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GEOMATICS ASSESSMENT OF COASTAL EROSION VULNERABILITY: A CASE STUDY OF AGADIR BAY, MOROCCO

SUMMARY

Coastal zones are characterized by a complex interaction between continental and marine ecosystems. They are often subject to anthropogenic and natural pressures such as urbanization, pollution, erosion, storms, and the impact of climate change. It is an environment that requires sustainable management to preserve its biodiversity and ecosystem services. This study focuses on assessing coastal vulnerability to erosion in the Bay of Agadir, one of Morocco's main tourist attractions. The methodology adopted is based on geomatic science such as GIS and geospatial remote sensing. This approach involved the preparation of a database for the study area, relating mainly to geomorphological parameters, topography, sea level rise, and shoreline change data. The latter was assessed using DSAS (Digital Shoreline Analysis System) tools and then all data were integrated into a GIS software to evaluate the Coastal Vulnerability Index (CVI). The first result shows that the EPR (endpoint rate) index reveals an erosion trend over the 8.3 km studied area. Over the 262 transects analyzed, the variations show a predominant erosion (92%) with rates of up to -13.5 m/year over 46 years. This justifies the use of the LRR (Linear Regression Rate-of-Change) index rather than the EPR for kinematic analysis of the coastline. The results of the CVI index show that 2.58 km of the coastal zone, and 1.68 km of the Bay are successively highly and very highly vulnerable to coastal erosion (20-60%). This study can be considered as a basic document, providing crucial information to guide decision-makers and planners in the implementation of effective coastal conservation strategies.

Keywords: Coastal erosion, Geomatics, Vulnerability index, Agadir Bay, Morocco.

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INTRODUCTION

The climate of Morocco is diverse, ranging from arid desert to humid north. Climate change can exacerbate erosion phenomena (Sabri et al., 2022), especially along coastal areas, by intensifying storms, raising sea levels, and altering precipitation patterns, thereby endangering fragile ecosystems and coastal infrastructure.

Coasts constitute dynamic environments shaped by various physical factors such as geology, geomorphology, sedimentology, and oceanic forcing, including wave action and sediment transport. With approximately 21% of the world's population residing in coastal areas (Brooks et al., 2006), these regions are increasingly impacted by a significant concentration of anthropogenic activities and socio-economic challenges.

The costs associated with climate change and larger natural disasters, whether economic, social, or ecological, are expected to further burden affected communities and government administrations (Thouret and Leone, 2003; Fairbank and Jakeways, 2006). Erosion induced by water constitutes a challenge with far-reaching environmental and socioeconomic implications across diverse global regions (Bouayad et al., 2023). Coastal erosion due to storm waves is a significant problem threatening economic stability (Martzikos et al., 2021), given its impact on tourism and major infrastructure (Thouret and D’ercole, 1996). It is considered one of the main factors in the modification of the coastal landscape (Arabadzhyan et al., 2021).

Beaches are not inevitably destined to disappear; they can shift inland by rolling upon them unless impeded by obstacles. These obstacles may be natural, such as an escarpment or a dormant cliff, or anthropogenic, like man-made constructions. In the latter scenario, where migration becomes impracticable, erosion accelerates, ultimately leading to the disappearance of the beach.

In recent years, the utilization of databases and Geographic Information Systems (GIS) in coastal scientific studies has led to a significant increase in the development of vulnerability indices for coastlines (Ariffin et al., 2023; Furlan et al., 2021; Subraelu et al., 2021). This is due to the intense development of coastal areas and the impact of climate change, which have heightened flooding risks. (Aitali et al., 2020). This approach can be explored by integrating the multi-criteria to enable better identification of areas with high vulnerability to sea-level rise and would enable better implementation of guidelines for the management of this coastline (Bagdanaviciute et al., 2015).

The Coastal Vulnerability Index (CVI) is the most common index for assessing coastal vulnerability to physical climate change and sea level rise (Rocha et al., 2023; Roy et al., 2023). All CVI methods are based on an index that simplifies a number of complex and interactive parameters and is widely used to measure coastal vulnerability on a global scale (Khouakhi et al., 2013; Koroglu et al., 2019). The choice of coastal variables is very delicate.

Previous studies from the late twentieth century demonstrate significant variation in the number of variables included in published Coastal Vulnerability

Index (CVI) methodologies (Rocha et al., 2023). At the time, former researchers believed that the more variables there were, the more reliable the result would be. The overall objective of this research is to assess the vulnerability of Agadir Bay to the threat of coastal erosion. The site was chosen because of its geographical location on the coast and its susceptibility to various coastal hazards: flooding, tsunamis (Fajri et al. 2021), based on the "CVI" index, which integrates geomorphological and physical parameters in order to generate a map of coastal vulnerability against erosion.

