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Coastline Dynamics And Its Impacts In The Northern Part Of The Southern Rivers: The Case Of The Northern Coastline Of Guinea Bissau

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Abstract – The objective of this contribution is to analyse the coastline dynamics and its impacts on the northern coastline of Guinea Bissau. The methodology adopted consists in extracting the coastline using multidate Landsat satellite images and analysing the kinematics of the coastline using the DSAS (Digital Shoreline Analysis System) tool under ARGIS. The results of the cartographic processing of the multi-date images show that the sandy beaches of Guinea Bissau are subject to intense erosion phenomena. The first segment analysed, extending from Nhiquim to Bolor, is marked by an alternation of eroding and prograding segments between 1973 and 2018. This part of the Bissau-Guinean coastline is eroding at variable speed. The speed of erosion follows a North-South gradient with 0.21 and 1.8 m/year. The speed of retreat of the coastline is more accentuated in the 1970s on either side of Valera, i.e., 12 m/year in the north and 32.3 m/year in the south. The second segment runs from Mata De Uco to Bote. The highest rate of recession is noted in this part of the coastline studied, particularly during the period 1973-1986. The whole sector is eroding with a speed varying between 53.2 m/year and 0.15 m/year. The average rate of retreat is 19.1 m/year and falls freely between 1986-2003 and 2003-2018. The prograding sectors are in the south with a rate of retreat varying between 2.59 m/year and 8.50 m/year.

Keywords – Dynamics, Coastline, Guinea Bissau, Coastline, Impacts.

I. INTRODUCTION

The evolution of the coastline is a natural phenomenon generated by the conjunction of a certain number of dynamic processes (marine, continental, and biological) and dependent on the geomorphological characteristics of coastal systems [1]. In recent decades, coastal areas have been subject to the effects of climate change with the rise in sea level [2]. The Fifth IPCC report states an average rise of 0.28 to 0.98 m, with strong regional variations by 2100 [3]. These effects make coastal areas dynamic entities about the coastal erosion that affects the world's coastal regions [4]. The coastline is a constantly evolving space, subject to several influences that vary according to the different types of coastlines. These influences come from hydrodynamic factors such as variations in mean sea level, tidal and wave action, which induce coastal currents, climate forcing and human activities [5]. The fragility of the coastline is also linked to the nature of the geological and geomorphological formations that determine its resistance to erosion. The northern coastline of Guinea Bissau belongs to the large geostructural complexes that extend from the Saloum in Senegal to the Mellancorée in the Republic of Guinea. It is characterised by sedimentary formations dating from the Cretaceous and Tertiary periods, made up of deeply altered sandstone and clayey sand, and loose formations of recent input made up of sandy-muddy sediments sheltering the mangrove formations [6]. It is a region where sediment transport is dominated by fluvial inputs marked by a strong interception of morphological units including mangrove and lowlands. These interceptions lead to low sediment stocks in the pre-littoral zone and make the coastline vulnerable to erosion. The vulnerability of coastal zones to the impacts of climate change is a joint result of the dynamics of the natural environment and humans that shape the socio-ecological system [7].

The study of coastline kinematics requires working on long data series and time intervals [8] and the choice of an indicator [9]. The development of a coastline extraction method depends on the chosen indicator. Indicators are numerous and varied. There are about 38 reference line indicators materialising the position of the coastline [10]. These indicators are often chosen according to environments such as beaches and dunes, rocky cliff coasts, maritime marshes, mangrove swamps and artificial coasts (structures in the absence of a beach). In this contribution, the shoreline has been chosen as an indicator of coastline. The shoreline refers to the physical interface between land and sea [11]. The line corresponding to the water limit at low tide was identified as an indicator of the shoreline and coastline. The objective of this contribution is to analyse the spatial-temporal dynamics of the coastline and its impacts on the northern coastline of Guinea Bissau.

II. Geographical Framework Of The Area Studied

The study area is located between 11° 30' and 12° 15' north latitude and 16° 30' and 15° 45' west longitude (Figure 1). The geomorphology of the coastline is marked by a vast plain that extends into the interior of the country where low plateaus appear. It is a huge deltaic complex that constitutes a transitional environment between the maritime and continental domains with a relatively low topography all along the coastal zone. The coastal zone is characterised by recent sedimentary formations, predominantly alluvial with a generally flat relief. This characteristic facilitates coastal erosion, which worsens with the rise in sea level linked to the increase in temperature. The area studied is marked by the density of the hydrographic network composed of rivers and saltwater channels constantly invaded by the tides. The Guinea Bissau coastline is characterised by a humid sub-Guinean climate with an average annual rainfall of between 1500 and 2500 mm. The region is marked by two seasons due to the alternating circulation of the trade winds and the monsoon. A non-rainy season from November to April and a rainy season from May to October.

