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Dynamic Evolution of the Joal and Djiffère Spits under the Influence of Atlantic Ocean Activity

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Abstract

Changes in the coastline are characterized by accretion and erosion. The aim of this study is to contribute to a better understanding of the dynamics of the coastline and the study areas with a view to mitigating and preventing the risk of coastal erosion in order to propose a coastal occupation model with planned development policies in the future. These phenomena lead to changes in the position of the coastline. After extraction, the satellite images are compiled, then superimposed and processed using Geographic Information Systems (GIS) for statistical calculation of coastline change rates. A morphosedimentary study is carried out using topography and sedimentology. The topographic method is used to calculate sediment volumes using monthly profiles. The sedimentological method is used to determine the granulometric variations in the morphological units by calculating sedimentological indices. With erosion rates of −2.13 m/yr and −2.17 m/yr respectively at Djiffère (Palmarin and Sangomar breccia) and Joal (Joal Fadhiouth and Ngazobil), the EPR index revealed a sediment deficit. Palmarin Ngallou and the island of Fadhiouth are undergoing accretion at rates of +1.43 m/yr and +1.14 m/yr respectively. From a topographical point of view, the respective accumulations of −13.74 m^3/m of beach and −8.65 m^3/m of beach at Djiffère and Joal respectively point to significant erosion on all the aerial beach units, while for the underwater beaches, accretion was noted with accumulations of +4.00 m^3/m of beach and +5.94 m^3/m at Djiffère and Joal respectively. As for the sedimentological results, the Mz index shows a decrease in grain size from the high beach to the surf zone. Some points show bimodal deposits, showing the impact of the dune on beach activity, confirmed by the dispersion on the Mz-sigma diagram. The three methods used in this work show that the Djiffère sector in Joal is dominated by erosion, even though accretion points can be noted.

Keywords

Coastline, Mapping, Erosion, Accretion, Morphosedimentary

1. Introduction

The dynamics of coasts and coastal massifs are one of the main environmental problems facing coastal areas around the world and in West Africa [1]. Senegal, a coastal country located at the extreme end of West Africa, is also subject to these changes [2] (Faye I, 2010), the factors of which may be intrinsic or external and strongly impacted by the activities of riverside populations. These populations are moving closer to the marine zone, which is conducive to income-generating activities. However, with climate change, coastal erosion [3] is becoming more pronounced, the extent of which depends on both geographical (swell, waves) and geological factors. As a result, coastal erosion has a major impact on the environmental balance, leading to a loss of surface area that can be deplorable. It is important today to combat this phenomenon in order to preserve our coasts and the infrastructures built on them, but also to protect the tourist industry, since most of the attractive sites and dedicated accommodations (hotels) are located there. This work will therefore involve defining the fluctuation of the coastline over the last few decades and its impact on the Joal and Djiffère sectors, two sites known for their tourist attractions, fishing and other coastal activities. Analysis of the evolution of the coastline has been the subject of previous studies in Senegal in various localities [4]. The overall trend identified by these studies is erosion at most of the sites studied using various methods. The aim of this article is to contribute to a better understanding of coastal dynamics using a cartographic and statistical approach. In order to do this, it is necessary to characterize the morphological units of beaches by studying variations in granulometric indices and the volumes of sediment mobilized by dynamic agents. We will therefore determine the rates of shoreline change at Djiffère and Joal using the DSAS 5.0 model under ArcGIS software, by calculating mobility indices (EPR and LRR) [5]. This will be validated by site visits to check compliance. The morphosedimentary evolution of this zone is studied using topographic and sedimentological methods. The topographic method consists of measuring the morphology of the beach using a series of profiles perpendicular to the shoreline, from the back beach to the surf zone; this makes it possible to observe the monthly morphological variations of the beach in response to the action of dynamic agents throughout the monitoring period [6]. The sedimentological analysis will make it possible to determine the granulometric variations of the transverse profiles by taking monthly soil samples in the different morphological units of these beaches and calculating the appropriate coefficients [7].

2. General Context of the Coast

Senegal's coastline is an area of strategic demographic, economic and environmental interest. The natural environments, in a relatively well-preserved state, produce vital resources for the Senegalese population [2]. Senegal's national economy is highly dependent on these coastal and marine resources, which are the main source of foreign exchange earnings, whether from fishing or tourism. On the

Senegalese coast, tidal currents have speeds of less than 0.15 m·s^{-1} [3] and play a minor role in the morphological evolution of the shoreline. Djiffère and Joal are two communes in the department of Mbour located on the short coast characterized by sandy beaches. In places, they are backed by a sharp micro-cliff of variable height, but less than 2 m, cut locally into shellfish sands. They are oriented NW-SE, approximately 130 km south of Dakar and 30 km from Mbour, with a straight coastline [8], dotted with dunes up to 1.80 m high, peaking at 4.20 m, and with maximum depressions of less than 1.10 m [9]. This coastline is characterized by the presence of mangroves, tan and shell mounds (**Figure 1**).

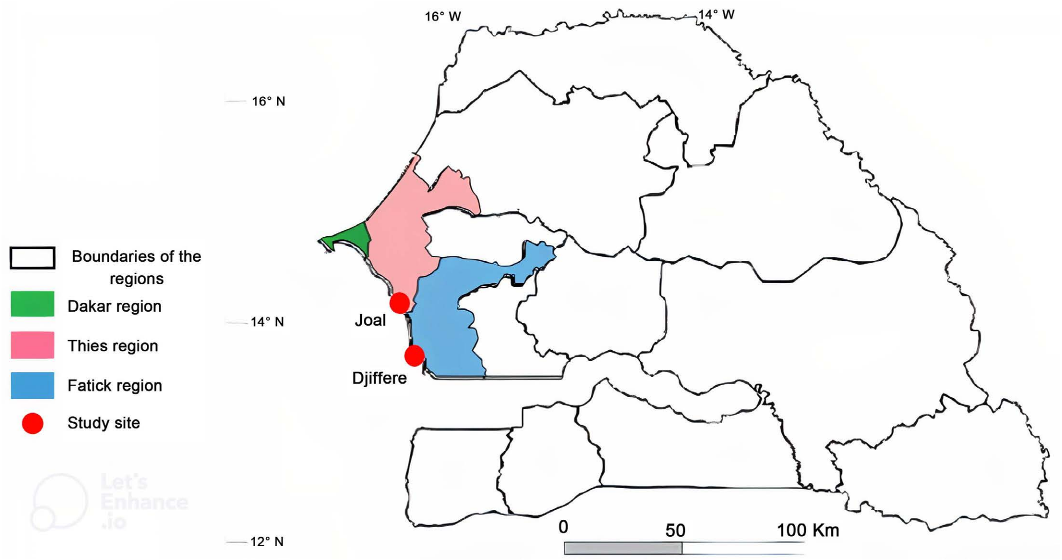


Figure 1. Location of study areas.

