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Hydrosedimentary dynamics and morphological evolution of the Abidjan harbor (Côte d'Ivoire): Implications for sustainable port management

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Abstract

Lagoons are environments conducive to the development of significant biodiversity. This characteristic gives them considerable economic value (fisheries, tourism, navigation). However, certain processes such as the silting up of bays, changes in water circulation, the presence of vegetation and the transport of sediments in the Vridi Canal are causing the lagoons to gradually fill up. This filling is impacting the morphology of the harbour bed. This study therefore aims to present the morphology of the bed and characterise the sediment dynamics of the port harbour of Abidjan. Bathymetric surveys were conducted in 2019 and 2023 by the hydrographic department of the Port Autonome d'Abidjan (PAA) in order to understand the impact of hydro-sedimentary processes on the morphological evolution of the harbour. Analysis of the bathymetric maps revealed that the harbour basin has a fairly irregular relief with depths of up to -26 m in 2019 and -95 m offshore in 2023. The characterisation of the channels revealed bathymetric profiles in the shape of a 'V', 'U' and intermediate shapes. Overlaying the bathymetric maps of the harbour basin from 2019 and 2023 revealed that the harbour basin underwent significant geomorphological changes between 2019 and 2023, with an estimated sediment budget of approximately +4 million m^3, or an average of +800,000 m^3/year. The rate of infill is estimated at 0.7 m/year in the harbour basin.

Keywords: Morphology; Hydro-sedimentary; Infill; Harbour basin; Abidjan

1. Introduction

Located in the heart of the Ébrié Lagoon, the Abidjan harbor area is a strategic zone for the economic development of Côte d'Ivoire and, more broadly, West Africa. Serving as an interface between continental and marine environments, it hosts the Port of Abidjan-one of the most important maritime hubs in the subregion, playing a central role in both regional and international trade (World Bank, 2018). However, the sustainability of its activities is highly dependent on the hydro-sedimentary processes that continuously shape the seabed morphology and control navigability (Brenon et al., 2004; Durand & Guiral, 1994).

In its broadest sense, a harbor is defined as a sheltered water body near the coast where ships can anchor while remaining connected to the open sea, and where marine waters mix with freshwater inputs from continental runoff. Such estuarine environments are characterized by intense hydrological dynamics-tides, winds, river discharges-and high sediment variability, making them key transition zones between continental and oceanic domains (Perillo, 1995;

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Brenon et al., 2004). Their study has gained growing importance, both scientifically and socio-economically, as nearly 60% of the world's population lives within 60 km of the coastline (Nicholls & Cazenave, 2010).

The Ébrié Lagoon estuary has been profoundly altered by the artificial opening of the Vridi Canal in 1950, an engineering project designed to provide maritime access to the city of Abidjan. This permanent connection to the Atlantic Ocean disrupted hydrodynamic exchanges, water renewal, and sediment transport pathways between the lagoon and the marine domain, with long-lasting consequences on morphological evolution and sediment budgets (Durand & Guiral, 1994; Giardino et al., 2018). Continental inputs to the lagoon are mainly from the Comoé River and other tributaries, whose variable discharges create strong seasonal and interannual patterns of sediment transport (Durand & Guiral, 1994).

The Abidjan harbor area, located at the confluence of the Ébrié Lagoon and the Comoé River, is therefore subject to multiple natural and anthropogenic influences. Rapid urbanization, industrial discharges, and upstream soil erosion increase sediment and pollutant inputs, leading to gradual siltation that may impair navigability and raise maintenance dredging costs (Scheren et al., 2004; Yao et al., 2022). These processes are further amplified by coastal modifications and unregulated land use associated with port development (World Bank, 2018).

In this context, a detailed understanding of the seabed morphology and sediment dynamics of the Abidjan harbor area is essential to anticipate morphological changes, optimize dredging operations, and ensure the long-term resilience of port infrastructure. The present study therefore aims to characterize the seabed morphology and sedimentary dynamics of the Abidjan harbor, providing robust scientific insights for sustainable management and strategic planning of port maintenance operations.

1.1. Study area

The harbor area is located within the Ébrié Lagoon in the southern part of Abidjan. It is connected to the Gulf of Guinea and the Atlantic Ocean by the Vridi sandbar. The port zone extends across the municipalities of Port-Bouët, Treichville, and Le Plateau over approximately 6 km. It covers a water surface area of about 1,000 hectares, with depths ranging from 10 to 15 meters, and lies between longitudes 4°3'20''–3°58'20'' W and latitudes 5°19'10''–5°14'10'' N (Figure 1).