The main goal of this study is the utilization of the Coastal Vulnerability Index (CVI) as a crucial metric for assessing vulnerability. By leveraging geomatics tools, we aim to provide a comprehensive understanding of the region's susceptibility to coastal erosion. The findings of this analysis are anticipated to contribute valuable insights for coastal management and resilience strategies in the Bay of Agadir. This paper thus serves as a vital contribution to the ongoing discourse on coastal vulnerability assessment and management practices.

MATERIAL AND METHODS

Study area. The study area is part of Agadir Bay in the Souss region of Morocco (Ambroggi, 1963), a country that is in Northern Africa, bordering the North Atlantic Ocean and the Mediterranean Sea, between Algeria and Mauritania. This position gives it a role of economic relay through which all north-south flows transit and it also has a strategic role in economic and socio-cultural terms (Aouiche, 2016a).

Agadir Bay's Geographic location is presented in Figure 1.

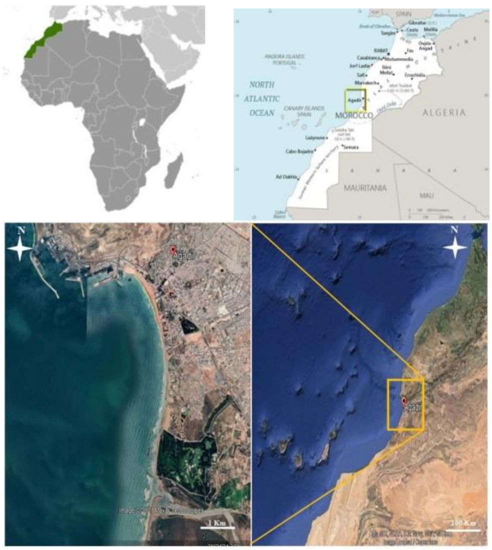

Fig 1: Study area, Agadir Bay's Geographic location
(Source: The World Factbook and Google Earth)

MATERIAL

Geomorphology

The Bay of Agadir is made up of three morphological zones:

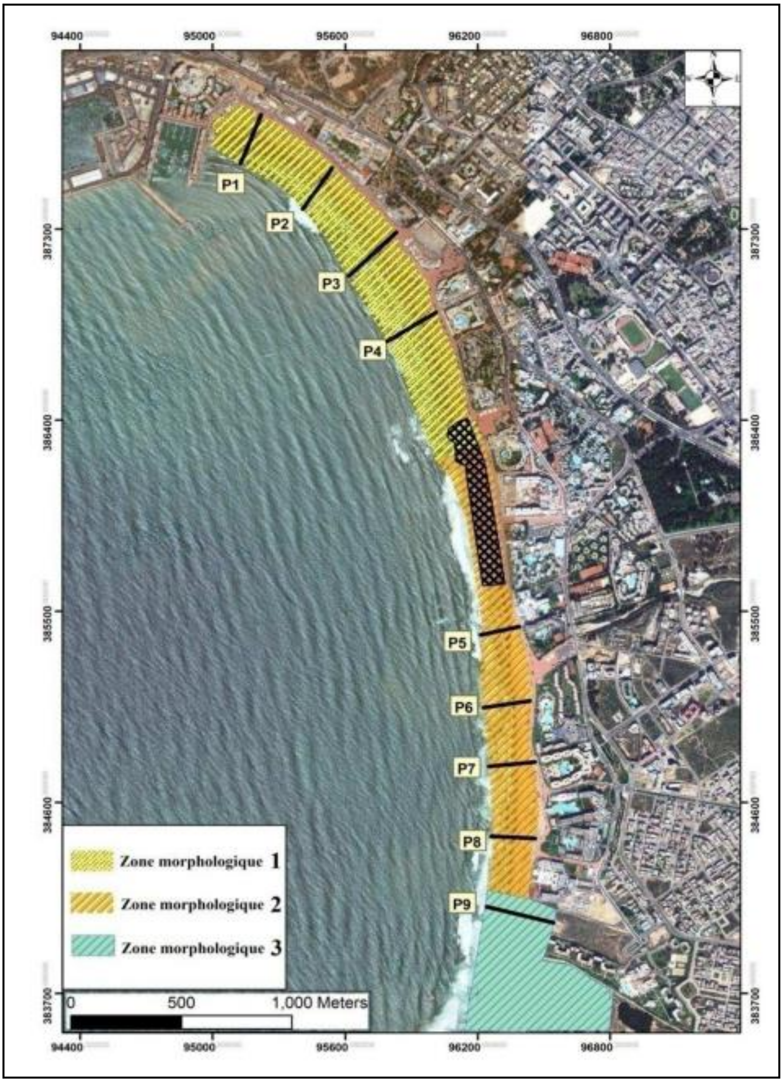

Figure 2: Location of topographical profiles and morphological zones of the beach in April 2015 (Aouiche, 2016a).

Morphological zone 1: Located to the north of the study area (Fig.2), it is characterized at the top of the beach by a vast platform almost 150 m wide with a very gentle slope. Approaching the mid-foreshore we observe a very marked break in slope.

