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Coastline Dynamics Analysis in Dakar Region, Senegal from 1990 to 2040

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Abstract

In the context of climate change, the study of shoreline dynamics is a critical issue concerning economic losses in coastal countries. Therefore, since it is an important parameter to study the impacts of climate change in coastal areas, scientists are more interested in littoral studies seeking deep existential knowledge. This study aims to depict separately the coastal dynamics from 1990 to 2020 in Dakar region. The difference in terms of geologic, geomorphologic and hydrodynamic conditions within the three different coasts of Dakar and the prediction until 2040 have been taken into account in comparison to the previous studies. To achieve this purpose, the Geographic Information System (GIS) approach which is among the most current methods to determine the coastline dynamics is used. Historical Landsat images from the USGS, QGIS 3.12.0, Arc GIS 10.4 and DSAS software have been used for the Landsat images pre-processing and coastline dynamic computation. After obtaining the coastline velocity rate, some predictions of future coastline position have been estimated using the formula of velocity. The results showed that the Dakar region is characterized by an average rate of retreat about −0.44 m/year on the northern coast. The western and southern coasts record respectively a rate of about 0.21 and −0.11 m/year. In 2030, the average rates of retreat of −4.4, 2.1 and −1.1 m/year were estimated respectively in the northern, western and southern coasts.

Keywords

Coastline Dynamics, DSAS, Erosion, Accretion, Dakar Region

1. Background

The coastline is sometimes assimilated to the shoreline. However, there are some nuances and complexity both in terms of practice and semantics (Faye, 2010). Chand and Acharya (2010), state that "the shoreline is the boundary between land and water body. The term is considered synonymous with coastline but it considers different so the precise definition of shoreline is considered as the line contacting between the mean high-water line and the shore". According to Bird (2008), "the coastline is defined as the edge of the land at the limit of normal high spring tides; the subaerial land margin, often marked by the seaward boundary of terrestrial vegetation. On cliff coasts, it is taken as the cliff foot at high spring tide level. The shoreline is the water's edge, moving to and fro as the tides rise and fall so that there is a low-tide shoreline, a mid-tide shoreline, and a high-tide shoreline. Shorelines thus move to and fro as the tide rises and falls, whereas coastlines are submerged only in exceptional circumstances (e.g., during storm surges)." In this study, the shoreline is considered as the limit between the continent and the sea. Due to the frequency of extreme events such as storm surge, flooding, etc. particularly in coastal areas in a few decades in the past, scientists are more and more interested in the coastline dynamic study.

In fact, in the context of climate change, the recorded temperatures in the world show an increase in the global trend. Consequently, global warming is noted. The effects of this global warming on the hydrosphere and cryosphere cause an ice melting and dilatation of seawater leading in most coastal areas in the world a coastline retreat resulting in sea-level rise. The effects of this rising sea level combined with human activities such as sand mining and abnormal settlement lead to coastal erosion which is accentuated by the effects of hydrodynamic agents. Therefore, this situation leads to the reduction of coastal areas; human displacement toward inland; disruption of economic activities such as fishing, recreational, hotel and industrial activities. These threats are accentuated by humankind through sand mining, pollution and illegal settlements (Pouye, 2016). Dakar region, like most of the world's capitals, is not safe from the impacts of climate change and coastal erosion because of its geographical position and low-lying areas. Advanced sea resulting from the rise in sea level is affecting the coasts. Some studies have been focused on coastal erosion in Senegal particularly in the Dakar region (Niang-Diop, 1996; Faye, 2010; Weissenberger et al., 2016; Pouye, 2016; Bakhoum et al., 2018b).

2. Materials and Method

2.1. Study Area

The Dakar region is located in West Africa between 17˚10 and 17˚32 West long and 14˚53 and 14˚35 North latitude. It covers an area of 550 km^2 or 0.28% of the national territory. It is bordered to the east by the Thiès region and by the Atlantic Ocean in the northern, western, and southern parts (Pouye, 2016). Our study areas are all coastal zones in the Dakar region (133.69 kilometers) (Bakhoum et al., 2018a) i.e., 18.91% of the total coast of Senegal. Its delimitation is based on the different types of coasts: the sandy coast in the northern and southern part and the western coast which is composed of cliffs. The shapes of these different coasts are linked to geology, hydrodynamic, climatic, and morpho-pedological conditions. According to Adjoussi (2001), three different activities determine the geologic history of the Dakar region: volcanic activities, marine transgressions, and regressions which were observed from the pre-quaternary period up to the quaternary period in the Dakar region. This geology is marked by significant faults. The morphology of the two horsts is accentuated by the occurrence of recent volcanic cones composed of both volcanic ash and basaltic lavas. The horsts develop indented and cliffy shorelines that have preserved a less degraded structure. On such shorelines, the direct impact of waves is consequently reduced and slows erosion. The morpho-pedological conditions of the Dakar region are characterized by five formations: recent volcanic formation, formation on Maastrichtian sandstone (Cretaceous), formation on marl-limestone rocks (Paleocene-Eocene), recent Ergs and littoral formations. These morpho-pedological conditions are among the most key important factors that shape the coast. In addition, climate conditions far from being negligible play an important role in the coastal dynamic. The climate of the Dakar region can be determined by airline conditions which are the trade wind maritime, harmattan and the monsoon. In the coastal area, the wind is among the key factor in the coastal system generating swell, sea currents and waves and plays an important role in coastal sediment transport. However, the perturbation of these airline conditions in coastal zones accentuates coastal erosion through an increase in storm surge frequency, coastal flooding, dune retreats, dune disappearances, etc. At a global level, an increase in temperature leads to a rise in sea level. As a result, the coastline moves backwards causing a disturbance in coastal zones. By the presence of a seafront surrounding almost the whole of the Dakar region, it is characterized, during the year by a microclimate marked by the influence of the sea trade winds; hence the existence of a fresh and a quasi-permanent and relatively high humidity of around 25%. However, the harmattan, Saharan continental trade wind, is felt weakly in the dry season further away from the coast. The minimum temperature varies between 17˚C and 25˚C from December to April and from 27˚C to 30 C from May to November (ANSD, 2007).

