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Analysis of the Impact of River Erosion in the Saloum Delta: The Case of the Mar Islands (Fatick, Senegal)

Omar Baldé, Mouhamadoul B. Diouf, Ibrahima Diouf, Abdou Sagne

Department of Geology, Cheikh Anta Diop University, Dakar, Senegal
Email: omar2.balde@ucad.edu.sn

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Abstract

This study analyzes the interactions between morphosedimentary dynamics and groundwater quality in the Mar area, located in the Saloum Delta (Senegal). It is based on the analysis of bathymetric, hydrodynamic and diachronic coastal line data, supplemented by hydrogeological and hydrochemical observations. The results show a marked asymmetry in the channel, characterised by greater depths and high current velocities on the concave bank, where shoreline retreat rates reach −0.62 m/year upstream and −0.96 m/year downstream of the Mar Islands. This dynamic reflects active erosion linked to the concentration of hydrodynamic energy and a deficit in sediment supply. Conversely, the convex bank is characterised by low-energy conditions favouring sedimentation and the smoothing of the bathymetric profile. From a hydrogeological perspective, shallow aquifers are highly susceptible to salinisation processes linked to the intrusion of estuarine waters, whilst deep Paleocene and Maastrichtian aquifers constitute the main sources of water supply, despite occasionally high mineralisation and fluoride concentrations exceeding drinking water standards. The study highlights a close relationship between coastal dynamics, hydrosedimentary processes and the gradual deterioration of groundwater quality. It thus underscores the vulnerability of the Saloum Delta's estuarine systems to natural and human-induced pressures, and the importance of integrated management of water resources and coastal environments.

Keywords

Saloum Delta, Coastal Erosion, Hydrosedimentology, Aquifer Salinisation, Estuarine Dynamics

1. Introduction

Estuarine areas are among the most dynamic coastal environments in the world. They are subject to the combined action of hydrodynamic, sedimentary and morphological processes that control the evolution of channels, banks and islands. These environments often experience riverine erosion and morphodynamic reshaping, which can profoundly alter landscapes and ecosystems. In many tropical estuaries, these transformations are also associated with variations in the salinity of surface and groundwater, influencing the ecological conditions and socio-economic uses of coastal areas. The Saloum Estuary, situated on the central coast of Senegal, is a remarkable example of these environmental dynamics. For several decades, it has been characterised by significant hydro-sedimentary changes linked to climate variability, a reduction in continental sediment input and the evolution of the Sangomar Point sand spit. The breach of this spit in 1987 led to a reconfiguration of the exchange between the Atlantic Ocean and the estuary, affecting hydrodynamic conditions, sediment distribution and salinity gradients within the delta. These changes have direct repercussions on human activities within the delta. Among these, tourism plays a significant role due to the region's rich ecology and scenic beauty. However, tourism infrastructure is particularly vulnerable to riverbank erosion and morphological changes affecting the islands and channels. Consequently, understanding the mechanisms of erosion and how they evolve is crucial for the sustainable management of these areas and the preservation of the economic activities that depend on them. This study aims to analyze the impacts of fluvial erosion on the Mar Islands, situated along the River Saloum, and to characterise its effects on the environment. It is based on the analysis of recent geophysical, bathymetric and morphological data, compared with the results of previous studies, in order to better understand the morphodynamic evolution of this sector of the delta.

2. Overview of the Study Area

The Mar Islands form part of the municipality of Fimela, located in the Fatick region near Ndangane (**Figure 1**). The site is accessible by sea from the Ndangane jetty.

The Mar Islands, situated in the Sine-Saloum Delta in Senegal, lie approximately 150 kilometres south of Dakar. They cover an area of around 15 km^2 by 10 km^2 and have an estimated population of 5500. The population is spread across four villages: Mar-Fafaco, with around 2500 inhabitants; Mar-Lodj, with 2200 inhabitants; Mar-Soulou, with nearly 500 inhabitants; and Wandié, a fishing hamlet on a neighbouring islet, home to around 300 inhabitants. Water resources are limited; the supply relies on a few wells and a borehole providing brackish water. The local economy is based primarily on subsistence farming (rice, millet, groundnuts, watermelons and some market garden crops), as well as livestock farming, fishing and tourism, particularly through tourist camps and handicrafts. The socio-economic situation in the Mar Islands is a mix of local dynamism, driven in particular by women and artisanal tourism, and significant environmental challenges leading to declining fish stocks and land disputes, prompting some young people to emigrate.