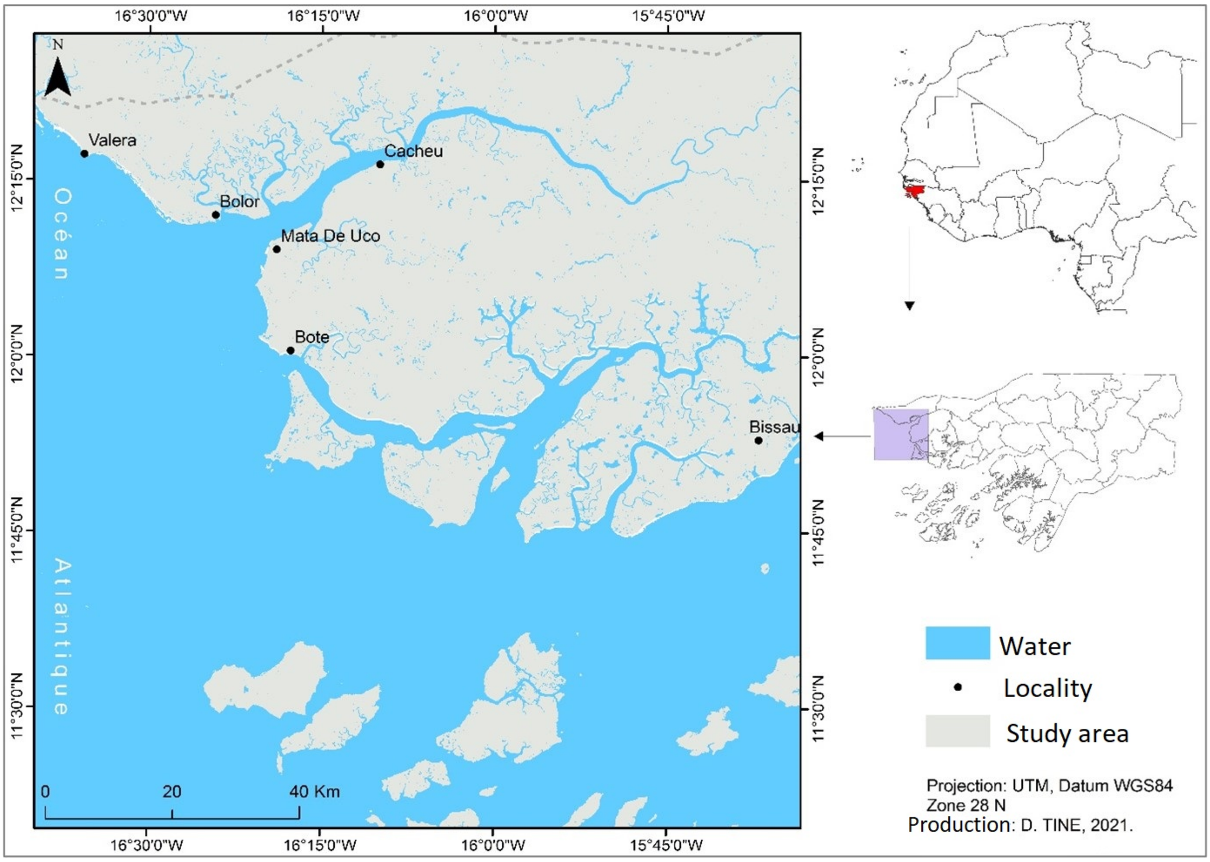

Figure 1: Spatial analysis sectors of the coastline evolution.

III. Materials And Methods

The methodological approach adopted in this study is different from the methodology frequently used in coastline kinematic studies using earth observation data. It is essentially based on the analysis of multi-date satellite images and automatic processing based on spectral thresholding.

3.1. The choice of the reference line

The shoreline corresponding to the water limit at low tide has been identified as an indicator of the shoreline and coastline. It is one of the indicators that can be retained insofar as the spatial resolution of the images is not fine enough to distinguish between this line and that of the high tide preceding the satellite's passage [12]. However, the spatial resolution of the images, their acquisition periods and the coastline are sources of error that must be considered. Tidal dynamics can be a source of error in coastline delineation based on the choice of shoreline. The alternation of high and low tides must be considered as well as the time of the satellite's passage over the regions studied.

3.2. Data used

The Landsat images used for this study (Table 1) were selected based on their availability, free access and age, covering a period from 1972 to the present day. They were downloaded from the Google Earth Engine (GEE) platform. The images contained in this platform undergo a series of corrections in order to increase the quality of the information and to minimise the uncertainty in the data, often linked to atmospheric disturbances. The corrected and ready-to-use data are made available to users free of charge. The GEE platform allows the analysis and visualisation of satellite images of our planet. This cloud platform brings together an archive of more than 40 years of satellite imagery, as well as tools with the computing power to analyse and exploit this huge geospatial database.

Table 1: Characteristics of the Landsat images used.

Sensor	Date of acquisition	Bands	Wavelengths	Resolution
MSS	1973	4-Blue	0,45-0,52 µm	60 m
		5-Green	0,52-0,6 µm	
		6-Red	0,63-0,69 µm	
		7- NIR	0,76-0,9 µm	240 m
Sensor	**Date of acquisition**	**Bands**	**Wavelengths**	**Resolution**
TM	1986	1-Blue	0,45-0,52 µm	30 m
		2-Green	0,52-0,6 µm	
		3-Red	0,63-0,69 µm	
		4- NIR	0,76-0,9 µm	
		5-SWIR 1	1,55-1,75 µm	
		7-SWIR 2	2,08-2,35 µm	
Sensor	**Date of acquisition**	**Bands**	**Wavelengths**	**Resolution**
ETM+	2003	1-Blue	0,45-0,52 µm	30 m
		2-Green	0,53-0,61 µm	
		3-Red	0,63-0,69 µm	
		4- NIR	0,78-0,9 µm	
		5-SWIR 1	1,55-1,75 µm	
		7-SWIR 2	2,09-2,35 µm	
Sensor	**Date of acquisition**	**Bands**	**Wavelengths**	**Resolution**
OLI	2018	2- Blue	0,45-0,51 µm	30 m
		3- Green	0,52-0,60 µm	
		4- Red	0,63-0,68 µm	
		5- NIR	0,84-0,88 µm	
		6- SWIR 1	1,56-1,66 µm	
		7- SWIR 2	2,10-2,30 µm	