The geology of the study area is part of the Senegal-Mauritania basin. The outcrops are of Upper Paleocene to Lower Eocene age, with successive horizons consisting of [10]: marl, attapulgite and flinty clayey limestone overlaid by alternating limestone and clay banks rich in fossils that have been eroded in some places. This is followed by a lateritic cuirass with ferruginous gravel and a sandy clay matrix discordant with the previous layers. This is covered by the dune sand found throughout most of the region. The two sandy coastal spits at Joal and Djiffère have been dated to the postglacial period (Post-Nouakchottian) at around 4500 BC [11].

3. Methodological Approaches

3.1. Visualisation of Coastal Development Trends

Several indicators can be used to determine the coastline [12]. In this work, it corresponds to the boundary between dry and wet sand (**Figure 2**).

In our case study, coastlines are extracted by digitally processing a series of Landsat 7 and 8 multi-date images for the periods 1985, 1997, 2009 and 2021. The downloaded images are imported into IDRISI Selva (a combination of three

Figure 2. Dry sand/wet sand boundary.

spectral bands deemed sufficiently clear) for processing and classification. The classified images are subjected to a colour composition in order to obtain colour images based on the signature of the objects. This classified image will make it possible to highlight the clear boundary between the populations of pixels representing the open sea area (dark pixels) and the land area (light pixels) (**Figure 3(a)**).

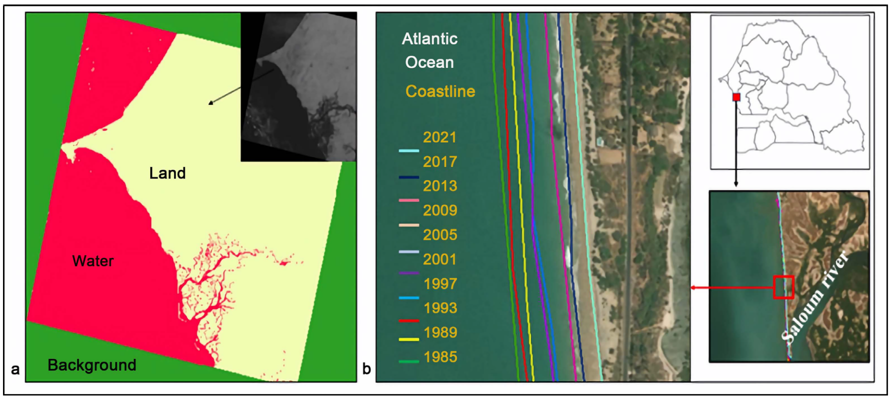


Figure 3. Classification and extraction of features ((a) Classification of downloaded image; (b) Digitisation of dimension lines).

The files recorded in shapefile format under IDRISSI as classified images are imported into ArcGIS for the extraction and digitisation of coastlines. The extraction of the coastline in Arcgis begins with an initial conversion of the raster image into a polygon. In an editing window, the population of pixels representing the terrestrial domain is removed. The polygon is then transformed into a polyline to obtain the marine domain. From the contours, we remove the contrasts on the polyline image and the contours to obtain the open sea/continent boundary. This corresponds to the digitized coastline. All of this is projected into a WGS_1985_UTM_Zone_28N coordinate system. These coastlines constitute the input data for the DSAS (Digital Shoreline Analysis System) extension, which will be used for statistical calculations of shoreline evolution rates (**Figure 3(b)**). The sum of the global coastline positioning errors for each time step is used to integrate the margin of error into the analysis results. These errors are calculated from Equations (1) and (2) [13].

$$Ept = \frac{\sqrt{(Ep)^2 + (Eg)^2 + (Ed)^2}}{1} \qquad \text{Equation (1)}$$

$$E\alpha = \frac{\sqrt{(Ept1)^2 + (Ept2)^2}}{\text{Période}} \qquad \text{Equation (2)}$$

Ept: Global coastline position error;

Ep: Pixel error (spatial resolution);

Eg: Georeferencing error (RMS);

Ed: Digitisation error;

Eα: Average overall error in m/year.

Once the data has been formatted in a personal geodatabase, a baseline is created and the shorelines imported into the personal catalogue (**Figure 4**). Indices are calculated using two shorelines of different dates. An estimate of the uncertainty associated with the method and the choice of statistics for calculating rates of change are taken into account [14]. Transects perpendicular to the shoreline are generated at 50 meters' intervals from the baseline. After calculation, the End Point Rate (EPR) and Linear Regression Rate-of-change (LRR) indices [2], were selected from the transect attribute table to plot the variation diagrams for coastline change rates using Excel.

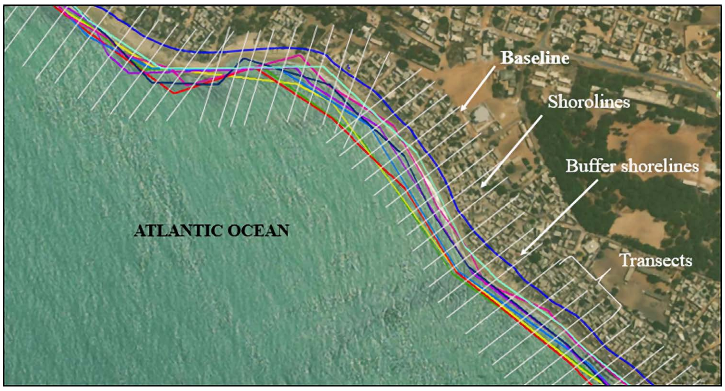


Figure 4. Entities in a custom geodatabase.