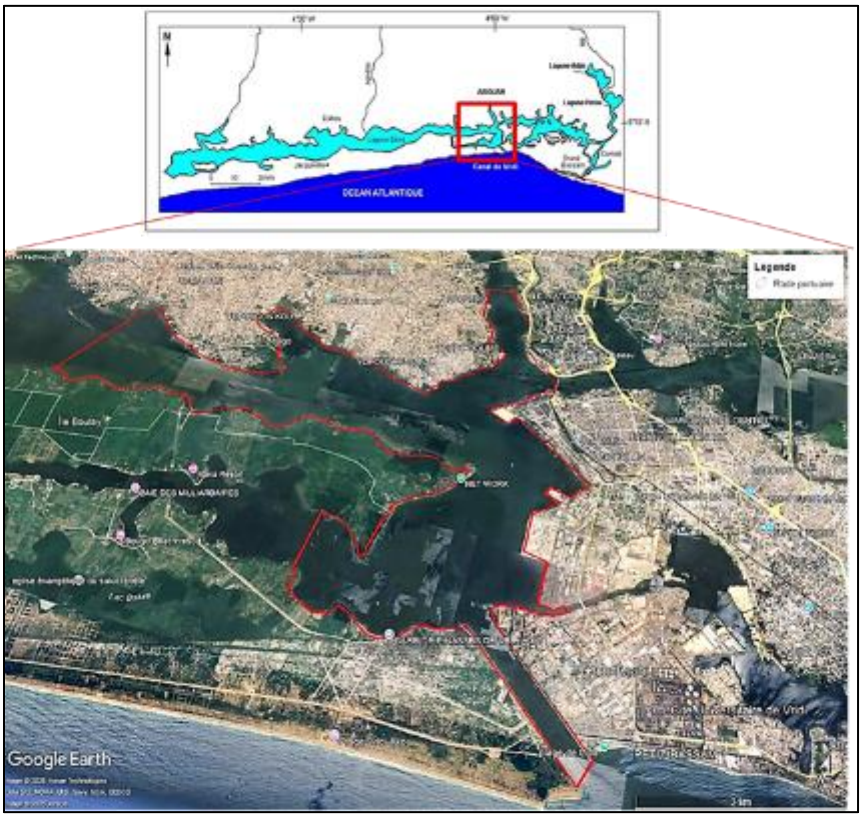


Figure 1 Location of the Abidjan Harbor Area

2. Methodology

2.1. Bathymetric Survey of the Abidjan Harbor

The morphological characterization of the seabed within the Abidjan harbor area was conducted through a series of high-resolution bathymetric surveys. These surveys were performed using a combination of modern hydrographic instruments designed to ensure precise spatial and depth measurements.

Data acquisition was carried out aboard a motorized hydrographic survey vessel specifically adapted for lagoonal environments (Figure 2A). Georeferencing of the bathymetric data was ensured through a Differential Real-Time Kinematic Global Positioning System (RTK-GPS). The system comprised a fixed base station-a LEICA GR10 unit-providing real-time correction signals to the mobile receiver, thereby guaranteeing centimeter-level positional accuracy (Figure 2B).

Depth measurements were obtained using a single-beam dual-frequency echo sounder operating at 33 kHz and 200 kHz (Figure 3). This configuration enabled the simultaneous acquisition of bathymetric data across both shallow and deeper zones, ensuring an accurate representation of the seabed morphology.

The combination of RTK-GPS positioning and dual-frequency echo sounding allowed for the generation of high-quality bathymetric datasets, which served as the foundation for subsequent Digital Depth Model (DDM) and geomorphological analyses.

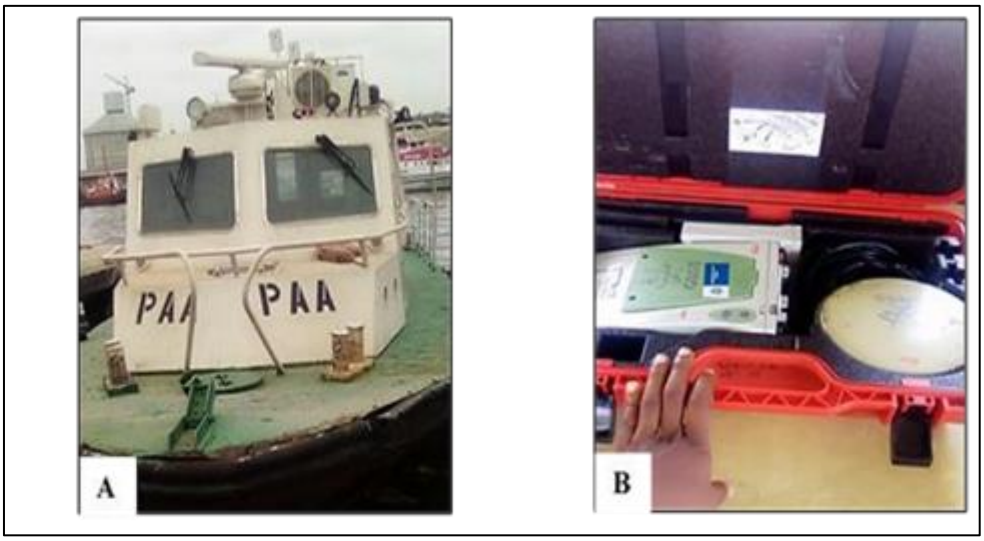


Figure 2 Survey vessel (A) and RTK-GPS system (B).

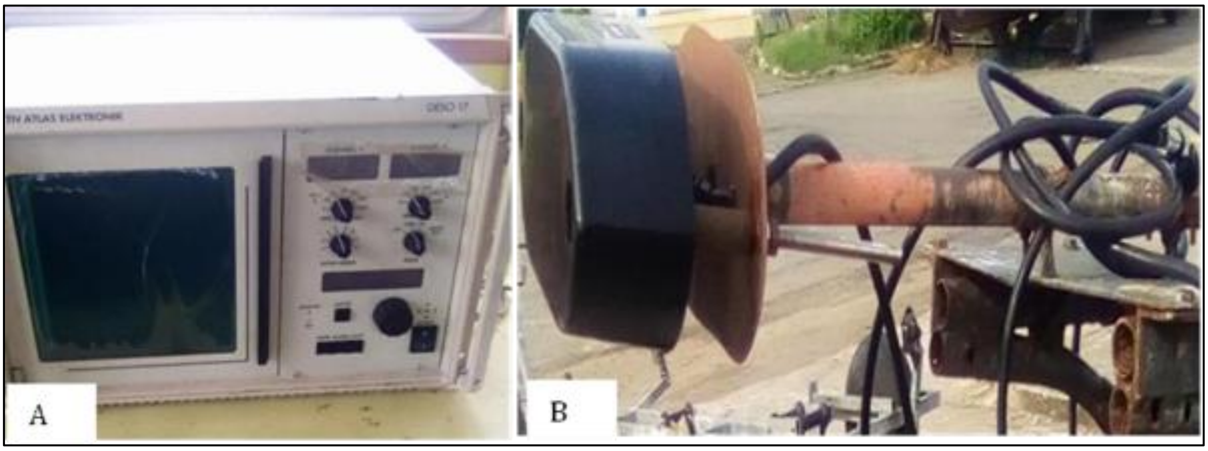


Figure 3 Single-beam echo sounder (A) and transducer (B).