The following **Figure 1** is about the location map of the coast of the Dakar region.

2.2. Data

The data used in this study are four different Landsat images from 1990, 2000, 2010, and 2020 which are Multi-Resolution Satellite Data (Landsat MSS, TM, ETM+, and OL_TIRS). These images are characterized by the provided satellite, sensor, path and row, the number of bands, and the acquisition date (**Table 1**).

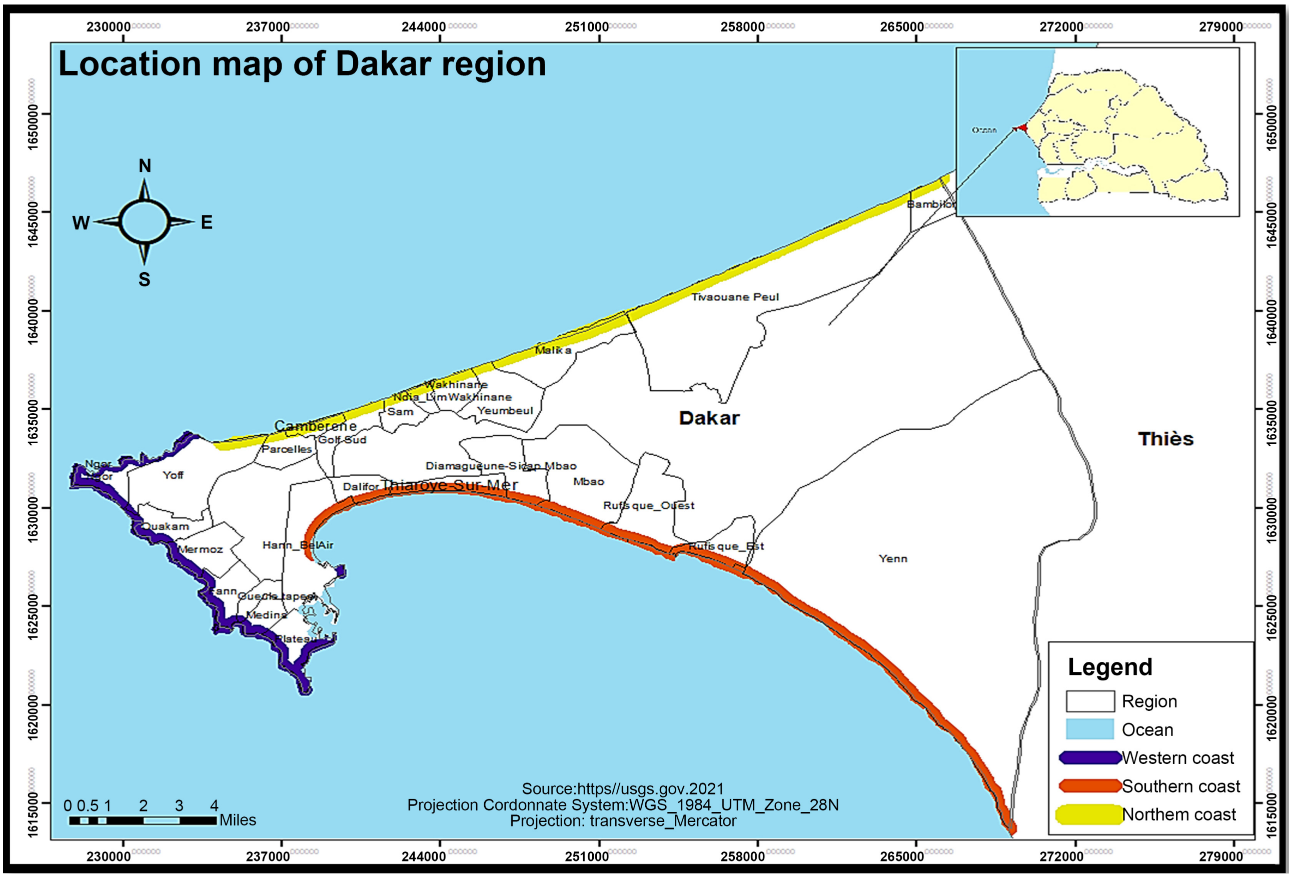

Figure 1. Location map of the coast of Dakar region. Source: glovis.usgs.gov.