3.2. Morph Dynamic Evolution of the Different Coastal Units

3.2.1. The Topographic Method

For monitoring purposes, a series of topographic profiles perpendicular to the shoreline are taken from the surf zone to observe the monthly morphological variations due to hydrodynamic agents [15]. Three beach profiles, P1, P2 and P3, were surveyed at each study site, covering the two main morphological units: the aerial beach (the foreshore, upper beach) and the underwater beach at each site (**Figure 5**).

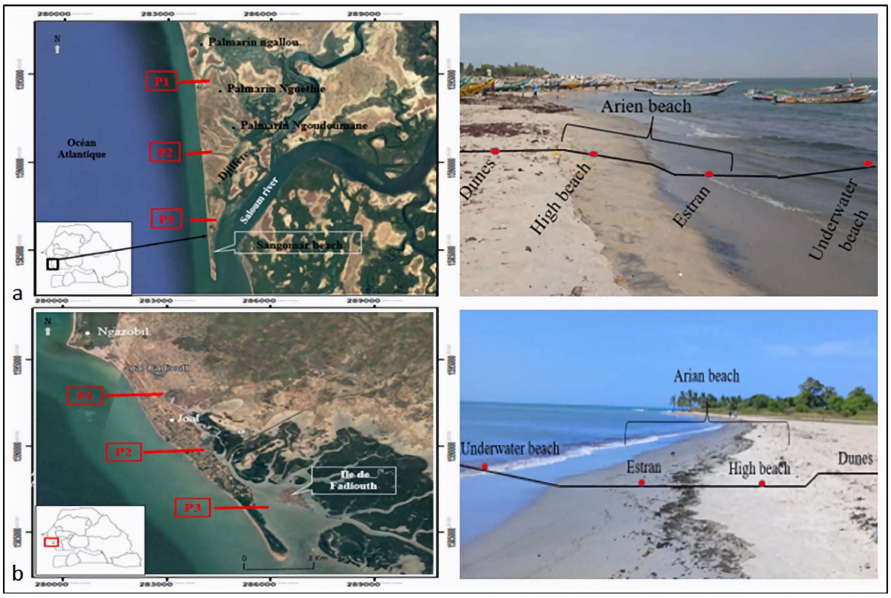


Figure 5. Position of profiles and morphological characteristics ((a) = Djiffère arrow, (b) = Joal arrow).

The data collected is integrated into Excel to determine the morphological units of the beaches and the volumes of sediment mobilized per meter of beach by the dynamic agents. Adobe Illustrator will be used to delineate and annotate these units. The average slope is defined by Equation (3). The volumes of sand eroded or accumulated in each profile are determined from Equation (4).

$$P(\%) = \frac{\Delta H}{\Delta D} * 100 \qquad \text{Equation (3)}$$

P = average slope in %;

ΔH = height difference (m);

ΔD = distance (m).

$$V = \mathrm{S} \times 1 \qquad \text{Equation (4)}$$

V = Volume eroded or accumulated in m^3;

S = Eroded or accumulated surface area in m^2;

1 = linear meter of beach.

3.2.2. The Sedimentological Method

The aim of the study of morphosedimentary evolution is to determine the monthly granulometric variations of the transverse profiles. Samples were taken along each topographic profile by simply scraping the surface layer of sediment to avoid having samples that were mixtures of different laminates [16]. Four sampling points were considered on each profile: the high beach, the mid-foreshore, the sea level, also known as the low foreshore, and the wave breaking zone located in the underwater beach (**Figure 6**).

Considering all the profiles, it can be seen that the study sectors are characterized by sandy sediments with a medium to fine grain size [17]. Textural analysis

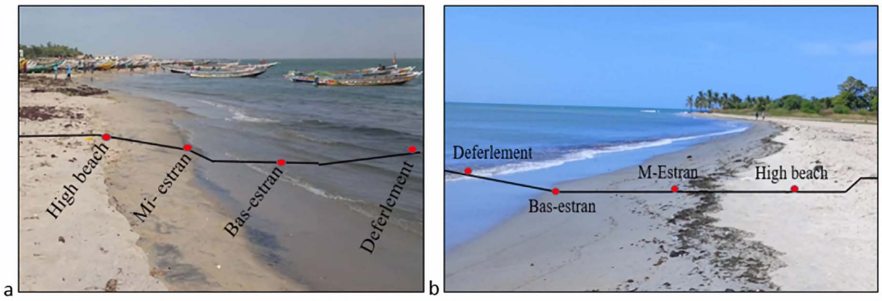


Figure 6. Sampling points on the beach ((a) Djiffère spit, (b) Joal spit).

was carried out using the usual granulometric techniques, by dry sieving samples of the coarse fraction (Ø > 63 µm), washed and dried, on a series of sieves from the "AFNOR" range. This washing consists of removing salts, impurities and the fine fraction usually made up of silt and clay. After drying, a weight of 180 g of these dry sediments was taken and cold-attacked with 30% dilute hydrochloric acid to eliminate the carbonates. The energy of the medium was characterized using the mean particle size Mz (Equation (5)) supplemented by the Wentworth classification. The grading index σ (Equation (6)) defines the grain size distribution and the asymmetry index SK (Equation (7)) is used to assess grain spread [18] (**Figure 7**).

$$Mz = \frac{Q_{16} + Q_{50} + Q_{84}}{3} \qquad \text{Equation (5)}$$

Q represents the quartiles.