Bathymetric surveys were conducted in 2019 and 2023 to investigate the seabed morphology of the Abidjan harbor. The surveys involved navigating a series of radial transects across the water body using a single-beam echo sounder mounted at the stern of the survey vessel. These transects were designed to comprehensively cover the study area, creating a dense spatial grid for accurate depth measurements. In total, 264,559 and 215,585 sounding points were recorded in 2023 and 2019, respectively, for subsequent laboratory processing (Figures 4 and *5*).

The single-beam echo sounder operates by emitting a short acoustic pulse vertically into the water column beneath the vessel. The instrument measures the travel time of the acoustic signal from emission to return. Knowing the speed of sound in water, the water depth can be calculated using the following formula:

$$D = \frac{1}{2} V * t \qquad \text{..........} \qquad (1)$$

where: D is the water depth, V is the speed of sound in water, t is the round-trip travel time of the acoustic pulse.

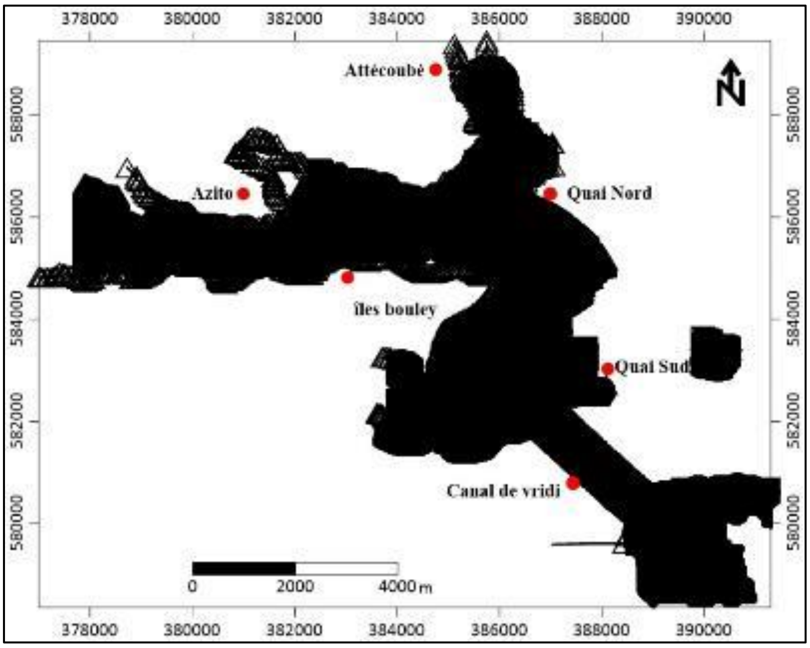


Figure 4 Positioning of sounding points in the Abidjan harbor in 2023

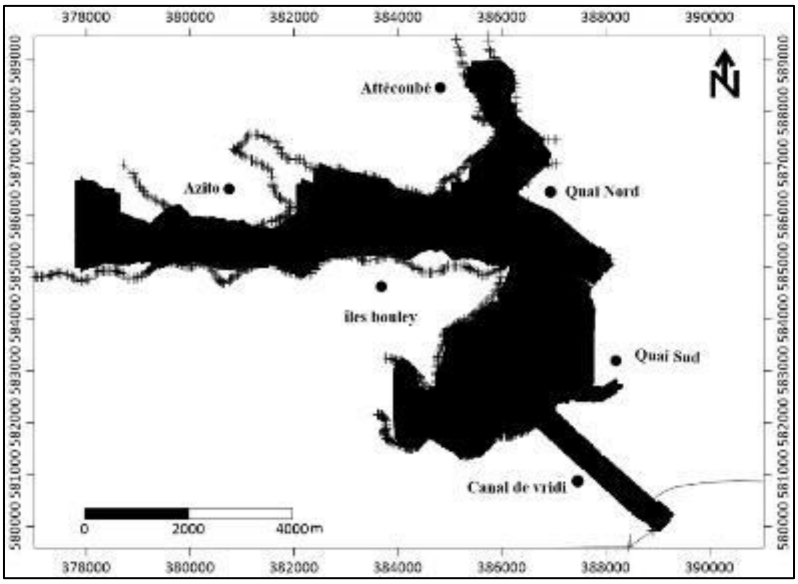


Figure 5 Positioning of sounding points in the Abidjan harbor in 2019

Prior to generating the bathymetric map, several data corrections were performed. The first step involved identifying and correcting depth measurement errors within the Excel dataset. Despite careful field procedures, bathymetric data may contain anomalies such as isolated excessively deep pits or missing points. These erroneous measurements were removed from the dataset. Subsequently, corrections were applied to account for the transducer draft. The true depth was obtained by adding the transducer immersion depth (30 cm in this study) to the recorded measurements, ensuring accurate representation of the seabed elevation.

The corrected depth (Sr) is expressed as:

$$\boldsymbol{S_r} = P_e + P_{it} \qquad \ldots\ldots\ldots\ldots \qquad (2)$$

where :

Sr : True depth (corrected depth); Pe : Echo sounder reading ; Pit : Transducer immersion depth

Bathymetric maps were generated using the Surfer 20 mapping software through kriging interpolation, a program developed by Golden Software Inc. The mapping process involved creating graphical files from the data files containing X (longitude), Y (latitude), and Z (transducer-corrected depth), organized in columns within the Surfer worksheet.

Channel characterization allowed for the identification of seabed morphological evolution in the Abidjan harbor through parallel and perpendicular transects along the NW–SE, N–S, NE–SW, and W–E directions. Six radial profiles were extracted from the 2023 bathymetric map to identify common types of bathymetric profiles in the study area. The shape of each channel provides insight into the dominant processes in each sector, namely erosion or sediment deposition (Konan et al., 2022).

