Monitoring the Evolution of the West African Coastline under Pronounced Climate Change: Challenges and Solutions for Coastal Protection

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Abstract. West African coastlines are increasingly exposed to the combined effects of climate change and human interventions, resulting in accelerated shoreline erosion, sediment imbalance, and heightened risks for coastal cities and infrastructures. This study investigates the recent evolution of the Senegalese–Mauritanian coastline, extending over approximately 300 km between the ports of Tanit and N'Diago, with a particular focus on the impacts of coastal engineering structures. An integrated methodology combining field measurements, multi-temporal satellite imagery (2005–2023), UAV surveys, and sediment grain-size analysis is applied to identify erosion and accretion patterns and assess sediment transport dynamics. Observations reveal significant shoreline retreat and accretion induced by port jetties and breakwaters, highlighting strong disruptions of longshore sediment transport. To complement these observations, simplified numerical modelling approaches based on one-line shoreline models and finite difference methods are implemented to simulate shoreline evolution under various scenarios. The results demonstrate the relevance of these models for predicting long-term coastal behavior in data-scarce environments. This work provides practical insights for integrated coastal zone management and supports the development of adaptive coastal protection strategies for vulnerable West African coastlines..

1 Introduction

The protection of coastal cities in the context of climate change has become a major global challenge. The EVF – City of the Future Conference highlights specific issues related to coastal urbanization, natural hazard management, and environmental sustainability. Coastal cities, particularly those located below sea level or in the vicinity of port infrastructures, are increasingly exposed to multiple threats, including sea-level rise, shoreline erosion, sediment imbalance, and extreme natural events such as tsunamis and coastal flooding.
In this context, shoreline evolution represents a critical indicator of coastal vulnerability. Along the Senegalese–Mauritanian coastline, extending approximately 300 km between the

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ports of N'Diago and Tanit, processes of coastal erosion, shoreline retreat, and disruption of sediment transport are now well documented.
Several studies conducted in similar West African coastal environments confirm the magnitude of these phenomena. For instance, Lawson et al. (2021) investigated the morpho-sedimentary dynamics of sandy spits in the Gulf of Guinea, highlighting the combined effects of anthropogenic modifications and wave climate on estuarine evolution [1]. More recently, Lawson et al. (2023) documented the impact of coastal engineering structures, such as sandbar breakwaters, on the trapping of longshore sediment transport along the Beninese coast [2].
Beyond academic research, large-scale initiatives such as the West Africa Coastal Areas Management Program (WACA), funded by the World Bank, aim to strengthen the resilience of West African coastlines in response to climate risks and rapid population growth [3]. During the EVF'2023 edition held in Nouakchott, several presentations addressed these challenges, notably those from University of Nouakchott) and Mauritanian Ministry of Environment, who emphasized the specific vulnerabilities of the Mauritanian capital and its surrounding coastal areas.
The present study builds upon these reflections through an interdisciplinary approach combining field observations, numerical modelling, and international scientific cooperation. The objectives of this article are threefold:

1. To document recent shoreline evolution along the Mauritanian coast using field observations and satellite data;
2. To test numerical modelling approaches (one-line modelling and finite difference methods, FDM) adapted to this geographical setting, drawing in particular on the work of Van Duy et al. (2024) on coastal erosion in Vietnam [4];
3. To propose coastal management and protection strategies consistent with the integrated approaches promoted by the WACA program [5].

2 The Senegalese–Mauritanian Coastline

The coastline extending between the Port of Tanit to the north and the Port of N'Diago to the south, at the border between Mauritania and Senegal, covers approximately 300 km. This coastal strip is characterized by high complexity, resulting from the interaction of geological settings, climatic conditions, marine hydrodynamics, and aeolian processes.

This coastline exhibits a wide range of geomorphological features, including:

- Coastal barriers: sandy accumulations shaped by longshore sediment transport;
- Aeolian dunes: formed through wind-driven sand transport;
- Floodplains: periodically inundated by tides or storm surges;
- Depressions: shaped by erosion or inherited sedimentary processes.