Morphological zone 2: Located in the extreme south of the study area (Fig.2), it represents a different morphology compared to the north. The platform detected in the north has disappeared; the shape of the foreshore is much narrower, steeper, and smoother.

Morphological zone 3: Located in the extreme south of the study area (Fig.2), it represents what remains of the dune system of the Bay of Agadir. The foreshore is quite smooth and less steep. The top of the beach is distinctive with the presence of a dune of 13m/Zh altitude.

The first two morphological zones 1 and 2 are marked by the presence of a promenade dike at the top of the beach, built in 2012. In the 1980s, this portion of the bay of Agadir was formed by a massive dune (12 to 14 m) and a gently sloping beach that extended to the underwater beach.

Coastal slope

According to the topographic data measured (Tab.1) according to the profiles (Fig.2):

–***Morphological zone 1:***

In this zone, 4 transverse profiles were produced P1 to P4.

–***Morphological zone 2:***

In this zone, 4 transverse profiles were made from P5 to P8.

–***Morphological zone 3:***

A single transverse profile was carried out in this zone P9.

Table 1: Measurement of the coastal slope of Agadir Bay

Morphological zone	Profiles	Average slope (degrees)
Zone1	P1	0.96
	P2	1.39
	P3	1.45
	P4	1.45
Zone2	P5	2.44
	P6	2.60
	P7	2.73
	P8	2.60
Zone3	P9	2.49

According to (Aouiche, 2016a).

Erosion and accretion at the coastline

For monitoring the coastline, we chose to work with:

–Panchromatic images from Landsat (Tab.2), with a projection of "WGS_1984_UTM_Zone_29 N"

–The topographic map (1976) of the city of Agadir 1/50,000.

Results are presented in the Table 2.

Table 2. Satellite images used in monitoring the coastline

Satellites/sensor	Date	Resolution
Landsat 7 ETM	09/18/2000	15m
Landsat 8 OLI	09/09/2011	15m
Landsat 8 OLI	05/11/2022	15m

Relative sea level change (mm/yr)

Using the Climate Change Knowledge Portal (World Bank Climate Change Knowledge Portal) which is the hub of climate-related information, data, and tools for the World Bank Group (WBG), it was possible to extract Morocco's sea level values in mm over 21 years (Fig.3):

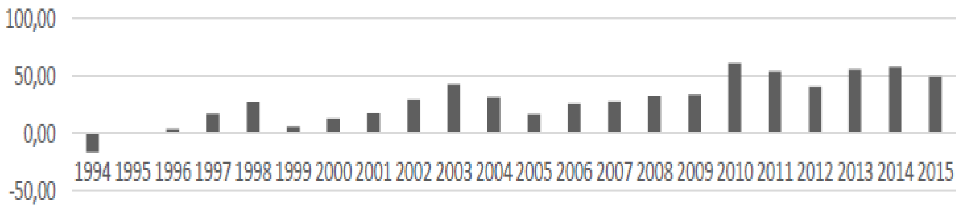

Figure 3: Relative sea level change in Morocco in mm, 1994-2015 (World Bank Climate Change Knowledge Portal).

Mean Tide (m)

Mean Tide (m) refers to the average height of the water level observed over a specific period, typically measured over several tidal cycles. This measurement helps to establish a baseline reference for tidal behaviour. It represents the middle point between the high tide and low tide levels, providing a standard measure of tidal variation. The tide in Agadir is semi-diurnal with a period of 12h25 min.

Mean Significant Wave Height (m)

Mean Significant Wave Height (m) refers to the average height of the highest one-third of waves in a given sea state. It is a statistical measure used to describe the typical height of waves over a specific period, usually measured over an extended duration to account for variations in wave height. MSWH is a crucial parameter in oceanography, providing valuable information about wave conditions and their potential impact on coastal areas, offshore structures, and marine activities. We used data (Fig.4) from the SIMAR database point 1040022(" puertos.es," n.d.), this dataset covers a period of twenty years (2002-2021):

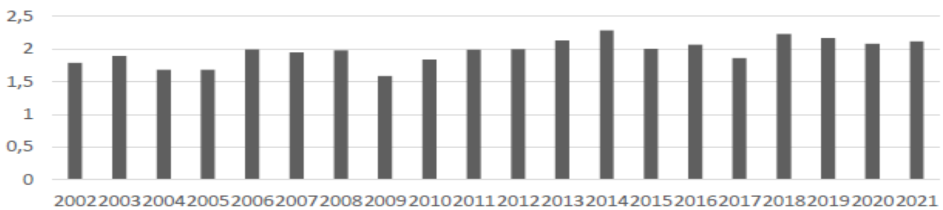

Figure 4: The average of the significant wave height, 2002-2021

CVI methodology and parameters

Geomorphology and Coastal slope. The bay of Agadir is a sandy beach.