The formula used is as follows:

$$\sigma = \frac{Q_{84} - Q_{16}}{4} + \frac{Q_{95} + Q_{5}}{6,6} \qquad \text{Equation (6)}$$

Skewness close to zero.

$$SK = \frac{(Q_{16} + Q_{84}) - 2Q_{50}}{2(Q_{84} - Q_{16})} + \frac{(Q_{5} + Q_{95}) - 2Q_{50}}{2(Q_{84} - Q_{16})} \qquad \text{Equation (7)}$$

4. Results and Discussion

4.1. Evolutionary Trend with the DSAS Model

Between 1985 and 1997, the Djiffère and Joal sectors recorded respective coastline advances of 16.05 m (**Figure 8(a)**) and 18.6 m between Ngazobil and Joal (**Figure 8(b)**), corresponding to erosion. On the other hand, to the south of the Joal sector, a retreat of 6.12 m was recorded at Fadhiouth and Fadhiouth Island (**Figure 8(b)**). Between 1997 and 2009, the variation was irregular, with a maximum retreat of 11.2 m towards Palmarin Nguethie and an advance of 8.12 m at Djiffère (**Figure 8(a)**), a retreat of 12.6 m between Ngazobil and the village of Joal and an advance of 24.15 m for the island of Joal (**Figure 8(b)**). Between 2009 and 2021, the recession became more significant along the entire beach, with an average value of 14.21 m at Djiffère (**Figure 8(a)**) and an average advance of 19.25 m at Joal

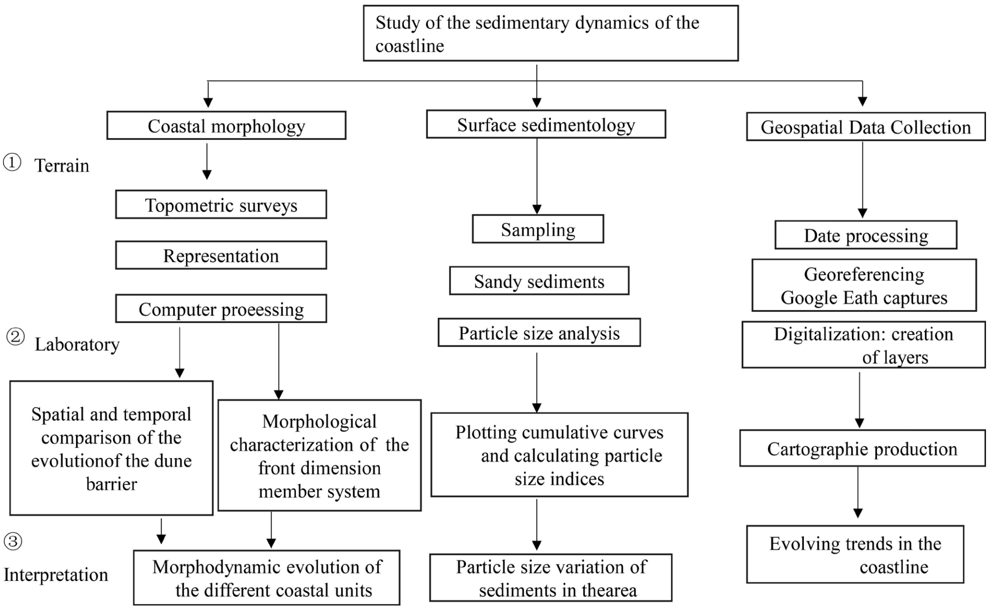
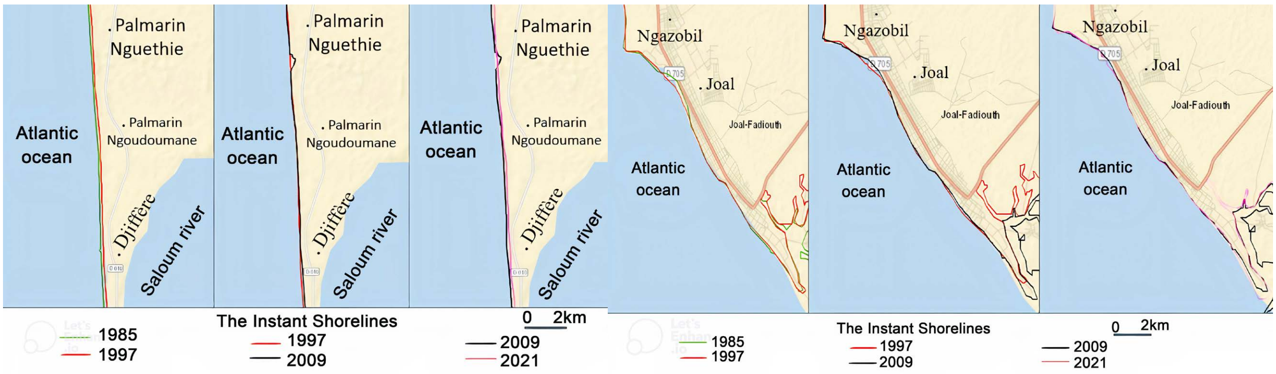


Figure 7. Methodology adopted in the study of sediment dynamics in the coastal system.

(**Figure 8(b)**). The EPR index between 1985 and 2021 shows a sediment deficit at Palmarin and on the Sangomar breach, with erosion rates of up to −2.13 m/year, although accretion is noted between 2009 and 2021 with an average rate of +1.43 m/year (**Figure 9**). For the same period, the Joal EPR index shows that the north of the segment (from Joal fadhiouth to Ngazobil) is eroding at a rate of −2.17 m/year, while the south (the island of fadhiouth) is accreting at an average rate of +1.14 m/year. Erosion is more intense at Joal than at Djiffère (**Figure 10**). This activity is the result of hydrodynamic factors. The accretion is partly linked to the ban on mining beach sand during this period.

