

The Tabounsou Estuary Facing Coastal Erosion in a Changing Climate

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How to cite this paper: Bah, T.B., Camara, S., Diallo, F.B.S., Diallo, A.K. and Diallo, A.I.P. (2026) The Tabounsou Estuary Facing Coastal Erosion in a Changing Climate. *Agricultural Sciences*, 17, 18-29.
<https://doi.org/10.4236/as.2026.171002>

Received: December 5, 2025

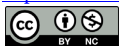
Accepted: January 19, 2026

Published: January 22, 2026

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Abstract

This study assesses coastal dynamics in the Tabounsou estuary, located south of Conakry, Guinea, over the 1975-2016 period. Landsat imagery was utilized through GIS and remote sensing approaches. Results reveal significant coastal retreat, with an average erosion rate of 13.14 m/year, and project its continuation at 8.35 m/year by 2036. Findings indicate a correlation between rising temperatures and intensified coastal retreat, highlighting the combined effects of climate change and local factors on the coastal environment. One key limitation lies in the study's exclusive reliance on data from a single satellite imagery source, thereby excluding the integration of multi-source data that could have enabled more robust analysis and cross-validation of results.

Keywords

Coastal Erosion, Shoreline, Estuary, GIS, Remote Sensing

1. Introduction

The estuarine ecosystem comprises a wide range of natural resources and supports multiple activities carried out by local populations, including fishing, agriculture, salt production, wood harvesting and trade, construction, and socio-religious practices. It represents a major asset for poverty reduction and for sustaining the most vulnerable segments of coastal communities. This ecosystem is a complex and dynamic space that is increasingly subjected to demographic, economic, and ecological pressures. It hosts a rich yet fragile environmental heritage, including diverse flora and fauna, as well as valuable landscapes and natural sites.

Globally, all coastal countries face two major phenomena: climate change and coastal dynamics. Originally natural processes, these phenomena are now being exacerbated by human activities. According to [1], anthropogenic activities have caused a global temperature rise of about 1.0°C above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is expected to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate.

Sea level remained relatively stable for 2 to 3 millennia, rising at roughly 0.5 mm/year. However, an acceleration has been observed since the late 19th century [2]. Two main factors account for roughly 75% of this rise [3]: i) The thermal expansion of the oceans caused by the warming of lower atmospheric layers; ii) The increase in ocean water volume due to the melting of glaciers and the ice sheets of Greenland and Antarctica.

[4] report that in France, the severe storms of recent decades and their impacts on coastal areas have highlighted the causal links between climate change and current shoreline changes, particularly those related to erosion and coastal flooding. The West African coasts, composed largely of estuaries and sandy beaches, are not exempt from this regressive evolution [5].

According to [6], the methodology for assessing risks related to coastal dynamics using geomatics is organized around three main steps, ranging from the collection of bibliographic data to fieldwork and the analysis and synthesis of results.

Regarding climate change and shoreline dynamics, [7] emphasizes that in the current context of climate change and increasing demographic pressure in coastal zones, it has become crucial to accurately characterize the physical processes driving the dynamics of sandy coastlines and to be able to predict future shoreline evolution across a wide range of spatial and temporal scales.

Studies on shoreline dynamics are highly diverse. Some authors [8]-[11] focus on shoreline retreat and advancement. Their findings show that shoreline retreat from Mauritania to Guinea-Bissau has occurred at variable rates but remained at or below 2.5 m/year over the past 50 years [9]. In Côte d'Ivoire, the Jacquville-Canal de Vridi sector recorded an accretion rate of 0.35 m/year between 1998 and 2015, while the Canal de Vridi-Wharf (Port-Bouët) sector experienced a retreat of 1.06 m/year between 2001 and 2015. Other authors examine landscape dynamics in relation to resource use and coastal land-use patterns [12] [13], while others focus on sediment budgets [14].