Table 1. Landsat images' information (1990, 2000, 2010, and 2020) of Dakar region Senegal.

Satellite	Sensor	Path/Row	Band number	Resolution	Acquisition date
Landsat 5	TM	205/50	7	30 m	05/12/1990
Landsat 7	ETM	205/50	9	30 m	05/30/2000
Landsat 5	TM	205/50	7	30 m	10/25/2010
Landsat 8	OLI_TIRS	205/50	11	30 m	07/02/2020

Source: glovis.usgs.gov.

These maps were downloaded from USGS Global Visualization Viewer (GloVis) (glovis.usgs.gov).

2.3. Methods (Figure 2)

In this study, the Geographic Information System (GIS) approach is used to determine the shoreline dynamic in the Dakar region through the QGIS 3.12.0 and DSAS software which is an extension within the System Research Institute (ESRI) (Thieler et al., 2009). It is very useful to calculate, quantify, measure, and monitor the shoreline rate-of-change statistics from multiple historic shoreline positions and sources. The application of DSAS is in the use of polyline layers as

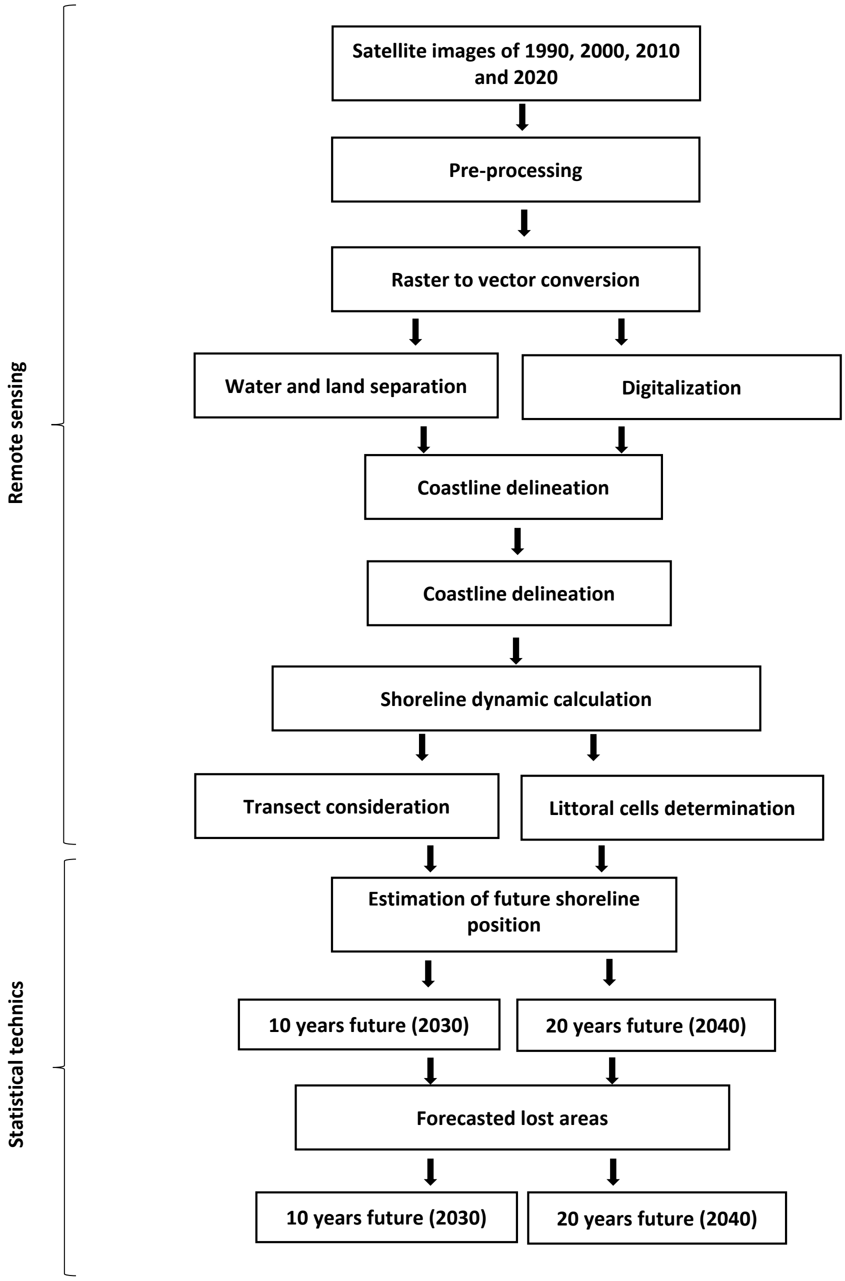

Figure 2. Flow chart showing the methodology adopted in this study inspired from Kumar, Narayana, & Jayappa (2010).

a representation of a specific shoreline feature at a particular point in time. A range of statistical change measures is divided within DSAS, based on the comparison of shoreline position through time. These include the Net Shoreline Movement (NSM), Shoreline Change Envelop (SCE), End Point Rate (EPR), Linear Regression Rate, and the Weighted Linear Regression (WLR) (Oyedotun, 2014).

