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Analysis of the Vulnerability of the Senegalese Coast between Djiffère and Dakar by Remote Sensing and Geographic Information System (GIS)

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Abstract

The Senegalese coastline is now subject to strong erosion activity, leading to the disappearance of more and more economic infrastructure. The aim of this work is to assess the vulnerability of these coasts on the Djiffère Dakar section with a focus on areas with high economic activity. The methodology consists of using remote sensing methods, Geographic Information System (GIS) and on-site prospecting. The study variables are the rate of erosion of the coastline, the type of relief, the slope, the significant wave height (Hs), the type of land cover and the geology. A GIS model was created to calculate a Coastal Vulnerability Index (CVI) using a weighting method. Based on the CVI values, the rating of these areas is categorized into four vulnerability classes: low, moderate, high, and very high. A vulnerability map of this area is then established. It shows that the odds from Djiffère to Rufisque are more vulnerable compared to that of Dakar with vulnerability indices that vary from 6.13 to 21.4 and from 1.72 to 14.8 respectively. These summary maps of the IVC reveal that the high intensity characterizes above all the highly urbanized sectors, as well as the low-lying reliefs and sandy parts on the coasts from Djiffère to Rufisque. On the other hand, the coasts of Dakar are not very vulnerable due to the rocky outcrops and cliffs which are better protected.

Keywords

Coastline, Mapping, Erosion, Remote Sensing, Vulnerability

1. Introduction

Most coastal areas are undergoing profound changes as a result of climate change. The Senegalese coast is not spared from such a phenomenon. As a result, it is necessary to have a better understanding of the factors responsible for erosion on the coast, from Djiffère to Dakar (**Figure 1**). These coasts are home to ecological diversity and important economic activities that are threatened by coastal erosion. The main objective of this study is to apply a method for assessing coastal vulnerability to erosion risk, through a reliable data processing method. The study will provide a replicable tool to support the planning, decision-making and development of coastal cities. The evolution of the Senegalese coast is impacted by various geographical (swell, wave) and geological factors, thus contributing to the modification of its shape and position. These factors are integrated into various methods widely used for the analysis of coastlines and the prevention of risks related to their erosive activities. Monitoring the coastal environment is often a tedious task due to time-consuming traditional techniques that do not cover an entire coastal system [1]. Remote sensing, geomatics and Geographic Information Systems (GIS) approaches can provide alternatives for this monitoring. Satellite images provide synaptic coverage and are useful for detailed monitoring applications [2]. Thus, their spectral properties can be used to extract several features, including coastal relief [3], land cover and geology. Gornitz (1991) [4] proposed that the Coastal Vulnerability Index (CVI) should be assessed on the basis of parameters derived from remote sensing and GIS. In this study, a version of the IVC is proposed by treating six variables conducive to microtidal ribs, based on the contribution of remote sensing and GIS.

2. Background and Study Areas

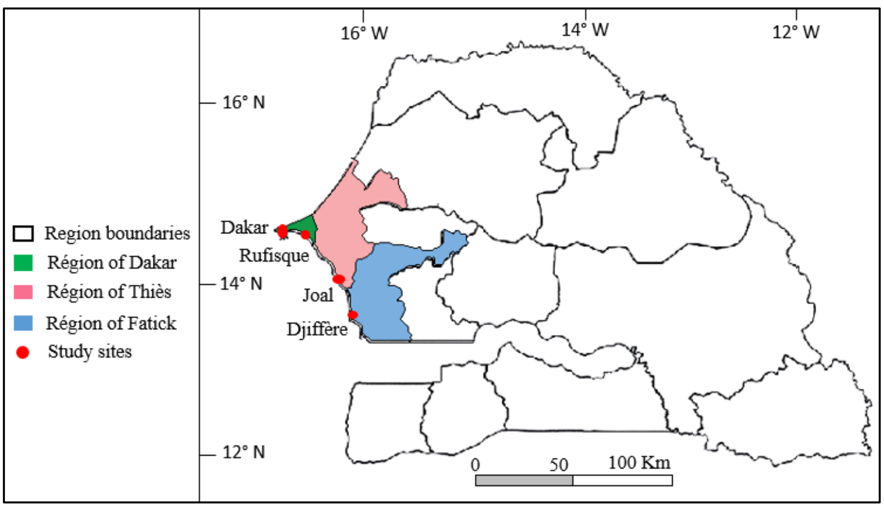

Figure 1. Location of study areas (Fall *et al.*, 2024 modified).