[15], working in the Gnikine-Diembéring area in Casamance, Senegal, found a shoreline retreat rate of 12.03 m/year between 1986 and 2004, and [9] reported a rate of 12.22 m/year between 1986 and 2000.

The above considerations lead us to formulate the following two research questions:

- 1) What is the rate of shoreline change in the coastal zone of Tabounsou between 1975 and 2016?
- 2) What are the interdependencies between climate change and shoreline dynamics in the Tabounsou estuary?

To address these questions, we defined one general objective and two specific objectives. The general objective is to assess the current state of coastal erosion in the Tabounsou estuary. The specific objectives are: i) To determine shoreline dynamics in Tabounsou; ii) To establish the relationship between shoreline dynamics and climate change in Tabounsou.

2. Materials and Methods

2.1. Materials

The Tabounsou estuary is located along the Guinean coastline in West Africa. The study area extends between longitudes 13°48' W and 13°30' W and latitudes 9°30' N and 9°39' N. It is a zone crossed by an extensive hydrographic network, the most important rivers being Tabounsou and Soumbouya. The area is bordered to the north by the municipalities of Manéah and Wonkifong and by the capital Conakry; to the northwest by Conakry; to the northeast by Wonkifong; to the southeast by Kakossa Island; and to the west by the Atlantic Ocean (see **Figure 1** below).



Figure 1. Study area.

For the present study, the Landsat images cover the temporal scales selected for analyzing shoreline evolution (see **Table 1** below).

Table 1. Landsat images used.

| Satellite/Sensor | Acquisition Date | Spatial Resolution |
|----------------------------------------------|------------------|--------------------|
| Landsat 2/Multi Spectral Scanner (MSS) | 25 March 1975 | 79 m × 79 m |
| Landsat 5/Thematic Mapper (TM) | 01 May 1994 | 30 m × 30 m |
| Landsat 5/Thematic Mapper (TM) | 25 October 2006 | 30 m × 30 m |
| Landsat 8/Operational Land Imager (OLI/TIRS) | 07 February 2016 | 30 m × 30 m |

2.2. Methods

Our methodology is divided into two parts as follows:

1) Determination of the Coastal Line Dynamics at Tabounsou

The study of shoreline dynamics in the Tabounsou estuary (Guinea) is based on the combined analysis of Landsat satellite imagery and local climate data, covering the period 1975-2016. Multispectral images from Landsat 2, 5, 7, and 8 satellites enabled the identification of shoreline variations, erosion, and accretion in estuarine, mangrove, and urban coastal environments. The visible, near-infrared (NIR), and short-wave infrared (SWIR) spectral bands were used to distinguish between land and water surfaces. The Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI) enhanced shoreline extraction, while the Normalized Difference Vegetation Index (NDVI) was used to monitor coastal vegetation. Level 2 images (surface reflectance) were analyzed using DSAS (Digital Shoreline Analysis System) software in a GIS (Geographic Information System) environment [16].

In this study, the methodology adopted to determine the distances and directions of coastal line movement at Tabounsou is based on approaches used in numerous studies [9] [17]-[21]. Indeed, there exists a wide range of methods for detecting, extracting, and monitoring coastal line dynamics. Our study relied on the analysis of Landsat satellite imagery data from different years, spanning 1975 to 2016. Two main steps were required to achieve this objective:

Collection, evaluation, and processing of the available data;

Data analysis and integration of the results into a Geographic Information System (GIS).

Thus, in this study, digital processing was implemented to analyze coastal line dynamics. The methodological approach used to determine coastal line dynamics was carried out in two main steps: data preparation and processing, followed by coastal line extraction and modeling.