2.3.1. Images Processing and Coastline Delineations

Landsat images for the years 1990, 2000, 2010, and 2020 were pre-processed in

QGIS 3.12.0. For that, the plugin SCP is installed. The following procedure was employed: go to Manager and install plugins and choose semi-automatic classification plugins and get the plugin SCP. In the SCP, go to Pre-processing and choose Landsat. In the section Directory Containing Landsat bands, load the Landsat images, and then for the section Selecting MTL file an MTL file would be loaded, and click on Run. As result, RT images which are undergone atmospheric correction with a resolution of about 30 meters and PAN Sharpening images done after atmospheric correction with a resolution of about 10 meters are observed. To have an image with high quality in terms of visibility and clarity, the loaded images must be merged. For the merging, go to Raster, and in this Raster section, click on Miscellaneous and Merge. The purpose of this preprocessing is to get high-quality images for better differentiation of the land and sea and accurate results.

The following **Figure 3** is about the pre-processed images for the years 1990, 2000, 2010 and 2020.

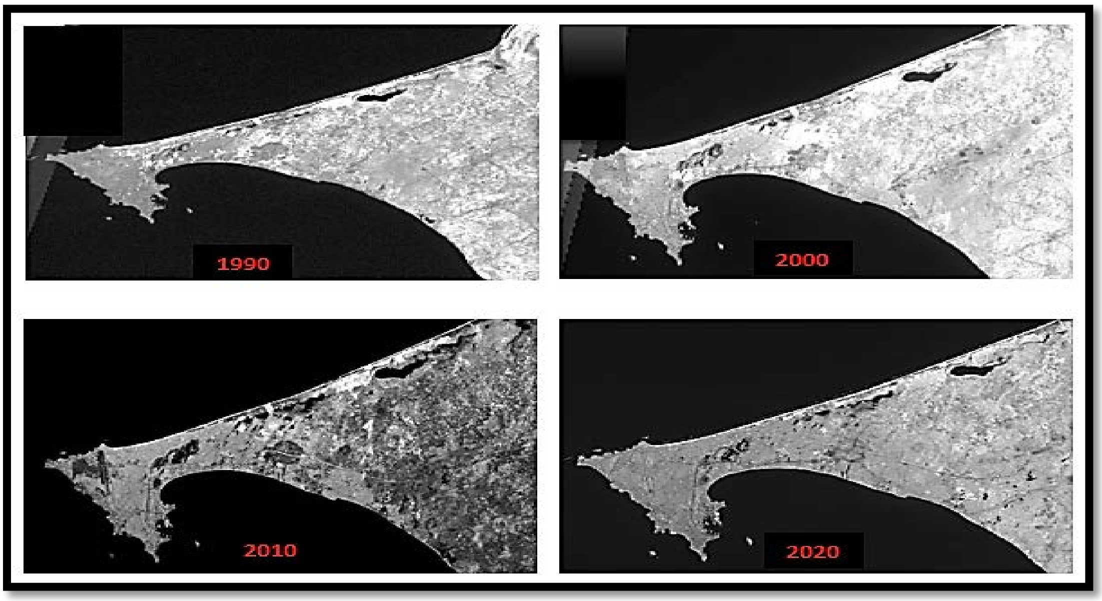

Figure 3. Four pre-processed Landsat images of the Dakar region (1990, 2000, 2010, and 2020). Source: glovis.usgs.gov.

After the processing of Landsat images, digitalization was performed to delineate the coastlines for the years 1990, 2000, 2010 and 2021.

2.3.2. Coastline Dynamic Calculation

The analysis of the coastline dynamics of the Dakar region from 1990 to 2020 is performed in the DSAS software which is an extension of ArcGIS. It is based on four different parameters: The Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), Linear Regression Rate (LRR).

- ❖ The Net Shoreline Movement is the distance between the most recent shorelines and the oldest shorelines for each transect and is measured in meters (m).

- The shoreline change Envelope (SCE) reports a distance (in meters), not a rate. The SCE value represents the greatest distance among the shorelines that intersect a given transect. As the total distance between two shorelines has no sign, the value for SCE is always positive. The transect rate file may be clipped to this span for display purposes (Himmelstoss et al., 2018).
- The End Point Rate (EPR) statistical method is computed by dividing the Net Shoreline Movement (NSM) by the time elapsed between the oldest and the youngest shorelines.
- The linear regression rate-of-change statistic can be determined by fitting a least-squares regression line to all shoreline points for a transect. The regression line is placed so that the sum of the squared residuals is minimized. It is the slope of the line. The method of linear regression includes these features: all data are used, regardless of changes in trend or accuracy, the method is purely computational, the calculation is based on accepted statistical concepts and the method is easy to employ (Dolan et al., 1991; Crowell et al., 1997 in Himmelstoss et al., 2018).