In the current context of global climate change, coastal erosion is a process that results from both natural and anthropogenic factors. It has a strong impact on the environment and socio-economic activities of the coastal zone [5]. The Senegalese coastline represents an area of strategic interest from a demographic, economic and environmental point of view. Natural environments, in a relatively preserved state of conservation, produce vital resources for the Senegalese population [6]. The Senegalese national economy is dependent on these coastal and marine resources, which are part of the main foreign exchange earnings, whether from fishing or tourism. Thus, the erosion of coastal areas would have a negative impact on the country's economy, hence the need to conduct rigorous studies in order to cushion this maritime activity.

3. Methodological Approaches

The present work consists of mapping coastal vulnerability by integrating into the tools of the Geographic Information System variables influencing the evolution of Senegalese coasts. The model developed is composed of six geophysical and socio-economic variables: erosion/accretion rate (m/year), landforms (geomorphology), slope (%), significant average wave height (m), land cover and geology. Based on their assumed impacts, weights are assigned to these variables [7] in the IVC model.

3.1. Data Processing

From a cartographic synthesis, geological description, to the use of modelling through the analysis of satellite images, of DTMs, various types of data sources were used to process the variables retained for the IVC model (**Table 1**).

Table 1. Work methodology and data processing approach.

Variables	Geomorphology	Evolution of the coastline m/year	Land use	Significant wave height (m)	Slopes	Geology	Weighted value
Weighting system	High cliff	<−2	Body of water. green/bare space	<0.55	>90	Healthy hard rock	1
	Medium Cliff	−2.0 - −1.0	Natural meadow	0.55 – 1.0	38 - 90	Hard rock	2
	Low cliff	−1.0 – 1.0	Drill	1.0 – 1.8	12 - 38	Soft rock	3
	Lagoone	1.0 – 2.0	Agricultural activity	1.8 – 2.50	5 - 12	Weathered rock	4
	Marsh. cordon	>2.0	Urban area industrial	>2.50	<5	Loose rock	5
Integration into a GIS model							
Calculation of the coastal vulnerability index							

3.1.1. Evolutionary Trends in the Coastline

A spatio-temporal analysis of the evolution of the coastline was developed in order to calculate the erosion rate. In this case, the analysis first consists of a classification supervised by digital processing of a series of multi-date Landsat 7 and 8 images over the period 1985 and 2021. The uploaded images are imported into

IDRISI Selva for processing and classification. Classified images are subjected to a color composition in order to obtain color images based on the signature of the objects. This classified image will highlight the clear boundary between the pixel populations representing the open ocean domain (dark pixels) and the terrestrial area (light pixels). Files saved in shapefile format under IDRISSI as classified imagery are imported into ArcGIS for extraction and digitization of coastlines. The work of extracting the coastline on Arcgis consists first of all in making an initial conversion of the raster image into a polygon. On an edit window, we delete the population of pixels representing the terrestrial domain. Then we transform the polygon into a polyline to obtain the marine domain. From the contours, we remove the contrasts on the polyline image and the contours in order to obtain the boundary between the open sea and the continent. It thus corresponds to the coastline after digitization. These coastlines constitute the input data for the DSAS (Digital Shoreline Analysis System) extension that will allow statistical calculations of the coastline evolution rates [8]. After formatting the data in a personal geodatabase, a baseline is created and the shorelines are imported into the personal catalog edition. The calculation of indices is carried out using the 1985 and 2021 coastline. Transects perpendicular to the coastline are generated with a measurement step of 50 meters from the baseline. After calculation, the End Point Rate (EPR) and the Linear Regression Rate-of-change (LRR) indices are retained from the transect attribute table to plot the variation of the rates of change of the coastline with Excel.

3.1.2. B-Coastal Relief (Geomorphology)

The data used to analyse the degree of vulnerability linked to the geomorphology of the coasts studied are taken from Digital Terrain Models (DTMs). These DEMs are obtained through the United States Geological Survey (USGS) online portal and on the open topography DEM extension on QGIS. The DEMs were merged with the data from the topographic maps and processed in QGIS to extract the study areas. On the layer style menu, a color palette has been created of type cpt-city catalog and the topography model is selected. A number of five classes are defined with an equal interval display mode. On raster, contour lines were generated with a spacing of 50m between them. The processing of the data made it possible to recognize the geomorphological facies of the coastline confirmed by field observations.

3.1.3. The Slope

The slopes of the coastal zone of our study areas were calculated from a grid of topographic elevations. These are obtained by processing the DTM by projecting it into a coordinate system WGS_1984_UTM_Zone_28N covering the study area. On the raster menu, a slope analysis was done to calculate the edges. On analysis, a Pseudo-color banded rendering is chosen with a shading factor of z = 5 for a multiple blending mode. This data was merged and processed with QGIS to establish a slope map.