3.3. Coastline extraction

In order to carry out a historical reconstruction of the coastline and to follow the spatial-temporal evolution, a spectral thresholding on the near-infrared channel was applied (figure 2). The land-sea contrast in the NIR justifies the choice of this band. The latter is extremely important in view of the information sought in the field. The result of the thresholding was vectorised followed by an automatic digitisation and storage of the coastline in a personal geodatabase.

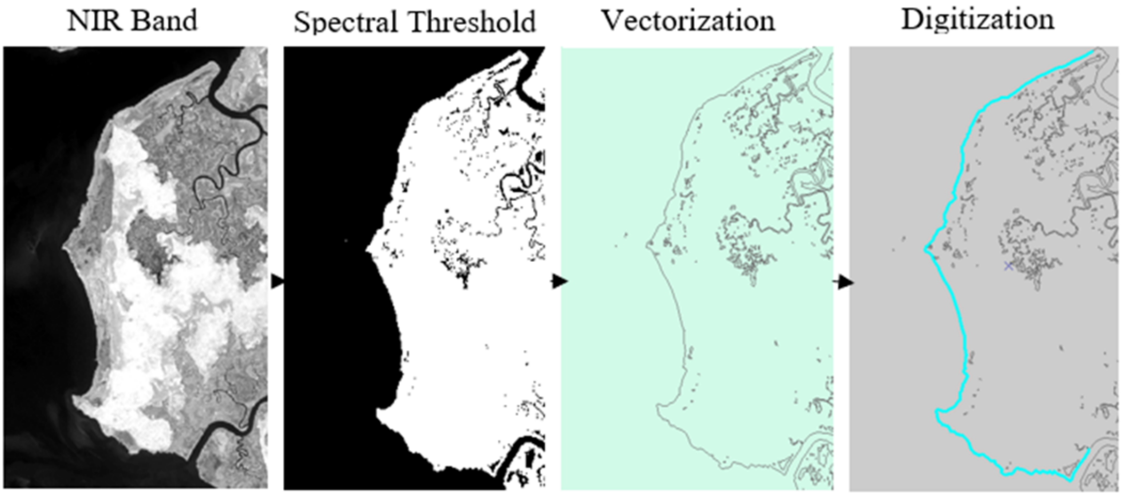

Figure 2: Method of coastline extraction by spectral thresholding.

3.4. Calculation of coastline evolution trends

The quantification of shoreline position changes is performed with the DSAS (Digital Shoreline Analysis System) extension designed by Thieler and Danforth in 1994. Three elements are fundamental to use the DSAS tool: two shorelines of different dates and an imaginary reference line. The parameterisation consists of defining the length of the transects (which must be greater than or equal to the distance between the two coastlines) and the measurement step. When all the input parameters are correctly entered, DSAS automatically generates transects perpendicular to the coastal lines, measures the distances between the coastlines and calculates the means of movement along each transect [12]. It is an extension that integrates the program (ESRI Arc Gis). It allows the calculation of the rate of shoreline change from different sets of shoreline locations in order to analyse historical beach changes. The DSAS tool generates statistical results by offering the user the possibility to choose the indices to work with. In this case we have chosen the EPR. The EPR or End Point Rate is calculated by dividing the distance between the oldest and the most recent coastline by the number of years between the two dates. The choice of the EPR is based on its ease of calculation and the minimum input data. The limitation of (EPR) in the calculation of several shorelines is manifested by additional beaches and changes in the size of the beach direction or cyclic fluctuations in behaviour to be neglected [13]. Figure 3 represents the processing steps of coastline analysis.