In order to use the topographic data on (Tab.1), it is necessary to convert it from degree to percentage (Tab.3):

Table 3: Measurement of the coastal slope of the Bay of Agadir (in %)

Morphological zone	Profiles	Average slope(degrees)	Average slope %
Zone1	P1	0.96	1.68%
	P2	1.39	2.43%
	P3	1.45	2.53%
	P4	1.45	2.53%
Zone2	P5	2.44	4.26%
	P6	2.60	4.54%
	P7	2.73	4.77%
	P8	2.60	5.54%
Zone3	P9	2.49	4.35%

According to (Aouiche, 2016a)

Erosion and accretion at the coastline

Digital Shoreline Analysis System (DSAS) Statistical Calculations. The digitization work was carried out on a GIS environment, from which statistical calculations of the rate of evolution of the coastline are carried out using the DSAS 5.1 extension. Indeed, DSAS is an extension developed by the USGS (United States Geological Survey) available free of charge that allows you to make calculations on the deviations of the coastlines already digitized from the selected images (Zonkouan et al., 2022).

The general principle of this tool is to measure the differences between the coastlines of the same series but also to calculate statistics on the rates of change (in m/year). To do this, the use of the tool requires rigorous formatting of the data in a personal geodatabase, the creation of a baseline and equidistant transects, an estimation of the uncertainty related to the method as well as the choice of statistics for calculating the rates of change.

Pre-calculation operations. At the very beginning, you have to create a personal Geo-database composed essentially of two entities: A first entity made up of already digitized coastlines called shorelines; A second entity containing one or more row(s) of references named baseline. For example, the buffer shoreline buffer stabilizes the linear space in which the coastlines have been digitized.

Shorelines. The shorelines represent the coastlines of the years 2000, 2011, and 2022 that are already digitized in the Geodatabase depending on the version

of the extension used. These are the coastlines to which the baseline must be parallel and must be used as a measurement in the DSAS environment. Thus, to be able to perform an index calculation (End Point Rate (EPR), Linear Regression Rate
(LRR)) the shorelines must be at least two entities of different dates or times.

Choosing the Reference Line. More than a dozen reference lines show the position of the coastline (Robin, 2002; Boak and Turner, 2005), for our study we used the high tide as a reference choice by Google Earth Pro and the topographic map of Agadir.

The Baseline. It involves digitizing an imaginary baseline from which DSAS creates transects that intersect the different coastlines. Thus, all transects are perpendicular to the baseline, which must also be parallel to the coast. However, sometimes the transects are distorted due to the irregularity of the coast. This sometimes results in aberrant or intersecting transects before they intersect on coastlines. In this way, they can be corrected, straightened, or deleted.

Buffer shoreline. To perform a calculation on DSAS, it is necessary to define the segment on which the measurements of variation in the evolution of the coastline will be carried out. It is the buffer zone that allows you to define on which side of the baseline the profiles will be drawn. Indeed, the buffer zone gives two possibilities of the position of the baseline (on the sea side or on the land side) and this depends on the direction of the baseline, defined by the start and end vertices. But in this process, all baselines were digitized from the boundary of the land side of the buffer zone with a distance of 500m separating it from the shorelines.

Calculated indices. This step was first done by the creation of transects, which are profiles perpendicular to the baseline that make it possible to measure the variation in the rates of evolution of the coastlines, then by the calculation of the indices and the graphical representation of the attribute tables of the indices calculated according to their relevance.

When all input parameters are correctly entered, DSAS automatically generates transects perpendicular to the coastal lines according to the defined measurement step, measures the deviations between the coastlines, and calculates the average displacement rates along each transect. Various statistics (Tab.4) are provided by the software to assess the dynamics of the coastline. We mainly used the following indices (EPR) regression statistics: a rate calculated by dividing the distance of the coastline change by the time elapsed between the oldest and newest coastline; LPR Point Change: is the slope of the regression line positioned in the scatter plot formed by the distance measurements between all the intersection points of each transect and the comparative coastlines.

Based on the previous study of coastline kinematics and the classification of the (Pendleton et al, 2004), the results of the RPA could be categorized: (Accretion:1.0-7.2; Stabilization: -1.0 to 1.0; Erosion: 1.0 to -23.3)

Table 4: Statistics calculated by DSAS

Abbreviation	Statistics
NSM	Net Shoreline Movement
SCE	Shoreline Change Envelope
EPR	End Point Rate
ECI	Confidence of End Point Rate
LRR	Linear Regression Rate
LES	Standard Error of Linear Regression
LCI	Confidence Interval of Linear Regression
WLR	Weighted Linear Regression Rate
WSE	Standard Error of Weighted Linear Regression
WR2	Standard Error of Weighted Linear Regression
LMS	Least Median of Squares

Relative sea level change (mm/yr). A certain alternation of sea level rise and fall with the lowest value -16.16mm in 1994 and the highest of 61.61mm in 2010 are recorded. To include this parameter in our index, it is necessary to calculate the average by dividing the sum of all the values over the number of years of twenty-one years, for which we gave an average of 30.28 mm/year. The relative sea level change of 30.28mm/year is classified as a very high level of vulnerability.