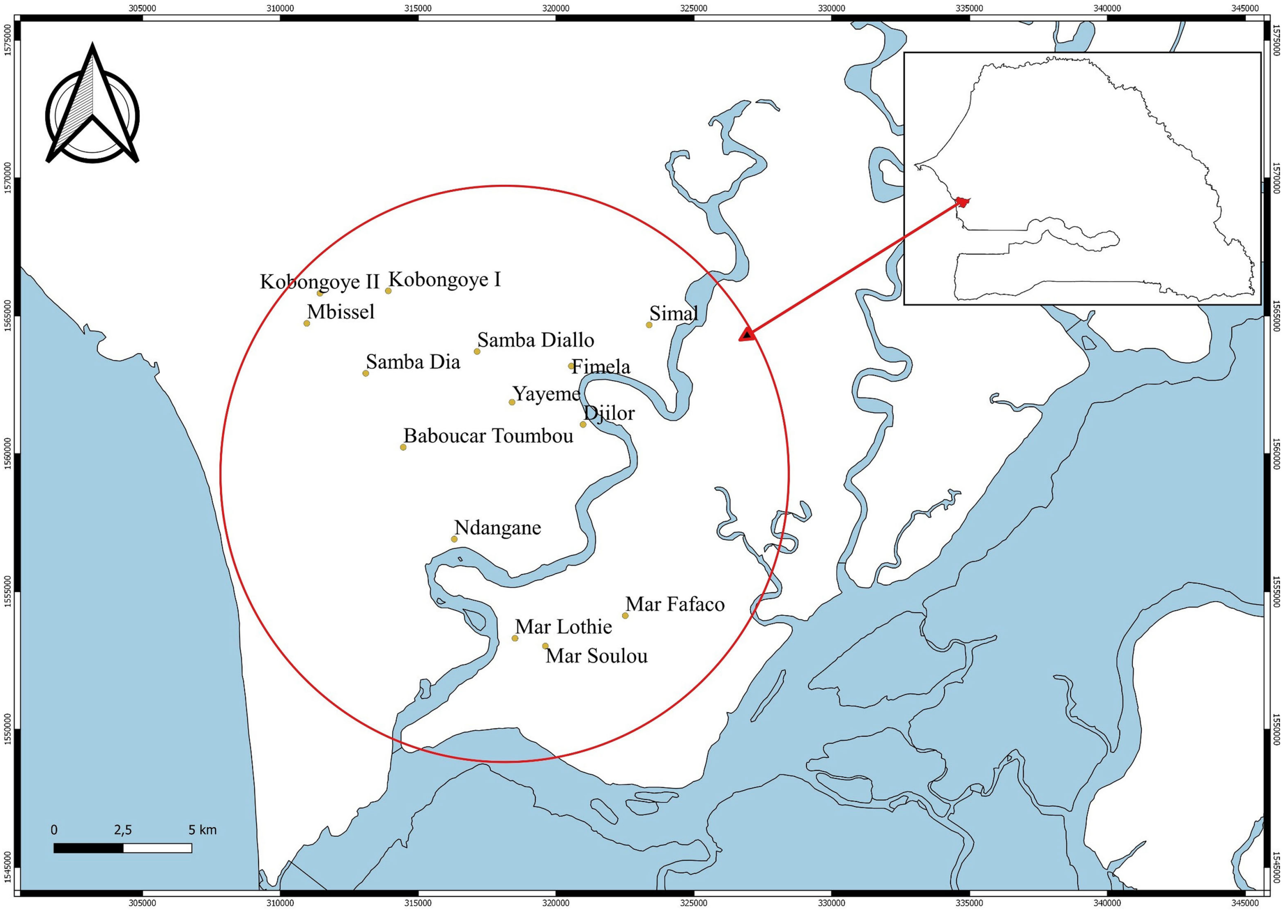

Figure 1. Map showing the location of the study area.

2.1. Geomorphological and Sedimentological Context

The Saloum Delta exhibits a complex geomorphological structure resulting from the interaction between marine, estuarine and eolian dynamics (Diarra, 1999). These dynamics have shaped the delta into several major morphological units, notably mangrove mudflats, sandbars, tidal flats and shell mounds. Mangrove mudflats, the dominant unit, consist of black clayey mud rich in organic matter and subject to the direct action of the tides. The mudflats serve as a prime habitat for mangroves, a halophytic formation that plays a crucial role in sediment trapping and stabilisation processes (Conand, 1994). As for the sandbars, they correspond to the highest topographical features of the Mar Islands. Mainly located in the north-western sector, they are home to the main villages in the area. These formations, of eolian origin and oriented north-north-west, consist of relatively homogeneous marine sands, remobilised and reshaped by the prevailing winds (Diop, 1978).

The sandy spits are covered with unweathered tropical ferruginous soils of the Dior type, on which a degraded savannah dominated by grasses and acacias grows (Soumaré, 1996). In contrast, the continental areas are characterised by a surface sedimentary deposit consisting of grey clayey mud enriched in organic matter (Faye, 2016), reflecting the influence of estuarine sedimentation processes. The tannes correspond to former mudflats now exposed, located in the upper part of the intertidal zone. They are characterised by acidic sulphate soils containing jarosite, which are saline on the surface and potentially acidic at depth (Thiam, 1986). The shell middens, mainly located to the east of the Mar Islands, are small in extent and bear witness to ancient human occupation, some dating back to around 5110 years BP (Marius, 1985). The mangroves of the Saloum Delta constitute one of the northernmost examples of the 'Rivers of the South', characterised by a strong interplay between ecological dynamics and human use (Marius, 1995; Cormier-Salem, 1999).