The coastline dynamic is an important parameter to study the evolution of the coast. It is not static whatever the type of coast and is very difficult to apprehend. According to Guariglia et al. (2006), due to specific events, the coastline position can be cyclical, long-term, or random. The cyclical changes of the coastline are linked to seasonality or tidal conditions. The long-term variations are due to the rising sea level or sand storing along the coast. The random variations are due to wave conditions, storms, or floods. In this random variation, the coastline can change in a very short period. To perform a study of the shoreline dynamics of the Dakar region using a GIS approach, a database is composed of different Landsat images from 1990, 2000, 2010, and 2020.

These images were pre-processed before depicting the coastlines. This pre-processing of images allows not only to make them more readable but also to enhance their quality. After the processing, images are digitalized to delineate the coastlines. Therefore, based on these coastlines, the shoreline velocity is evaluated between two dates for example 1990 and 2020. For that, the statistical method is computed by dividing the distance of shoreline movement by the time elapsed between the oldest and the youngest shorelines using the Digital Shoreline Analysis System (DSAS version 5) software which is an extension in Arc GIS 10.4. The advantage of this statistical method is that it is computed easily and does only require two shoreline dates through the shoreline through the Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR) and Linear Regression Rate (LRR) (Himmelstoss et al., 2018).

2.3.3. Prediction

In this study, predictions of the future shoreline positions and lost areas in 2030 and 2040 have been made. For that, a simulation is automatically performed using the Buffer tool based on the current velocity rate. For the prediction of the shoreline position, the formula of velocity V = Distance/Elapsed time between

2020, 2030 and 2040. If the year 2020 is taken as the origin, with a rate of change in the retreat of the coastline equal to X meters, it will emerge that assuming this average constant rate of change at that date, the coastline will retreat to a distance of Y meters in 2030 depending on its current position. For the predictions of the lost areas, the coastlines of the years 2020, 2030 and 2040 were merged. After that, the conversion of the merged shapefile to the polygon is performed from which the lost or gained area along the coast were determined.

2.3.4. Estimation of Uncertainty

All measurements are subject to error which analysis is an important part of any scientific experiment. The analysis of error is the evaluation of uncertainties which allow scientists to estimate the accuracy of their results and reduce uncertainties if necessary (Taylor, 1997). In this study, the estimation of the shoreline uncertainty using the End Point Rate of two shoreline positions (1990-2000) is computed by adding their square. The square root of the summation of squares is divided by the number of the year (10 years) between the two shorelines to determine the uncertainty of the End Point Rate (EPRunc) (Himmelstoss et al., 2018) (**Table 2**).

2.3.5. Limits of the Method

Despite the advantages of this statistical method (the easy computation of the shoreline dynamic through almost two shorelines), some limits are noted: in the Digital Shoreline Analysis System (DSAS) version 5.0 user guides: U.S. Geological Survey Open-File Report, it is stated that if there are more than two shorelines, certain additional information provided by shorelines are omitted. Some gap is also noted for example the changes in sign, magnitude, or cyclical trends (Himmelstoss et al., 2018) and the inability of the DSAS software to determine the forcing of morph dynamics (Oyedotun, 2014). In this study, four Landsat images (1990, 2000, 2010, and 2020) were used to analyze the coastline dynamic from 1990 to 2020. Therefore, it is better to work with more than two shorelines otherwise the LRR does not appear. In certain cases, one can work with only two coastlines for more accurate results but the LRR can be omitted. The tide aspect was not taken into account in this study.

3. Results

The following **Table 2** is about the Shoreline Change Envelope, Net Shoreline

Table 2. Uncertainty of short- and long-term shoreline change from 1990 to 2020.

Periods	Annual error (m/year)
1990-2000	±1.41
2000-2010	±1.36
2010-2020	±1.46
1990-2020	±0.47

Movement End Point Rate, and Linear Regression Rate of the Dakar region from 1990 to 2020.

The coastline dynamics analysis of the Dakar region from 1990 to 2020 shows two principal trends: erosion and accretion (**Table 3**).

Table 3. Shoreline dynamic statistics of Dakar region from 1990 to 2020.

Coasts	EPR (m/year)				Prediction of the coastline (m/year)		Forecasted lost areas (m^2)	
	1990-2000	2000-2010	2010-2020	1990-2020	2020-2030	2020-2040	2020-2030	2020-2040
Northern coast	0.45	−4.12	−2.57	−0.44	−4.4	−8.8	706,883	1,025,472
Western coast	−0.81	0.71	0.20	0.21	2.1	4.2	52,995	89,372
Southern coast	−0.08	0.13	0.29	−0.11	−1.1	−2.2	101,395	141,649

Source: Personal work.

4. Discussion

The analysis of the coastline dynamics in the Dakar region from 1990 to 2020 shows two principal trends: erosion and accretion. Since the hydrodynamic, geologic, geomorphologic, topographic conditions are not the same in the northern, western and southern coasts, it is obvious that the dynamic is different.