Mean Tide (m). The Bay of Agadir is characterized by an average spring water of 2.9 amplitude (m) with a medium vulnerability.

Mean Significant Wave Height (m). The average SWH of the Bay of Agadir (Fig.33) was between 1.76 m in 2009 and 2.11 m in 2014 when the area experienced many storms. The calculated average is 1.96m with a very high vulnerability.

The investigation into vulnerability to coastal erosion was conducted utilizing the Coastal Vulnerability Index (CVI). The specific equation employed for calculating the CVI is outlined as follows:

$$CVI = \sqrt{(\frac{axbxcxdxexf}{6})}$$

where: (a) is geomorphology, (b) shoreline erosion and accretion rate (m/yr), (c) coastal slope (percent), (d) relative sea-level rise rate (mm/yr), (e) mean tidal range (m), and (f) mean wave height (m).

RESULTS AND DISCUSSION

Cartographic results and statistical analysis. The DSAS calculation was utilized to determine and extract the following parameters: A map model was generated based on the calculation of the (EPR) between three dates.

After the mapping of the coastline (Fig.5) for the years 1976, 2000, 2011, and 2022, and the calculation of the DSAS, it was possible to extract the first EPR index which expresses the distance between the oldest and most recent coastline. Variations in the position of the high tide line during these 46 years (1976-2022) show a regressive trend along the 8.3 km of the coastline studied. Indeed, of the 262 transects analyzed, 240 (92%) are in erosion and 29 (8%) are in accretion. With a visible change at the mouth of Oued Souss.

For its spatial analysis, we superimposed the curve and the End Point Rate map to build our first cartographic model (Fig.6), we noticed: Accretion after the first and second wave breezes that can reach from 7.2 m/year to 0.5 m/year; Strong erosion after the spur and at the level of the boom from -23.3 to -4 m/year.

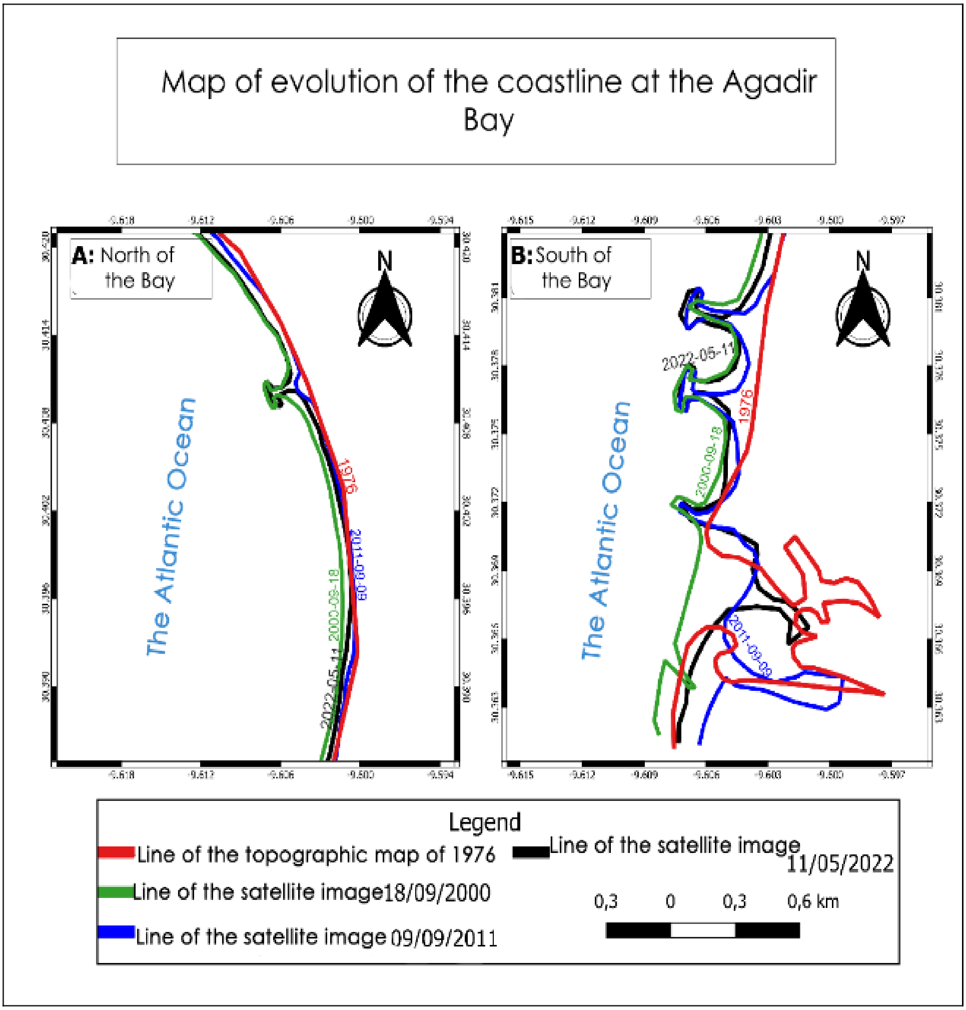

Figure 5: Map of the evolution of the coastline at the Agadir Bay (1976-2022)