2.2. Sediment Volume Estimation Techniques

2.2.1. Least Squares Method

The least squares method, applied to trapezoids and triangles, allows for the determination of eroded or deposited surface areas when two bathymetric profiles are superimposed (Konan, 2023). Let g(x) and f(x) represent two functions associated with bathymetric profiles collected at different times, where g(x) is the most recent profile and f(x) is the older profile.

Trapezoidal surface calculation: The x-axis is divided into multiple segments of width dx, considering the area between the two profiles. Straight lines connecting the profiles divide the area into several trapezoids (*Figure 6*). For a trapezoidal area S, the surface is calculated as:

$$\mathrm{S} = \frac{(\mathrm{B}+\mathrm{b})*\mathrm{h}}{2} \ldots\ldots\ldots \qquad (3)$$

where:

B = length of the larger base of the trapezoid; b = length of the smaller base; h = height of the trapezoid.

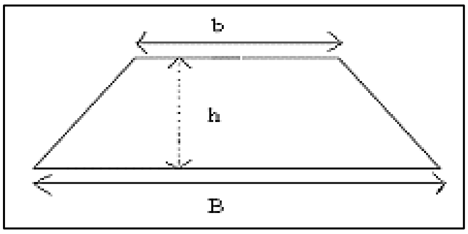


Figure 6 Diagram of a trapezoid

Triangular Area Calculation: The x-axis is subdivided into multiple segments, each of width dx, to define the area between two bathymetric profiles. Straight lines connecting the profiles partition this area into several triangles (*Figure 7*). The area S of a triangle is calculated as:

$$S = \frac{(b \times h)}{2} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

b = base of the triangle; h = height of the triangle.

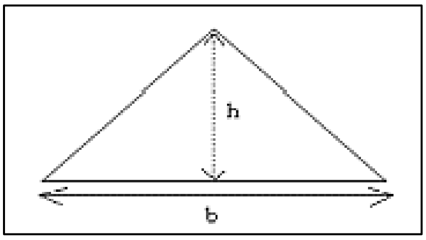


Figure 7 Diagram of a triangle

The area bounded by the two profiles is expressed as:

$$S = \frac{[g(x+n) - f(x+n)] * dx}{2} \ldots\ldots\ldots\ldots \quad (5)$$

where g(x+n) is the value of the recent profile, f(x+n) is the value of the older profile, and dx is the width of the segment along the x-axis.

The planimetry of the area between the superimposed profiles allows for the summation of positive and negative surfaces (Figure 8). Positive surfaces represent sediment deposition (+), whereas negative surfaces correspond to erosion (−).

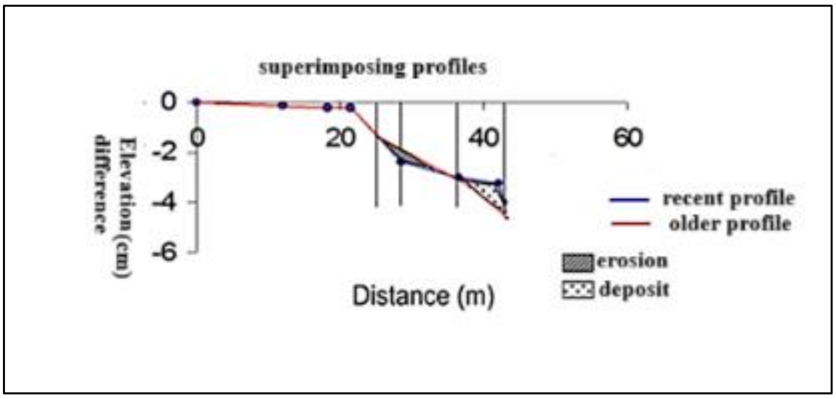


Figure 8 Determination of eroded or deposited area by superimposing profiles

2.2.2. Sediment Volume Determination Using Numerical Simulation in Surfer

The estimation of sediment volume requires two separate datasets in Excel or Surfer (Kouamé, 2017). Each dataset contains longitude, latitude, and depth values. While the longitude and latitude coordinates are identical for both files, the depth values differ, representing the upper and lower surfaces of the superficial sediment layer. The steps to determine sediment volume are as follows:

- In the toolbar, click "Grid" and select "Volume". An "Open Grid" dialog box opens, where the file for the upper surface is specified for volume calculation.
- After specifying the upper surface, the lower surface file is selected.

Clicking OK in the Volume Grid dialog generates a volume report that provides the total sediment volume.

2.2.3. Evolution of Sediment Dynamics

Bathymetric monitoring of the harbor, integrating both sediment input and loss processes, required two surveys conducted in 2019 and 2023. Sediment deposition or erosion was estimated by calculating the depth difference at each corresponding point between the two maps (Castaings, 2008). This difference was then integrated over the study area to assess the overall evolution. The results can also be represented cartographically using software to visualize the intensity of sediment deposition or erosion across the water body (Figure 9).

The temporal trend of sediment dynamics was analyzed using Surfer 20. Common reference points between the 2019 and 2023 bathymetric maps (Figure 10) were identified to generate bathymetric profiles, allowing the evaluation of morphological changes. These reference points also enable the calculation of eroded sediment volume and deposited sediment volume, providing a comprehensive understanding of sediment redistribution in the harbor.