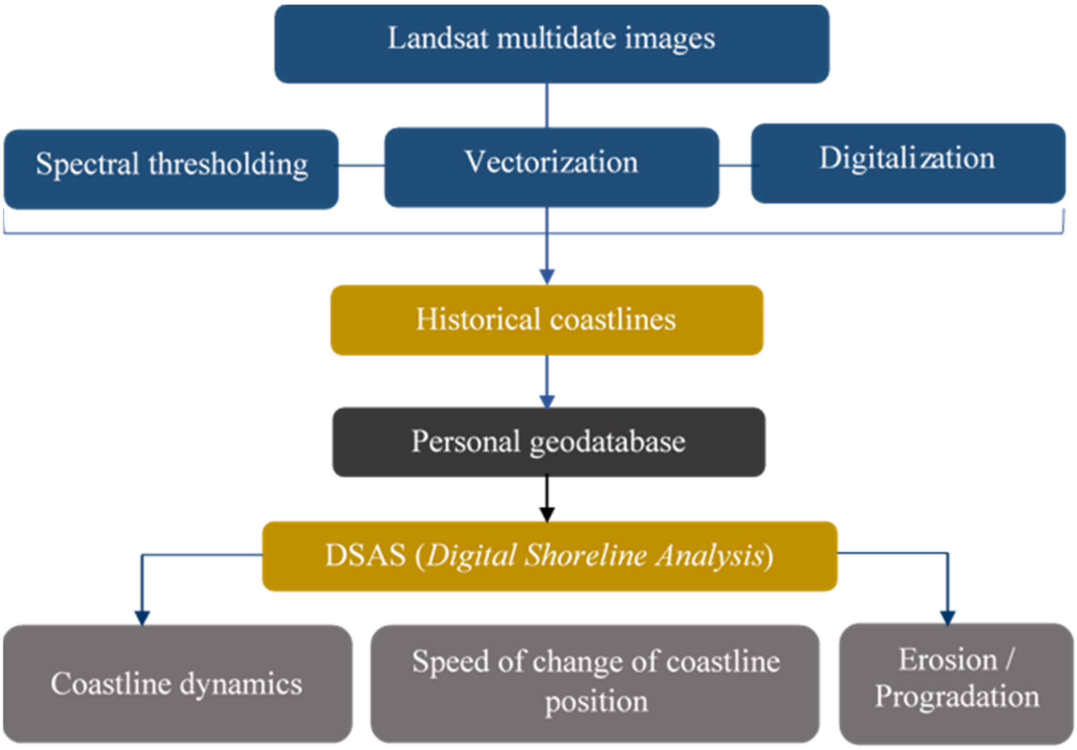

Figure 3: The processing and analysis stages of the coastline evolution.

IV. Results

4.1. Coastline dynamics from Nhiquim to Bolor from 1973 to 2018.

The dynamics of the coastline are controlled on the one hand by the nature of the geological and geomorphological formations and on the other hand by strong demographic pressure. The coastline is characterised by sedimentary formations with a predominantly alluvial character and a low relief and sedimentary deposits from the Quaternary period. The topography of the coastal zone is generally low with altitudes below 50 m. This coastal plain facilitates saline intrusion and makes the coastline vulnerable to coastal erosion, which worsens under conditions of rising temperatures and mean sea level. Figure 4 represents the mapping of the average annual rate of change of the coastline from Nhiquim to Bolor from 1973 to 2018 in Guinea Bissau. The analysed coastline extends over 25 km. The maximum retreat of the shoreline measured during a period is 33.43 m/year between 1973 and 1986 while the maximum coastline advance is noted at the same period with 33.07 m/year. Regarding the speed of mobility, it is important to note that the retreat was much slower between 2003 and 2018 than it was between 1986 -2003.

From an overall perspective, this part of the Southern Rivers is eroding at a variable rate. Compared to the shorelines analysed above, the speed of erosion follows a north-south gradient and varies between 0.21 and 1.8 m/year. This recession, although slow, depends on the morphodynamic and hydrodynamic characteristics of the coastal environments. The granulometric characteristics of the littoral sediments, the dune ridges, the topography, the climatic forcing and the fluvial sedimentary inputs play an important role in the kinematics of the coastline. The highest erosion rates are located south of Valera for the three periods analysed. The rate of retreat is more accentuated in the 1970s on both sides of Valera, i.e., 12 m/year to the north and 32.3 m/year to the south. This dynamic can be linked to the natural factors mentioned above. It should be noted that in the 1970's and 1980's, the coastline was not subject to any coastal erosion control policy and consequently it has been exposed to marine hydrodynamic actions and climatic forcing for over 20 years. The loose and mobilizable nature of the accumulation patterns in the study area accentuates its vulnerability in a context of climate change. An accumulation zone is observed towards the south and may be linked to the influence of the northern swell which remobilises the fluvial sediment flows towards the Guinean coast. This situation combined with the large quantities of sediments drained by the Rio Gêba, Rio Mansoa and Rio Cacheu, leads to the formation of a shallow submarine plain between the continental part and the Bijagós archipelago.