The coastal dynamics of this region result from the combined influence of several factors:

- regional tectonic activity,
- marine erosion,
- fluvial and coastal sedimentation, and
- wind-driven processes affecting mobile dune systems.

Together, these mechanisms make the coastline particularly vulnerable to instability. The poorly consolidated sedimentary formations are highly erodible, leading to progressive shoreline retreat. Dune systems play a dual role: they act as natural barriers against marine intrusion, while also posing potential risks to urbanized areas when they migrate landward.

Integrated coastal zone management therefore emerges as a major strategic challenge, requiring coordinated actions to protect infrastructure, preserve fragile ecosystems, and promote sustainable economic development.

3 Methodology

3.1 Study Framework and Data Sources

The methodological approach aims to establish a detailed assessment of shoreline evolution along critical segments of the Mauritanian coast, including the ports of Tanit and N'Diago, the city of Nouakchott, and adjacent natural areas such as the Banc d'Arguin National Park (PNBA).
Shoreline monitoring was based on a multi-source dataset combining:

- Geodetic surveys, using fixed benchmarks installed along the coast (55 geodetic benchmarks and 210 reference markers);
- Multi-temporal satellite imagery (2005–2023);
- Unmanned Aerial Vehicle (UAV) surveys to capture fine-scale shoreline changes.

This integrated approach enabled the identification of erosion and accretion hotspots, as well as the assessment of the impacts of coastal infrastructures such as ports, jetties, breakwaters, and access roads.

3.2 Study Area and Zoning

The study area extends from the Port of Tanit (north) to the Port of N'Diago (south), covering approximately 300 km of coastline. Based on geomorphology and the density of coastal infrastructures, the coastline was subdivided into three main zones:

- Zone I: Port of Tanit to Blawakh (PK50), characterized by recent port infrastructure and strong sedimentary responses;
- Zone II: Blawakh to PK28 (Nouakchott metropolitan area), marked by intense urbanization, tourism, fisheries activities, and dune system degradation;
- Zone III: PK28 to the Port of N'Diago, including tourist areas and the Ndiago port complex.

The temporal evolution of benchmark positions relative to the shoreline was used to quantify shoreline retreat or advancement, while sediment sampling supported the interpretation of sediment sources and transport pathways.

3.3 Shoreline Evolution and Infrastructure Impacts

3.3.1 Port of Tanit (2005–2023)

Prior to port construction, the area was weakly anthropized. The progressive extension of the Tanit jetty (up to ~850 m) induced a strong sedimentary imbalance:

- North of the jetty, rapid accretion was observed, exceeding 500 m of shoreline advance by 2023, with an average rate locally reaching ~4 m/month;
- South of the jetty, shoreline retreat intensified, with bay intrusion reaching ~400 m inland, threatening nearby buildings.

These results indicate a severe interruption of longshore sediment transport caused by the port infrastructure (Figures 1 - 5).

Figure 1: South of Tanit port, there is a bay whose shoreline extends 210 m inland from the former coast.

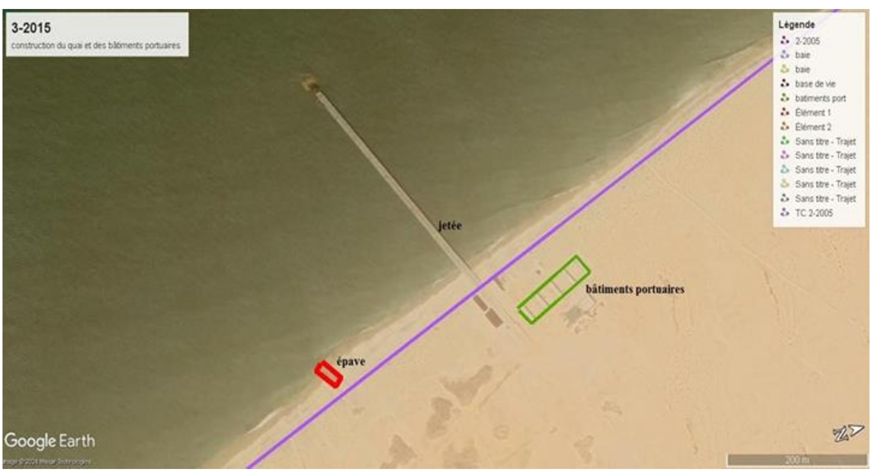

Figure 2: South of Tanit port, a shipwreck is located 242 m, and a building is 390 m from the shoreline.