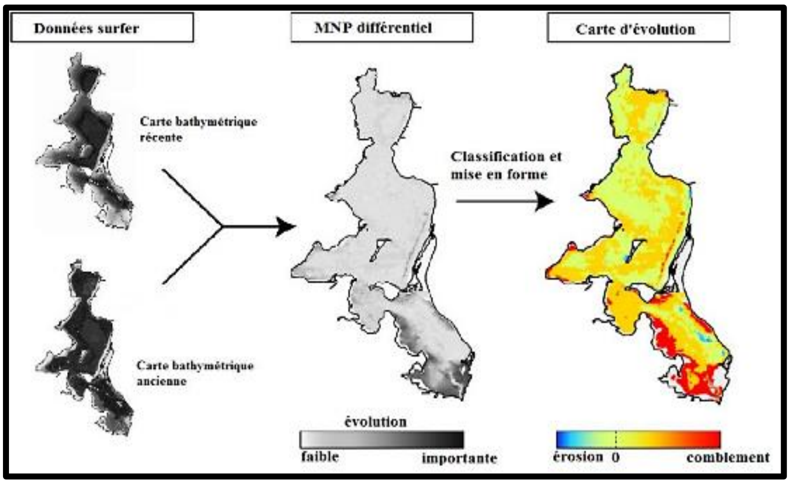


Figure 9 Schematic diagram illustrating the principle of bathymetric evolution analysis (Castaings, 2008)

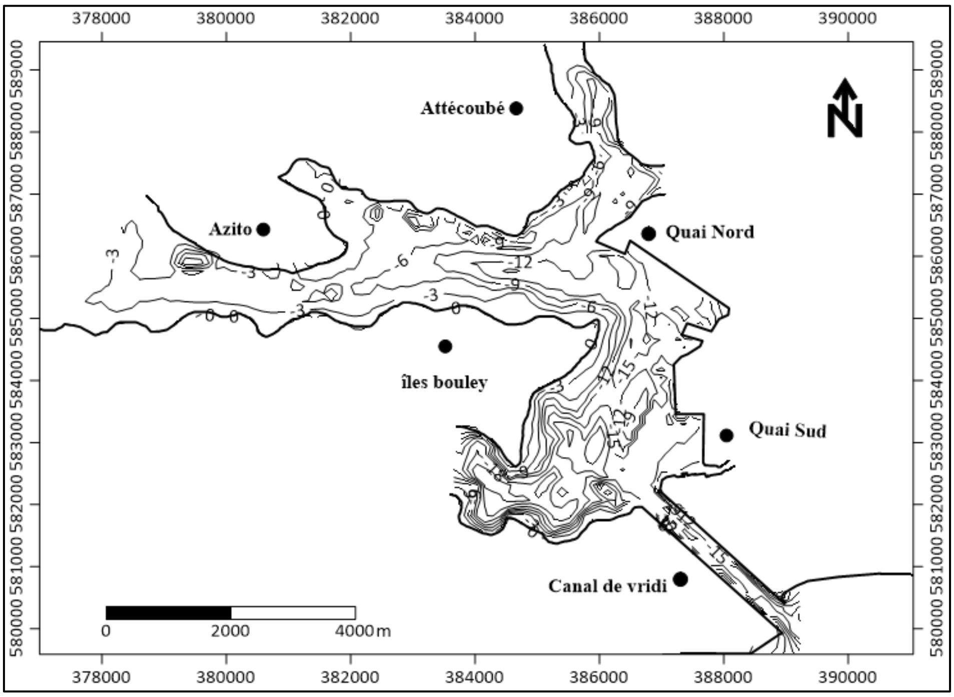


Figure 10 2D Bathymetric map of the Abidjan harbor area in 2019

3. Results

3.1. 2D Bathymetric Map of the Abidjan Harbor in 2023

The 2D bathymetric map of 2023 reveals depths reaching up to –95 m, with an average depth of approximately –10 m. The isobaths are spaced at 3-meter intervals. The greatest depths (–16 m to –95 m) are located offshore, within the

Vridi Channel, and along the northern and southern quays. However, in the vicinity of Boulay Island, Azito, and Attécoubé, the depths are generally shallower, ranging from −1 m to −10 m (Figure 11).

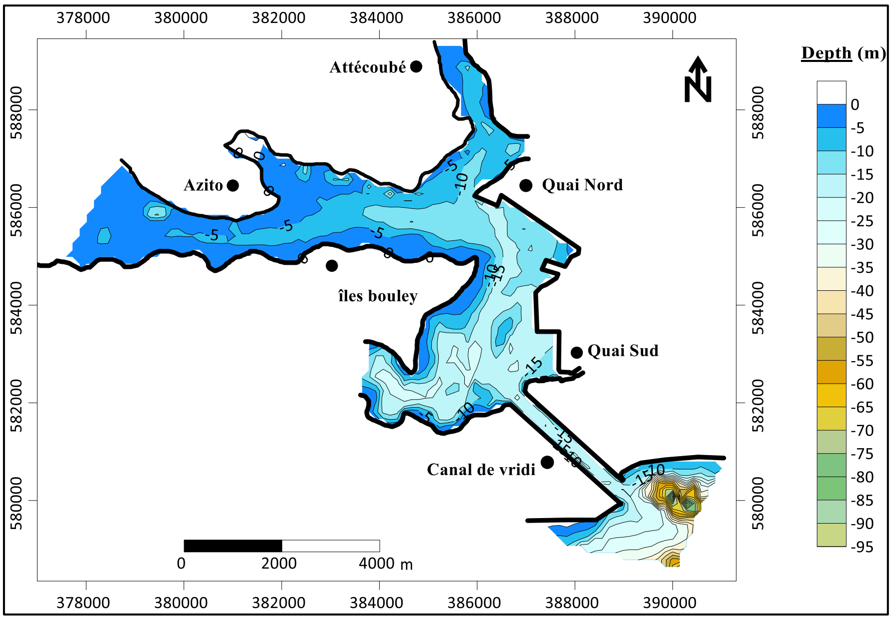


Figure 11 2D Bathymetric map of the Abidjan harbor area in 2023

3.2. Digital Depth Model (DDM) of 2023

The 3D maps, or Digital Depth Models (DDM), highlight the geomorphological features characterizing the Abidjan harbor in 2023 (Figure 12). The 3D map shows an irregular seabed morphology, with the presence of shoals and depressions. The shoals, located near the southern quay, reach depths of approximately −8 m and indicate relatively low hydrodynamic conditions, allowing sediment accumulation. In contrast, the depressions reach depths of up to −95 m offshore and −20 m in the Vridi Channel, reflecting intense erosion, mainly associated with dredging activities within the harbor.