3.1.4. The Significant Height of the Waves at the Coast (Hs)

A numerical model of the MIKE21-DHI is used in this study to calculate significant wave heights at the coast (Hs). We will first delineate the study area on ArcGIS using the Google Earth map. All the data necessary for the simulation (bathymetric, meteorological and sea level data) are collected. Return periods of 8 s and 14 s, respectively, for the Dakar and Djiffère to Rufisque sectors respectively allow us to assess the sensitivity related to this variable.

3.1.5. Land Use

The land cover of the study area was determined through QGIS processing of NTMs, as well as Pleiades images uploaded through the livingatlas.arcgis.com online portal to the Land Cover Explorer menu for a directed classification approach. On raster, the data collected were superimposed with the administrative map of Senegal to extract our NCD study areas. Then a shading factor z = 25 is applied to the layer style window. A validation stage was undertaken to establish the occupancy map.

3.1.6. Geology

The data used to analyse the degree of vulnerability related to coastal geology are taken from the World Geologic Maps and the administrative map of Senegal. These maps are obtained through the United States Geological Survey (USGS) online portal. They were merged and processed under QGIS to extract the study areas. The processing of digital and field data made it possible to establish the geological map of the study area.

3.2. Calculation of the Coastal Vulnerability Index (CVI)

The coastal vulnerability index was obtained by processing each variable in a GIS model by applying a weighting system to 6 degrees of scoring (a code from 1 to 6) according to a 30 m*30 m cell calculation grid [9]. Each variable is assigned to a degree depending on the potential magnitude of its exposure and its contribution to physical changes in the coast. The 6 degrees obtained are calculated using Equation (1) [6].

$$CVI = \sqrt{\frac{a.b.c.d.e.f}{6}} \qquad \text{Equation (1)}$$

a = Erosion rate; b = geomorphology; c = slope; d = wave heights, e = land use; f = geology.

4. Results and Discussions

The results of the processing of the data for each variable and the degree of their vulnerability are presented below.

4.1. Variable Results

4.1.1. Evolutionary Trends in the Coastline

The rates of change during the period studied reveal significant erosion in several parts of the sandy coast from Djiffère to Joal [10] and Rufisque (more than 2 m/year) (Figure 2(c)), therefore, a weighted value of 5 has been assigned to them. This could be linked to the massive construction on the dune ridges and the unregulated extraction of sand (looting) [6]. For the same period, the EPR index shows moderate to low erosion on the coast of Dakar (maximum 1.02 m/year) (Figure 2(a)), a weighted value of 4 has been assigned to them. This low erosion noted in Dakar is linked to the presence of hard rocks that are resistant to sea forcing.