➢ **Northern coast**

Generally speaking, the coastline's trend of the northern coast of the Dakar region is mainly characterized by a high erosion (−0.44 m/year). This dynamic is justified by: the fact that the northern coast is under the predominant influence of the North-West swells which induce a coastal drift, directed towards the South (Pinson-Mouillot, 1980; Barusseau, 1980; Sall, 1982; Pedersen and Tarbotton, 1985 in Niang-Diop, 1996). In addition, the northern coast records powerful waves generated by winds. These waves play an important role in this dynamic since the coast is built by soft materials (mainly composed of sandy coastal dunes and marine beaches—Raw mineral soils), the wave force breaks on the coast bringing materials offshore. The wave force breaks on the coast accumulating the materials onshore generating dune retreats inland which is estimated by Niang-Diop (1996) about 200,000 and 1500,000 cubic meters per year. Due to this wave, swell conditions and sand mining activities, the northern coast records an average of all erosional rates about −1.4 m/year and an average of all accumulation rate of about 0.56 m/year. The district musicality of Malika where the higher erosion is recorded (−3.44 m/year) is the most truncated area in the northern coast of Dakar from 1990 to 2020 because it lodges the extension of the Mbeubeuss dump where sand mining activities also are operated (at least 100 tip trucks per day, i.e., about 5 million cubic meters per year are extracted) (**Figure 4**). This causes problems in sediment dynamics (Quensière et al., 2013). Despite the high dynamic, this northern coast is less vulnerable to coastal erosion due to the powerful dunes system which can be considered as a barrier between the sea and coastal infrastructures.

The following map is about the ERP of the northern coast of the Dakar region from 1990 to 2020.

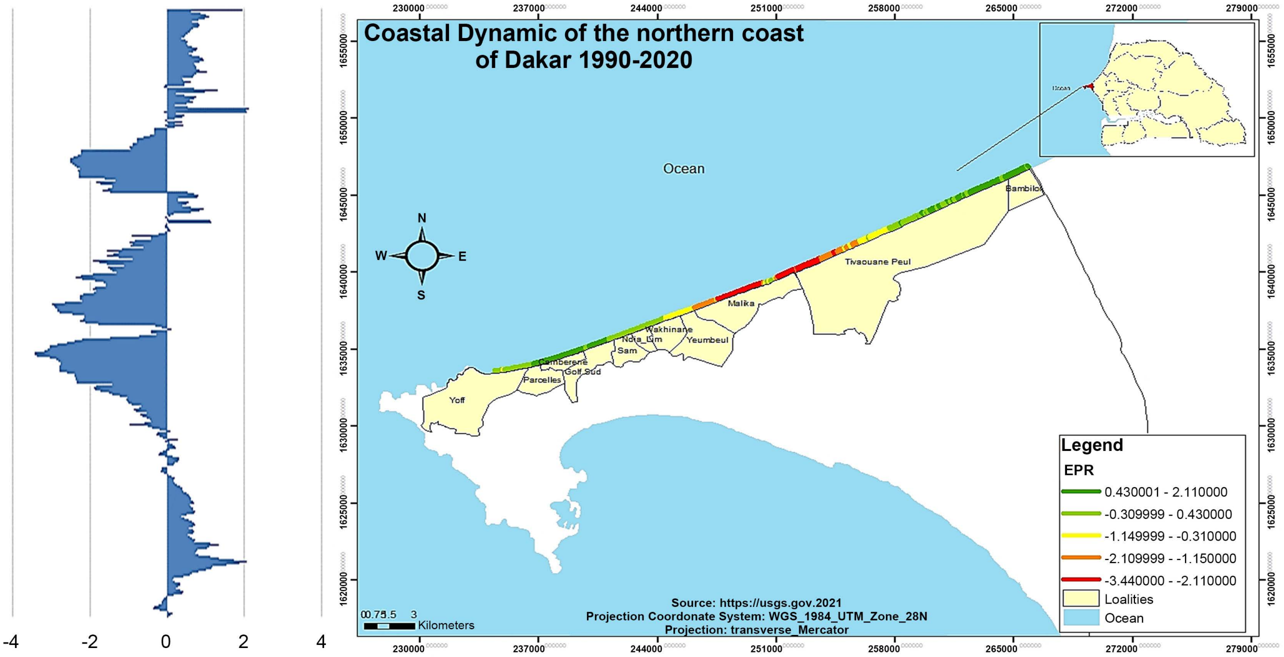

Figure 4. ERP of the northern coast of Dakar region from 1990 to 2020. Source: glovis.usgs.gov.

In 2030 and 2040, on the northern coast, an average rate of retreat of −4.4 and −8.8 m/year is estimated. The forecasted lost areas are estimated respectively in 2030 and 2040 about 706,883 and 1,025,472 m^2 causing a loss of coastal areas and infrastructures. For example, in the district municipality of Malika (which is the most locality at risk), the VDN highway will be affected disrupting the urban traffic and economic activities such as fishery activities in Yoff and Camberene. This situation is accentuated by the woodcutting activities for settlement habitat implantation in this locality (Malika). Dune retreats in these localities along the northern coast will be more intensified.