In our work, using the DSAS 5.0 software, coastal line uncertainties for the two positions used in the calculation of the end point are each squared and then summed (sum of squares). The square root of the sum of squares is then divided by the number of years between the two coastal lines to determine the end point rate uncertainty (EPRunc), as shown in the following formula:

$$EPRunc = \frac{\sqrt{(\text{uncyA})^2 + (\text{uncyB})^2}}{\text{dateA} - \text{dateB}} \quad (1)$$

where:

uncyA: A is the uncertainty of the attribute field of coastline A;

uncyB: B is the uncertainty of the attribute field of coastline B;

dateA: the date of coastline A (the most recent);

dateB: the date of coastline B (the oldest).

The sum of these square roots gives the error for a given time step under study. Thus, to incorporate the margin of error into the analysis results, it is necessary to

obtain the cumulative sum of the overall coastline position errors for each time step analyzed.

Regarding the standard estimation errors, the same guide indicates that the predicted (or estimated) values of y (the distance relative to the baseline) are calculated for each shoreline point using the values of x (the date of the shoreline) by solving the equation for the best-fit regression line:

$$y = mx + b \quad (2)$$

where:

y : the predicted distance relative to the baseline

m : the slope (rate of change)

b : the y -intercept (where the line crosses the y -axis)

The standard error of the estimate measures the accuracy of the predicted y values by comparing them to the known values of the shoreline point data. It is defined as the Standard Error of the Estimate (SEE) for ordinary linear regression and the Weighted Standard Error (WSE) for weighted linear regression:

$$\text{LSE or WSE} = \sqrt{\frac{\sum (y - y')^2}{n - 2}} \quad (3)$$

where:

y : the known distance from the baseline for a given shoreline data point;

y' : the predicted value based on the best-fit regression line equation;

n : the number of coastlines used.

As an advantage, this approach allows for statistical extrapolation and trend calculations that are used in the diachronic analysis of shoreline movement [22].

2) Establishing the Link between Coastal Line Dynamics and Climate Change at Tabounsou

Climate data (temperature, precipitation, wind) from the National Meteorological Directorate stations were verified and interpolated when necessary. They were processed in R to calculate trends and anomalies and correlate these parameters with shoreline changes, allowing assessment of the impact of climate change on coastal dynamics [23].

At this stage, the data collected on temperature, precipitation, and winds, along with the data on coastal line evolution for the period 1975-2016, are integrated into R software to analyze the correlations between climate change—through these three variables—and coastal dynamics using the Pearson correlation method.

3. Results

3.1. Coastal Line Dynamics in the Tabounsou Estuary between 1975 and 2016

The Tabounsou Estuary, extending from Tabounsou to Soumbouya, encompasses a coastal segment of approximately 17 km. **Figure 2** below presents the raw coastlines extracted from Landsat images of 1975, 1994, 2006, and 2016, along with the baseline. Their overlay illustrates the retreat, stability, or advance of the coastline

at the Tabounsou site.