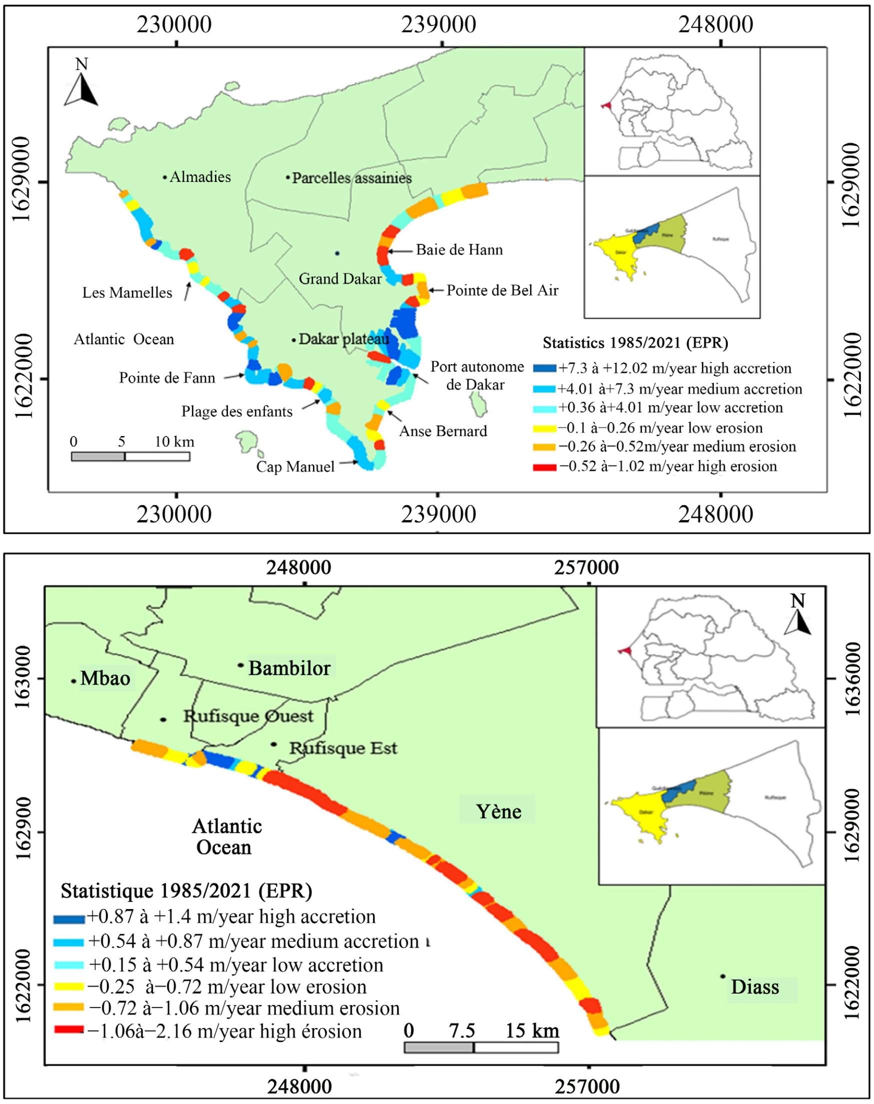

Figure 2. Net rate of change of coastline by year EPR 1985-2021 ((a) = Dakar; (b) = Rufisque).

4.1.2. Determination of the Slope

Figure 3 shows that the gradient of the slope of the coastal reaches studied varies between 0.1% and 90%. At the level of Djiffère, Joal and Rufisque, on this part consisting mainly of beaches with slope gradients of less than 5% (Figures 3(a)-(c)) are more likely to undergo sediment leaching against the current. Therefore, at low slopes, the coast is expected to recede faster than steep slopes. These zones are assigned weighted values of 4. In contrast, the rocky coasts of Dakar (Figure 3(d)), which have gentle slopes with a gradient of up to 89%, are more resistant to erosion, hence a weighting of 2.

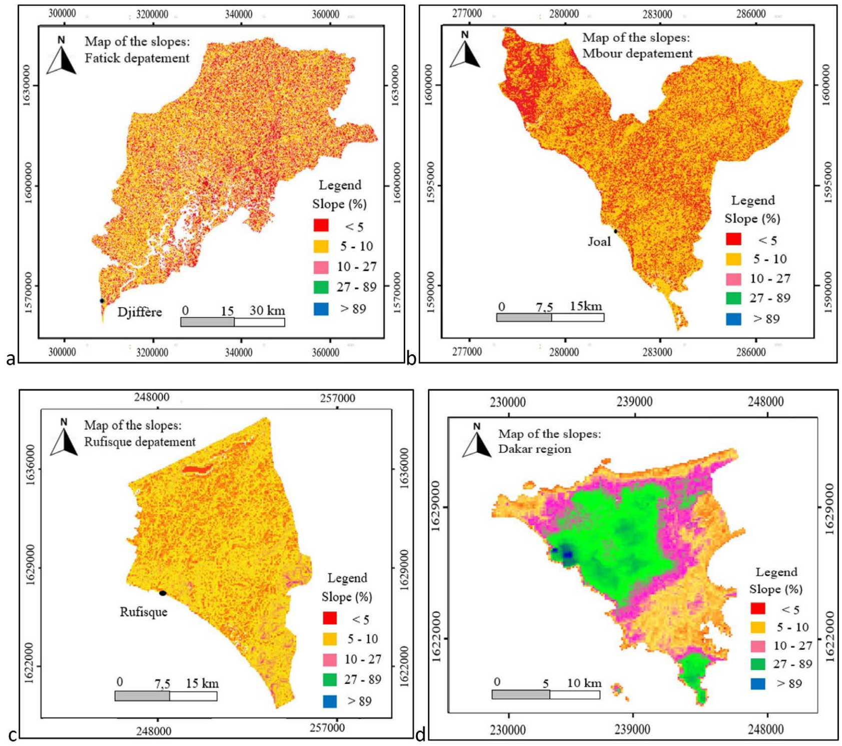

Figure 3. The slope map ((a) = Djiffère; (b) = Joal; (c) = Rufisque; (d) = Dakar).