2.2. Hydrological and Hydrogeological Context

Water resources consist of surface water and groundwater. Hydrogeological studies carried out in the Sine-Saloum region highlight the Fafoye estuary, a branch of the sea that runs from Ndangane to Faoye via Fimela, Simal and Rho (**Figure 2**).

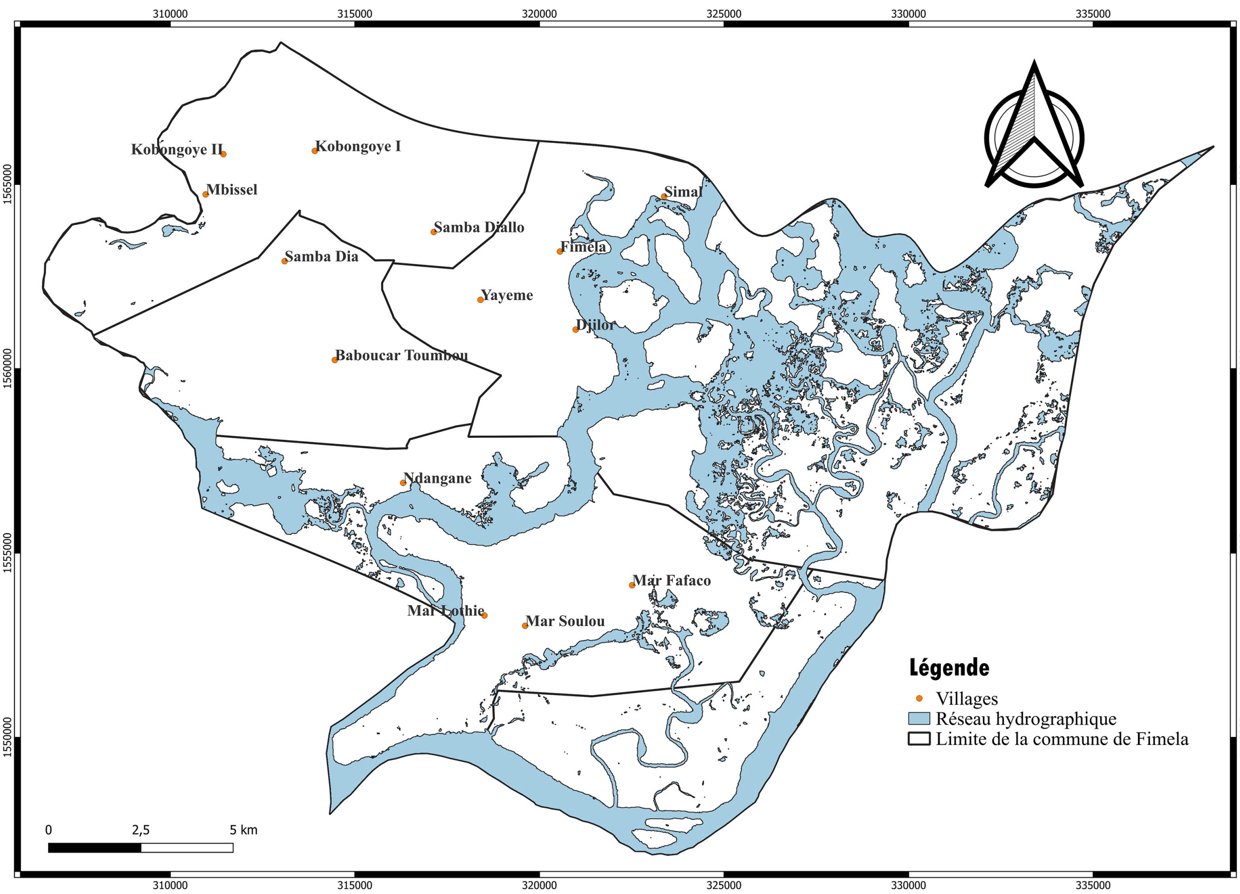

Figure 2. River system of the Mar Islands.

The distinctive feature of the Saloum Estuary lies in its reversed salinity gradient: unlike conventional estuaries, where freshwater dilutes the salinity downstream of the estuary, the Saloum exhibits a salinity that increases from the mouth upstream, reaching very high levels (up to four times the salinity of seawater) far inland, upstream of Kaolack, a phenomenon due to intense evaporation and specific hydrodynamic conditions (Cissé, 2008). With insufficient freshwater inflows during the dry season, salinity levels increase in the direction of Ndangane-Fimela. At its mouth, the river branch out into several channels, giving rise to a number of islands (Mar Island, Palmarin, etc.). The aquifer systems present in the study area are the Quaternary/Eocene, the Palaeocene and the Maastrichtian (**Table 1**).