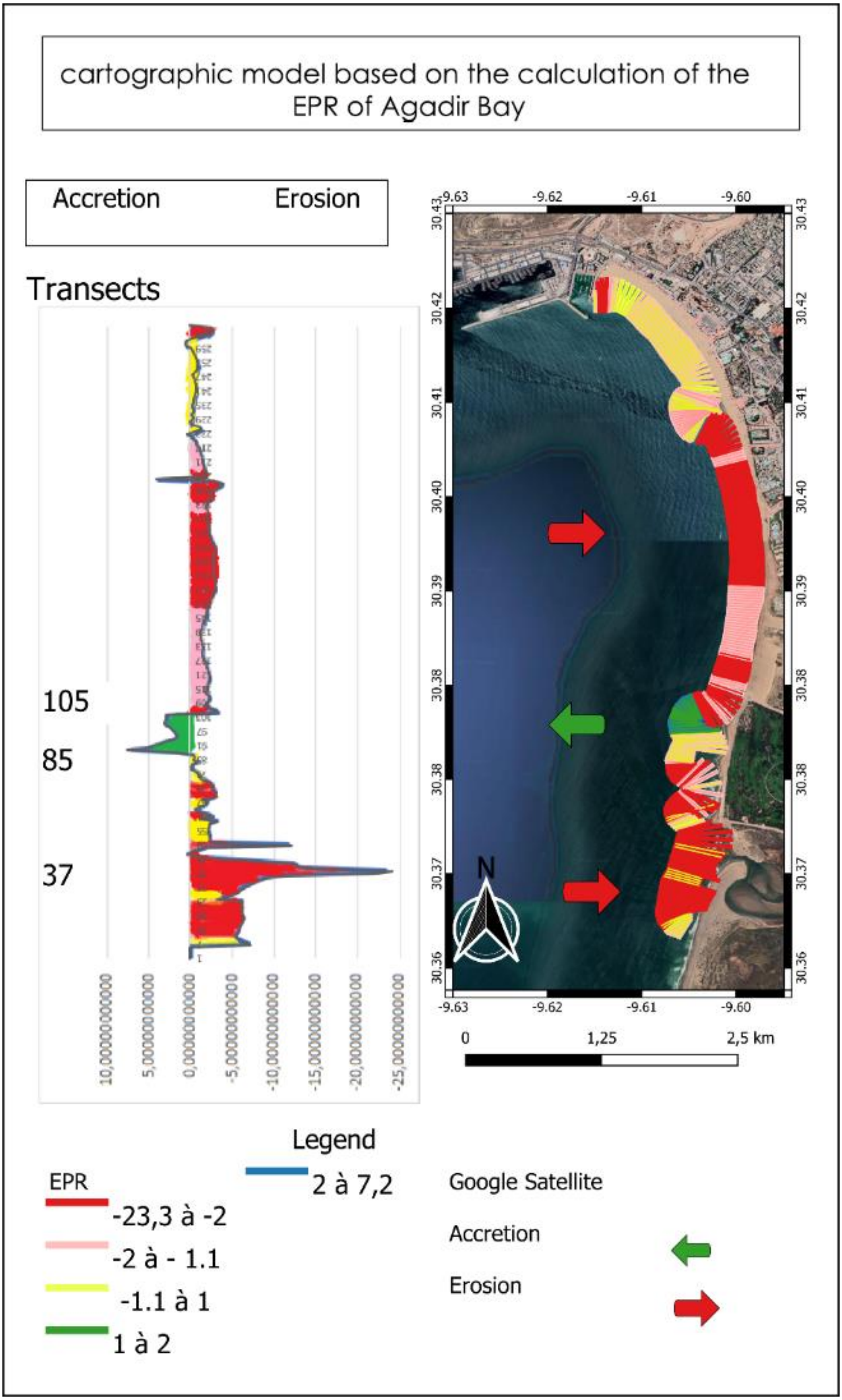

Figure 6. Cartographic model based on the EPR of Agadir Bay

The map model based on the calculation of the LRR (Linear Regression Rate-of-Change) between three dates. The Linear Regression Rate-of-change (LRR) is the slope value of a linear regression line positioned in the scatter plot formed by the distance measurements between all the intersection points of each transect and the compared dimension lines. This attribute, which also reflects the annual rate of change of the reference line along each transect, is interesting for analyzing coastal kinematics over more than three dates, as the calculation method takes into account the evolution of the coastline over the entire period considered, as shown by the results of the study by (Emran et al., 2019) in Bangladesh. Figure 8 illustrates the use of this attribute for a case study based on three shorelines.

