Urban Resilience and Sustainability

Research article

Geomatics-based assessment of coastal vulnerability in Kribi (southern Cameroon)

Clotaire Jose Pako Perabi[1],*, Raphael Onguene[2], Kevin MBA Djuka Zebaze[1], Abdoul Aboubakar[1], Gregoire Ondoa Abessolo[3] and Pierre Ele[4]

[1] Institute of Geological and Mining Research (IRGM), P.O. Box 4110, Nlongkak, Yaoundé, Cameroon
[2] University Institute of Technology Douala, P.O. Box 8698, Douala, Cameroon
[3] Institute of Fisheries and Aquatic Sciences at Yabassi, P.O. Box 7236, Douala, Cameroon
[4] National Advanced School of Engineering of Yaounde, P.O. Box 8390, Yaounde, Cameroon

* Correspondence: Email: perabipako@gmail.com; Tel: (+237)656640644, (+237)678355219.

Abstract: Located in southern Cameroon, at the bottom of the Gulf of Guinea, the Kribi coast has contributed over the years to the country's economic development (seaside tourism, mining and oil exploitation, etc.). In recent decades, the coastline has been subject to a number of stresses, such as coastal erosion. However, virtually no work has been done in this area to assess the degree of vulnerability of this coastline to erosion. The objective of this article was to assess the physical and socio-economic vulnerability of a 31.5-km stretch of the Kribi coastline using geographic information systems (GIS). The results obtained have made it possible to map the vulnerable areas on this coast. More than two-thirds (68.3%) of the Kribi coastline are highly physically vulnerable to erosion risks, consisting mainly of sandy accumulations and creeks, while nearly one-third (31.7%) of the coastline has low to moderately vulnerability, consisting of rocky promontories and rocky shores. On the other hand, more than half (58.7%) of the coastline is highly vulnerable to erosion from a socio-economic perspective, consisting mainly of densely populated urban areas with well-developed road networks and a rich heritage. More than a third (41.3%) of the coastline has low to moderate socio-economic vulnerability, consisting of areas that are difficult to access and almost unexploited. The results of this study can be used as a decision-making tool to anticipate critical areas and guide development policies for sustainable coastal management, given that an industrial and port complex is gradually being built around the deep-water port of Kribi. It also contributes to enriching the assessment techniques used to date.

1. Introduction

Coasts are dynamic landscapes, whose changes depend on the physical factors that characterize them (geology, geomorphology, etc.) and marine forces (wave action, sea level, etc.), but also on anthropogenic factors. Given that 10% of the world's population lives in coastal areas less than 10 m above sea level [1], these coasts are subject to significant and growing concentrations of socio-economic activities and problems [2]. Indeed, natural dynamics and extreme weather events make these coastal areas particularly vulnerable. The coast of Kribi, located in the southern region of Cameroon, is one such example. Over the last decade, specifically since the launch of the Kribi autonomous port project in early 2010, it has experienced rapid urbanization and population growth. Population growth trends are now higher than the national average of 3% [3]. Similarly, it faces a number of challenges due to its strategic position in the Central African sub-region. In industrial terms, the city of Kribi aims to be a hub of development par excellence through its industrial port complex, which is being built around the deep-water port of Kribi and the new city. Ecologically, this coastal strip is rich in biodiversity. The villages of Lolabé, Eboundja, and Mboro, for example, are nesting sites for sea turtles [4].

The Kribi coast also includes important forest ecosystems that are disappearing due to increasing urbanization. The rapid degradation of the coastal strip due to the destruction of vegetation and the widespread use of concrete also seriously detracts from the aesthetic value of the landscape, as does the accumulation on the shore of dead trees uprooted by the sea and various types of waste washed up on the coast by the waves. All of the factors listed above make this coastline vulnerable to climatic hazards (coastal erosion, sea flooding, and inland flooding). This has motivated this research on the concept of vulnerability in order to make it measurable. The objective is to provide a method and vulnerability maps enabling stakeholders involved in coastal issues to address the causes and prevent the consequences for effective governance.

Given the complexity of this field, which lies at the intersection of several factors, assessment methods require a systemic approach. One of the first attempts to assess coastal vulnerability by calculating a coastal vulnerability index (CVI) was made by Gornitz [5]. Following his study, numerous versions of the CVI were developed at different scales. Indeed, many studies on coastal vulnerability have been conducted in most countries in order to anticipate the effects of sea level rise on their coasts. The first studies conducted in 1989 on the coasts of North America (United States) took into account eight variables such as relief, lithology, coastal geomorphology, subsidence, erosion/accretion rates, mean tidal range, wave height, and storm frequency [5–7]. A few years later, Pendleton et al. [8] grouped these variables into two factors: Geological (coastal geomorphology, relief (altitude), coastal slope, and coastal erosion and accretion rates) and physical (relative sea level change, mean significant wave height, and tidal range). This work identified that high-risk areas are characterized by low coastal relief, erodible substrate, past and present signs of subsidence, significant coastal retreat, and high wave and tidal energy [9,10]. Subsequently, several studies have been conducted around the world, this time incorporating socio-economic variables such as population density, land cover and land use, road networks, habitats, etc. [11,12].

In Cameroon, studies assessing coastal vulnerability are rare, mainly due to a lack of data. The main vulnerability studies on the Cameroonian coastline have focused on assessing vulnerability to flooding [13–15]. This study of the Kribi coastline will complement the studies already cited above. To this end, the physical and socio-economic vulnerability of the Kribi coastline was assessed using the most influential variables of overall coastal vulnerability, based on the method of [7] for the physical vulnerability index, and [8] for the socio-economic vulnerability index, using a geographic information system (GIS). Kribi is one of Cameroon's oldest coastal towns, with a rich cultural heritage (Kribi Lighthouse, Mayi Festival, etc.) and natural heritage (Lobé Waterfall, Loup Rock, turtle nesting site, etc.), making it a major tourist attraction. Hence, there is a need to assess the vulnerability of this coastline for its sustainable management.

2. Methods and data

2.1. Study area overview and data sources

The Kribi coastline, the subject of this research study, is located on the Atlantic coast in the South Cameroon Region, capital of the Ocean Department. The coordinates of Kribi are: 2°56′6.00″N, 9°54′36.00″E (Latitude: 2.9350; Longitude: 9.9100), about 150 km south of Douala. Kribi borders the vast South Cameroon plateau. It is built on low-lying coastal plateaus composed mainly of sedimentary rock, which is found in the coastal plain. There are rocky coasts, sandy coasts, and small curved coves. The lowest relief is to the west of the region, in contact with the ocean. This is a strip of sedimentary terrain less than 100 meters high. It continues eastward at an altitude of between 100 and 300 meters [16,17].
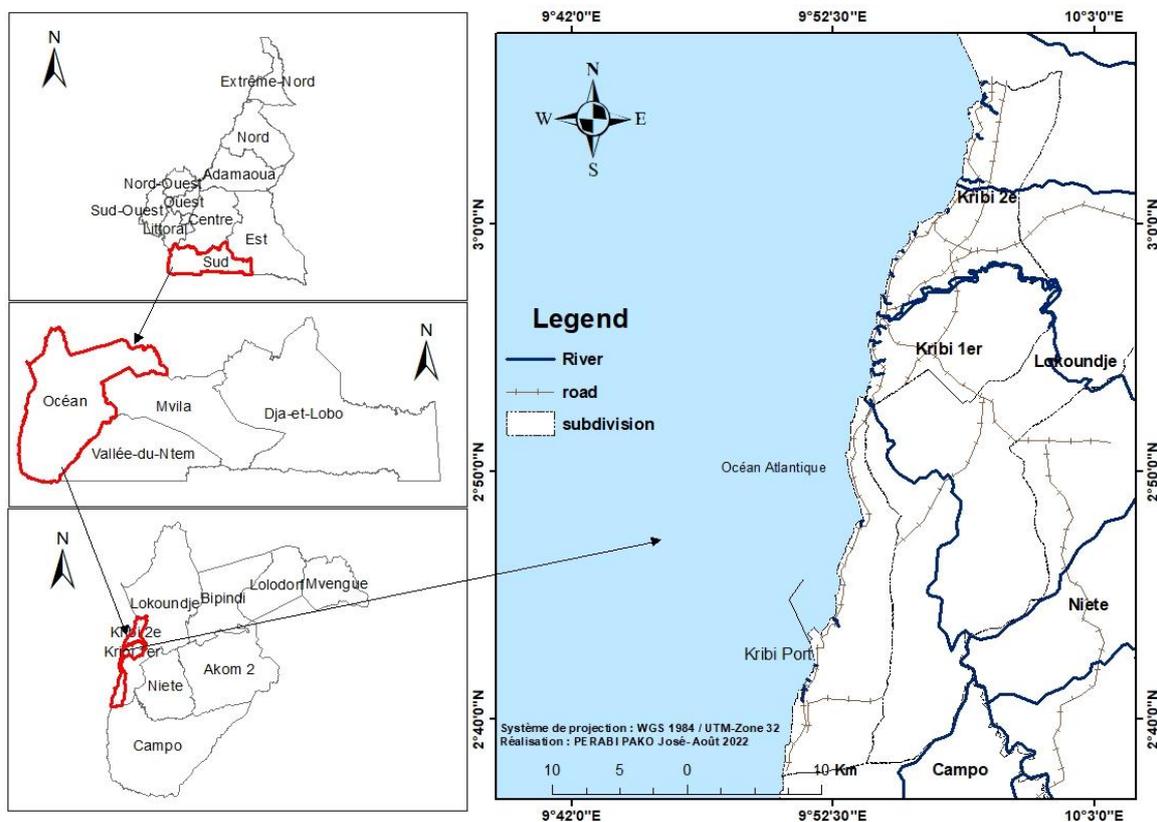

Figure 1. Location of study area.