In the area described, the Quaternary aquifers (sands, clays) of the Saloum Formation (formerly the Continental Terminal) are of limited yield and are used mainly for village wells, providing water of variable quality, often good to moderate, except in the valleys near the Sine Saloum where the salt wedge renders it brackish (Direction de l'Hydraulique, 2015). The most extensively exploited groundwater resources come from deep Palaeocene and Maastrichtian aquifers, abstracted at average depths of approximately 150 m and over 300 m respectively. These aquifers generally have favourable hydrodynamic characteristics, with satisfactory flow rates allowing them to be utilised for water supply. Nevertheless, their physico-chemical quality is sometimes limited by relatively high mineralisation, manifested by total dissolved solids (TDS) of up to 1500 mg/l, as well as by fluoride concentrations frequently exceeding the recommended threshold for human consumption, which is 1.5 mg/l according to World Health Organisation guidelines. In some areas, fluoride levels reach or exceed 3 mg/l, which poses a significant constraint on the exploitation of these water resources. The most extensively exploited groundwater resources in the Saloum Delta region originate from deep Palaeocene and Maastrichtian aquifers, abstracted at average depths of approximately 150 m and over 300 m respectively. These aquifer formations constitute the region's main water resources due to their regional extent and generally satisfactory flow rates (Custodio & Llamas, 1982; Direction de l'Hydraulique, 2015). However, their physico-chemical quality presents significant constraints. The water is generally characterised by moderate to high mineralisation, with total dissolved solids reaching or exceeding 1500 mg/L in certain areas. The dominant hydrochemical facies are of the sodium chloride and calcium bicarbonate types, reflecting both water-rock interactions and the influence of salinisation processes linked to estuarine dynamics (Faye et al., 2003; Ndoye et al., 2018). Electrical conductivity varies significantly between areas and can reach several thousand µS/cm in zones affected by saline intrusions. Furthermore, fluoride concentrations frequently exceed the guideline value of 1.5 mg/L recommended by the World Health Organization for water intended for human consumption.

In some areas, concentrations exceeding 3 mg/L have been recorded, which may contribute to the development of dental and skeletal fluorosis (Faye et al., 2005; Dieng et al., 2017). Relatively high levels of boron and chlorides have also been reported in several boreholes, reflecting the combined influence of evaporation, mineral dissolution and the intrusion of saline water into coastal aquifers (Edmunds & Gaye, 1997; Faye et al., 2005).

Table 1. Hydrogeological and mineral characteristics of selected boreholes in the municipality of Fimela (Direction de l'Hydraulique, 2015).

ID	Aquifer	Depth (m)	Top (m)	Wall (m)	Senegalese standards (m)	Flow rate (m^3/h)	Residual solids (mg/l)	Fluoride (mg/l)
Mar Fafaco	Palaeocene	192.35	136	183	46.5	29.1	2910	0.9
Samba Dia 1	Palaeocene	150	107	145	3.9	34	1990	5
Samba Dia 2	Palaeocene	175	-	-	-	-	1010	3
Ndangane	Eocene	56	35	40	5	15	1930	−1
Ndangane	Maastrichtian	388	158.6	181	4.1	62.5	2000	3

3. Methodology

This study aims to analyse the impacts of river erosion in the Saloum Delta, particularly around the Mar Islands. It is based on a combination of bathymetric and geophysical data, integrated within a spatial analysis framework.

- The bathymetric survey was carried out using a CADDEN dual-frequency single-beam echo sounder (200 kHz and 30 kHz). The echo sounder emits an acoustic pulse via a beam directed vertically from the vessel and calculates the time taken for the signal to travel the path from the vessel to the seabed and back; this enables the water depth to be calculated. The Bali Bathy-500 MF echo sounder is coupled with a GPS receiver, enabling real-time positioning. To improve the accuracy of the measurements, the system is connected to a differential GPS (DGPS) system, which transmits corrections via a radio link. This configuration allows positioning errors to be corrected and high-precision geographical coordinates to be obtained. The bathymetric surveys were carried out using a regular grid comprising longitudinal and transverse profiles. Measurement points were recorded every 5 m along the channel, whilst the transverse profiles were also spaced at 5 m intervals, providing detailed coverage of the study area and an accurate representation of the seabed morphology.
- Georeferenced Landsat images from 2013 and 2023 were used to digitise the coastline of the Mar Islands. They can be downloaded free of charge from the USGS website (http://earthexplorer.usgs.gov/). Their 30-metre resolution is suitable for analysing changes in the coastline. The total uncertainty associated with the position of the coastline was estimated using a quadratic combination of the various sources of error (pixel error, georeferencing, digitisation and coastline oscillation), in accordance with the approaches developed by Crowell et al. (1991), Thieler and Danforth (1994), Fletcher et al. (2003), Juigner et al.

(2012) and as outlined in the DSAS guide (Himmelstoss et al., 2018). In this study, the georeferencing error is directly accounted for and automatically corrected by the ArcGIS software. The indicator for the shoreline and coastline was the instantaneous shoreline, which corresponds to the low-tide water's edge. Coastline markers may be directly visible in the image, as is the case with the Landsat images used in this study. The DSAS 4.3 application was used to calculate statistics relating to coastline evolution. The 'Digital Shoreline Analysis System' is in fact an extension of ArcGIS software that enables calculations to be carried out on the differences between coastlines that have already been digitised from the selected images.