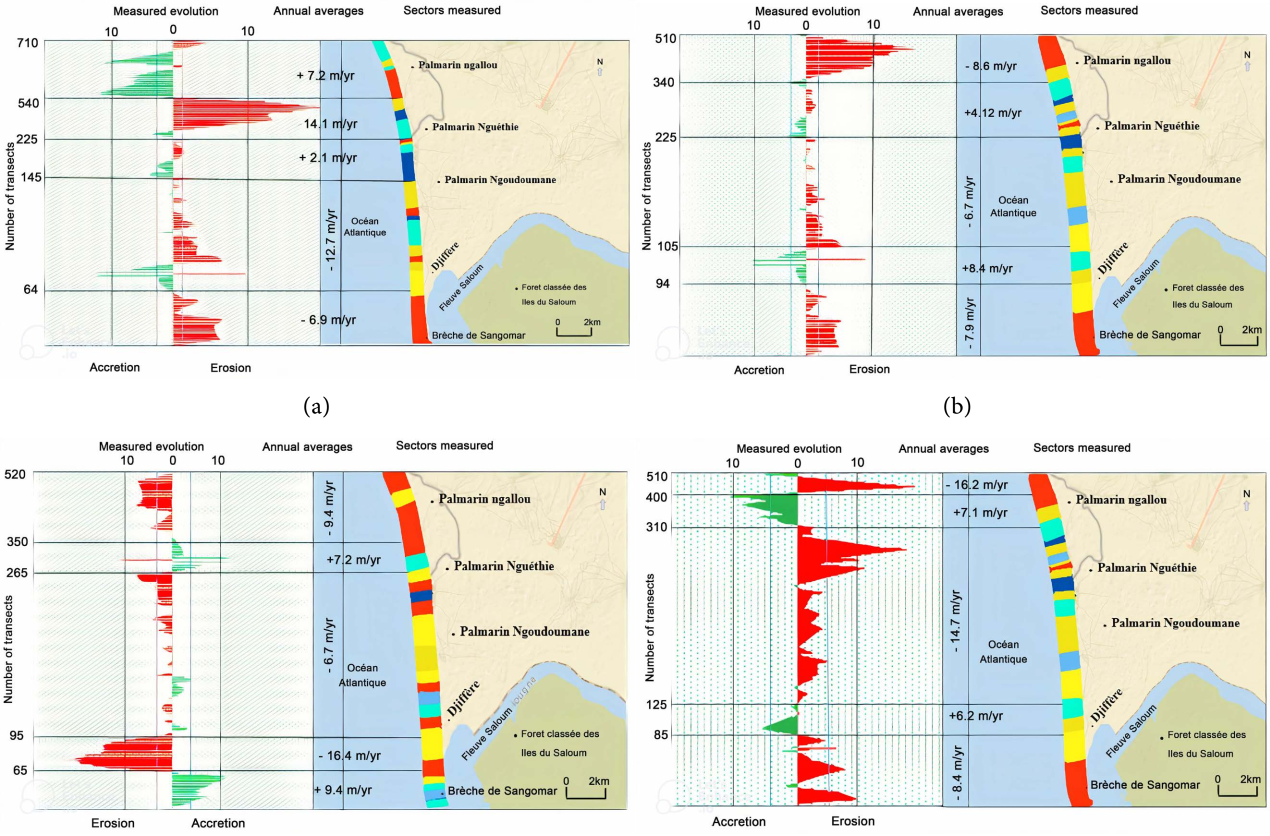
4.2. Morphosedimentary Evolution

Superimposition of the topographic profiles shows strong erosion activity with some accumulation points (**Table 1**). The evolution of the profiles over time and space, as well as that of the morphological characteristics, confirms the erosion dynamics of the sites studied. Erosion dominates at P1 and P2 for Djiffère and P2-P3 for Joal, with respective accumulations of −13.74 m^3/m of beach and −8.65 m^3/m of beach at the aerial beach. Positive accumulations were noted at profile P3 for Djiffère and P1 for Joal, with +4.00 m^3/m and +5.94 m^3/m of beach respectively. These accumulations were noted on the aerial beach at Joal and the underwater beach at Djiffère (**Table 1**). For both sectors (Djiffère and Joal), the volumes of sediment involved on the upper beach are greater than those on the foreshore (**Table 1**). From a sedimentological point of view, the monthly change in the mean particle size at the stations is more significant at the foreshore level, regressing at the surf level between November 2022 and December 2022 and increasing very rapidly during the January-April 2023 period for P2 and P3. For P1, it is still regressive (**Figure 11** and **Figures 12(a)-(c)**). The mean particle size Mz along the profiles shows that the upper beach has the coarsest sediments and their diameters gradually decrease towards the surf zone (Figure 11 and Figure 12(d)). Analysis of the morphosedimentary evolution shows a predominantly positive asymmetry indicating a spreading of the particles towards the fines. The Mz-sigma scatter plot shows the bimodal nature of the sediments, with energy variability (Figure 13).



(a) (b)

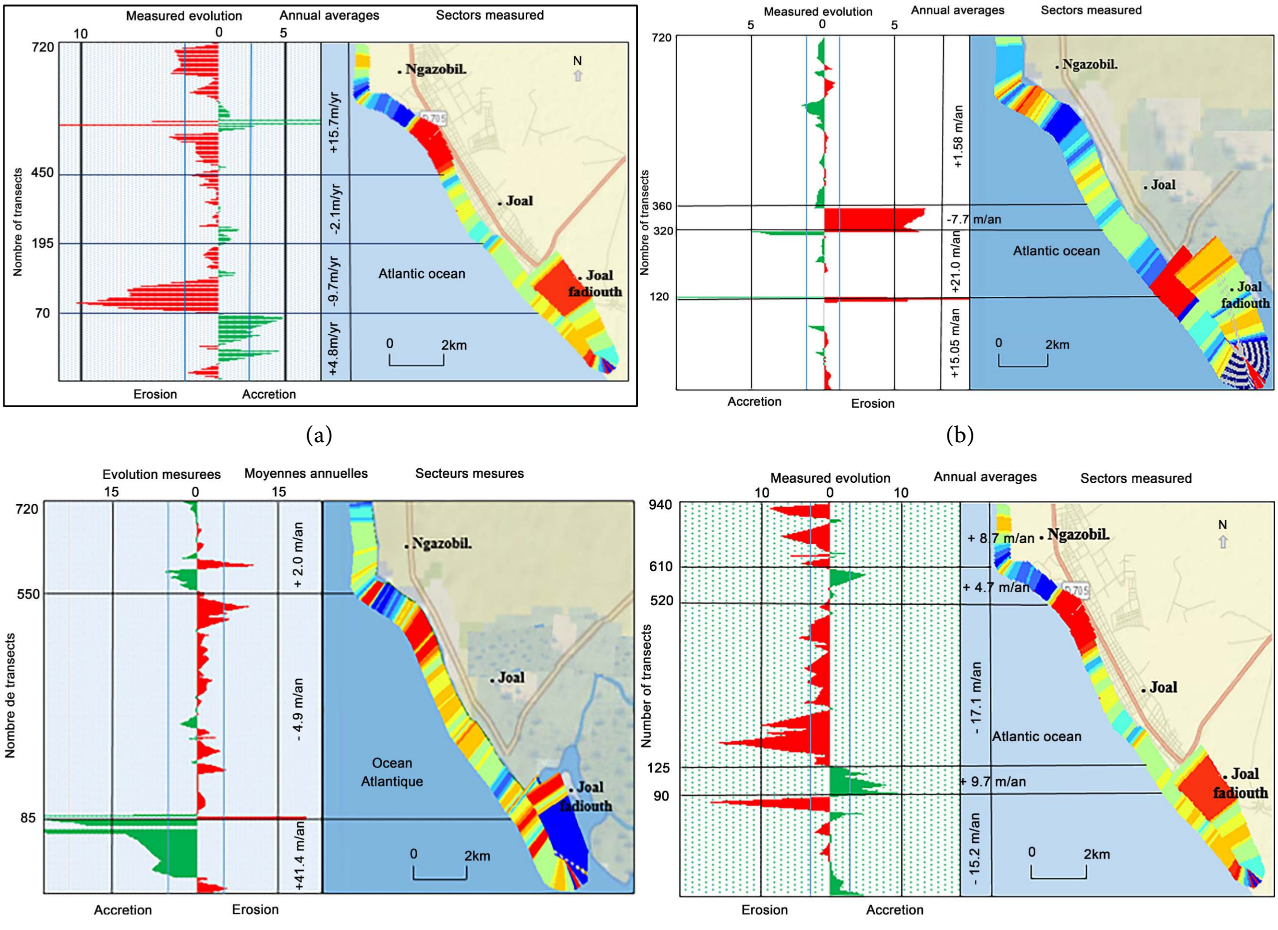
Figure 8. Position of the shoreline between 1985, 1997, 2009 and 2021: ((a) Djiffère site; (b) Joal site).