4.1.3. Determination of Coastal Relief

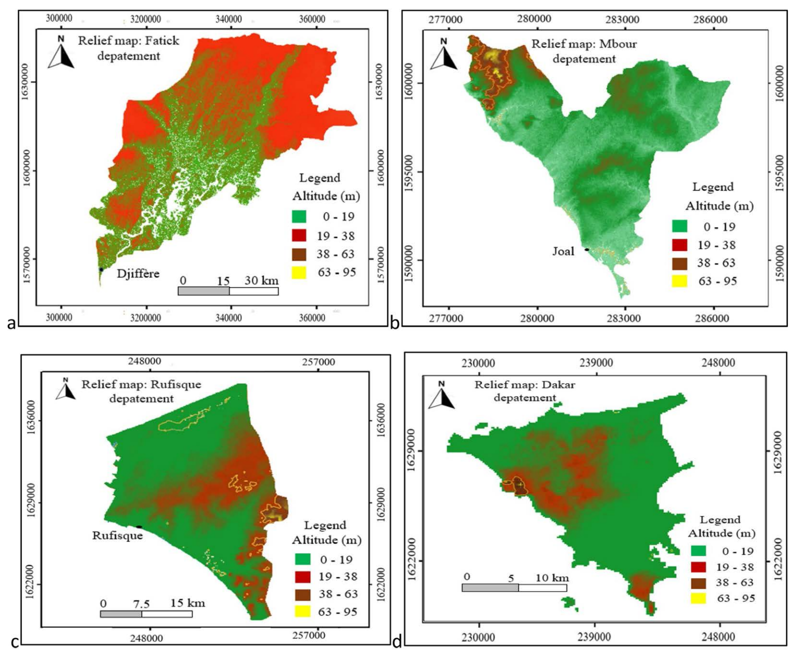

Figure 4. Relief map ((a) = Djiffère; (b) = Joal; (c) = Rufisque; (d) = Dakar) (dérivée du MNT).

The study areas have alternating beaches, dunes, d'une ridges, cliffs, capes and rocky bays (**Figure 4**). Depending on the relief encountered, the risks of coastal erosion are more and more important at the level of the Djiffère section in Rufisque and more or less important at the level of the Dakar coast. Coastal landforms that are at low altitudes (<10 m) (**Figures 4(a)-(c)**), such as sandy beaches, are assigned a value of 5 because they have a high potential for flooding or marine submersion. The coasts in the Dakar sector with cliffs and rocky shores have an altitude (>40 m) (**Figure 4(d)**) and are considered less vulnerable because they are more resistant to sea forcing and sea level rise. As a result, they were assigned a weighted value of 2.

4.1.4. Determination of Wave Height

The output models show that almost the entire coastline from Djiffère to Rufisque and especially to Dakar is exposed to wave and swell action (**Figure 5**). This high exposure is linked to the fact that coastal and underwater morphology dissipates little marine energy. The coastal areas of the Dakar study area show an increase in wave height of more than 2.8 m (**Figure 5**), releasing more energy on the coast, resulting in significant erosion or subsidence of beaches. As a result, a weighted value of 5 was assigned to these ratings. The low-energy waves from Djiffère to Rufisque (**Figure 5**) produce a lower wave height (<1.6 m) which leads to accretion processes due to the accumulation of sediments. Therefore, a weighted value of 3 was assigned to these low wave height areas.

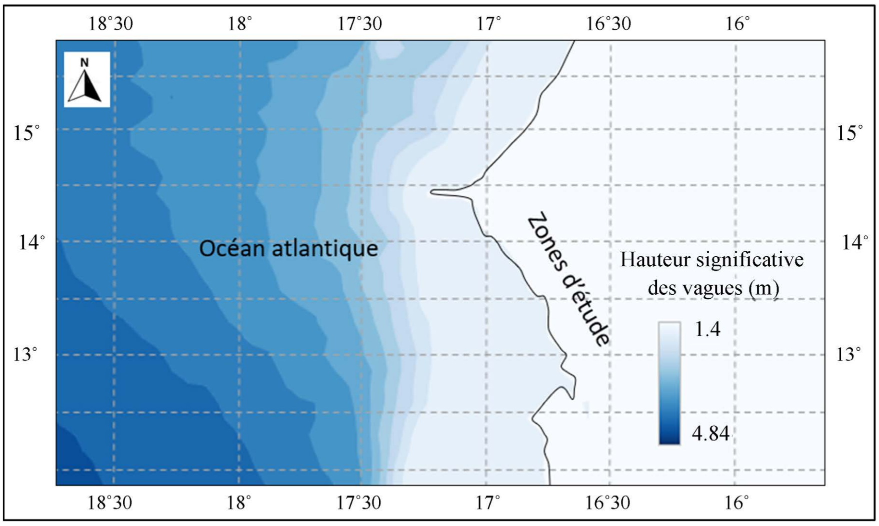

Figure 5. Wave heights at the Mike-21 model calculated.