- The geophysical methods ERT (Electrical Resistivity Tomography) and SEM (Electromagnetic Spectroscopy, often also referred to as EM or Electromagnetic) are subsurface imaging techniques based on measuring the electrical and electromagnetic properties of terrestrial materials in order to map their structure, lithology and hydrology, with ERT measuring electrical resistivity (resistance to current) to determine composition and water content, whilst EM methods quantify the medium's ability to conduct current.

These techniques have made it possible to characterise the surface stratigraphic organisation, identify sedimentary discontinuities and highlight the structures that promote erosion.

All the data were integrated into a Geographic Information System (GIS) and cross-referenced with hydrological and environmental information in order to produce erosion vulnerability maps and analyse the impact of fluvial dynamics on bank stability. For this study, one ERT profile and two SEM profiles were carried out (Figure 3).

Figure 3. Location of geophysical profiles.

4. Results and Discussion

The results of the electrical resistivity tomography (ERT) survey enable us to characterise the subsurface structure and its relationship with the hydrological and morphological dynamics of the Mar area. Two main geoelectric units have been identified (**Figure 4**). The first, extending from the surface to a depth of 10 - 15 m, exhibits resistivities ranging from 200 to over 2000 Ω·m and corresponds to Quaternary dune sands, containing a shallow groundwater table vulnerable to saline intrusion (ORSTOM, 1989; Senghor, 2017). The high salinity measured in this aquifer confirms the influence of tides and sea-land exchanges (Cissé, 2008).

The second unit, characterised by high resistivities (3200 to > 5000 Ω·m), corresponds to Eocene limestones (Diop, 1978). A local decrease in resistivities within this formation indicates the presence of a deep aquifer, an interpretation confirmed by electromagnetic surveys. However, hydraulic continuity with the shallow aquifers and the strong marine influence suggest an increased risk of progressive salinisation of the Eocene aquifer, particularly in areas close to active channels (Cissé, 2008; Senghor, 2017). These geophysical results are set against a morphodynamic context characterised by low continental energy. The catchment areas of the Saloum Delta have moderate gradients and low elevations, limiting freshwater inflows and reinforcing the dominance of marine processes (Senghor, 2017). Tides penetrate up to 100 km inland, causing the salt wedge to advance and increasing the salinisation of groundwater, particularly during the dry season, when concentrations can exceed those of the ocean (Diarra, 1999; Cissé, 2008). The morphological evolution of the Sangomar spit is a factor exacerbating these processes. The breach in the dune ridge in 1987 altered the estuary's hydrodynamic flow, promoting bank erosion, channel widening and the degradation of mangrove mudflats (Diarra, 1999; Thomas et al., 2003). The shift in the channel axis and the observed bathymetric depths reflect active erosion dynamics, with an estimated coastal retreat of 1.20 m/year between 2013 and 2023, progressively affecting the Mar Islands. The decline in mangrove mudflats, combined with the salinisation of soils and groundwater, weakens coastal ecosystems and reduces their role as a natural defence against erosion and saltwater intrusion (Conand, 1994; Marius, 1995). This feedback loop exacerbates the delta's environmental vulnerability.

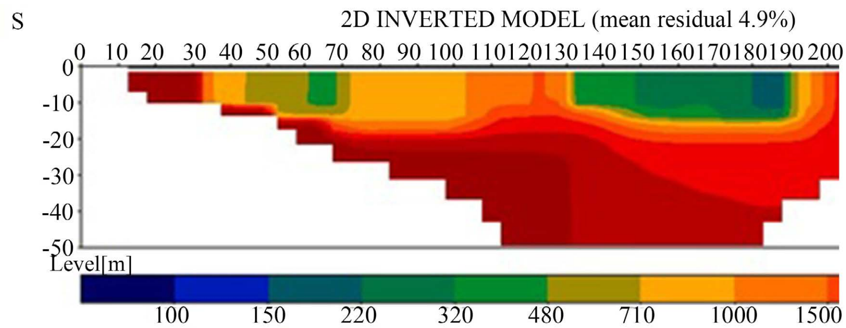

Figure 4. Electrical resistivity tomography (ERT) profile.

A local decrease in resistivity within the limestone, in the north-central part of the profile (between x = 150 m and x > 260 m), is interpreted as evidence of an aquifer. The results of the electromagnetic surveys confirm this interpretation and enable better delineation of the Eocene aquifer, as well as the Palaeocene and Maastrichtian formations present in the study area (Figure 5). These geophysical data from the Mar area indicate high salinity in the groundwater, with total dissolved solids reaching 2910 mg/l, whereas World Health Organisation standards suggest normal values of between 900 mg/l and 1200 mg/l.