In the study area, there is also a deepwater port at Mboro, whose 1.5-km-long breakwater, built in 2010, is not without consequences for sediment transit in the area. The dike acts as a barrier (sediment trap) to the sediment flow that feeds the beaches downstream of the harbor dike, resulting in a sediment deficit on the beach downstream of the dike, which is currently eroding [18].

The present work formulates two geographic information system (GIS) models of the coastal vulnerability index (the physical vulnerability index and the socio-economic vulnerability index) in a socio-eco-systemic context, taking into consideration variables conducive to micro-tidal coasts, such as the Kribi coast. Table 1 below shows the various data used.

Table 1. Variables used to assess physical and socio-economic vulnerability.

Variable	Data source	Resolution	Period
Geomorphology	Archive of Geological and Mining Research Institute. Geological map of Cameroon In situ observations	1/500 000	2021
Slopes	SRTM satellite imagery https://earthexplorer.usgs.gov/	30m	2002
Accretion/erosion	Landsat 7 and Landsat 8 satellite image https://earthexplorer.usgs.gov/	30 and 15 m	2001 and 2021
Significant wave height at the coast	Global Ocean Waves Analysis and Forecast Era Interim ECMWF https://data.marine.copernicus.eu/products	0.125° × 0.125°	1993 to 2019
Mean tidal range	Port Autonome de Kribi		
Land use	Landsat 7 and Landsat 8 satellite image https://earthexplorer.usgs.gov/	30 and 15 m	2001 and 2021
Agglomeration	Urban Master Plan for the City of Kribi In situ observations		2015
Road network	Urban Master Plan for the City of Kribi In situ observations		2015
Cultural heritage	Urban Master Plan for the City of Kribi In situ observations		2015

2.2. Method for assessing the physical vulnerability index

The physical vulnerability study of the study area is based on a participatory approach, which takes into account the following variables: Geomorphology; shoreline erosion/accretion; coastal slope; mean swell height; mean tidal range. This approach, proposed by [5,6] and improved by [7], aims to assess vulnerability on the East Coast of the United States, in order to identify areas at risk and those most exposed to a rise in sea level.

The method in [7] is based on the fact that the topic under consideration is structured around two components, "sea forcing" and "geological factors", which render (or not) the coastal zone vulnerable. Each variable is assigned a relative risk value based on the potential importance of its contribution to physical changes to the coast. These variables are ranked on a linear scale from 1 to 5, in increasing order of vulnerability due to erosion and submersion. The value 1 corresponds to a very low risk and 5 to a higher risk [7].

According to [6], coastal segments with high index values will have low relief, easily erodible substrate, significant shoreline recession, and will be exposed to high wave energies. Once each section of coastline is assigned a risk value based on each specific variable, a coastal vulnerability index is calculated using the Eq 1 developed by [7]. Where *a* is the coastal geomorphology, *b* is the coastal

slope, c is the erosion/accretion of shoreline, d is the mean tidal range, and e is the significant wave height at the coast.

$$IVCphysique = \sqrt{a * b * c * d * \frac{e}{5}}. \tag{1}$$

These five variables represent the five factors or variables taken into account for the calculation of the vulnerability index (Table 2).

Table 2. The five (05) levels of the USGS coastal classification of variables on the U.S. Atlantic Coast (Source: [7,8]).

| CVI Variable	Very low 1	Low 2	Moderate 3	High 4	Very high 5
a) Coastal geomorphology	Rocky coast with high cliff	Coast with medium cliff	Low cliff coast	Lagoon	Beach, deltaic coasts, marshes, dunes
b) Coastal slope (%)	>12	12 to 9	9 to 6	6 to 3	<3
c) Shoreline erosion/accretion (m/year)	>2.0	2.0 to 1.0	−1.0 to +1.0	−1.1 to −2.0	<−2.0
d) Mean tidal range tide (m)	<1.0	1.0 to 1.9	2.0 to 4.0	4.1 to 6.0	>6.0
e) Significant wave heights at coast (m)	<0.55	0.55 to 0.85	0.85 to 1.05	1.05 to 1.25	>1.25
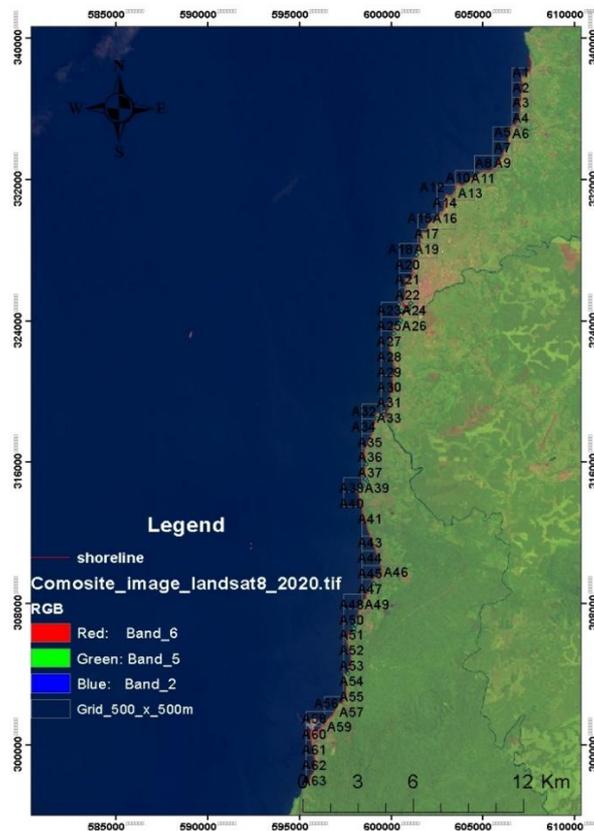
Figure 2. Kribi coastline divided into transect of identical lengths on a 500 × 500 m grid using the method from [7].

Prior to any calculation and statistical analysis, a graphical presentation of the calculation cells is required, along with an optimal choice of dimension for these virtual entities. Following the method of [7], we have chosen cells of dimensions 500 × 500 m, as the study is carried out on a large scale (31.5 km) (Figure 2). The calculation cells are numbered from 1 to 63 from north to south. In order to develop a database for assessing the vulnerability of the study site, data relating to each of the six variables were collected.

2.3. Method for assessing the socio-economic vulnerability index

The assessment of socio-economic vulnerability is a prerequisite for estimating the degree of sensitivity that can affect socio-economic issues and protect them [6]. Most coastal vulnerability studies focus on the physical aspect. Several authors have admitted that including the socio-economic aspect in vulnerability assessment improves study quality and identifies the most vulnerable coastal zones ([5,6,8,19]). Generally, the study of the socio-economic vulnerability of a coastline requires six variables: Settlements, road network, railroads, land use, cultural heritage, and protection status [7,8,20]. According to the scientific community, these variables are essential components of the world's coastal regions. Each socio-economic variable is ranked on a scale of 1 to 5 according to its degree of vulnerability to coastal erosion and marine submersion. The value 1 corresponds to a very low risk, while the value 5 corresponds to a very high risk (Table 3). As a result, the most vulnerable coastal segments are those containing major urban fabrics, a well-developed road network, and historical and cultural sites. The least vulnerable correspond to areas free of any human intervention. The five variables used were combined to calculate the socio-economic vulnerability index. This index is calculated using the Eq 2 developed by [8]; where a is a road network, b is land use, c is cultural heritage, and d is agglomeration.

$$CVI\ socio - economic\ = \sqrt{a * b * c * \frac{d}{5}}. \tag{2}$$

Table 3. Socio-economic variables used to calculate the socio-economic CVI (Source: [7,8]).

Socio-economic variables	Very low 1	Low 2	Moderate 3	High 4	Very high 5
a) Road network	Absent		Secondary road		Highway/national road
b) Land use	Water body	Dense forest	Shrub savannah	Plantation/bare ground	Urbanized area (built-up)
c) Cultural heritage	Absent			−	Present
d) Agglomeration	Absent	Village		Urban ring road	Urban center

2.4. Data processing

Various types of data sources were used to process the variables selected for calculating the physical and socio-economic vulnerability indices (Table 1).