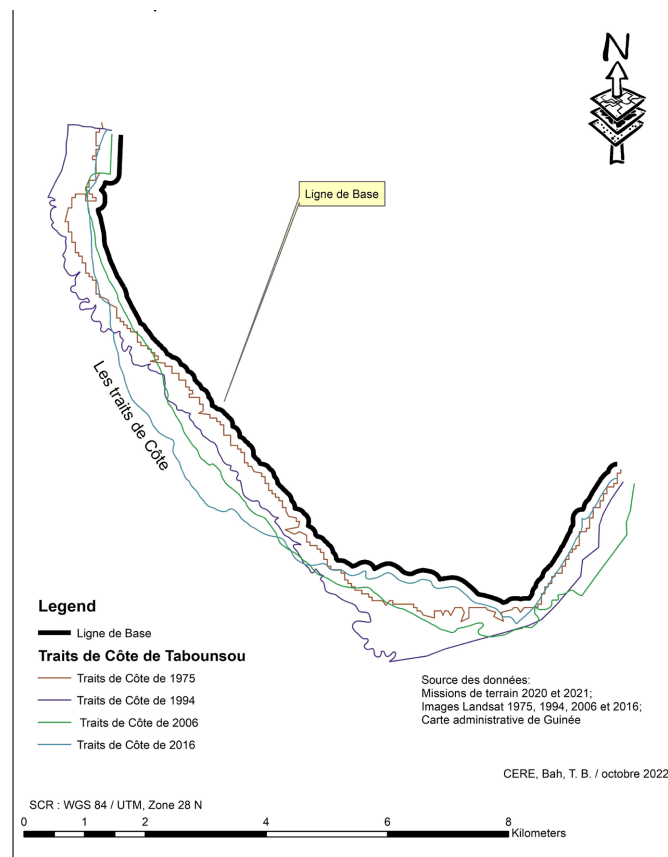


Figure 2. Coastlines of the Tabounsou site between 1975 and 2016.

Overall, during the period 1975-2016, the Tabounsou site experienced significant changes due to both erosion and progradation processes. The results indicate strong erosion in the central part of the site and pronounced progradation at both extremities, particularly in the southern area (see the map in **Figure 3** below).

The calculation of coastal change rates using the End Point Rate (EPR) method provided detailed results, as it accounts for intermediate changes. At Tabounsou, the overall coastline evolution is characterized by an average retreat of approximately 4.89 m/year (± 0.02 reduced uncertainty), with an average erosion rate of 13.14 m/year across the entire study site. The average confidence interval associated with the rates is 0.35. The percentage of all transects exhibiting statistically significant erosion is 51.59%, with a maximum erosion value of 38.86 m. In contrast, progradation reaches a maximum of 18.95 m/year, with an average accretion rate of 5.77 m/year. The percentage of all transects experiencing progradation is 43.65%, with 42% showing statistically significant progradation.

Furthermore, the Linear Regression Rate (LRR) method yielded the following results: an average coastline retreat rate of 4.39 m/year (± 8.21 reduced uncertainty); an average confidence interval associated with the rates of 27.55; an average erosion rate of 11.39 m/year; 25.99% of all transects exhibiting statistically

significant erosion; maximum progradation of 16.73 m/year; an average accretion rate of 7.47 m/year; 37.1% of transects showing progradation, and 0% of transects exhibiting statistically significant progradation.