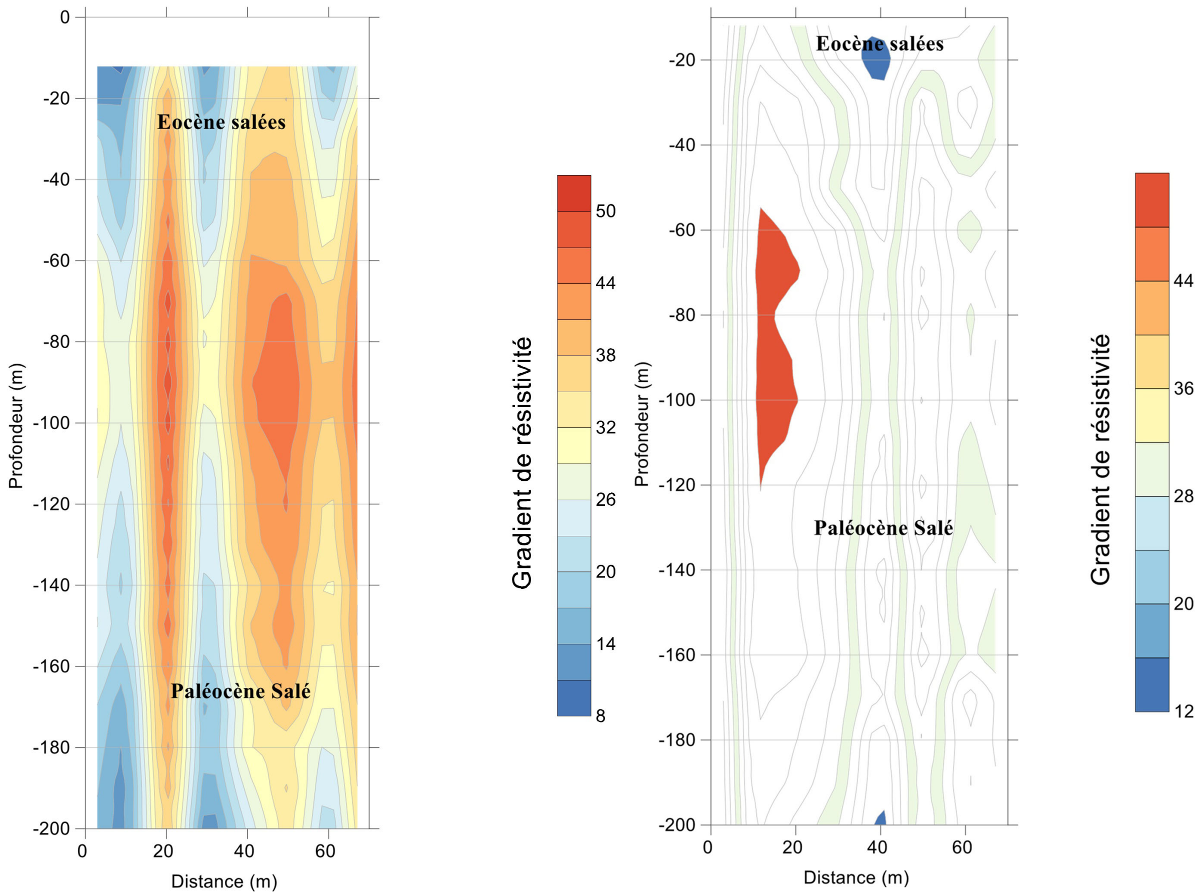

Figure 5. SEM electromagnetic survey profiles.

4.1. Evolution of the River Channel

Following processing of the bathymetric data using Global Mapper software, the resulting maps show depths ranging from −1.39 m to −5.04 m. Analysis of the channel morphology reveals marked transverse asymmetry, with the bathymetric axis shifted towards the concave bank (Figure 6). This configuration is characteristic of meandering channels, whose dynamics are controlled by the asymmetric distribution of current velocities and the shear stresses exerted on the banks (Leopold et al., 1964; Schumm, 1977). The concave, steep bank, which is subject to active erosion, corresponds to the deepest part of the channel. Hydrodynamic measurements indicate current velocities of up to 0.38 m/s at the surface and 0.17 m/s near the bed. These relatively high values promote lateral erosion and channel deepening, in accordance with the mechanisms described in classical models of river dynamics (Leopold et al., 1964; Bridge, 2003). Conversely, the convex bank exhibits lower velocities, of the order of 0.13 m/s at the surface and 0.08 m/s at depth. This reduction in hydrodynamic energy promotes the settling and accumulation of sediment particles, leading to the formation of deposits on the inner bank of the meander (Schumm, 1977; Knighton, 1998). The spatial distribution of depths and velocities observed in this channel thus reflects the typical hydrosedimentary behaviour of meandering systems, characterised by a concentration of erosion on the concave bank and preferential sedimentation on the convex bank (Leopold et al., 1964; Bridge, 2003). This morphodynamic organisation contributes to the gradual evolution of the meander through lateral channel migration.