(a) (b)

(c) (d)

Figure 9. Spatial and temporal evolution of the shoreline on the Djiffère spit ((a) = EPR 1985/1997, (b) = EPR 1997/2009, (c) = EPR 2009/2021, (d) = synthesis over the whole EPR 1985/2021 period).



(a)

(b)

(c)

(d)

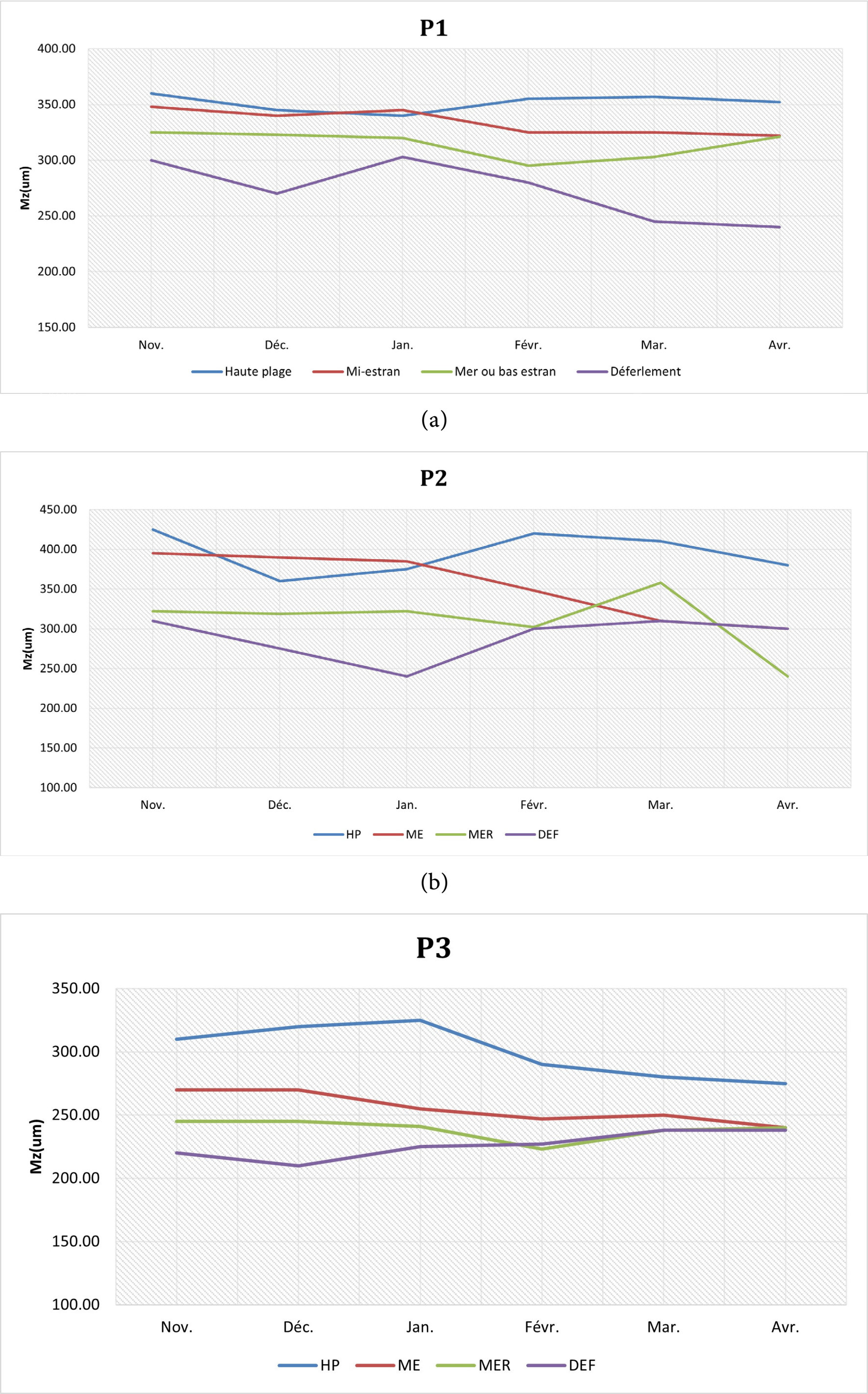
Figure 10. Spatial and temporal evolution of the shoreline on the Joal spit ((a) = EPR 1985/1997, (b) = EPR 1997/2009, (c) = EPR 2009/2021, (d) = synthesis over the whole EPR 1985/2021 period).

Table 1. Evolution of vertical movements (expressed in m^3/m of beach) on the different morphological units of the Djiffère spit and the Joal spit.