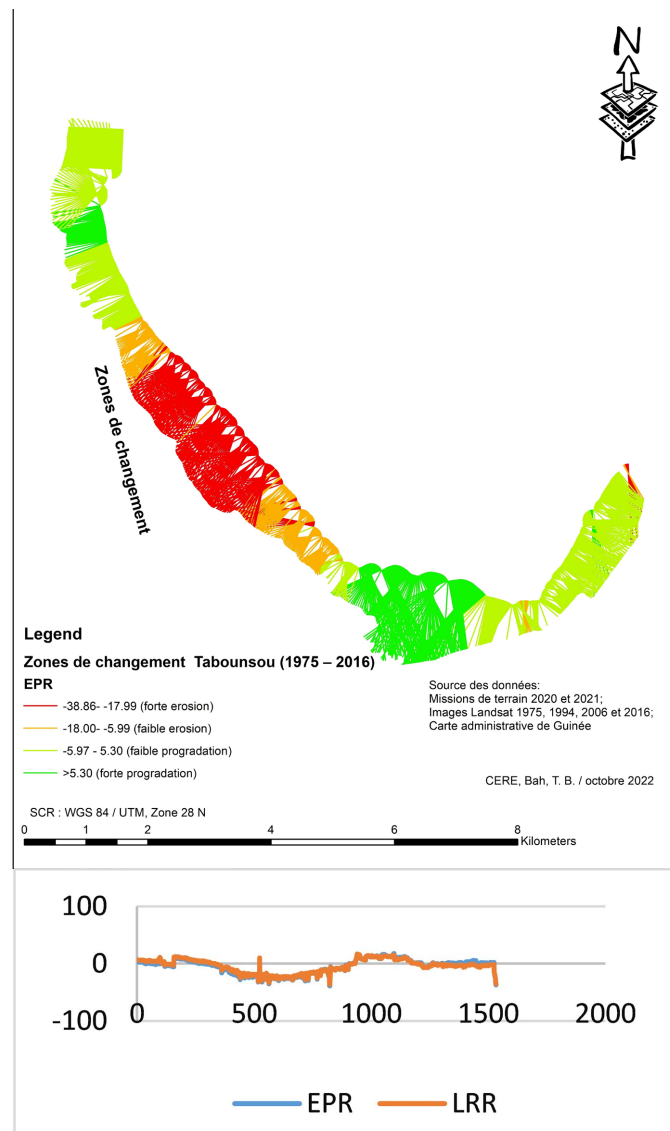


Figure 3. Coastal line evolution at tabounsou between 1975 and 2016.

The Weighted Linear Regression (WLR) method, based on a total of 1,512 transects, shows the following for the Tabounsou site: an average retreat rate of 4.39 m/year; 25.99% of transects showing statistically significant erosion; an average erosion rate of 11.39 m/year; an average accretion rate of 7.47 m/year; and a maximum progradation value of 16.73 m/year.

Considering a 20-year projection period, DSAS 5.0 provides models of coastline evolution for 2036 at the three sites, as shown in **Figure 4** below. According to this projection, the coastline is expected to experience an average retreat of 8.35 m/year over the next 20 years.



Figure 4. Coastal line projection for 2036 at tabounsou.

3.2. Link between Coastal Line Dynamics and Climate Change at Tabounsou

The correlation coefficient measures the linear dependence between two variables:

$$-1 \leq r_{xy} \leq 1, \text{ and therefore ranges from } -1 \text{ to } 1.$$

Specifically:

The closer r is to $+1$, the stronger the positive correlation; as one variable increases, the other tends to increase in parallel.

The closer r is to -1 , the stronger the negative correlation; as one variable increases, the other tends to decrease in parallel.

When r is close to 0 , the variables are not significantly correlated; changes in one variable provide no information about changes in the other.

Figure 5 below records and illustrates the correlations between the parameters studied in the Tabounsou Estuary. While all the variables used are interdependent, it is important to note the highly significant influence of temperature on coastal line dynamics (EPR and LRR). It can be observed that, through the correlation matrix, the increase in temperature has a negative impact on the evolution of the

coastline. The higher the temperature, the greater the risk of coastal erosion. Wind and precipitation are ranked second in influence.