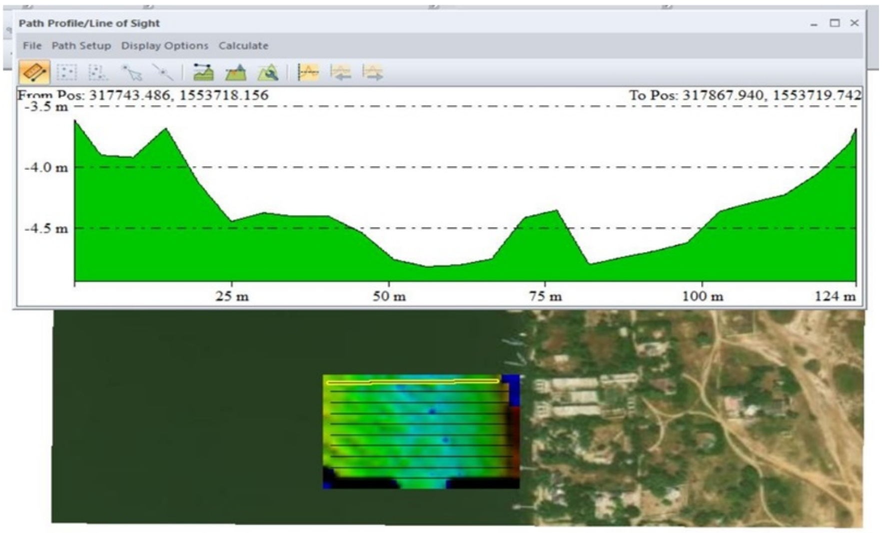

Figure 6. Bathymetric profile of the channel off the Mar Islands.

4.2. Dynamics of River Erosion in the Mar Islands

A diachronic study of the coastline conducted between 2013 and 2023 has enabled the estimation of the rates of coastal retreat observed in the Mar area. The results show widespread coastal erosion, with an average rate of retreat of around −0.62 m/year upstream of the Mar Islands. Downstream, this process is more pronounced, reaching nearly −0.96 m/year (**Figure 7**). These values indicate significant morphological instability of the banks in this sector. This erosive process mainly affects the concave bank of the channel, which is characterised by a relatively steep slope and greater depths. It results from the concentration of hydrodynamic energy on the outer bank of the meander, where higher flow velocities increase the shear stresses exerted on the bed and banks, thereby promoting their erosion (Leopold et al., 1964; Schumm, 1977; Bridge, 2003).

This phenomenon is exacerbated by a shortage of sediment supply capable of compensating for losses due to erosion. Conversely, the convex bank exhibits a pattern of sediment accumulation. The low current velocities observed in this area reduce the transport capacity of particles and encourage their deposition. This gradual sedimentation contributes to the smoothing of the bathymetric profile, resulting in shallower depths and a less steep gradient. This spatial organisation of erosion and deposition processes corresponds to the classic behaviour of meandering channels, in which erosion predominates on the concave bank whilst sedimentary deposits develop on the convex bank (Knighton, 1998; Hooke, 2003). Thus, changes in the coastline in the Mar area appear to be closely linked to the interactions between the channel morphology, local hydrodynamic conditions and sediment availability, which together govern the erosion and accretion processes observed.