2.4.1. Physical variables

a. Coastal geomorphology variable

The data used to analyze the degree of vulnerability linked to the geomorphology of the coastline studied were taken from digital terrain models (DTMs), obtained via the online portal of the United States Geological Survey (USGS), as well as Landsat satellite images. The DTMs were merged with data from the topographic map and then processed in GIS (ArcGis® 10.1) to produce the geomorphological map of the Kribi coast (Figure 3). Landsat images were processed to identify the geomorphological facies of the coastline. It should be noted that knowledge of the site's geomorphological features acquired during field trips facilitated the assessment. The shape of a coastline has a considerable influence on its reaction to the aggressiveness of the marine environment. Rocky coasts express a very low risk, while beaches show a very high risk, when assessing vulnerability to erosion (Table 2).
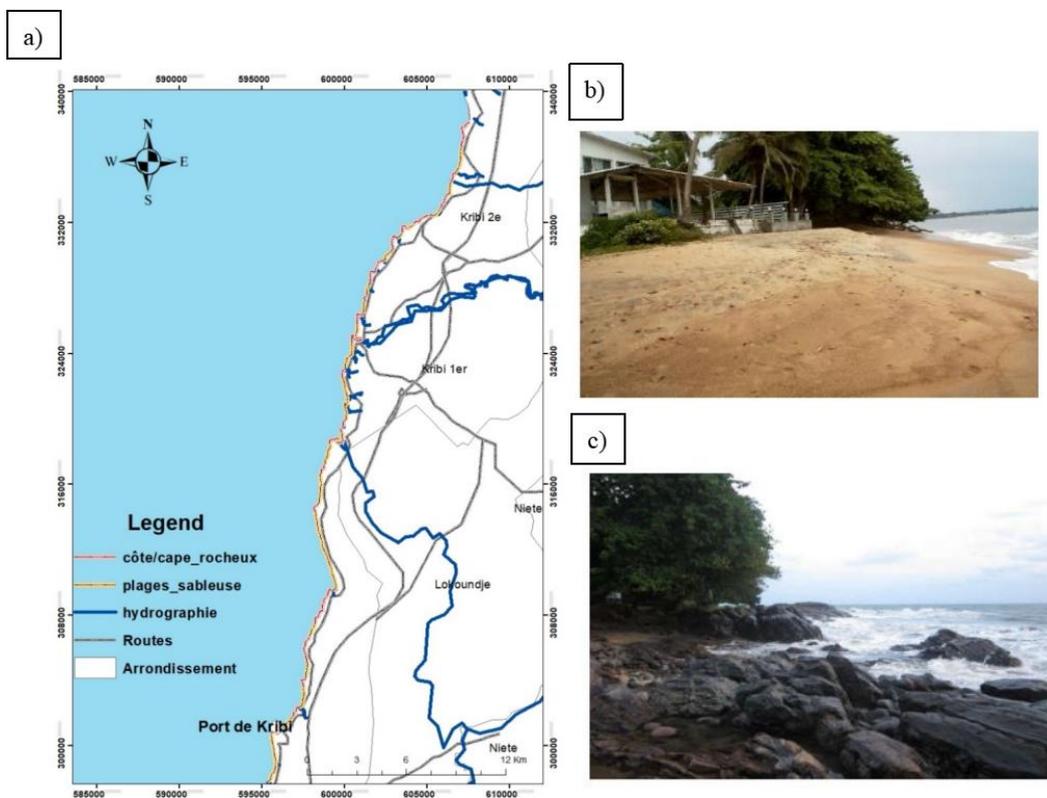
Figure 3. a) Geomorphology of the Kribi coast; b) example of a sandy coast; c) example of a rocky coast.

b. Coastal slope variable

The regional slope of the coastal zone was calculated from a grid of topographic elevations, produced by processing from the digital terrain models (DTMs) and the bathymetric grid, with digital data extracted from the Spouses of Heads Mission (SHOM) nautical chart supplied by the Port of Kribi. These data were merged and processed using GIS software (ArcGis® 10.1) to produce a slope

map (Figure 4). Coastal slope is a quantitative variable, as low-slope coastal strips are more sensitive to erosion, storms, and tsunamis than steep-slope coastal strips [21]. In terms of physical vulnerability, low-slope coastal areas (<3%) have a very high degree of vulnerability, while steep-slope coastal areas (>12%) have a very low degree of vulnerability (Table 2).
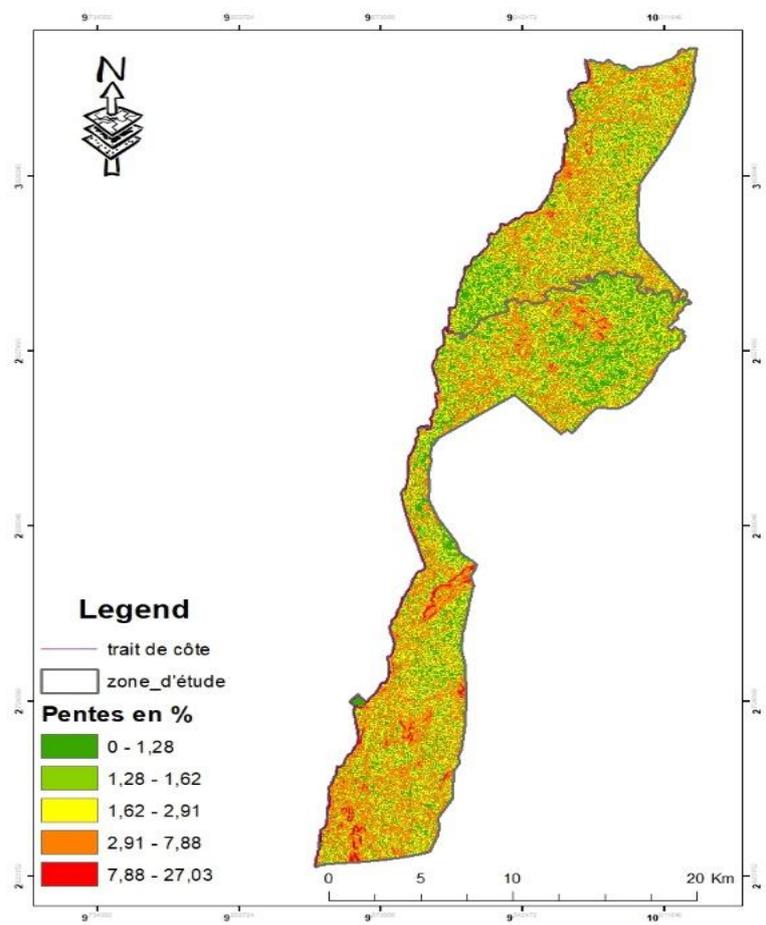

Figure 4. Map of slopes in (%).

c.   Shoreline erosion/accretion variable (m/year)

A spatio-temporal analysis of coastal evolution (coastline) was conducted to calculate the erosion rate by comparing the old and recent positions of coastlines automatically extracted from two Landsat 7 satellite images from 2001 and 2021. In addition, Garmin MONTANA 650T GPS surveys were carried out in the study area to recalibrate the satellite images. Atmospheric, radiometric, and geometric corrections were made to these images using ArcGIS 10.2 software. The Landsat 7 panchromatic band (ETM+) was used to increase the resolution of the other bands from 30 to 15 m by applying a method based on principal component analysis [22]. In this method, the multispectral bands are first sampled at 15 m (by bilinear interpolation) and decomposed into principal components. Then the first principal component is replaced by the panchromatic band after matching the histograms and retransformed into the original panchromatic band. Next, a colorimetric composition of the ETM+ sensor bands is performed. Traditionally, coastline detection is performed in the near- or mid-infrared

due to the low reflectance of water in the infrared region of the electromagnetic spectrum [23]. On this basis, bands 7, 3, and 2 of the Landsat ETM+ images were combined to highlight the contact between the upper beach (sediments and vegetation) and the water. Next, we performed unsupervised classification using the iso cluster unsupervised classification algorithm, which allowed us to differentiate the vegetation boundary. The result was imported into ArcMap to digitize the visible vegetation line (the shoreline) (Figure 5). The DSAS (Digital Shoreline Analysis System), an extension of ESRI ArcGIS, was used to calculate their rate of change. The extracted coastlines were integrated into the DSAS model. Endpoint rate (EPR) values were calculated on equidistant transects of 200 m. This rate is calculated by dividing the distance between the position of the initial shoreline (2001) and that of the most recent shoreline (2021) by the elapsed time (20 years) according to Eq 3. The EPR has the advantage of requiring a minimum of data (two coastlines) [22].

$$EPR = \frac{NSM}{T}, \tag{3}$$

where *EPR* (m/year) is the speed of coastline change, *NSM* (m) is the length between the two coastlines studied, and *T* (year) is the time elapsed between the two coastlines studied.
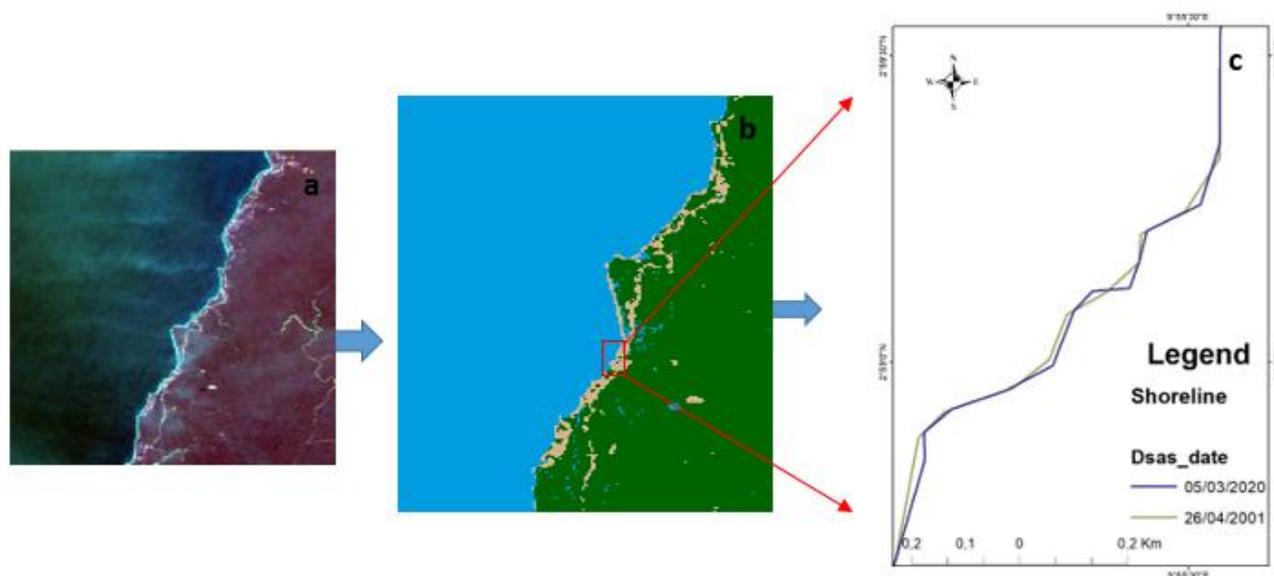