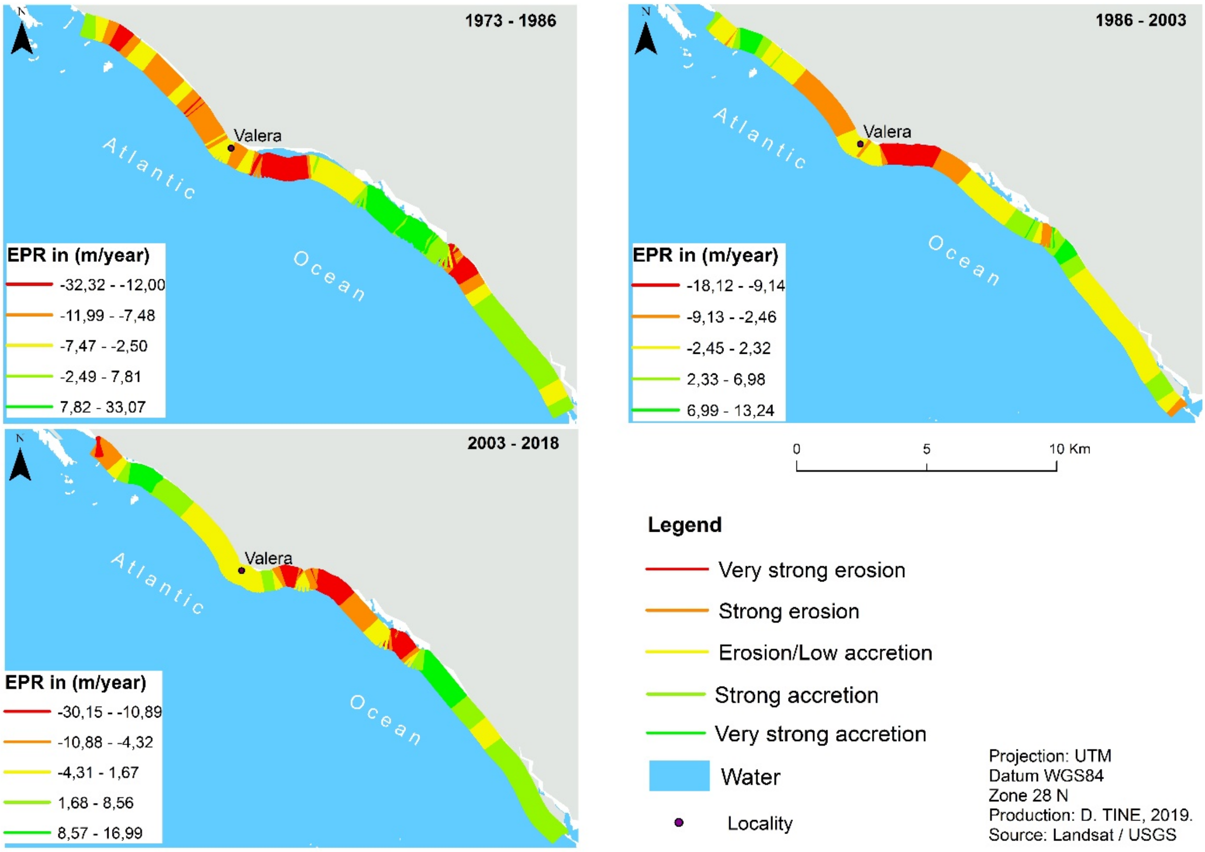

Figure 4: Variation of the annual mean change rate of the coastline from Nhiquim to Bolor from 1973 to 2018.

4.2. Dynamics of the coastline of Mata De Uco in Bote from 1973 to 2018.

This sector shows that erosion is evident on the Guinea-Bissau coastline. The increase in erosion rate is confirmed with an average of 6.71 m/year, much higher than the previous sector. The highest erosion rates are always observed during the first period. However, the rate of erosion in this sector remains the highest with a recession rate of 53.20 m/year. It is a very enclosed sector due to the density of the saltwater channels and the mangrove vegetation cover.

The analysis of the coastline dynamics in this sector shows that erosion remains the dominant phenomenon for the three periods selected (Figure 5). The highest rate of recession is noted in this part of the coastline studied, particularly during the period 1973-1986. The whole sector is eroding with a rate varying between 53.2 m/year and 0.15 m/year. The study of the kinematics of the coastline reveals that the period 1973-1986 is the most erosive. The average rate of change is -19.1 m/year and is gradually decreasing for the last two periods 1986-2003 and 2003-2018.

However, there were major spatial changes between 1986 and 2003 in terms of the rate of change of erosion rates and the establishment of fattening areas. Erosion rates vary between 14.75 m/year and 1.14 m/year and occupy most of the study area. However, accumulation sectors are highlighted, particularly towards the south, with an erosion rate varying between 2.59 m/year and 8.50 m/yearr. This period shows the lowest rates of erosion and accretion. Its character shows that the coastline dynamics do not follow any spatial trend. The third and final period (2003-2018) saw the areas of nourishment identified in the previous period transformed into areas of erosion. Accumulation rates remain higher but only affect small areas south of Mata De Uco. Erosion remains spatially dominant but the high accumulation rates have made the average rate of change positive at 1.05 m/year. Hence the limit of the calculated arithmetic means, which is always influenced by the extreme values. This positive rate does not correspond to the spatial behaviour of the End Point Rate (EPR). Slight spatial variations of the coastline can be observed during this period.

An alternation of erosion and accumulation with a very low rate of change can lead us to consider this segment as more or less stable. This stability may be due to a strong mangrove vegetation cover which consequently plays a protective role for the coastline against meteorological and marine forcing. It is a coast of mangrove mudflats characterised by a multitude of saltwater channels that make it difficult to access the coastline, especially at high tide. Apart from the vegetation cover, we noticed that the Rio Cacheu drains a large quantity of sediment, which once in contact with the sea, is remobilised towards the south and feeds the coastline.

These fluvial sediment inputs are largely dependent on the amount of precipitation observed upstream of the catchment areas. The reduction of these fluvial inputs can lead to strong erosion insofar as they constitute sedimentary reserves which participate in the stabilisation of the coasts and slow down coastal erosion. This was the case in the first and second periods, which experienced episodes of drought and a rainfall deficit.