4.1.5. Land Use Assessment

Figure 6 illustrates the spatial distribution of the land cover type of the sectors studied. This analysis made it possible to detect several land cover classes varying from one sector to another. The overall analysis revealed that the coasts studied are highly urbanized and industrialized at the level of Dakar (**Figure 6(d)**), mainly in its parts close to the coast. Agricultural activity, flooded vegetation and trees, are more frequent from Djiifère to Joal (**Figures 6(a)-(c)**), particularly in areas close to the sea. These natural and anthropogeni+639-c actions impact the plant tissue and the encroachment of the dune barriers. The latter, which are considered as a natural protective barrier, are experiencing a significant rate of decrease. They were assigned a weighted value of 5.

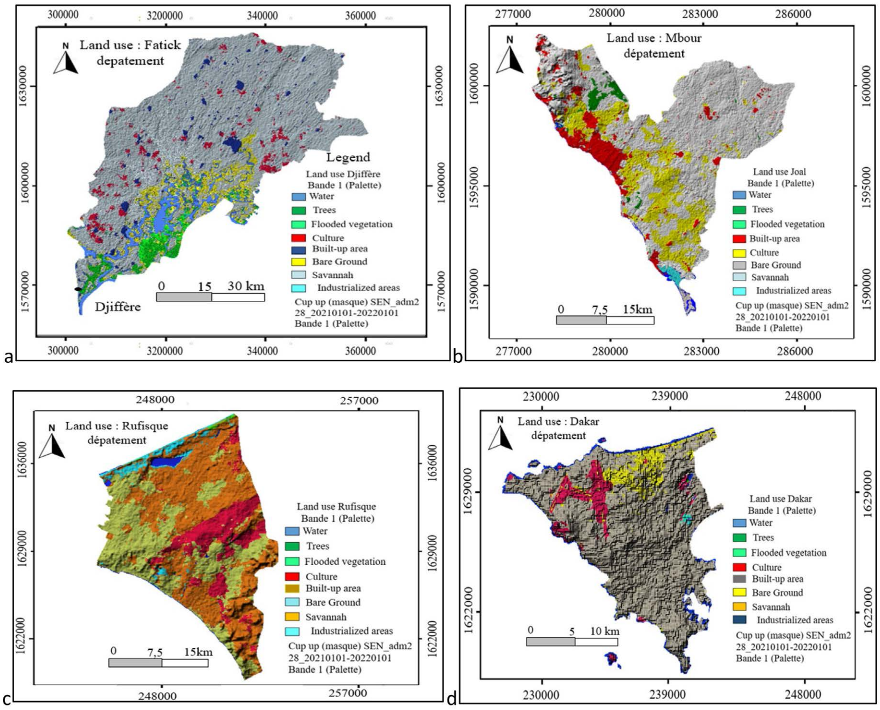

Figure 6. Land cover map of the coastal fringe ((a) = Djiffère; (b) = Joal; (c) = Rufisque; (d) = Dakar).

4.1.6. Characterization of Geology

From a geological point of view, the study areas present several geological facies, as a result, their exposure and resistance to marine agents. Indeed, local geology plays a decisive role in the rate of coastal erosion. Coasts composed of soft rocks or loose sediments are more prone to erosion than those made of hard rocks. The low resistance of the loose formations that make up the coast from Djiffère to Rufisque (**Figure 7(a)** and **Figure 7(b)**) causes a significant retreat of the beaches. Therefore, a weighted value of 5 was assigned to these ratings. The coasts in the Dakar sector with hard and soft cliffs (**Figure 7(a)**) are considered less vulnerable because they are more resistant to sea forcing and sea level rise. In addition, some places have moderate intensities of vulnerability due to the geological structure of the coherent and resistant rocks. This tectonic structure is identified by a few faults in the region, and is characterized by a sub-horizontal tabular structure. Nevertheless, it partly influences the morphology of the coastal zone, the division of the coastline and the dynamics. In addition, limestone cliffs are particularly susceptible to erosion, as limestone is more soluble in water, resulting in the formation of caves, arches, and other spectacular coastal formations. As a result, they were assigned a weighted value of 3.