Figure 5. Extraction of coastline: a) color composition 237; b) classification; c) digitization of coastline.

d.   Average tidal range (m)

Cameroon's coast is microtidal, which means that tidal amplitude is generally low. The average tidal range in Cameroon varies, but is generally less than 2 m [24]. The Kribi coastline has the lowest tides compared with the Wouri estuary. The average tidal range is 1.2 m, although there is considerable variation by sector [25].

e.   Significant wave heights at the coast (m)

Wave parameters (significant height Hs, period Tp, and direction) are extracted from the European Centre for Medium-Range Weather Forecasts server (ECMWF) (https://www.ecmwf.int/en/forecasts/datasets) on a 0.125° × 0.125° grid, along the Cameroon coast with a time lag of one day of resolution, from January 1986 to August 2020. These wave data are part of the ERA-Interim dataset, the Ers-1&2, Envisat, and Jason-1&2 altimetry missions, which involve the analysis of global meteorological variables. These wave data have been extensively validated against buoy and altimeter data [26], with maximum wave height (Hs > 5 m) and minimum wave height (Hs < 1 m) tending to be under- and over-estimated, respectively [26]. The time series of Hs for the grid points closest to the coast was extracted, followed by the time averages of wave parameters over the entire Cameroon coast for a period of 33 years. To estimate wave characteristics at the breaking point along the 9592 segments of the entire Cameroon coast, the formula suggested by [27], $hb = (\lambda c)/g$ (3), was used as the data do not directly cover the Cameroon coast. Here, hb represents the wave height at the point of breaking, λ is the wave breaking threshold, C is the wave propagation speed toward the coast, and g is the acceleration due to gravity. Wind roses were calculated for the period 1993 to 2022, taking wave direction into account, showing predominantly south-south-westerly (S-SW) wave directions, as well as their significant heights (Hs), which decrease from north to south (Figure 6).
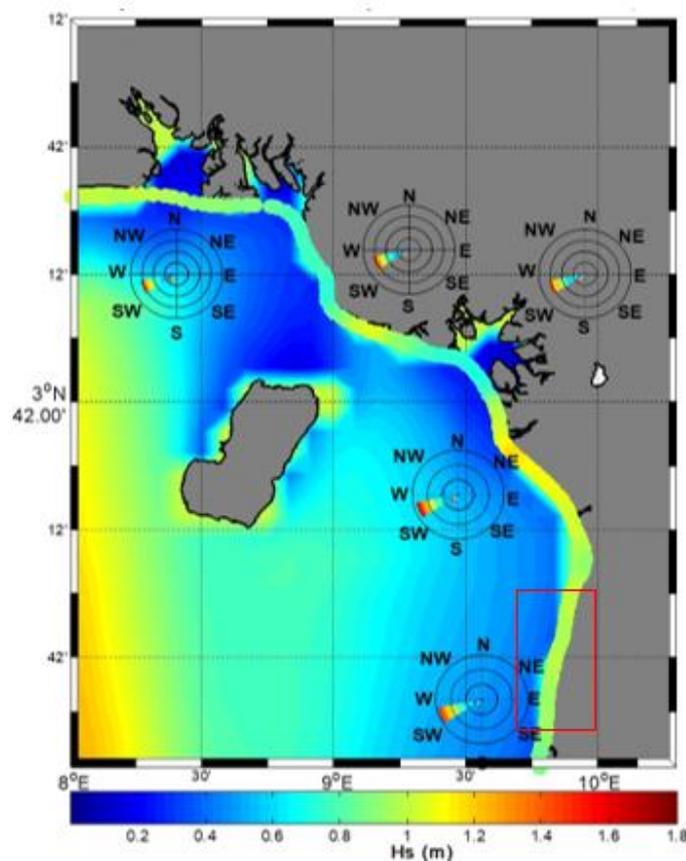

Figure 6. Illustration of the spatial distribution in the Cameroon coast of significant wave heights and their dominant directions (wave rose) in different sectors. The red rectangle represents the study area.

2.4.2. Socio-economic variables

a. Road network variable

The road network was extracted from the master urban plan of the city of Kribi. The road network is a key factor in the social and economic development of coastal areas. It allows people to move around and goods to be transported. Coastal areas with well-developed road networks are more vulnerable, as damage to these networks caused by erosion or flooding results in significant economic and commercial losses [8] (Table 3).

b. Land use

The land use of the coast determines its economic importance and influences its vulnerability. Urbanized and industrialized areas are considered highly vulnerable, while natural areas are less vulnerable [8] (Table 3). Land use type was determined by image processing using a supervised classification approach. ArcGis software was used to produce a land cover map based on Landsat 8 satellite images acquired in 2021. Here, radiometric bands providing information on vegetation cover were superimposed by additive synthesis of primary colors. Thus, the false color composition with the combination of bands 3, 4, and 5 for the OLI-TIR image was used. The supervised classification method based on the maximum likelihood algorithm was used. The classification established and the colors used to represent each land cover category were adapted from the Corine Land Cover (CLC) nomenclature. The accuracy and kappa index, and the superposition of the land cover map produced from the Landsat 8 satellite image acquired in 2021 with the 2021 high-resolution image available on Google Earth, were complementary and essential steps in validating the classifications (Figure 7). Overlaying allowed us to correct the classifications and bring them closer to the reality on the ground. The resulting land-use map provided the basic data for the vulnerability analysis.
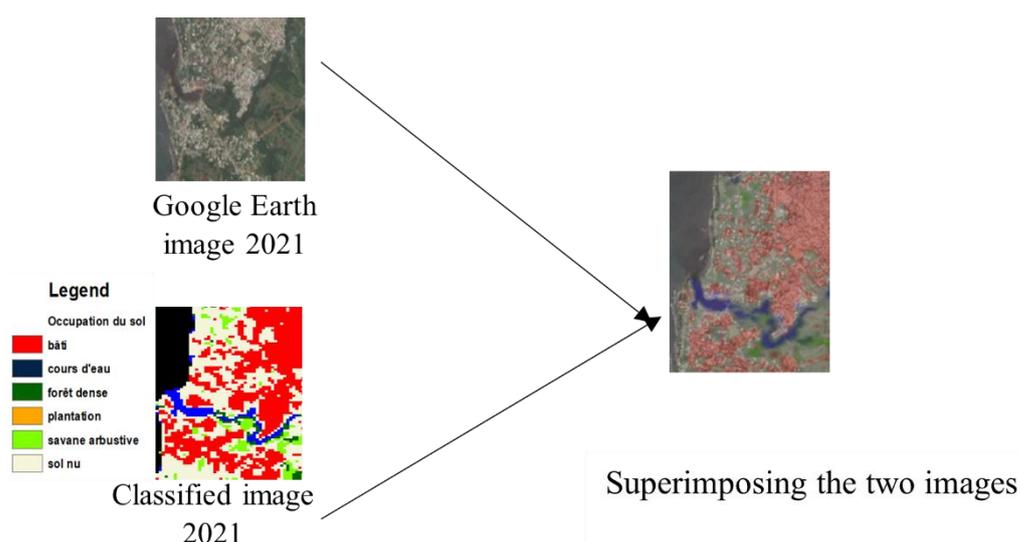

Figure 7. Classified image 2021 superimposed on the Google Earth image.

c. Cultural heritage

This variable concerns the historical monuments and cultural sites located in the study area, as well as cemeteries, places of worship, etc. These vestiges are of great tourist, social, and cultural value. Their presence indicates that the coastal segment is highly vulnerable, and their absence indicates that the coastal segment is not vulnerable [8]. All the cultural sites were determined by in situ observations and a survey of local populations, as well as by data from the master plan for the town of Kribi.

d. Agglomeration

In this research context, an agglomeration is defined as a group of buildings close enough together to form villages, urban centers, etc. A densely populated coastline has great economic value [28]. Thus, an urban center is more densely populated than a village, and its impact on the development of the region is greater, making it more vulnerable (Figure 8). The data used for the "road network" and "agglomeration" variables in our study come from shapefiles from the Kribi urban master plan [29] and field observations. They were used to validate the various variables used.
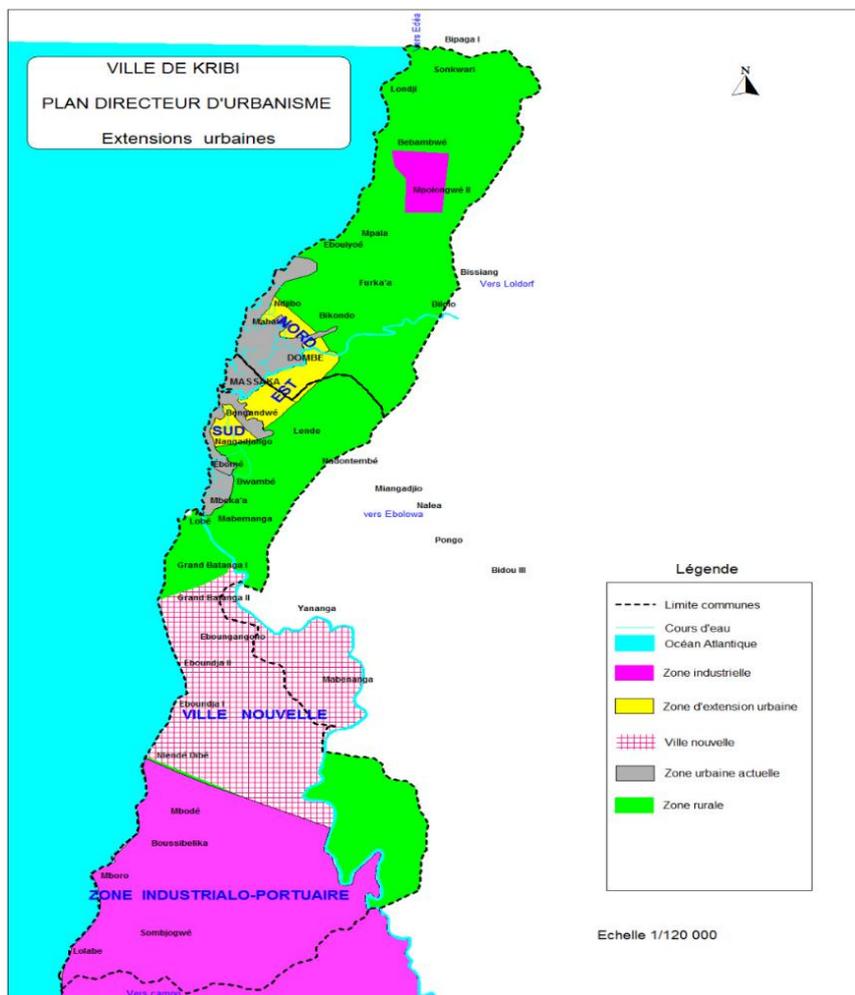