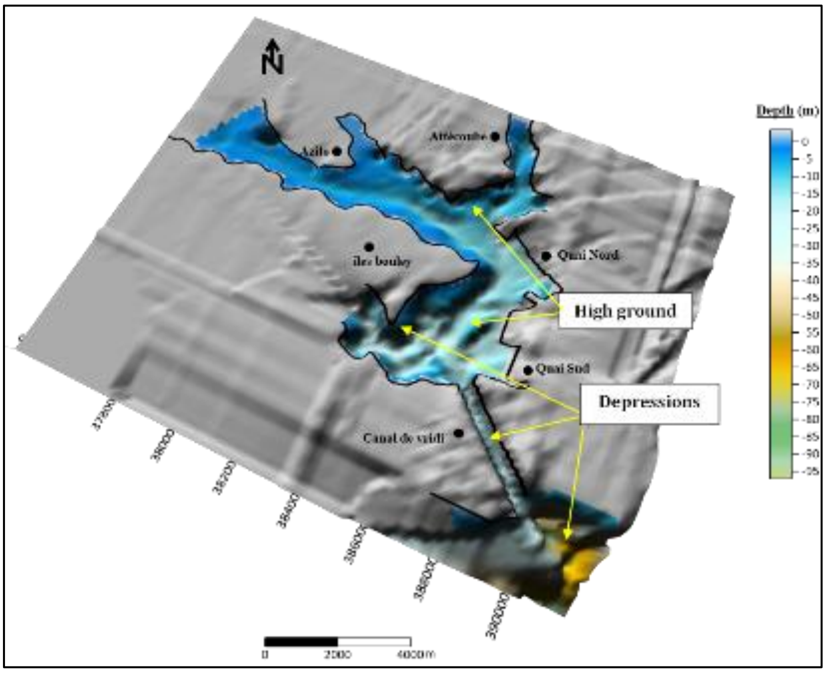


Figure 12 3D Bathymetric map of the Abidjan harbor area in 2023

3.3. Channel Characterization

Figure 13 shows that the radial profiles R1, R3, and R4 exhibit “V”-shaped bathymetric profiles. These profiles are sharply concave, smooth, and angular (Figure 14), reflecting intense erosional processes. Radials R2 and R5 display intermediate profiles, falling between “V” and “U” shapes, indicating channels that have not yet reached equilibrium. Radial R6 reveals a “U”-shaped bathymetric profile, characteristic of sediment accumulation zones.