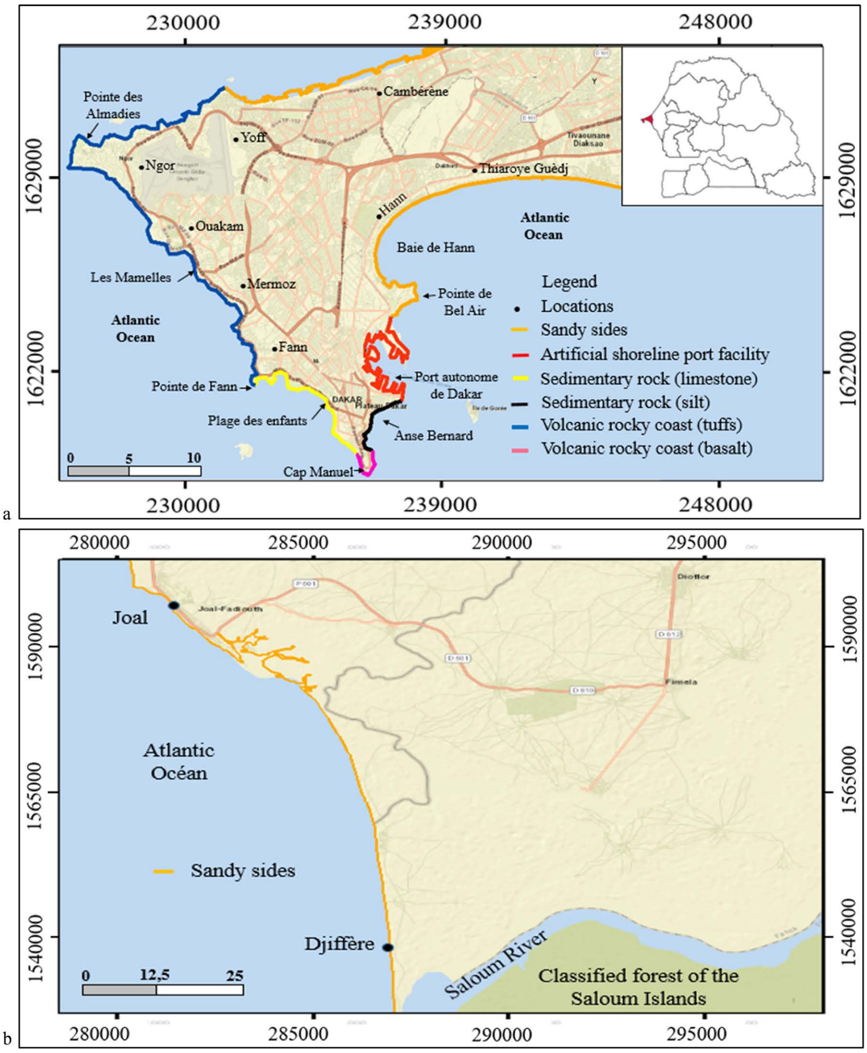

Figure 7. Geology map ((a) = Dakar-Rufisque; (b) = Joal-Djiffère).

4.2. Calculation of the Coastal Vulnerability Index (CVI)

The results show that the IVC values vary from 6.13 to 21.4 in the Djiffère sector in Rufisque and from 1.72 to 14.8 in the Dakar sectors. Based on these ranges of values, coastal areas are categorized into four classes ranging from low to very high vulnerabilities to moderate and high. The VIC maps (**Figure 8**) show the degree of coastal vulnerabilities along the sectors studied. The coastal linear areas (Km) are shown in **Figure 9**. The linear area studied on the Joal Spit (**Figure 9(a)**) extends over 18.5 km, of which 33.08% to 40.54% has a high to very high degree of vulnerability, 16.64% of this linear is characterized by medium intensity. On the Djiffère spit (**Figure 9(b)**), the average intensity dominates with 36.37% compared to 20.45% to 34.29% from strong to very strong over a 24 km linear study. Over the 16 km studied on the Rufisque line (**Figure 9(c)**), from 16.25% to 26.87% is characterized by respective degrees of vulnerability from very high to high compared to 43.13% average and 13.75% low intensity. These summary maps of the IVC reveal that the high intensity characterizes above all the highly urbanized sectors, as well as the low-lying reliefs and sandy parts on the coasts from Djiffère to Rufisque. The coast studied in Dakar (**Figure 9(d)**) extends over a 42 km line, of which 4.28% to 13.57% is a strong to very high degree of vulnerability, 41.42% of this line is characterized by medium intensity. In addition, 35.95% of this linear area has a low degree of vulnerability. The same goes for rocky and cliff coasts (elevation greater than 10.0 m) which are better protected.