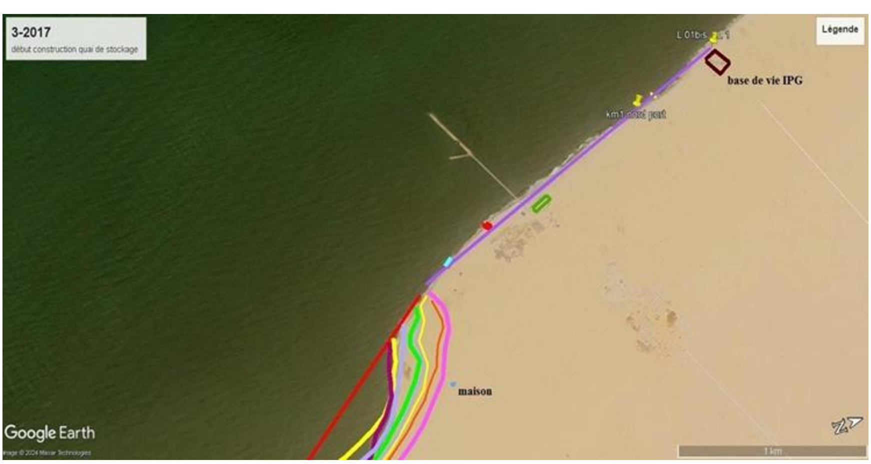

Figure 3: The pier length estimated at 850 m; slight sediment accumulation observed north of the port

over 1 km.

Figure 4: The bay continues to evolve inland toward the north and east, with the building now only 191 m from the bay's edge.

Figure 5: Tanit port in 2022.

3.3.2 Nouakchott Coastal Barrier System

The coastal barrier protecting Nouakchott is characterized by a degraded dune cordon with:

- Narrow and low crests (locally >3 m elevation but discontinuous);
- Extensive moderately elevated zones (2–3 m), insufficient to ensure effective protection against marine flooding;
- Multiple breaches, many resulting from long-term sand extraction and vehicle traffic.

Six major breaches were identified, some exceeding 200 m in width, several of which have already allowed marine incursions. Although pilot dune-fixation projects (black geotextiles, typha palisades) have locally increased dune elevation, the overall system remains highly vulnerable.

3.3.3 Port of N'Diago (2017–2023)

The construction of the main breakwater (up to ~1,035 m) led to:

- Significant accretion north of the structure, reaching ~900 m by 2023, with an estimated rate of ~9 m/year;
- Persistent erosion south of the breakwater, despite the addition of a groyne;
- The emergence of sediment bypassing, with mobile sand accumulating beyond the breakwater and threatening the navigation channel.

These patterns highlight the need for sediment management strategies to ensure port sustainability (Figures 6 - 12).

Figure 6: Overview of N'diago port.

Figure 7: Initial condition of N'diago port (image 2017-03).

Figure 8: Start of construction works at N'diago port (image 2018-04).

Figure 9: Seven months after the construction of the breakwater at N'diago port (image 2018-11).

Figure 10: N'diago port in 2019 (image 2019-09).

Figure 11: N'diago port in 2022 (image 2022-01).

Figure 12: N'diago port in 2023 (image 2023-11).

3.4 Sediment Grain-Size Analysis

Surface sediment samples collected at five representative sites were analyzed to characterize sediment texture and origin. All samples exhibited:

- A dominance of fine sands (0.125–0.25 mm);
- Good to moderate sorting;
- A single modal distribution, indicating homogeneous sediment sources.