Djiffère arrow	High beach			Foreshore			Underwater beach		
	P1	P2	P3	P1	P2	P3	P1	P2	P3
November-December 2022	−3.34	+8.95	−4.05	−0.41	−3.44	+5.49	−0.96	+1.47	−5.19
December 2022-January 2023	−4.57	−8.91	+7.41	−9.55	−2.11	−3.14	+6.30	−3.42	+8.45
January-February 2023	+12.11	−1.3	+2.75	+4.75	−8.13	−0.21	+3.44	−1.91	−7.72
February-March 2023	−4.67	−6.37	−11.44	+2.36	+11.32	−0.29	+3.61	−0.44	−1.36
March-April 2023	+4.01	+2.98	+6.66	−4.38	−11.38	+2.15	−5.12	+3.02	−1.13
Cumulative	**−0.47**	**−4.65**	**+1.33**	**−7.23**	**−13.74**	**+4.00**	**+7.27**	**−1.28**	**−6.95**
Joal arrow	**High beach**			**Foreshore**			**Underwater beach**		
	P1	P2	P3	P1	P2	P3	P1	P2	P3
November-December 2022	+5.19	−2.71	−1.73	+3.95	+6.58	+2.25	+0.76	−1.6	−1.64
December 2022-January 2023	+3.39	−5.44	−3.67	−0.91	−9.61	−4.19	−4.25	−7.49	+2.49

Continued

January-February 2023	−11.26	−6.42	+4.04	−8.73	−3.92	+2.92	−5.12	−1.05	+4.47
February-March 2023	+13.47	+9.26	+3.44	+12.63	+6.30	−4.37	+4.78	+3.29	−4.47
March-April 2023	−4.85	−3.34	−5.08	−2.63	−1.64	+3.25	−4.32	−2.82	−2.16
Cumulative	**+5.94**	**−8.65**	**−3.00**	**+4.31**	**−2.29**	**−0.14**	**−8.15**	**−9.67**	**+1.31**



(a)

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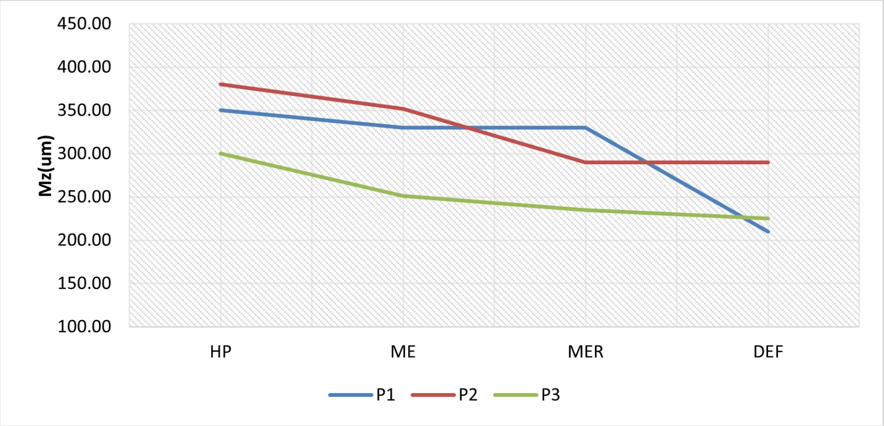
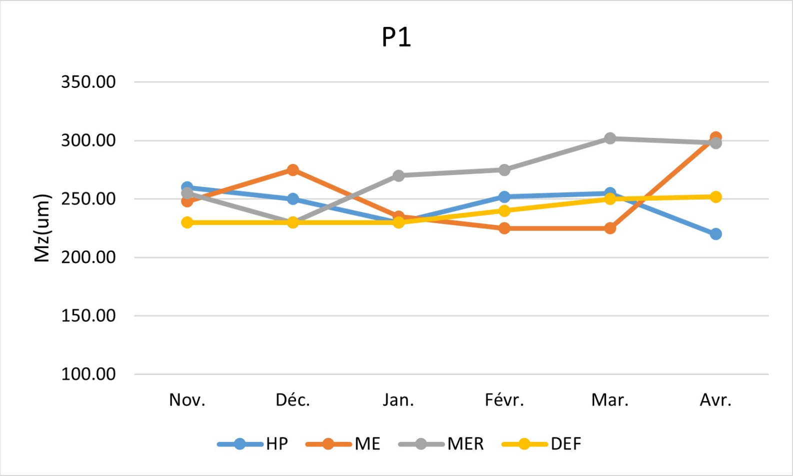
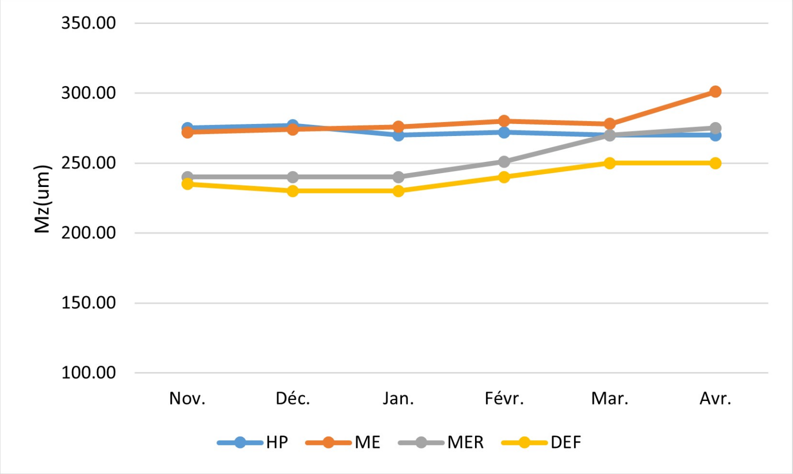


(d)

Figure 11. Variation of the granulometric indices on the various morphological units of the Djiffère sector ((a) = variation of the granulometric averages of P1, (b) = variation of the granulometric averages of P2, (c) = variation of the granulometric averages of P3 and (d) = Variations of the Mz average along P1, P2 and P3).



