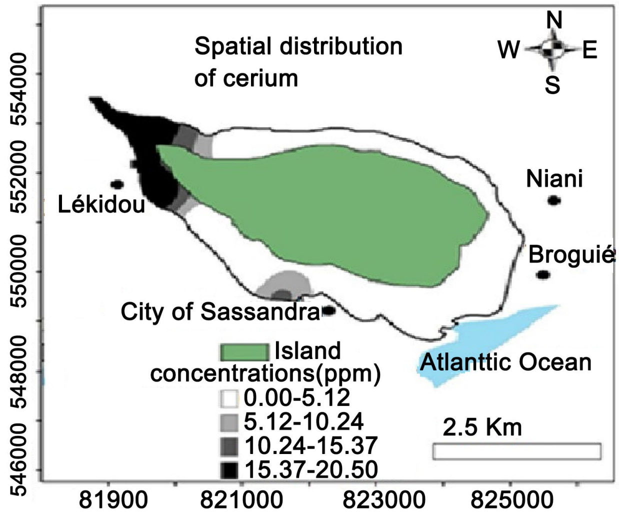

Figure 11. Distribution of cerium in surface sediments.

5. Discussion

5.1. Nature and Distribution of Surface Sediments

The sedimentary fill of the estuarine bottom comprises all grain-size classes, ranging from sands to muds. The distribution of these surface sediments shows little difference from that reported by [8] [9], with the same sediment types observed. According to the map by [9], coarse sands cover almost the entire estuarine bottom, while muds accumulate mainly along the margins. This comparison highlights the instability of sediment deposits, which may be attributed to seasonal variations in energy and hydrodynamic conditions. During their studies, energy levels in the main channel were high [9], which likely transported fine particles while leaving coarser grains in place. The accumulation of mud around the island may result from the deposition and decomposition of plant debris originating from the island. Their dark color could partly reflect the transformation of organic matter derived from this debris, a phenomenon also noted by [10] for the superficial sediments at the mouth of the Comoe River. Sands in the main channel are generally coarse to medium. The mixed characteristics observed, with coarser and finer sediments combined, are consistent with a transitional environment [11].

5.2. Carbonate Content

The relatively low carbonate content (mean 2.29%) can be attributed to the silicobioclastic nature of the sediments, dominated by detrital materials with a siliceous composition. In contrast, these values are considerably lower than those reported by [12] for sediments of the Moulouya estuary, where carbonate contents approach 40%. This difference is mainly explained by the predominance of shell debris in the sediments of the Moulouya estuary [12].

5.3. Surface Condition and Chemical Composition of Sandy Sediments

Sand grains from the Sassandra River estuary are characterized by numerous fractures and cracks with black coatings, which often leave reddish-brown stains. Several factors may explain the formation of these fractures and cracks. They may result from aquatic impacts or from violent collisions between grains, particularly when some grains are considerably coarse. During water flow, coarse sediments collide while rolling or sliding, generating shear stresses that induce cracks and fractures [13].

The black coatings observed on the grain surfaces may consist of iron oxides, which would explain the yellowish-red to brown coloration of the sands. Rare earth element (REE) contents are very low and are more frequently detected in sediments exhibiting these black coatings. Indeed, Carpentier [14] reports that in the sediments of the Lesser Antilles, iron oxides can trap rare earth elements. Similarly, Matias [15] notes that REEs are generally associated with amorphous or crystalline iron oxides.

Chemical elements such as phosphorus, calcium, sodium, and potassium trapped in the sediments are likely related to human activities. Their presence may result from urban effluents or agricultural practices, such as the application of phosphate fertilizers [16]. Through erosion and leaching from fertilized agricultural lands, these agrochemicals can enter the aquatic system and become incorporated into the structure of the sand grains. This is consistent with findings by [17], who reported that agriculture in southwestern Côte d'Ivoire is primarily extensive, with significant soil leaching.

Mapping of sediments and determination of their chemical composition constitute fundamental tools in coastal engineering. However, estimating the volume of detrital sediments over multiple years is necessary to fully understand the dynamics of sedimentary infilling.

6. Conclusions

The hydrodynamics of the environment play a crucial role in sediment distribution. Mapping and analysis of sediment characteristics at the mouth of the Sassandra River, using grain-size, descriptive, and geochemical approaches, highlighted two types of sediment deposits:

- **Type 1** corresponds to sands with a range of grain sizes. These sands are characterized by low carbonate content and are mostly moderately sorted. Coarse to medium sands cover the bottom of the channels (western part towards the pass), while medium to fine sands with a very small proportion of coarse sands are found near the pass, in the northern part, and around the large island.
- **Type 2** corresponds to muddy sediments located around the large island and in the northern branch of the estuary.

Sand grains are mostly angular to sub-angular, containing very little carbonate and rare earth elements. They are largely coated with chemical elements such as silicon, iron, aluminum, sodium, phosphorus, calcium, potassium, and magnesium. Rare earth element concentrations in the surface sediments are very low.

Acknowledgements

We would like to thank Dr. AKA Natchia, Dr. ABY, and the technician from the Marine Geology Laboratory at the Centre de Recherches Océanologiques in Abidjan (Côte d'Ivoire) for their assistance in collecting sediment samples from the bottom of the water body.

Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this article.

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