➢ **Western coast**

Whether the northern and southern coasts are all sandy, the western coast is characterized by cliff records with a dynamic rate of about 0.21 m/year (**Figure 5**). It is less exposed to erosion than the northern and southern coasts. The average of all erosional rates is about −0.35 m/year whereas the average of all accretional rates is about 0.50 m/year. This dynamic is justified by the nature of geologic, hydrodynamic and topographic conditions. Due to its geologic structure which is marked by volcanic rock such as basaltic, tuffaceous and sedimentary rocks generated (Sane & Yamagishi, 2004), the substratum of the western coast is not porous and do not allow important erosion dynamic rates. According to Strahler (2013), when the waves meet resistant rocks, the result is sea cliffs which on the hydraulic pressure of waves and the abrasion by rock fragments trust against the cliffs and sculpt the scarf. Consequently, the block rocks from cliffs fall in the surf zone and the coastline retreats gradually. In addition, this western coast is also less exposed to coastal erosion because it lodges the plateau of Dakar which where the latitude is above 50 meters (Sane & Yamagishi, 2004).

The following map is about the ERP of the western coast of the Dakar region from 1990 to 2020.

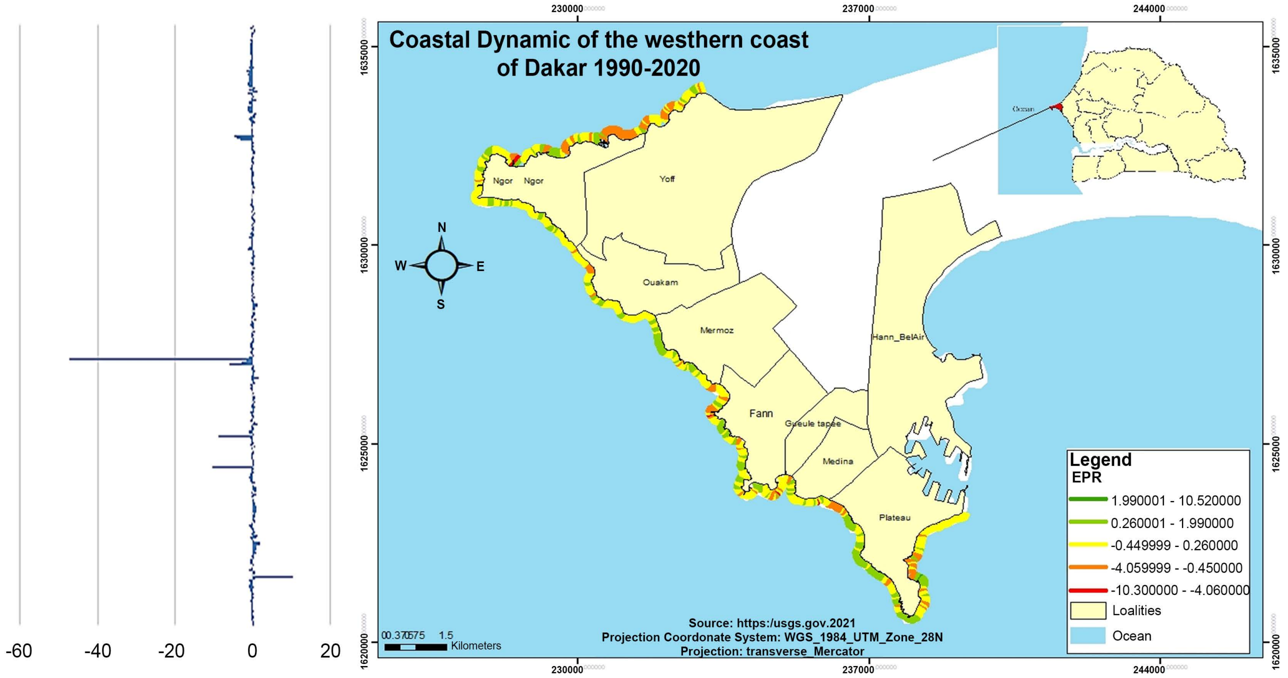

Figure 5. ERP of the western coast of Dakar region from 1990 to 2020. Source: glovis.usgs.gov.

On the western coast, the coastline dynamics are estimated in 2030 and 2040 respectively about 2.1 and 4.2 m/year. This loss of coastal areas is estimated at 52,995 m^2 in 2030 and 89,372 m^2 in 2040. Even if the western coast is globally less exposed to erosion due to its geologic and swell conditions, some coastal areas are subjected to erosion such as the Soumbedioune village which is among the most important fishing point in Senegal.

➢ Southern coast

The southern coast (from Hann to Djiffere) is segmented in a succession of capes and bays whose arrangement is controlled by tectonics. The sandy beaches are backed by a shallow barrier beach. This coast is subject to a northwest swell whose energy is reduced due to refraction and diffraction around the Cape-vert peninsula. Although a south-eastward coastal drift is present and the estimates of sediment transport indicate that the provision is much less important than along the northern coast, 10,500 to 300,000 cubic meters per year (Niang-Diop, 1996). In contrast to the north and west coast, the southern coast remains more vulnerable to erosion due not only to its high population but also the industrial and touristic infrastructures along the coast. An average rate of retreat with an uncertainty of about −0.11 +/− 0.47 m/year have been recorded, with the highest retreat (−1.38 m/year) noted on the coast of Rufisque east. This dynamic is also justified by the limestone plateau of the Bargny-Rufisque district, whose substratum is part of limestone and Marl of Eocene age. In addition, in the graben, geomorphological units are portrayed by low topography, high porousness, and less resistant materials. The characteristics of the geomorphological units in the graben are one of the primary drivers of the vulnerability of Dakar to coastal erosion (Sane & Yamagishi, 2004).