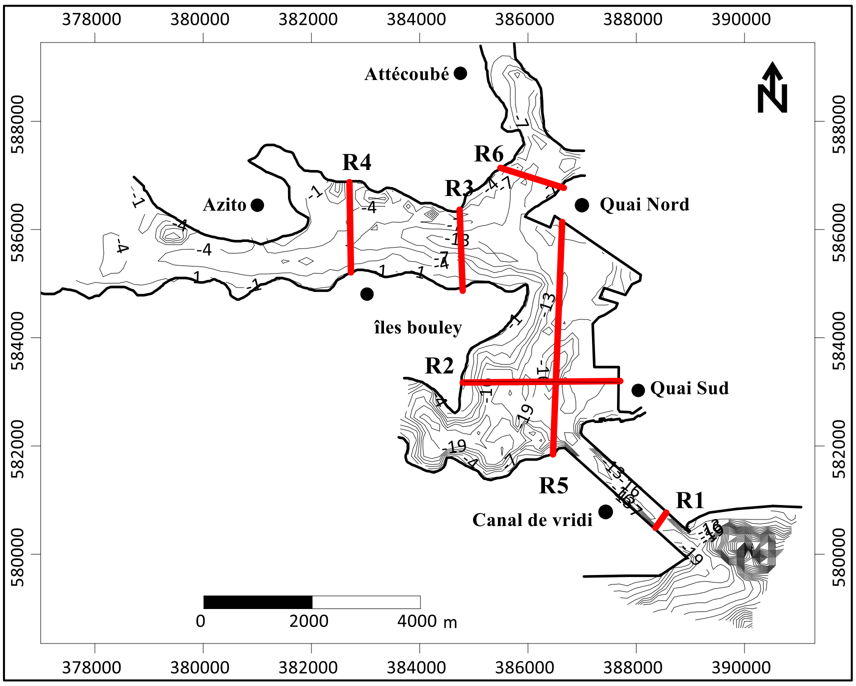


Figure 13 Positioning of the 2023 bathymetric radials

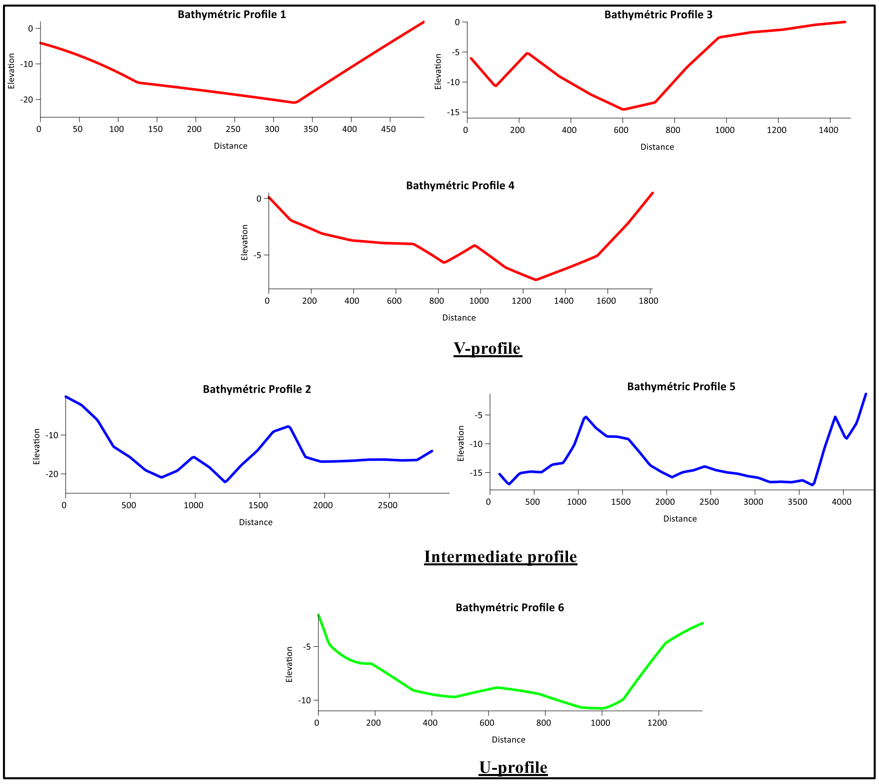


Figure 14 Bathymetric profiles of the channels

3.4. Evolutionary Trend of Harbor Channels from 2019 to 2023

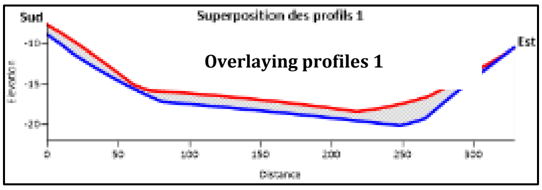
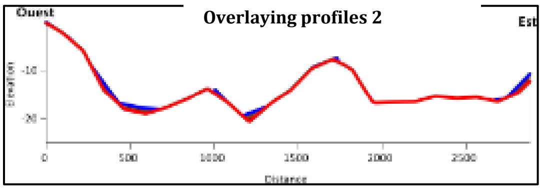
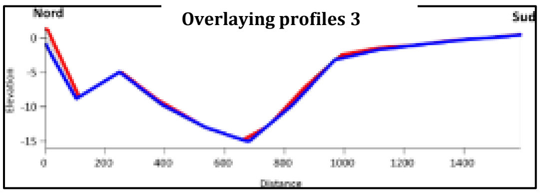
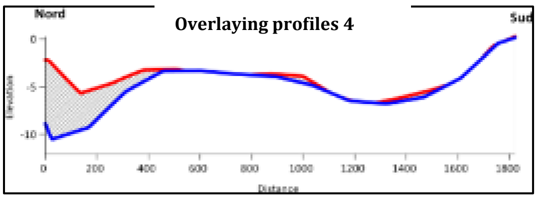
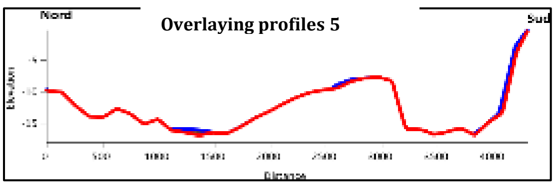
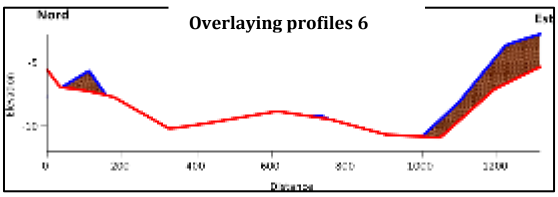
3.4.1. Comparative Analysis of Seabed Morphology in 2019 and 2023

The 2D bathymetric maps reveal significant depth differences between 2019 and 2023. Depths in 2019 ranged from 0 to –24 m, with an average of –10.1 m, whereas in 2023, depths reached up to –95 m, with an average of –15 m. Analysis of the Digital Depth Models (DDM) shows that most of the depressions present in 2019 were filled by sediments in 2023, with sediment deposition observed at certain quay locations. Additionally, the shoal near the southern quay, which had a depth of –9.45 m in 2019, is now at –8.5 m in 2023, highlighting a localized trend of sediment accumulation.

3.4.2. Superimposition of Channel Bathymetric Profiles

Overlaying the bathymetric profiles from 2019 and 2023 generally indicates erosion of the seabed (Figure 15). The eroded sediment volume is approximately 2.6 million m^3, while sediment accumulation is estimated at +1.6 million m^3 along bathymetric profiles 2 and 6 (Table 1).

Table 1 Superimposition of bathymetric profiles of the Abidjan harbor

Superimposed bathymetric profiles from 2019 to 2023.	**Description**
	Erosion of the seabed with an estimated volume of (-323,384.69 m^3)
	Sediment accumulation with an estimated volume of (+19.844,06 m^3)
	Erosion along the northern quay of approximately (-41.893 m^3)
	Erosion along the northern quay of approximately (-2,3 millions m^3)
	No sedimentation or erosion
	Sedimentation along the quay areas of approximately (+1,6 millions de m^3)

3.5. Sediment Volume and Deposition Rate

Figure 15 provides indicative values on the sediment dynamics of the Abidjan harbor, allowing an assessment of seabed changes between 2019 and 2023. Overall, the harbor experienced sediment accumulation. The volume of deposited sediment is estimated at approximately +37 million m^3 over an area of 1,098.626 ha (10.98626 km^2). In contrast, the volume of eroded sediment over the same period is around –33 million m^3. The resulting sediment budget is therefore approximately +4 million m^3, corresponding to an average of 800,000 m^3/year. The sedimentation rate is estimated at 0.7 m/year within the harbor.