Figure 8. Location map of variable agglomeration.

3. Results

The results of processing the data for each variable and the degree of their vulnerability in the 500 × 500 m grid using the method of [7] are presented in the table below.

3.1. Evaluation of physical variables

a. Coastal geomorphological variable

The geomorphological facies of the Kribi coastline, with the exception of the port of Kribi, is dominated by two forms of relief: One friable and the other rocky. According to the results (Figure 9 and Table S1), more than half of Kribi's coastline (60.3% or 19 km), containing sandy beaches and soft cliffs, is very highly vulnerable. On the other hand, 39.7% (12.5 km) of the rocky coastline has low vulnerability.
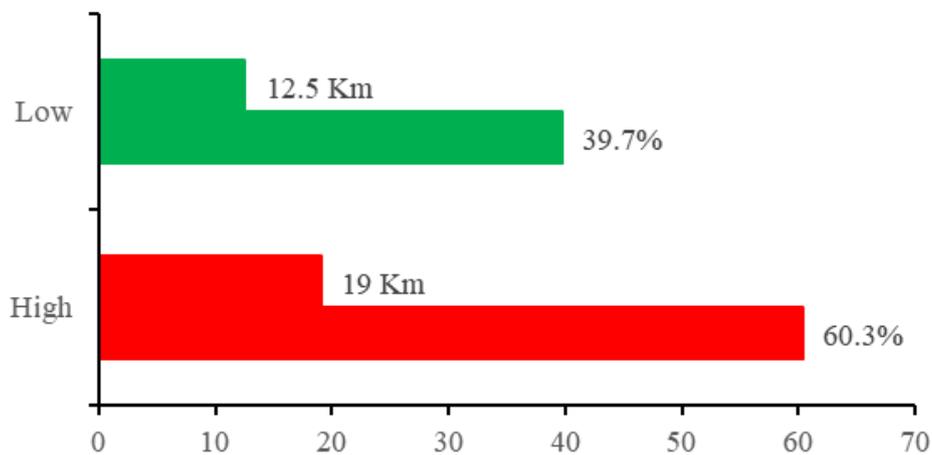
Figure 9. Histogram representing the degree of vulnerability of the geomorphological variable on the *y*-axis and the relative percentage and distance in kilometers on the *x*-axis along the Kribi coastline according to the calculation grid.

b. Coastal slope variable

The results obtained by mapping this variable show that 3.2% or 1 km of Kribi's coastline has low vulnerability, with coastal slopes greater than 7%, along the small headlands of rocky coasts (Elabé, Boussibiliga, etc.). More than a quarter (23.8% or 9 km) of the coastline is moderately vulnerable, with coastal slopes of between 6 and 9% along small, low-lying rocky coasts. On the other hand, 71.4% of the coastline (22.5 km) is exposed to high vulnerability, with slopes ranging from 3% to 6% along sandy beaches, while 1.6% (0.5 km) of the coastline has very high vulnerability, with slopes <3% along small coves (Mpalla, Ebomè, etc.) (Figure 10 and Table S1).
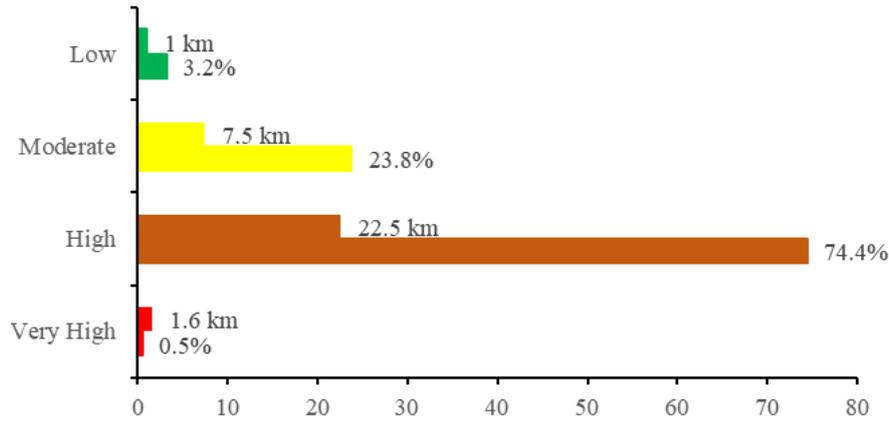
Figure 10. Histogram representing the degree of vulnerability of the slope variable on the *y*-axis and the relative percentage and distance in kilometers on the *x*-axis along the Kribi coastline according to the calculation grid.

c. Erosion rate/shoreline accretion variable

The results obtained for shoreline evolution show that 61.9% (19.5 km) of the coastline is moderately vulnerable, with alternating erosion and accretion, with rates varying between + 0.1 m/year and −0.9 m/year. On the other hand, 1.6% (0.5 km) of the coastline is at high risk, with rates of change fluctuating between −1 and −1.3 m/year. Similarly, 34.9% are at low risk, with a rate of change of between 0.2 and 1.9 m/year, and 1.6% are at very low risk, with a rate of change greater than or equal to 2 m/year (Figure 11 and Table S1).
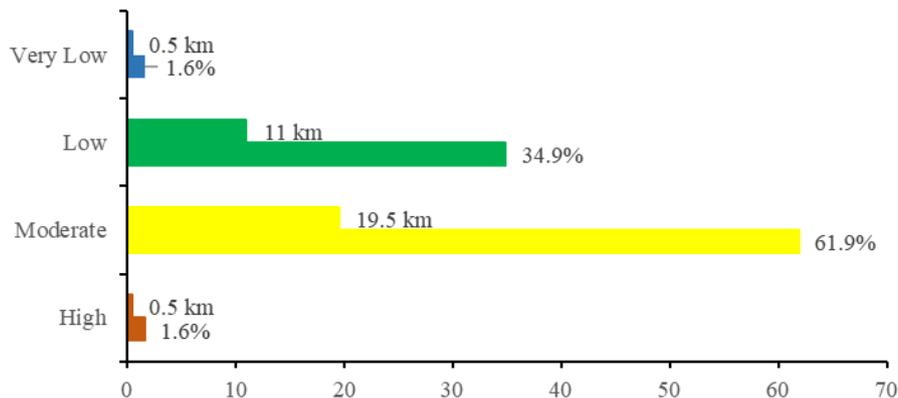

Figure 11. Histogram representing the degree of vulnerability of the erosion rate variable on the *y*-axis and the relative percentage and distance in kilometers on the *x*-axis along the Kribi coastline according to the calculation grid.

d. Mean tidal range

The Cameroon coast is characterized by a microtidal coastline, which means that tidal amplitude is generally low. The average tidal range in Cameroon varies, but is generally less than 2 m [24]. The

average tidal range on the Kribi coast is 1.2 m [25], making its vulnerability low to coastal erosion (Figure 12 and Table S1).

e. Significant wave heights at the coast

Wind roses calculated for the period from 1993 to 2022, taking wave direction into account, show predominant wave directions from south-southwest (S-SW), as well as their significant heights (Hs), which decrease from north to south (Figure 6). Significant wave height values on the Kribi coast are <1.25 m. Consequently, the entire coastline is in the Moderate vulnerability class (Figure 12 and Table S1).
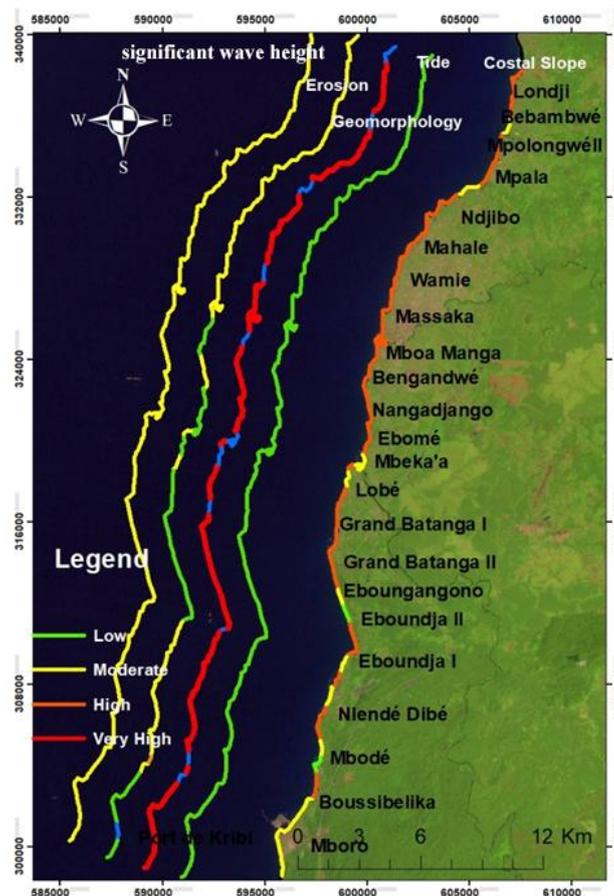

Figure 12. Relative risk factors for different physical and geomorphological variables: (a) coastal slope; (b) tide; (c) geomorphology; (d) erosion rate/shore accretions, and (e) mean wave height.