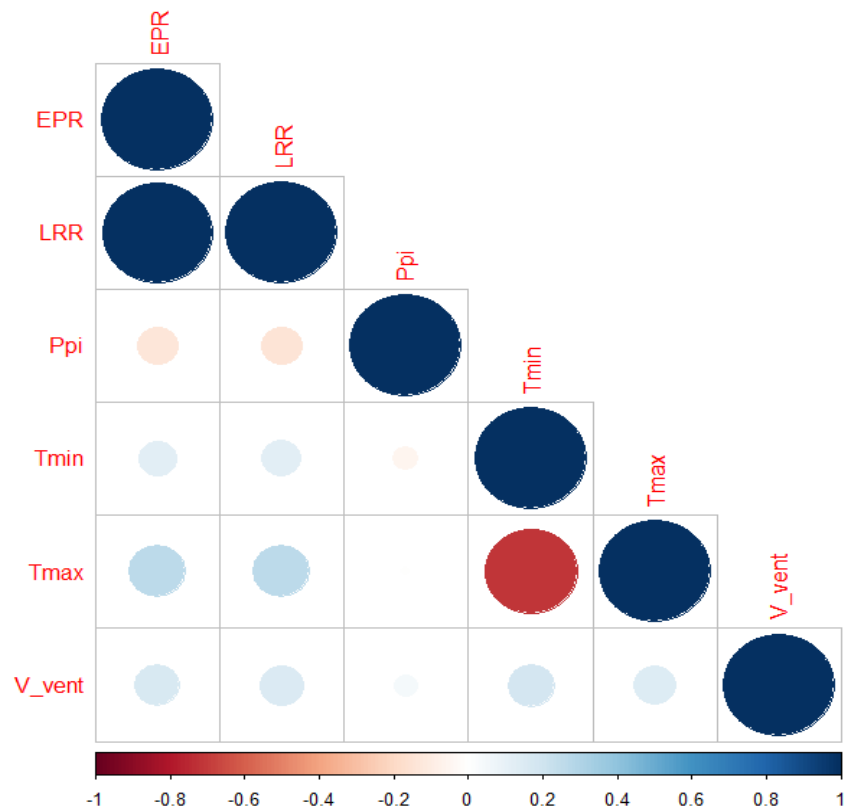


Figure 5. Graphical representation of the correlation matrix.

4. Discussion

Our research on the Tabounsou Estuary, in the context of coastal erosion and climate change, primarily focused on a spatio-temporal analysis of this ecosystem. This study allowed us to detect the movements (retreat, advance, and stability) of the coastline and changes in surface states over a period of forty-one years (1975-2016).

The fragile coastal ecosystem of the Tabounsou estuary, located south of Conakry, Guinea, is threatened by intensive human activities due to its proximity to an urban area and local actions, which are accelerating its degradation. Examples of these activities include overfishing, urbanization, excessive logging of mangrove trees, agriculture, salt production, etc.

Using ArcGIS 10.4, we determined coastline kinematics ranging from 4.88 m to 13.12 m per year for retreat at Tabounsou, with an average advance of 5.85 m/year. In Europe, according to [24], the current millimetric sea-level rise is negligible compared to storm surge heights: 1.60 m in Brest during the hurricane of 16 October 1987 (SHOM); 0.78 m in Concarneau during Storm Johanna on 10 March 2008; 1.53 m in La Rochelle during Storm Xynthia; and 3 m in the southwestern Netherlands during the storm of 31 January-1 February 1953 [25].

Rising temperatures, projected to reach +2°C in West Africa by 2100, are accelerating ice melt and contributing to a sea-level rise of up to 1.06 m. This results in increased coastal erosion due to flooding and intensified wave action. These changes are also disrupting rainfall patterns, reducing river sediment deposition and increasing estuarine salinity, thereby increasing the vulnerability of coastal areas [26]. Our study area is not exempt from this sub-regional reality.

Regarding coastline modeling, our study indicated that the Tabounsou coastline is projected to retreat at an average rate of 8.35 m/year over the next 20 years relative to its current position, according to DSAS 5.0 predictions. The main results obtained by [27] highlight two evolutionary trends for the coastal stretch of interest: in the long term, an average annual coastline retreat rate of 1.09 m/year between 1979 and 2018, and medium-term trends.

Correlation analysis between coastline dynamics and climatic variables (temperature, wind, and precipitation) using R software revealed their interdependencies. Increases in temperature can negatively influence coastline dynamics, whereas wind and precipitation do not show such interdependence with coastal changes. Similarly, [4] reported that in France, the intense storms of recent decades and their impacts on coasts have emphasized potential causal links between climate change and current shoreline evolution under erosion and inundation pressures.

5. Conclusions

The Tabounsou Estuary experiences intensive processes across natural, social, and economic domains. It represents a complex systemic organization that can be severely impacted by the absence of a development strategy that respects natural balances and ensures the sustainability of its resources.

Cartographic methods remain a powerful tool for studying coastline dynamics. The use of this approach allowed us to assess the current state by identifying areas of change, measuring distances and directions of coastline movement, and modeling the coastline over a twenty-year period within our study area. Our study also highlighted the interactions between climatic variables and coastline dynamics.

It would be desirable to extend this research to the rest of the Guinean coastal zone, utilizing multiple sources of imagery and historical maps.

Conflicts of Interest

The authors make no mention of any conflict of interest.

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