(a)



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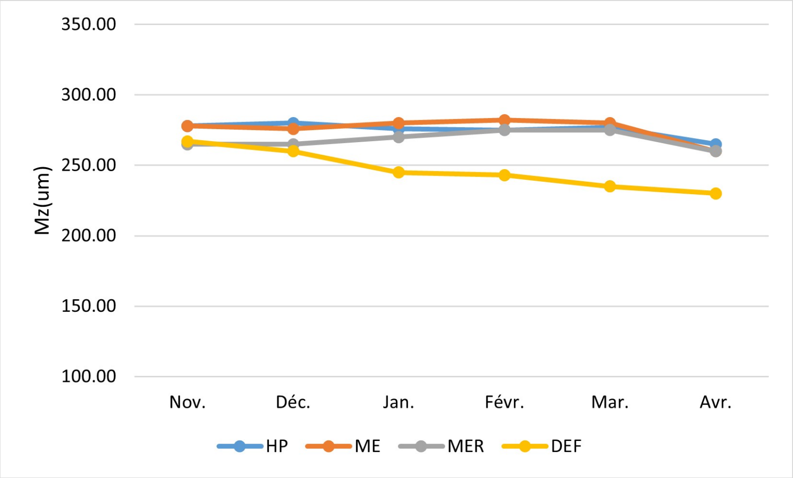

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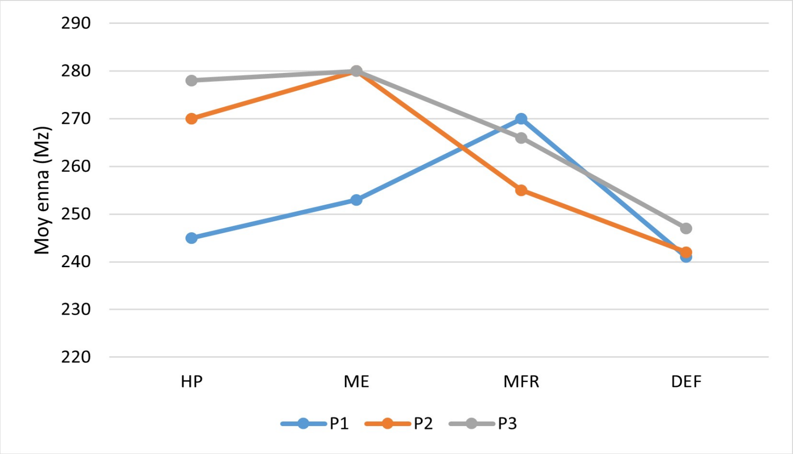
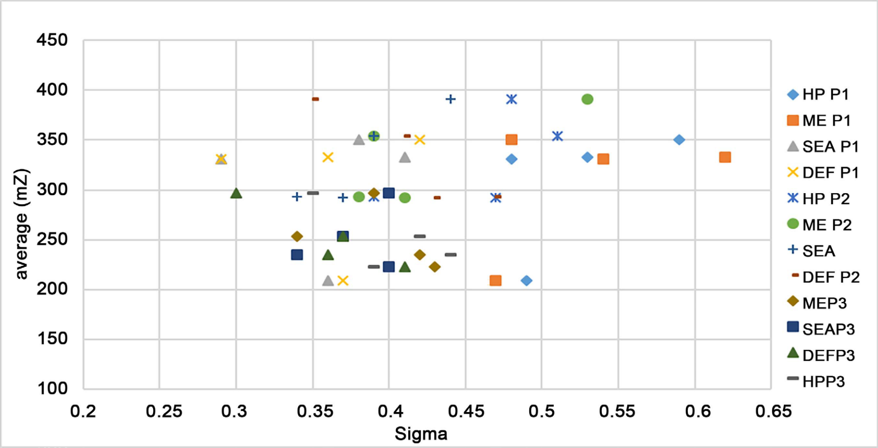
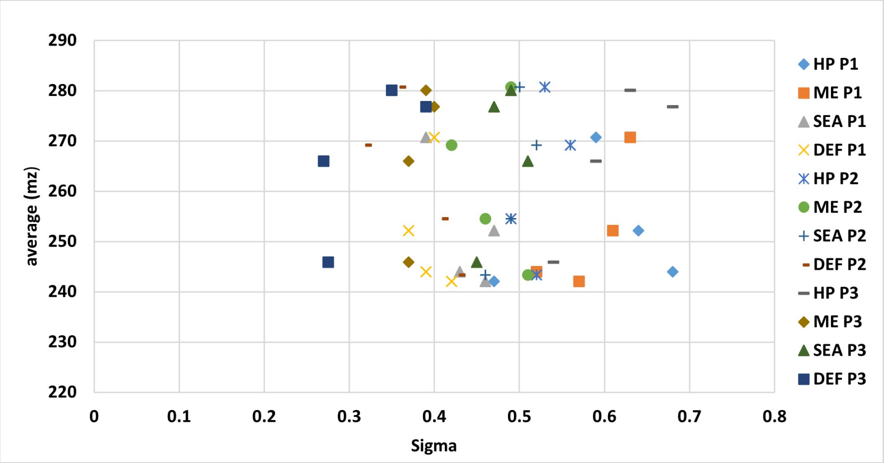


(d)

Figure 12. Variation in particle size indices for the different morphological units in the Joal sector ((a) Variation in average particle size for P1, (b) Variation in average particle size for P2, (c) Variation in average particle size for P3, (d) Variation in average Mz along P1, P2 and P3).



(a)



(b)

Figure 13. Mz-Sigma scatter plot as a function of morphological units in P1, P2 and P3. ((a) = in the Djiffère sector, (b) = in the Joal sector).

5. Conclusion

The study area is part of the "petite côte", whose dominant economic activities are fishing and related activities. We are increasingly witnessing the disappearance of this special area, threatened by natural and man-made phenomena. The need to protect coasts against erosion has become a major concern. The methodology consists, first of all, of visualizing the evolutionary trends of the coastline by processing satellite images with various applications. In this way, erosion and accretion rates at the coastline level will be determined. This will be followed by topographical studies to define the slopes of the shoreline at Joal and Djiffère. In addition, sedimentological analysis uses granulometric indices to define the granulometric distribution in order to deduce sediment dynamics. Both the topographic and sedimentological studies define the dynamics of the different coastal units. The evolution of the shoreline shows an overall erosive trend for the portion of the short coast from Joal to Djiffère. This leads to progressive beach loss. Erosion rates can reach -2.7m/year. These trends are confirmed by the monthly erosion profiles of the various morphological units and by the granulometric indices.

Conflicts of Interest

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

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