3.2. Calculation of the physical vulnerability index

The combination of the five parameters was used to determine the coastal vulnerability index. The values of this index range from 4.9 to 17.9, with a median of 13.4. The four levels of coastal vulnerability are obtained by statistical processing of the CVI data. Thus, the 25%, 50%, and 75% quartiles were identified to determine the four levels of coastal sensitivity (low, moderate, high, and

very high risk). The CVI values for low, moderate, high, and very high risk are, respectively: Between 4.9 and 7.7, between 7.7 and 11.0, between 11.0 and 13.4, and between 13.4 and 17.9 (Figure 13).
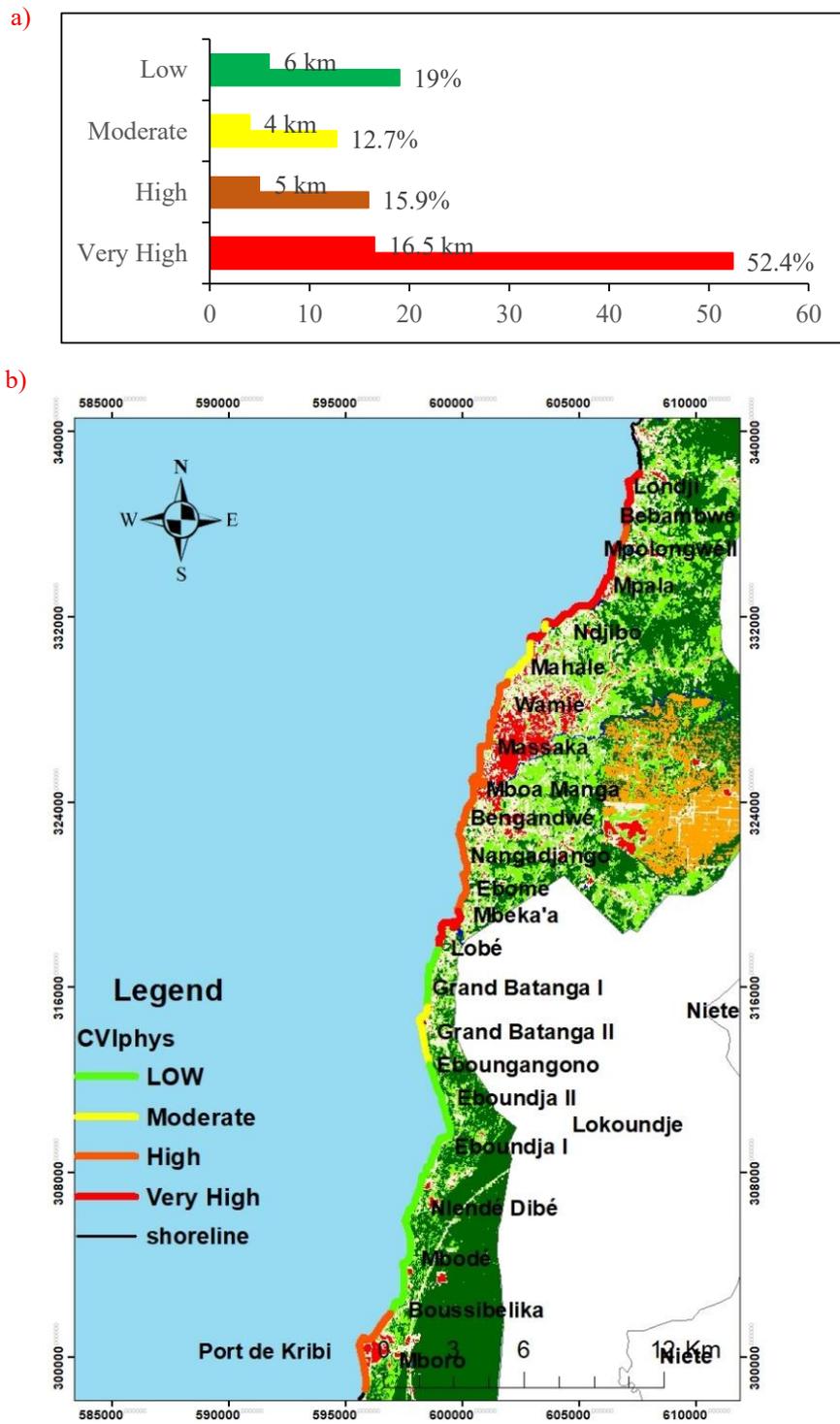

Figure 13. (a) Histogram representing the variation in the physical vulnerability index on the *y*-axis and the relative percentage and distance in kilometers on the *x*-axis along the Kribi coastline according to the calculation grid. (b) Map showing the coastal vulnerability index (CVIphys) for the Kribi coastline.

The results obtained on the histogram (Figure 13b) show that almost two-thirds (31.7%) of Kribi's coastline has a low to moderate vulnerability in terms of rocky coastline over a 10.5-km stretch, and more than half (68.3%) has a high to very high vulnerability in terms of physical characteristics such as sandy accumulations over a 21-km stretch of coastline.

In fact, of the 31.5 km of coastline studied, almost a quarter (19%) has a low vulnerability to erosion risk in relation to the physical characteristics of the coast (i.e., 6 km) and is characterized by cliffs and rocky coasts. These are located from south to north on the small capes of Elabé, Boussibiliga, etc. Part of the coastline (12.7%) is characterized by a moderate vulnerability to erosion risk in relation to the physical characteristics of the coast (i.e., 4 km) and is characterized by relatively low rocky coasts with a height of no more than 4 m. This vulnerability is due to the morphological structure and the moderate slope, which varies from 6 to 9%. More than half of Kribi's coastline (52.4%) is exposed to very high vulnerability, i.e., 16.5 km, and 5 km are exposed to high vulnerability to erosion risks in relation to the physical characteristics of the coast (i.e., 15.9% of the coastline). These are characterized by sandy beaches with a low accumulation rate, such as the beaches of Ngoye, Grand Batanga, Ebomé, Eboundja, etc.

3.3. Socio-economic vulnerability assessment

The assessment of socio-economic vulnerability shows that high-vulnerability areas belong to highly urbanized centers with dense road networks and a strong cultural heritage. On the other hand, low-vulnerability zones are those with no human settlements. The influence of each parameter is shown in the table below (Table S2).

3.3.1. Assessment of the various socio-economic variables

a. Land use

Heavily urbanized areas have a very high vulnerability, with half of Kribi's coastline concentrated in the north, while the segments of coastline where the deep-water port of Kribi is located, and some of which contain portions of the road network, have a high vulnerability, with a quarter of the coastline concentrated in the south. The remainder of the region, devoid of any human activity, is characterized by open spaces (shrub savannah), bare soil, and occasional forests; these coastal segments have a very low to moderate vulnerability and represent a quarter of the Kribi coastline (Figure 14a and Table S2).