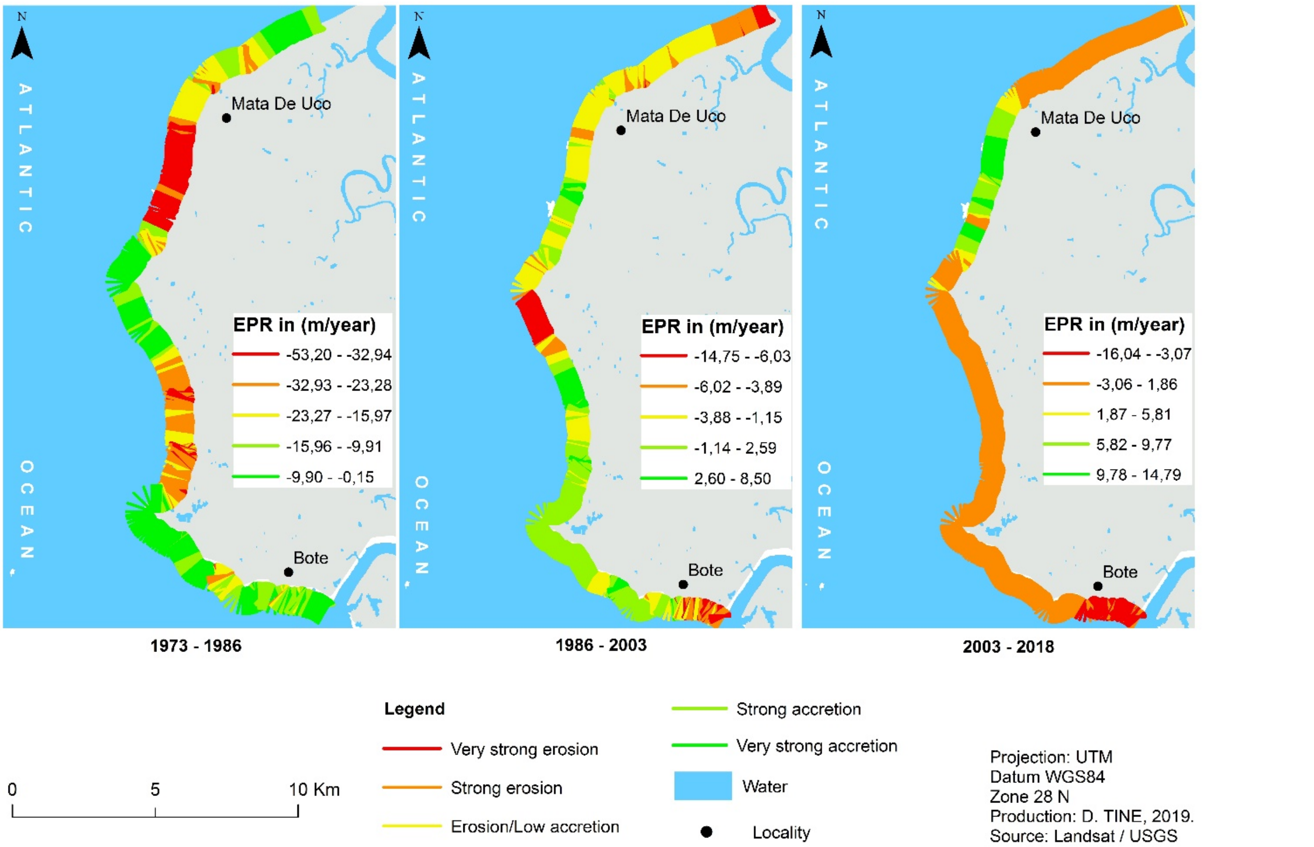

Figure 5: Variation in the annual average rate of change of the coastline from Mata De Uco to Bote from 1973 to 2018.

4.3. Extent of coastal erosion

The analysis of the coastline dynamics has allowed the identification of sectors with strong erosion, also confirmed by field data. Erosive activity is intense in the Varela sector. The current trend is towards erosion, and we are witnessing a retreat of the coastline and a reduction in sedimentary stocks. These highly eroding areas are mainly made up of sandy coastlines whose dynamics are governed by meteorological and marine forcing. The extent of the micro-cliffs and the accelerated degradation of the coastal vegetation bear witness to the aggressiveness of the hydrodynamic actions. The speed of retreat of the coastline in these sectors shows the complexity of the factors involved. It is a very complex meteorological and marine system, made up of many natural factors (waves, currents, storms, sedimentary inputs, etc.) that act simultaneously. Their synchronised actions result in alternating erosion and nourishment phenomena. In the 1970s, almost all the coastlines show eroding coasts. However, an alternation of regression and progradation phases, sometimes strong, sometimes weak, or even null, is observed after superimposing the different shorelines of the years 1986, 2003 and 2018. These results are confirmed by the field reality data contained in figure 6.