Figure 8 illustrates an accretion of 3 to 7.2 m/year just after the second wave breeze; alternating erosion between -13.5 and -1.1m/year and accretion up to 3 m/year.

As a deduction from (Fig.8): LRR is more adequate in the littoral kinematic analysis for more than two dates as in our case, which indicates the choice of using the Linear Regression Rate-of-change (LRR) index instead of the EPR as the main parameter for our study.

Figure 7. Study area photograph (Source: Spalevic, 2018)

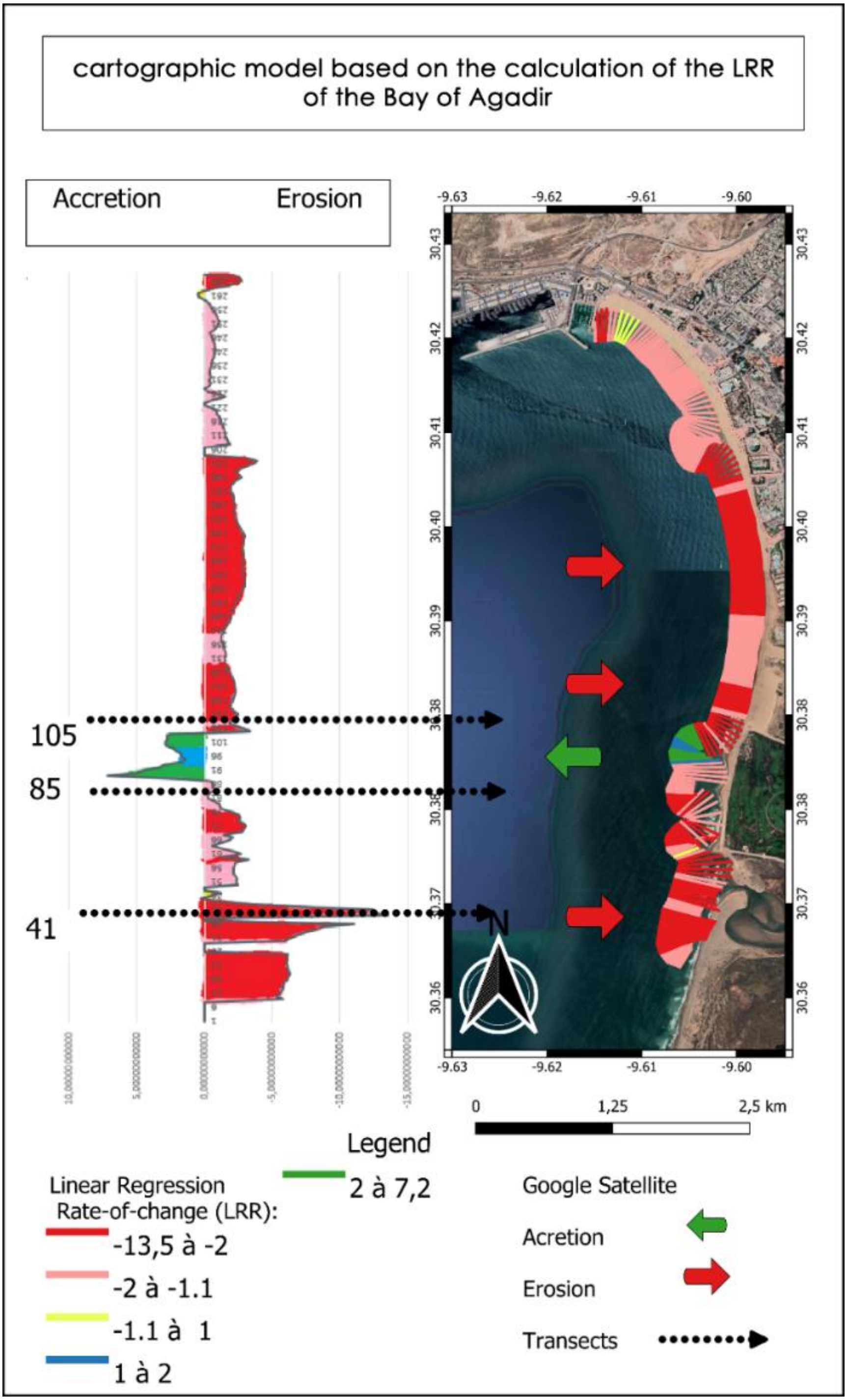

Figure 8. Cartographic model based on the LRR of Agadir Bay

Coastal Vulnerability Index (CVI) Mapping Result. The study of the Coastal Vulnerability Index (Fig.9) has identified: that 1.68km of the coastal zone has a very high vulnerability; 2.58 km of the bay has a high coastal vulnerability.