No significant spatial grain-size gradient was detected along the study area, suggesting a relatively uniform sediment supply and transport regime.

3.5 Methodological Synthesis

The combination of field measurements, remote sensing, UAV surveys, and sediment analysis provides a robust framework for quantifying shoreline dynamics and diagnosing infrastructure-induced sediment imbalances. These observations form the empirical basis for the numerical modelling presented in the following section and for the development of integrated coastal management strategies.

4 Coastal Modelling and Ongoing International Collaboration

4.1 Transition from Observation to Numerical Modelling

Building on the observational phase, a second stage of the project was initiated through an international scientific collaboration involving Mauritania (University of Nouakchott), Japan (Tohoku University), and France (ECAM-EPMI). This cooperation enabled a transition from qualitative shoreline observations to the quantitative analysis of coastal processes, with a particular focus on longshore sediment transport and shoreline response to coastal structures. The main objective of this modelling phase is to simulate shoreline evolution under various climatic and infrastructure-related scenarios, and to provide predictive tools that can support coastal management decisions in data-scarce environments.

4.2 Modelling Framework and Theoretical Background

To address the complexity of sediment dynamics along the Mauritanian coast, the study adopts simplified numerical models commonly used in coastal engineering, which offer a robust balance between physical realism and data requirements. The modelling framework is based on:

- One-line shoreline evolution models, and
- Numerical solutions using the finite difference method (FDM).

These approaches have been successfully applied in comparable contexts, such as the sandy spits of the Gulf of Guinea (Lawson et al., 2021; 2023) and erosion-dominated coastlines in Vietnam (Van Duy et al., 2024), where long-term shoreline dynamics are driven primarily by gradients in longshore sediment transport.

4.3 One-Line Shoreline Modelling

The one-line model is founded on the principle of sediment mass conservation along the shoreline. The beach profile is assumed to maintain an average, time-invariant shape between the berm height (D_B) and the closure depth (D_C), such that shoreline movement can be represented by a single contour line (Figure 2).

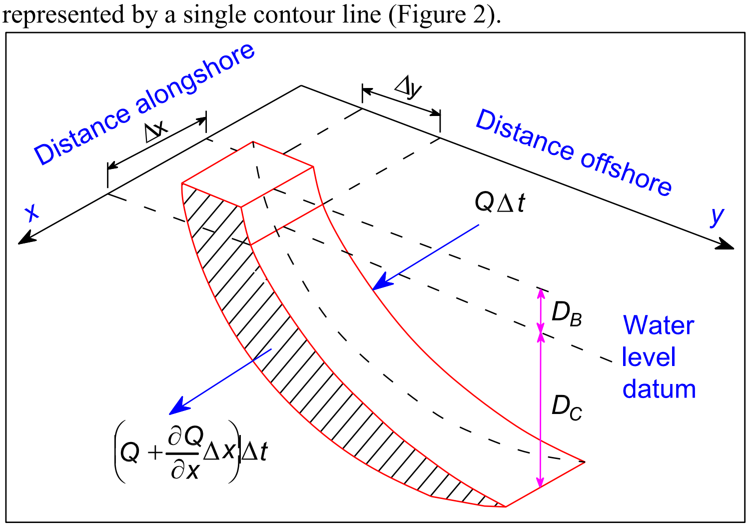

Figure 13 : One-linemodelling

The temporal evolution of the shoreline position *y(x,t)* is governed by the balance between shoreline displacement and spatial variations in the longshore sediment transport rate *Q*:

$$\frac{\partial y}{\partial t}=-\frac{1}{D}\frac{\partial Q}{\partial x} \quad (1)$$

$$D=D_B+D_C \quad (2)$$

where *D* represents the active vertical extent of sediment exchange.

This formulation highlights the central role of sediment transport gradients, which are strongly influenced by coastal structures such as jetties and breakwaters, as observed at the ports of Tanit and N'Diago.