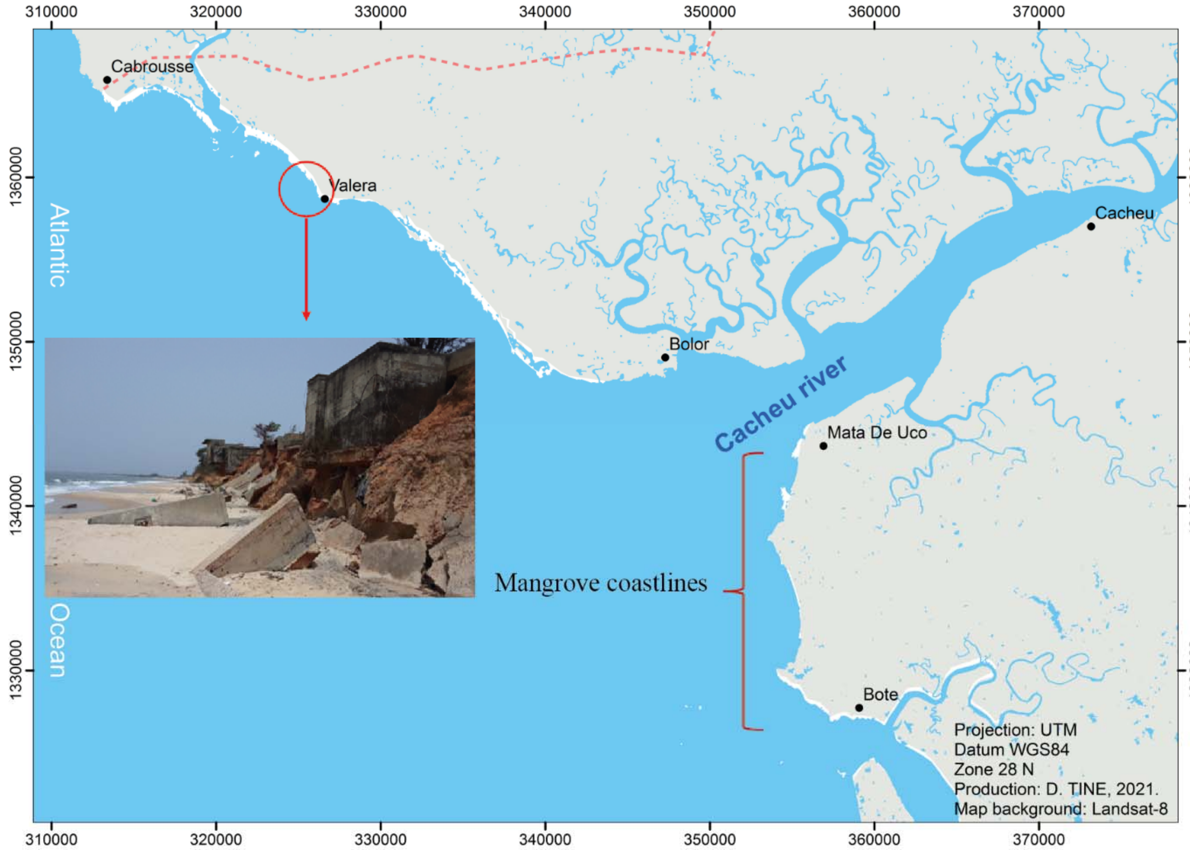

Figure 6: Location of the area of high coastal erosion in Varela.

4.4. The impacts of the dynamics of the coastline

The impacts of coastal dynamics are observed on all coastlines of the world. These effects are caused by wave action, wind, coastal storms and structures that impede the natural circulation of coastal sediments and have been accentuated in recent decades by climate change and sea level rise. Marine hydrodynamic actions, more pronounced during high tides and storms, erode beaches by moving sediments offshore. This results in a retreat of the coastline and a degradation of the coastal environment. This state is observed on the coast of Guinea Bissau.

4.5. Impacts on agriculture

The rice field soils are extremely saline to the point that they become unsuitable for rice cultivation. This leads farmers to abandon these salty lands. The hyper salinity of the water increases its osmotic pressure and makes it difficult for the plants to absorb water through their root system. The plants wither because the roots do not absorb enough water to replace that lost through evapotranspiration. This usually leads to malformation of the grains, and consequently to a reduction in yield. This phenomenon leads to a reduction in rice-growing areas and leads the population to food insecurity. This is the case nowadays, where vast areas of salted rice fields can be observed along the coastal fringe (17,5581.36 ha in 2018) but also several kilometres from the coast.

There is more saline land in coastal areas than in the interior of the continent. It has increased from 52758.72 ha in 1973 to 175581.36 ha in 2018, i.e., an increase of 4%. Population growth has led to anthropic pressure on arable land. The exploitation of lowlands for rice growing is increasingly observed upstream of rivers, including the Rio Gêba. These practices have increased the area cultivated each year despite the loss of fertile land due to salinisation (Figure 7).

Figure 7: Rice fields contaminated by salt in Como, Guinea Bissau.

4.6. Hydrological and hydrogeological impacts

Coastal erosion has a strong impact on the freshwater resources of the coastal areas of the Southern Rivers. The rainfall deficit of the 1970s and 1980s led to a drop in river regimes and the upwelling of marine waters upstream in the catchment areas. Freshwater reserves have been severely degraded and despite the improvement in rainfall conditions in recent years, these reserves are still unsuitable for any agricultural or domestic use. This high salinity of oceanic waters affects, in some places, the water tables, particularly in low-lying areas where stagnation can last a very long time. Saline effervescence can also be observed in low-lying areas that have been flooded for a long time by sea water. All this is facilitated by the flatness of the relief, which is materialised by a vast coastal plain in this northern part of the Southern Rivers. The rise in sea level, the modification of recharge conditions and the alteration of freshwater quality by saline intrusion in the coastal environment constitute a danger for biodiversity (Figure 8).

Figure 8: Stagnation of hypersaline waters with salt effervescence at the surface in Biombo.