The following map is about the ERP of the southern coast of the Dakar region from 1990 to 2020.

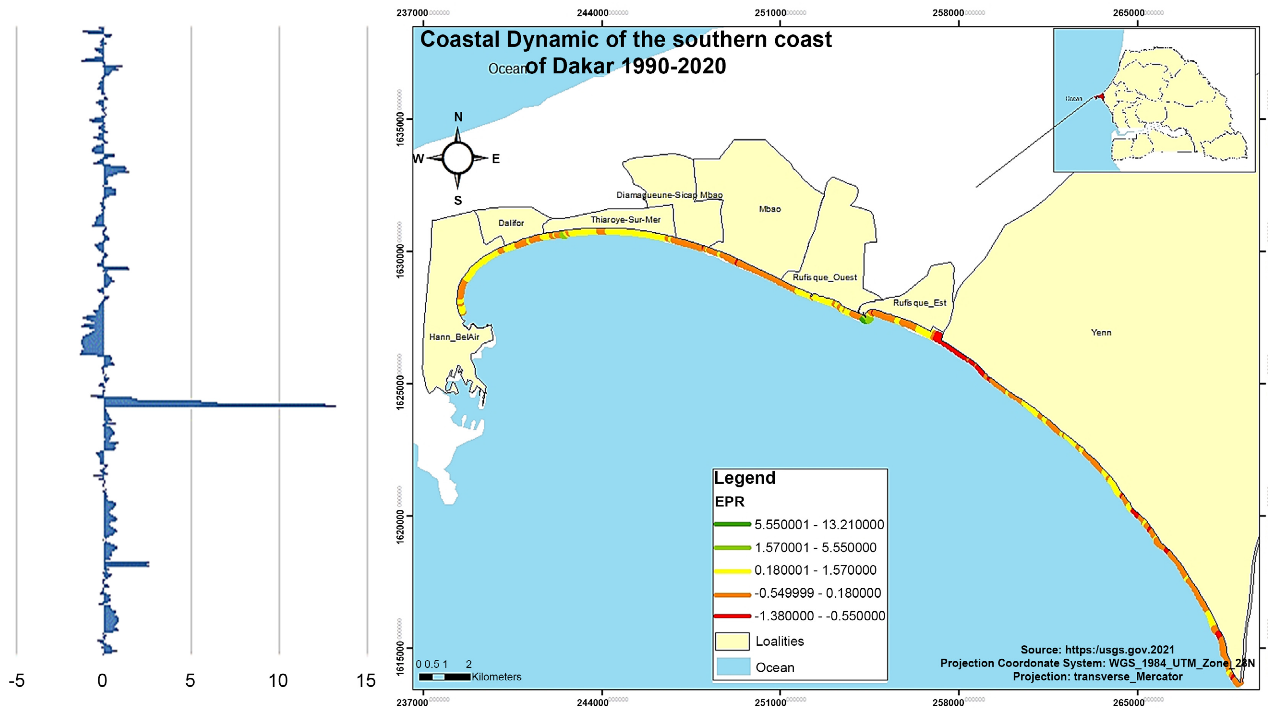

Figure 6. ERP of the southern coast of Dakar region from 1990 to 2020. Source: glovis.usgs.gov.

Being the most exposed to erosion due to its population and geologic and topographic conditions, the coastline dynamics are estimated in 2030 and 2040 respectively about −1.1 and −2.2 m/year in the southern coast of Dakar. These dynamic rates will generate a loss of coastal areas which is estimated at 101,395 m^2 in 2030 and 141,649 m^2 in 2040 (**Figure 6**).

5. Conclusion

In summary, the shoreline dynamic is generated by hydrodynamic, climatic, geologic, and morpho-pedologic conditions. It is an important parameter to analyze the climate change impacts in the coastal area. Dakar is among the most vulnerable regions in the world to coastal erosion due to its geographical position and low-lying area. In this study, the shoreline dynamic depiction is performed through the GIS approach using the DSAS tool which is an extension of ArcGIS software using four Landsat images (1990, 2000, 2010, and 2020). The results show that the region records the respective average rate retreats about −0.44 m/year, 0.21 m/year, and −0.11 m/year at the northern, western, and southern coasts. These rates are linked not only to the nature of the coasts but also to hydrodynamic agents' behaviors. Even if the hydrodynamic, geologic, climatic, and morpho-pedological conditions play an important role in the morphology of the littoral, human activities through the abnormal settlement and sand mining accentuate this erosion.

Conflicts of Interest

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

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