4.4 Shoreline Change and Simplified Diffusion Model

A simplified form of the one-line model can be expressed as a diffusion equation, where shoreline evolution is controlled by a diffusion coefficient ε:

$$\frac{\partial y}{\partial t}=\varepsilon\frac{\partial^2 y}{\partial x^2} \quad (3)$$

ε is the diffusion coefficient

This equation is mathematically analogous to classical diffusion processes encountered in physics, such as heat conduction, mass diffusion, and viscous momentum transfer. Such analogies facilitate interpretation of shoreline smoothing and spreading processes induced by wave-driven sediment transport.

The diffusion-based formulation is particularly suitable for long-term, large-scale simulations, where detailed hydrodynamic forcing is not available but the dominant sediment transport mechanisms can be parameterized.

4.5 Numerical Implementation Using Finite Difference Methods

The governing equations were discretized using an explicit finite difference scheme (Figure 4), allowing time-dependent shoreline evolution to be computed as:

$$y_{s\,i}^{n+1}=y_{s\,i}^{n}-\frac{\Delta t}{D\Delta x}\left(Q_{i+1}^{n}-Q_{i}^{n}\right) \quad (4)$$

Boundary conditions were defined assuming zero sediment flux (Q = 0) at domain limits, consistent with closed or controlled coastal compartments.

This numerical framework enables the simulation of shoreline response to engineering interventions, such as:

- the construction and extension of jetties,
- breakwaters and groynes,
- and delta or spit growth induced by sediment trapping.

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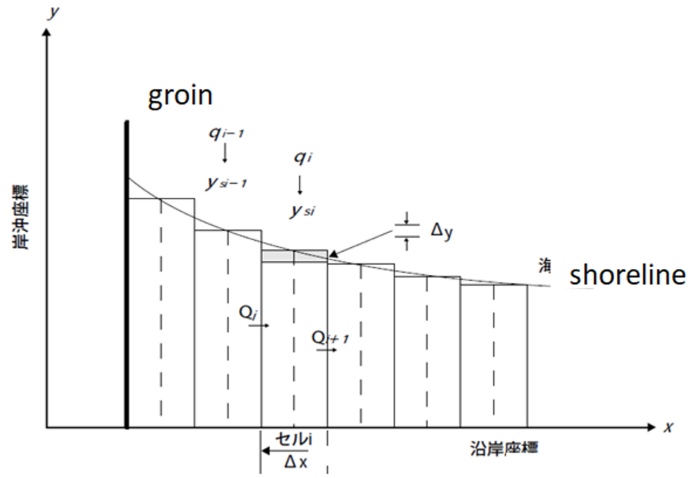


Figure 14 : Numerical computation usingfinitedifferencemethod (FDM)

4.6 Model Validation and Reference Applications

The modelling approach was validated against published case studies, including:

- Cua Dai coast (Vietnam), where FDM-based simulations successfully reproduced observed shoreline retreat patterns (Figure 5);
- Delta and sandy spit growth scenarios, illustrating the capacity of the model to capture sediment accumulation and shoreline advance (Figures 6 and 7).

These reference applications demonstrate the reliability of simplified one-line models for predicting shoreline evolution in sediment-dominated coastal systems.

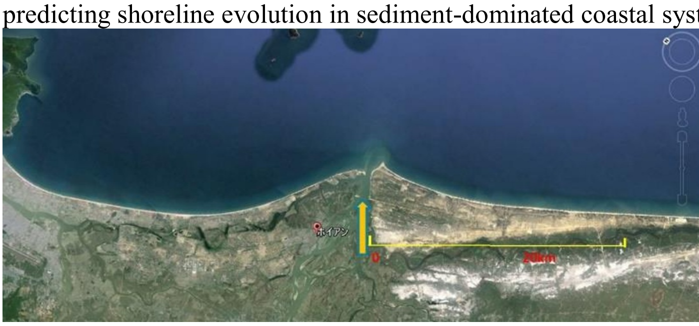
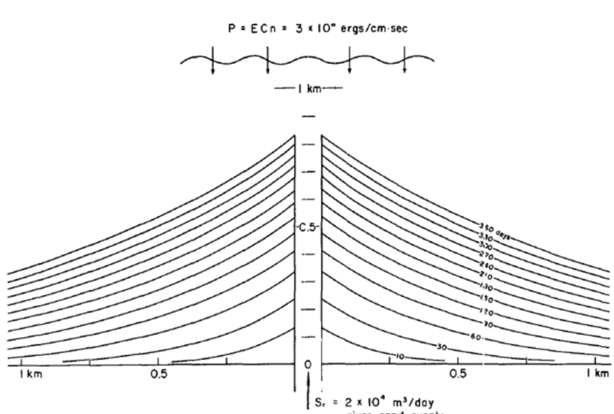