b. Agglomeration

These are concentrated along the central axis of National Highway No. 7 (N7). The North/North-West zone, located at the most important entrance to the town and close to the Kribi-Edéa road, is the most urbanized part of the town, along with the central axis. Moving southward, the settlements become less important, such as the villages of Mboa-Manga, Ebomé, etc., on the way to the port area at Mboro, where the new town will be built. This means that the northern side of the coast is more vulnerable to the agglomeration parameter than the southern part (Table S2 and Figure 14b).
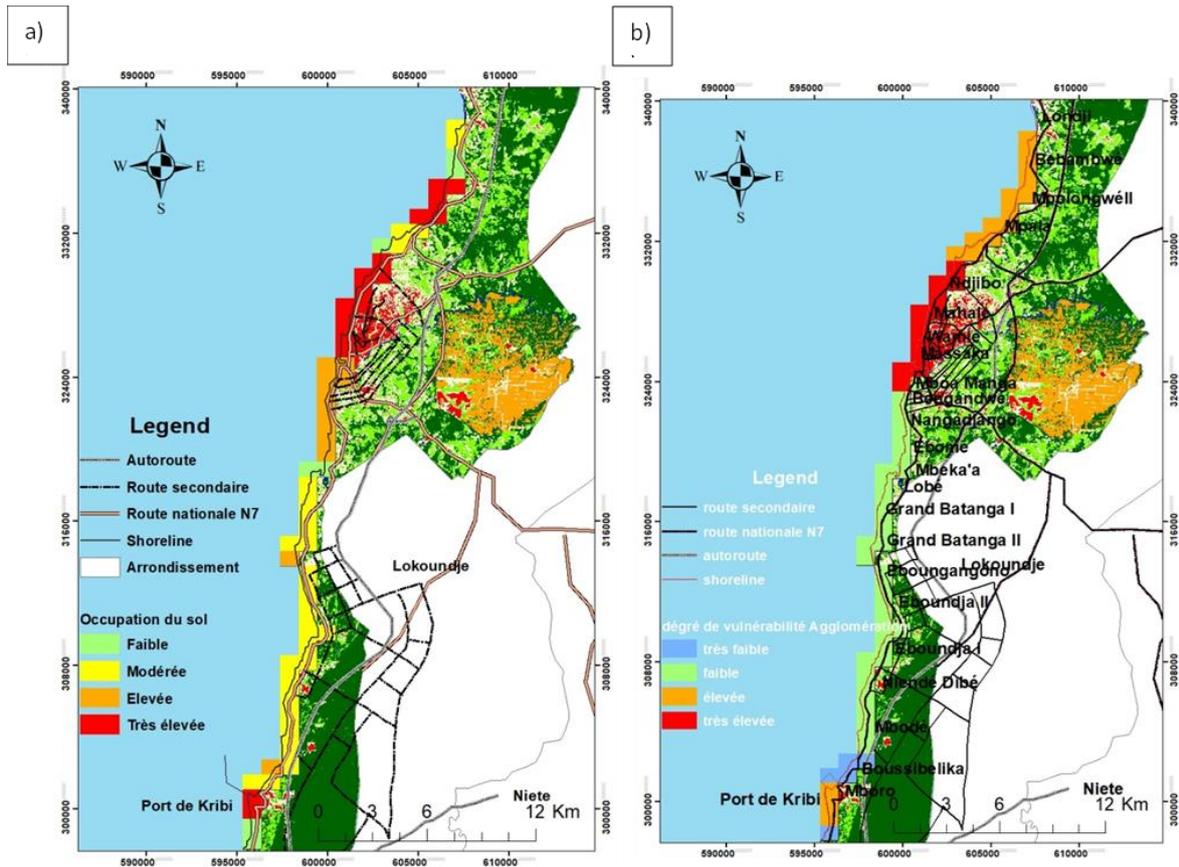
Figure 14. (a) Graphical representation of the degree of vulnerability relative to the land use variable; (b) graphical representation of the degree of vulnerability relative to the agglomeration variable, influential in determining the index of socio-economic vulnerability due to erosion of the Kribi coastline.

c. Road network

Two types of road networks cross the communes of Kribi 1st and 2nd: national road number 7, which almost skirts the two communes, and secondary roads with high vulnerability and a freeway with very low vulnerability (Figure 15a).

d. Cultural heritage

Cultural heritage is dominated in the southern part, in the villages of Grand Batanga I, Lobé, Mboa-Manga, and so on. These include cemeteries, the Madiba monument, the Art Gallery Museum, the Fare monument, the Presidency of the Republic, etc. These vestiges constitute the cultural heritage of the communes of Kribi 1st and 2nd, and therefore have a very high vulnerability rating. The remainder of the coastline studied contains no historical remains, and therefore the rated vulnerability is very low (Figure 15b and Table S2).
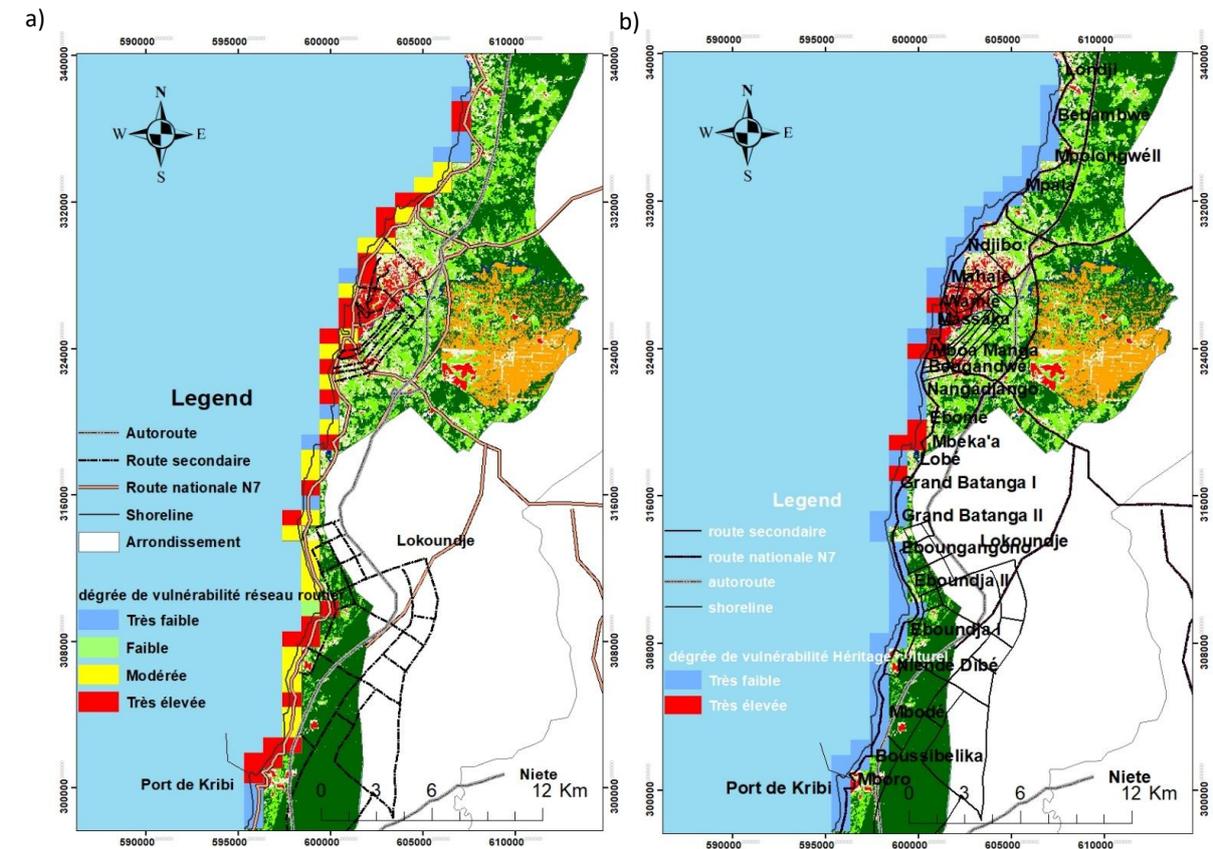
Figure 15. (a) Graphical representation of the degree of vulnerability relative to the variable road network; (b) graphical representation of the degree of vulnerability relative to the variable cultural heritage influential in determining the index of socio-economic vulnerability due to risks of erosion of the Kribi coastline.

3.3.2. Calculation of the socio-economic vulnerability index

The values obtained by calculating the socio-economic vulnerability index for the Kribi coast range from 0.7 to 11.2. Four classes of vulnerability are distinguished: low, moderate, high, and very high (Figure 16). These results reveal that 3.2% (7.17 km) of the coastline has a low socio-economic vulnerability to erosion risk, with CVIsocio-eco values ranging from 0.7 to 1.5 covering the Mboro area located upstream of the port dike. 38.1% (12 km) of the coastline shows moderate vulnerability, with CVIsocio-eco values ranging from 1.6 to 2.5, covering the villages of Boussibelika, Mbodé, Eboundja II, Eboungangona, Grand Batanga II, Mpolongwé, and Bebambwé. 33.3% (10.5 km) of the coastline is highly vulnerable, with CVIsocio-eco values ranging from 2.6 to 3.9, covering the villages of Eboundja I, Nlendé Dibé, Mbeka, Ebomé, and the urban periphery of Mpala and Mpolongwé II. 25.4% (8 km) of the coastline is very highly vulnerable, with CVIsocio-eco values ranging from 2.6 to 3.9, covering the villages of Eboundja I, Nlendé Dibé, Mbeka, Ebomé, and the urban periphery of Mpala and Mpolongwé II. while values between 4 and 11.2 cover the urban center of Kribi and the village of Lobé.
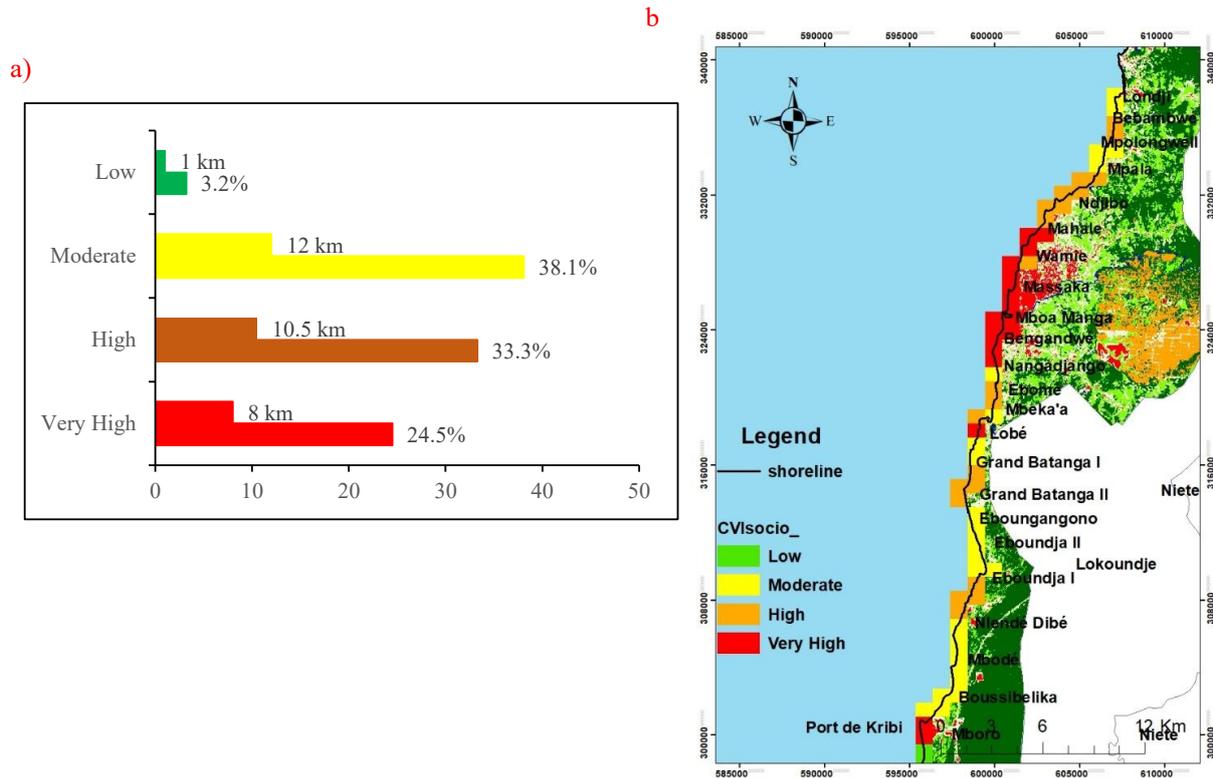
Figure 16. (a) Histogram representing the variation in socio-economic vulnerability index on the *y*-axis and the relative percentage and distance in kilometers on the *x*-axis along the Kribi coastline according to the calculation grid; (b) index of socio-economic vulnerability (CVIsocio-eco) to coastal erosion on the Kribi coastline.