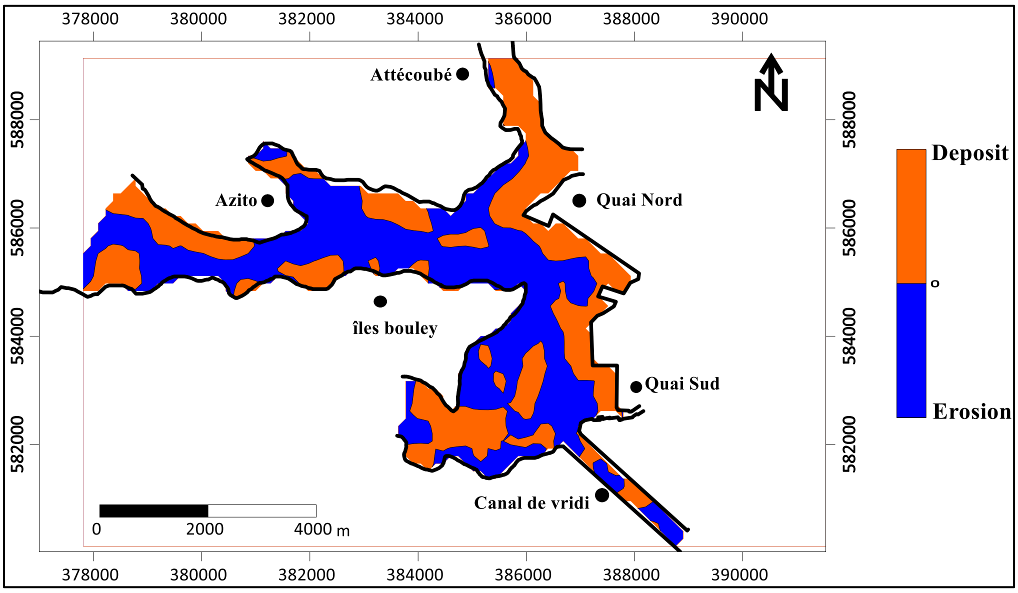


Figure 15 Residual map of the Abidjan harbor from 2019 to 2023

4. Discussion

4.1. Combined analysis of bathymetric maps and Digital Depth Model (DDM)

The combined analysis of bathymetric maps and the Digital Depth Model (DDM) reveals a rapid and contrasting evolution of the seabed in the port area of Abidjan between 2019 and 2023. This dynamic reflects a complex interaction between natural processes and human interventions, characterized by marked erosion zones and areas of sediment accumulation.

4.2. Morphodynamic evolution and sedimentary processes

The main channel exhibits "V"-shaped profiles, typical of active scouring caused by strong currents. Such morphological features are generally associated with environments undergoing intense erosion, as confirmed by Monde (2004) and Samassy (2014). Moreover, the sediment dynamics observed in Abidjan show similarities with those of the Port of Lomé in Togo.

Giardino et al. (2018) noted that, although the Port of Abidjan is relatively large, its influence on littoral transport remains moderate compared to other ports in the region. However, more recent studies suggest that human activities such as dredging and the construction of breakwaters disrupt sediment transport, resulting in localized erosion zones and rapid sediment accumulation areas.

4.3. Sediment budget and coastal connectivity

The sediment budget assessment indicates a net gain of approximately +4 million m^3 over the study period, with about 37 million m^3 of deposits compared to 33 million m^3 of losses. This positive balance, equivalent to an average silting rate of 0.7 m/year, suggests that despite port developments, the bay remains connected to the coastal sediment transport system. This observation is consistent with the findings of UNESCO (1980), which estimated the littoral drift at around 800,000 m^3/year before the construction of major port infrastructures.

4.4. Seabed morphology and grain size distribution

The 3D bathymetric maps reveal a rugged seabed morphology characterized by deep depressions and irregular reliefs. Depressions reaching –95 m offshore and –20 m in the Vridi Channel coincide with former dredged zones or areas affected by concentrated currents. The work of Mathurin et al., (2024) on sediment grain size confirms the coexistence of two sedimentary regimes: coarse sands in exposed offshore areas and fine sands in more sheltered inner zones, illustrating the simultaneous action of erosion and deposition processes.

4.5. Implications for sustainable port management

The current hydro-sedimentary dynamics of the Abidjan harbor result from a continuous interaction between natural factors and human activities. Dikes, quays, and dredging operations significantly modify current patterns and disrupt littoral drift, leading to sediment trapping near port structures. This phenomenon, widely documented in other tropical ports (Tiemelé et al., 2019; N'doufou et al., 2019), generates an imbalance characterized by alternating zones of localized erosion and rapid sedimentation, keeping the system in a state of quasi-permanent morphodynamic instability. From an operational standpoint, these processes have direct implications for port navigation and maintenance. The high sedimentation rate requires frequent dredging of the Vridi Channel to maintain the minimum navigable depths. This represents a significant financial burden for port authorities and highlights the need for sustainable sediment management strategies that account for both morphodynamic processes and anthropogenic pressures.

5. Conclusion

The bathymetric surveys conducted in the Abidjan harbor in 2023 reveal a complex and irregular seabed morphology, characterized by the coexistence of shallow areas and deep depressions. The deepest zones, ranging from –16 m to –95 m, are located offshore, within the Vridi Channel and along the northern and southern quays, while the areas near Boulay Island, Azito, and Attécoubé exhibit relatively shallow depths (–1 to –10 m). The 3D mapping and channel characterization highlight "V"-shaped profiles in the main channel, indicating active erosion, as well as localized depositional zones on the shallow banks, reflecting weaker hydrodynamic conditions.

The comparison between the 2019 and 2023 bathymetric maps quantifies the recent geomorphological evolution of the harbor. Over a total area of 1,098.626 hectares, the total volume of deposited sediments is estimated at approximately +37 million m^3, while the eroded volume reaches –33 million m^3, resulting in a positive sediment balance of about +4 million m^3, equivalent to an annual average of +0.8 million m^3 and a silting rate of 0.7 m/year. This balance indicates a general trend toward sediment accumulation in low-energy hydrodynamic areas, while emphasizing the presence of localized erosion zones, particularly within the main channels.

These findings confirm that the sediment dynamics of the Abidjan harbor result from complex interactions between natural processes and human interventions (dredging, quay construction, and breakwater development). They provide essential insights for the sustainable planning of port operations and dredging management, enabling the anticipation of areas prone to siltation and the optimization of navigability maintenance strategies. In perspective, regular monitoring that integrates bathymetry, sediment grain-size analysis, and hydrodynamic modeling is indispensable to ensure the long-term sustainability and safety of port infrastructures in the context of economic growth and evolving sediment inputs

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

Statement of Ethical Approval (geological studies)

As this study did not involve human participants or animals, no ethical approval was required.

Statement of Informed consent

Not applicable. This study does not involve human participants.

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