4.7. Impacts on the mangrove

Mangrove ecosystems are suffering from the impacts of climate change in the Southern Rivers. Rising sea levels are submerging mangrove areas and coastal wetlands and subjecting them to increased salinity. Water salinity regimes, especially in the northern domain, have been strongly modified in recent years [14]. The rainfall deficit of the 1970s, 1980s and 1990s and the flatness of the terrain have facilitated the upwelling of the salt tongue upstream of the rivers. This continuous intrusion of hypersaline marine water in a context of climate change leads to the degradation of the mangrove and continental vegetation (Figure 9). Although adapted to brackish environments, mangroves can only play a mitigating role for a short period in the face of rapid and significant sea level rise [15]. Sea level rise is not accompanied by mangrove development upstream of the rivers.

Figure 9: Degradation of the mangrove by the hyper salinity of the marine water in Ondame.

4.8. Impacts on coastal development

Coastal regions have always been shaped by erosion. However, the loss of sediment is often compensated by continental sediment supply. This natural process ensures the balance of beaches by mitigating coastal erosion. This dynamic balance is nowadays disturbed by the effects of climate change such as sea level rise. In addition to coastal erosion, climate fluctuations such as rising temperatures are causing populations to move towards the coast. These populations are at the origin of numerous coastal developments such as fishing wharves and dwellings, which are added to the tourist installations threatened, today, with destruction by coastal dynamics. Several tourist infrastructures have suffered the assaults of waves and storms, which have left them in a very advanced state of degradation. Some buildings are directly exposed to continuous wave erosion which destroys them (Figure 10). The damage caused by coastal erosion can be observed everywhere along the studied coastline.

Figure 10: Destruction of tourist infrastructure and coastal habitats in Varela.

V. Discussion

The use of spatial remote sensing has made it possible, through advanced image processing methods, to monitor the spatial-temporal evolution of the coastline. The analyses show that the coastlines analysed are fragile and unstable environments. The results of the study of the evolution of the coastline reveal very dynamic coasts under the action of longshore drift currents. To monitor the dynamics of the coastline, reference lines were chosen according to the sectors selected. Landsat images were used to extract indicators using image processing methods based on spectral thresholding in the near infrared channel. They show a spatial variability of coastline recession, particularly in sectors with erosive dynamics.

The coastline dynamics are more pronounced in the south, with an increase of 9.78 m/year over a short distance south of Varela and a considerable retreat of between 4.42 m/year and -6.95 m/year over the period covered by the satellite images. The sector from Mata de Uco to Bote, Guinea Bissau, is a mangrove coastline whose coastline dynamics can be linked to its development or degradation. This condition is one of the limitations of the processed satellite data. The resolution of the Landsat sensors is not fine enough to delineate more precisely the coastline along the mangrove coastline.

Statistical and comparative analysis of the rates of shoreline change (Figure 11 and 12) observed over the three periods highlights a first period (1973-1986) that was totally erosive on all the shores analysed. This period also holds the record for the rate of erosion with -19.1 m/year. The EPR analysis of the first period shows an interrupted retreat of the shoreline. The average rate of erosion increased from -1.7 m/year to -19.1 m/year, following a north-south gradient. The periods of strong coastal erosion can be linked to the rainfall deficits observed during the 1970s and 1980s, which led to a deficit of fluvial sedimentary input, contributing to the stability of the coastline. These fluvial sediments, remobilised by the northern swell, form sedimentary reserves that maintain the balance of the coastline. Therefore, their absence leads to a direct exposure of the coastline to marine hydrodynamic actions, resulting in increased erosion. Compared to the first period, the speed of shoreline change has dropped between 1986-2003 and 2003-2018.

The results of this study present some differences with previous studies, carried out by Faye (2010). The latter show that the eroding coastline segments are located on the front of the barrier beaches isolating the mangroves in the roots of the Varela spits (Guinea-Bissau). The estimated average erosion rates are in the order of -16 to -24 m/year for the spits, -13 to -24 m/year for the barrier beaches, whereas the results of this study show erosion rates varying between -1.18 to -6.22 m/year for the Varela barrier beach. A similarity is noted about the prograding areas located at the tip of the spits and the Guinea-Bissau barrier beaches (Cape Roxo, Rio Cacheu).

VI. Conclusion

The analysis of the spatial-temporal dynamics of the coastline was carried out using the DSAS tool and ENVI 5.3 software. The monitoring of the spatial-temporal evolution shows that the period 1973-1986 is marked by erosion with an average varying between -8.31 m/year and -1.20 m/year on the Nhiquim-Bolor segment. The periods of progradation are observed between 1986-2003 and 2003-2018 with an average rate varying between 0.78 m/year and 12.23 m/year. The segment from Mata De Uco to Bote is marked by erosion during the periods 1973-1986 and 1986-2003 with erosion rates varying between -1.34 m/year and -25.69 m/year. The balance of the statistical analysis indicates that this segment is eroding for the entire period studied.

The Guinea-Bissau coasts are characterised by mangrove coastlines that constitute the maritime façade of mangrove mudflats, muddy to sandy marshy areas criss-crossed by a network of tidal channels and populated by mangrove forests [12]. These coastlines are home to two major families of mangroves, including Rhizophoraceae and Avicennia. However, the extraction of the shoreline of these types of coastlines from satellite images remains complex due to several factors. The alternation of high and low tide, as well as the time of the satellite pass, must be considered.

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