Figure 15 : Numerical computation for CuaDaiusingfinitedifferencemethod (FDM)



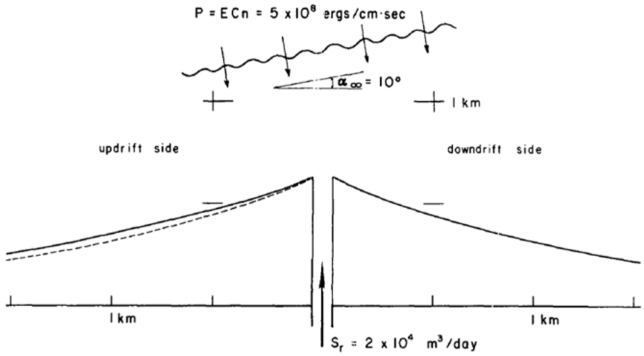


Figure 16 : Delta growth by numerical simulation

4.7 Perspectives for the Mauritanian Coast

Ongoing work focuses on adapting the modelling framework to the specific geomorphological, climatic, and socio-economic conditions of the Mauritanian coastline. In the present study, shoreline evolution was partly derived from Google Maps imagery, which provides valuable long-term spatial coverage but remains limited in terms of spatial resolution and positional accuracy.

Future developments should therefore prioritize the acquisition of high-resolution data, notably through systematic Unmanned Aerial Vehicle (UAV) surveys, which would allow more precise detection of shoreline changes and coastal features. In addition, the geodetic benchmarks installed along the coast should be fully integrated into future monitoring efforts, as they provide reliable ground control points for the calibration and validation of remotely sensed data.

Planned developments also include:

- calibration using field observations and satellite-derived shoreline positions,
- scenario-based simulations incorporating sea-level rise and infrastructure expansion,
- integration into decision-support tools for integrated coastal zone management (ICZM).

These improvements will enhance the robustness of shoreline change assessments and strengthen the predictive capacity of the modelling framework, thereby supporting anticipatory coastal planning and sustainable coastal management.

5 Conclusion

This study highlights the complexity of coastal processes, which involve intricate interactions between the sea, wind, climate, and human activities. Despite these complexities, the results provide valuable insights for coastal engineering, particularly for predicting shoreline evolution and designing effective protection structures.

The application of fluid mechanics and sediment transport principles to environmental engineering challenges demonstrates the effectiveness of simplified models, such as one-line and diffusion approaches, in addressing practical issues even when field data are limited. These models allow for quantifying erosion and accretion risks and simulating alternative management or adaptation scenarios under different climatic and development conditions.

Beyond practical applications, this work contributes to both fundamental and applied research, enhancing understanding of the dynamic processes shaping desert and semi-arid

coastlines. It also underscores the importance of a multidisciplinary approach, combining oceanography, geomorphology, engineering, and satellite data analysis to tackle complex coastal management challenges.
Finally, the international collaboration involved in this project illustrates the value of scientific exchange, enabling teams from different countries to share expertise, methodologies, and lessons learned from other geographical contexts. This collaboration ensures that modeling tools are adapted to local realities while benefiting from global best practices.
In summary, this study provides a robust framework for forecasting, planning, and integrated management of coastal zones, bridging theoretical advances with practical applications.

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