4. Discussions

The assessment of the physical vulnerability of the Kribi coast revealed the extent to which the various coastal segments could be adversely affected by erosion risks. It revealed a more or less worrying reality and confirmed the good condition of two-thirds of the coastline, which is resistant to these risks, these segments being represented by rocky headlands and hard rocky coasts. The poor condition of the coast concerns low-slope, geomorphologically friable accumulation coasts, and small coves that are already eroding. This erosion is the result of human settlements, such as the port of Kribi, and sand extraction on the beach for construction purposes (sand quarry).

The southern part is more vulnerable than the other coastal segments downstream of the port, as is the central part toward the urban center, characterized by a succession of small coves and narrow beaches. The difference in vulnerability of the coastal segments of the Kribi coastline is due to geological variables, which confer a specific vulnerability to each coastal segment. The most vulnerable stretches of coastline have a gentle slope, an almost flat geomorphology and are made up of friable materials (sandy beaches). The high vulnerability of the southern and central parts of the coast is compounded by the erosion experienced in recent years in the town of Kribi. This erosion is explained by the reduction in sediment supply due to the construction of the 1.5-km-long harbor breakwater, which acts as a sediment trap, triggering a sediment crisis on the Nlendé, Boussibelika,

and Mbodé beaches downstream [18], as well as the extraction of sand from localized areas of the coast in response to construction needs. In the case of rocky headlands, the hard lithology, steep slope, and high average regional altitude have helped to mitigate the risk of erosion (Figure 17).

Coastal erosion has a direct impact on human settlements and economic activities in the city of Kribi, hence the need to assess socio-economic vulnerability. The results obtained for the Kribi coast show that 41.3% of the coastline (i.e., 19.17 km) has a low to moderate socio-economic vulnerability to erosion, and 58.7% of the coastline (i.e., 18.5 km) has a high to very high vulnerability (Figure 17). The coastal segments with very high socio-economic vulnerability to erosion correspond to the urban center of Kribi. This very high vulnerability is explained by the presence of a highly urbanized urban center with a dense road network and an important cultural heritage. High vulnerability corresponds to areas of high human occupation, such as the city center and the port area, which are highly urbanized zones with a developed economic vocation and extensive road networks. Areas of moderate vulnerability correspond to fishing villages (Figure 17). These results are similar to those for the coastline of central western Algeria [30].
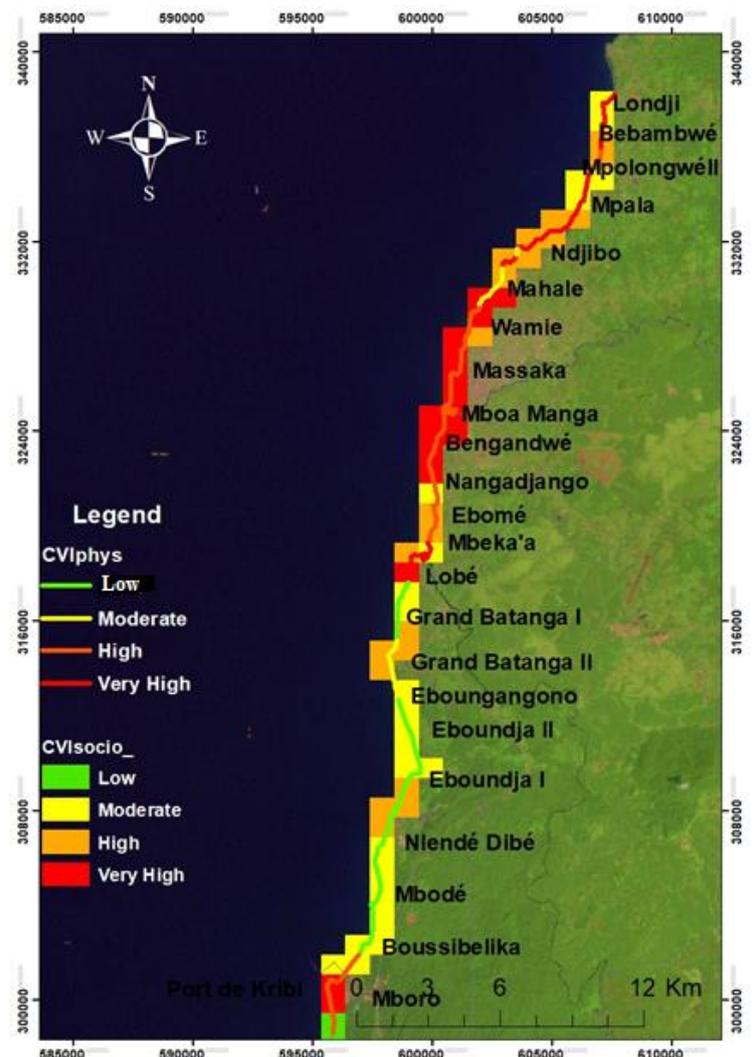

Figure 17. Vulnerability map obtained by superimposing the physical and socio-economic vulnerability indices of the Kribi coastline.

The limitation of this study lies in the relatively low resolution of the data. This study is based on data collected during field and satellite observations. Less data is available for the Kribi coastline than for the Maghreb and European countries. There are few studies focusing on coastal vulnerability and strategies for mitigating or adapting to coastal risks on the Cameroonian coast. In addition, temporal variations in coastal processes range from daily to multi-year periods at the climate level; however, current data collection techniques do not allow this temporality to be captured with sufficient accuracy. Globally, data collection methods have evolved considerably since most of these studies were conducted, particularly through the use of new digital technologies. It is necessary to study coastal vulnerability using better quality data and constant observation; emerging technologies such as unmanned aerial vehicles (UAVs) equipped with airborne sensors and LiDAR can contribute to a better understanding of coastal vulnerability in Kribi.

5. Conclusion

Determining the most vulnerable portions of the coastal strip using the methods developed by [7] (CVIphys) and [8] (CVIsocioéco) highlights the areas most vulnerable to erosion on the Kribi coastline. We were thus able to draw up a map of physical vulnerability to coastal erosion, showing high to very high vulnerability to erosion in sandy accumulations, and low to moderate vulnerability in small coves and rocky coasts. On the other hand, the socio-economic vulnerability map reveals high vulnerability corresponding to urbanized areas with an economic vocation, a major road network, and cultural sites. On the other hand, low vulnerability coincides with areas devoid of any human intervention.

The vulnerability maps provide support for decision-makers and planners in developing strategies not only for mitigating or adapting to erosion risks on each segment of coastline, but also for current and future coastal management. These results call for the current and future integrated management of Kribi's coastal strip. As a large proportion of the population lives in coastal areas, it is essential to assess the vulnerability of these communities to natural hazards, as they will be greatly affected by climate change.

Based on the results of this study, a strategy for adapting and protecting people and property is becoming a necessity. However, for local decision-makers and planners, it is difficult to identify where, when, and how to adapt to the risk of erosion in coastal areas. To combat the risk of future erosion on the Kribi coast, a number of protection techniques are available, including beach nourishment, reforestation of beach tops, identification of footpaths on beaches, urbanization management, and protection of the coastal strip (300-m strip) inland from all types of human intervention.

The analysis reveals that the majority of existing data are collected from satellite data or field observations that are of very low resolution and are not continuous. This research can be used as a primary assessment for the design of a resilience assessment framework for erosion risk management and should play a key role in decision-making to reduce the vulnerability of this coastal area and could also improve its resilience. Only a few CVI parameters were taken into account, and the data used was of relatively low resolution. Further research is needed to observe, measure, and evaluate adaptation and mitigation measures in this region to improve resilience.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that might appear to influence the work presented in this article.

Author contributions

Clotaire Jose Pako Perabi: Drafting of the original project, revision, and methodology. Raphael Onguene: Formal analysis and data processing. Software. Kevin MBA Djuka Zebaze: Development of methodology, drafting, and revision. Abdoul Aboubakar: Drafting and revision. Drafting of the original project. Gregoire Ondoa Abessolo: Proofreading of the original document and revision. Pierre Ele: Supervision and revision.

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