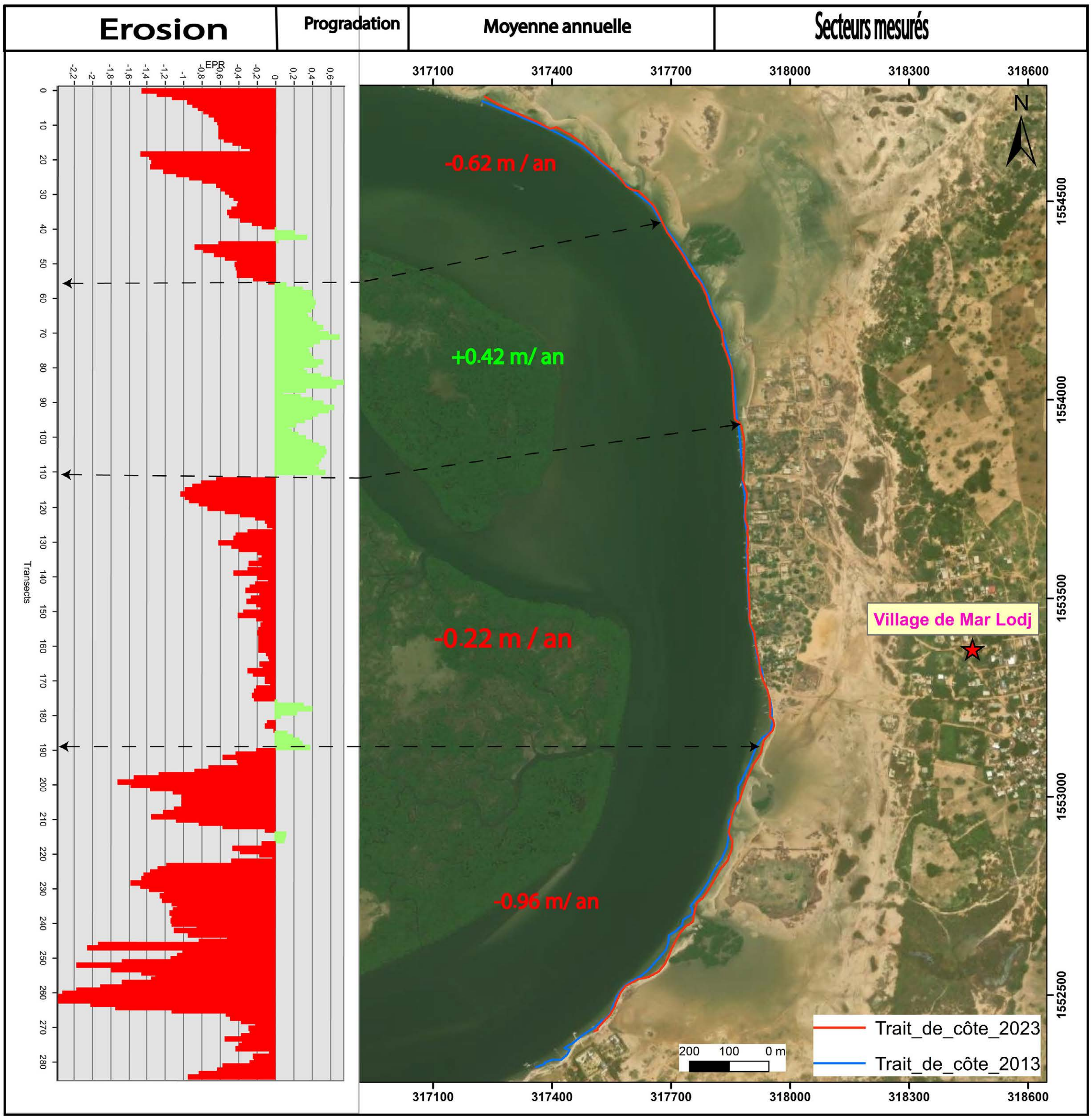

Figure 7. Changes to the coastline between 2013 and 2023 in the Mar Islands.

The study's findings show that active bank erosion and lateral channel migration are gradually altering local hydrodynamic and hydrogeological conditions.

The retreat of the coastline, combined with the deepening of the channel on the concave bank, promotes exchange between estuarine surface waters and shallow aquifers. In the context of the Saloum Delta, characterised by high salinity in estuarine waters, this exchange can exacerbate saltwater intrusion into shallow aquifers, leading to a deterioration in groundwater quality (Faye et al., 2003; Faye et al., 2005).

Furthermore, the reduction in freshwater inflow and the increase in areas subject to tidal influence contribute to the concentration of dissolved salts in surface formations. Evaporation processes, which are particularly intense in the Sudano-Sahelian regions, also contribute to increased groundwater mineralisation. This situation results in high concentrations of chlorides, sodium and sulphates, as well as an increase in the electrical conductivity of the water (Ndoye et al., 2018).

Conversely, areas of sediment accumulation located on the convex bank may encourage the development of fine clay-silt deposits that could locally restrict exchange between estuarine waters and shallow aquifers. However, across the Saloum Delta, the progression of salinisation remains largely controlled by estuarine dynamics, climatic fluctuations and the geological conditions of the aquifers. Thus, the erosion and sedimentation processes observed in the Mar area do not merely alter the morphology of the banks; they also influence recharge conditions and hydraulic exchange between surface water and groundwater. This interaction contributes to the gradual deterioration of surface water quality, which is already affected by saline intrusion and high concentrations of dissolved elements observed in several areas of the Saloum Delta.

5. Conclusion

In conclusion, the study of the Mar Islands highlights a morphosedimentary dynamic that is strongly controlled by the hydrodynamic processes governing the evolution of the channels in the Saloum Delta. Bathymetric, hydrodynamic and diachronic analyses of the coastline reveal active erosion of the concave bank, characterised by greater depths, high current velocities and retreat rates of up to 0.96 m/year. Conversely, the convex bank constitutes a zone of sediment accumulation favoured by low current velocities and conditions conducive to sedimentation. This spatial pattern of erosion and deposition processes reflects a gradual lateral migration of the channel, which is likely to cause lasting changes to the morphology of the islands and banks. Beyond its geomorphological impacts, this dynamic also influences local hydrogeological conditions. Bank erosion and the deepening of the channel promote exchange between estuarine waters and shallow aquifers, exacerbating the salinisation phenomena already observed in the Saloum Delta. Thus, morphological changes to the environment act as an aggravating factor in the deterioration of groundwater quality, particularly in the areas most exposed to saline intrusion. The results therefore highlight the existence of close interactions between coastal dynamics, hydrosedimentary processes and the quality of water resources. A better understanding of these mechanisms appears essential for the sustainable management of the island ecosystems and water resources of the Saloum Delta, in a context marked by increasing climatic and anthropogenic pressures.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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