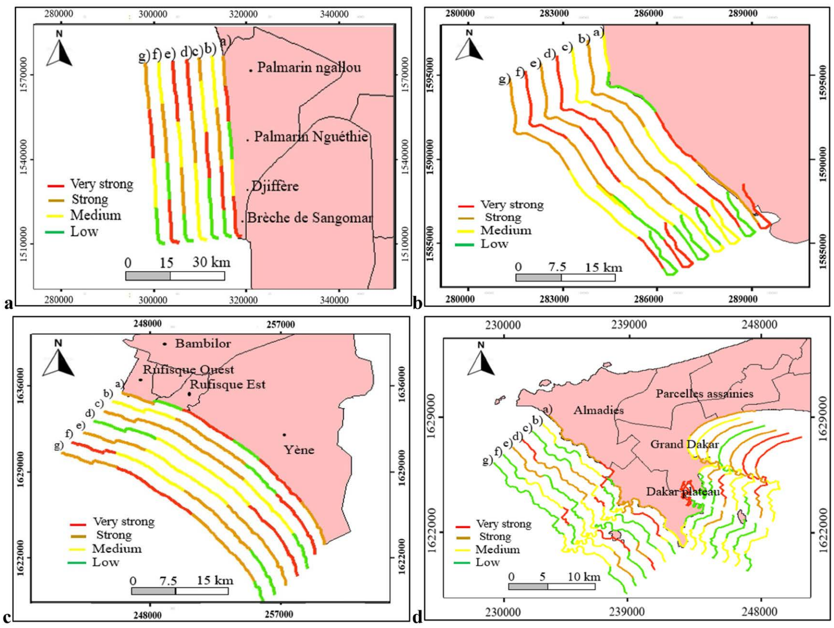

Figure 8. Map of coastal vulnerability, (a) vulnerability to the coastline variable, (b) vulnerability to slope, (c) vulnerability to the coastal relief variable, (d) vulnerability to the Hs variable, (e) vulnerability to the land cover type variable, (f) Coastal Vulnerability Index of the areas; (g) Vulnerability index in relation to geology.

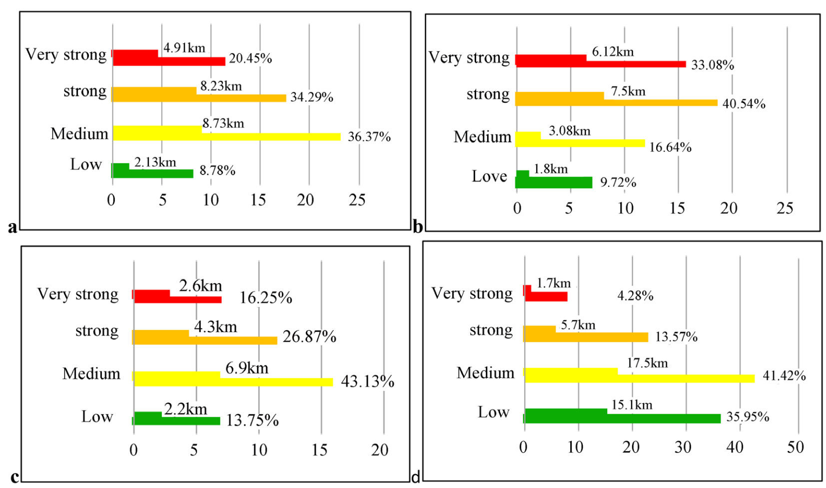

Figure 9. Graphical presentation of the degree of vulnerability in terms of percentage of coastal line ((a) = Djiffère; (b) = Joal; (c) = Rufisque; (d) = Dakar).

The variables in the CVI model can be selected based on the location and characteristics of the coasts. In the model developed here, six variables were processed by methods of geomatics, remote sensing and geology. Thus, their effectiveness in making coastal vulnerability measurable has been proven thanks to the rating system of 6 levels according to the intensity intervals of each variable that have heterogeneous units, by homogenizing their dimensions. The results of the variables through modeling and image processing were demonstrated and validated by *in-situ* observations. In addition, to analyse the level of exposure of socio-economic activities to the risk of erosion, the DVI model developed here has integrated the type of land use and the geology.

5. Conclusion

With a view to spatializing risks, this study has made it possible to develop a method for assessing vulnerability to erosion risk according to a geospatial and geological approach. Based on the results, several hotspots (high vulnerability) were identified in different locations. The use of integrated remote sensing and GIS methods in addition to fieldwork generated a database on coastal terrain, dynamic processes and socio-economic factors. The supervised classification of the Pleiades images has shown great potential in the treatment of variables, especially for the extraction of the coastline and the type of land cover. All of these variables are integrated into a GIS model. This identification of areas makes it possible to better draw up coastal development plans with a view to sustainable development and the management of a system of unavoidable potentialities.

Conflicts of Interest

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

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