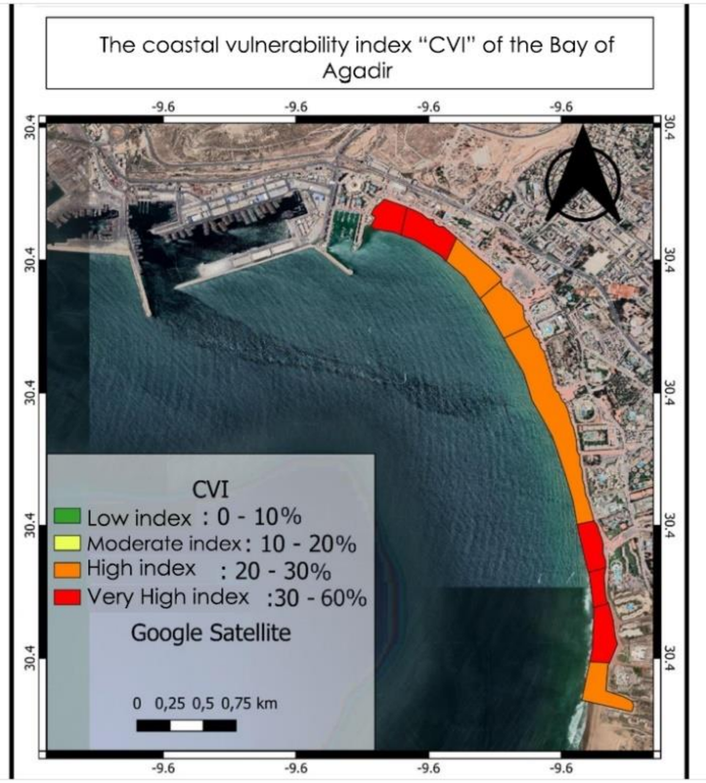

Figure 9. Map of the coastal vulnerability index "CVI" of the Bay of Agadir

The retrospective study of the morphological evolution of the coastline showed that this coastline has been heavily stressed, for several decades (Aouiche et al. 2016b), by development activities, particularly urban and tourist, with an increase in land for buildings and green space. These activities interfered with the hydro-sedimentary dynamics of the coastal system and caused strong erosion of the beaches, considered as an economic capital of prime importance for seaside tourism in the region (Aouiche et al. 2016c), and as an essential buffer reserve for the readjustment of the seaside profiles beach in a state of erosion.

This study, the objective of which was to assess coastal vulnerability to the hazard of coastal erosion on the coast of Agadir Bay in Morocco, revealed a strong socio-economic vulnerability of this coastline. The prospective study was based on the analysis of a large number of available data and information, the fragmentary and sometimes imprecise nature of which must not be concealed. However, despite these weaknesses and the margins of uncertainty contained in the established evolution scenarios, the work made it possible to assess vulnerability to accelerated sea level rise. The analysis highlighted that the southern coast of this coastline was generally more vulnerable to flooding phenomena, due to the low altitude of the coastal fringe.

Indeed, according to the report by (Stern, 2015), the benefits of firm and early action far outweigh the economic costs of inaction. It is, therefore, possible to avoid, or at least reduce these impacts, by acting in a global context, and by implementing anticipatory, ecologically acceptable and financially feasible adaptation and mitigation measures. These options should be reassessed regularly due to: changes that may affect coastal dynamics and therefore vulnerability, scientific understanding of processes, developments in technology, etc. The majority of the scientific community considers that global warming is the major issue of the 21st century. We must therefore act quickly because adopting the scenario of indifference would have very serious consequences. Only general and concerted awareness among socio-economic actors will enable the success of such strategies, as well as the implementation of relevant coastal conservation measures as a guarantee of protection of coastal populations and infrastructure against potential impacts—climate change.

The study of vulnerability to coastal erosion was carried out using the coastal vulnerability index “CVI”. Indeed, the established maps show a high to very high coastal vulnerability of 20% to 60%.

CONCLUSION

Risk, defined as the probability of damage, is a reality for exposed companies, but which only materializes through events considered random. The existence of natural risks for a society obliges us to seek to reduce the possible impacts of these events.

The prospective study was based on the analysis of a large number of available data and information, the fragmentary and sometimes imprecise nature of which must not be concealed. However, despite these weaknesses and the margins of uncertainty contained in the established evolution scenarios, this study nevertheless made it possible to assess the vulnerability of the coastline studied.

The work carried out on the Bay of Agadir has certainly provided important and unprecedented results on the vulnerability of this coastline to coastal erosion, it nevertheless remains perfectible. It requires more in-depth studies to improve knowledge and to remove certain uncertainties using high-resolution drone images for coastline monitoring. Furthermore, it opens the way to additional research, which must be carried out in collaboration with other specialists, particularly in the following areas:

- The development of territorial planning and evacuation strategies based on information relating to the maximum wave height contained in the model.
- Economic evaluation, using cost-benefit analyses, of adaptation options
- and damages caused in the event of a “do nothing” policy
- Raising awareness of risks via web mapping to popularize information on risks on a large scale.

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