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# Coastal Vulnerability Assessment from Rabat to Tangier along Morocco's Northern Atlantic Coasts

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Coastal zones are increasingly threatened by the compounded effects of climate change, particularly sea level rise, extreme wave events, and shoreline erosion. This study provides a comprehensive assessment of the physical vulnerability of Morocco's northern Atlantic coast, a region marked by low-lying terrain, fragile estuarine ecosystems, and intense anthropogenic pressure. Using multitemporal Landsat imagery (1990–2023), Digital Shoreline Analysis System (DSAS), and eight environmental indicators including sea level rise, wave height, elevation, slope, and coastal geomorphology we applied a multi-criteria Analytic Hierarchy Process (AHP) to generate a coastal vulnerability index (CVI). Results show that shoreline erosion rates reach up to 10 mm/year in several locations, with severe retreat observed near Rabat, Moulay Bousselham, and Assilah. Estuarine areas such as Bouregreg, Sebou, Lokkous, and Tahaddart emerge as critical vulnerability hotspots due to their geomorphological sensitivity and exposure to hydrodynamic forces. These findings underscore the urgent need for integrative coastal zone management strategies, combining nature-based solutions and engineered infrastructure to enhance the resilience of socio-ecological systems along the Moroccan coastline.

**Keywords:** coastal vulnerability, shoreline erosion; climate change; remote sensing, AHP method, Morocco Atlantic coast.

## Introduction

Climate change is one of the most urgent problems facing humanity today (IPCC, 2022). Due to the fact that coastal areas offer various ecosystem services, including fishing, aquaculture, tourism, and abundant ecological and biological productivity (Maanan et al., 2018), the coasts seem to be particularly vulnerable to the effects of climate change due to risks such coastal erosion, escalating storms, and rising sea levels

(Michener, 1997). These changes can have serious effects, including damage of infrastructure, habitat loss, flooding, and a variety of other negative effects.

The Moroccan coastline, stretching over 3500 km, is facing significant vulnerability to the impacts of climate change (Schilling et al., 2020 and reference therein), especially in the North Atlantic area (e.g., El. Moussaoui et al., 2017; Tahri et al., 2017; Haddaoui et al., 2025a). The North Atlantic zones, in particular, has experienced a rise in temperatures, erratic rainfall patterns, and an increase in extreme events like coastal erosion, which have put the communities and ecosystems along the coastline at great risk (Snoussi et al., 2010). In addition, the areas are highly vulnerable to coastline recession due to a combination of natural factors such as the presence of coastal cliffs, rocky shores, and limited sediment supply, as well as human activities such as urbanization, tourism development, and port construction (Hakkou et al., 2011; Snoussi, 2020; Agharroud et al., 2023).

The only way to identify changes over time in the field, which is crucial for making educated decisions for the future, is to compare current data with previous data (Welden et al., 2021). Remote sensing and photogrammetry are increasingly used in coastal area management and the tracking of changes to the coast, bringing a number of benefits (Olgun, 2012).

Remote sensing presents significant possibilities for acquiring information in such applications. The primary objective of remote sensing projects, including those focused on coastal areas, is to identify and track movements along coastlines. By utilizing cost-effective multitemporal satellite data, it becomes convenient to detect erosion and deposition rates within the coastal zone (Ekercin, 2007).

In this study, we aim to analyses shoreline changes and to assess the vulnerability of the Northern Morocco Atlantic coasts to climate change implications. The shoreline changes over the period between 1990 and 2023 will provide a thorough understanding of the extent and nature of changes that have occurred in the study area. Using various forcing factors related to climate changes, including the shoreline changes analysis, we evaluate the susceptibility of these coastal areas. This assessment will identify hotspot zones where coastal areas are likely to be impacted by climate change effects and deserve more prior management.

Although several studies have examined the impacts of climate change on coastal regions, particularly in Morocco and North Africa (Agharroud et al., 2023; Almar et al., 2021; Snoussi, 2020), there remains a critical need to specifically assess the vulnerability of Morocco's northern Atlantic coasts. Many of these studies focus on broader climate change issues or distant geographic regions, leaving a significant knowledge gap regarding the specific coastal dynamics of this area, where natural and anthropogenic factors interact. In particular, detailed analyses of estuarine zones and fragile shorelines, considering the complex interplay of sea level rise, wave intensity, and coastal morphology, are lacking. This study addresses a key gap in the literature by identifying areas of high coastal vulnerability and providing relevant data for decision-makers. The findings of this research will enable more targeted coastal management strategies that are better suited to local specificities, helping to strengthen the resilience of Morocco's coastal ecosystems in the face of climate change.

## Materials and Methods

### Study area

The study area is located along Moroccan northern Atlantic coast, spanning roughly 340 km of shoreline between Cap Spartel in Tangier to the north and Rabat to the south (Cap Spartel: 35°48′N, 5°54′W to Rabat: 34°00′N, 6°57′W) (*Fig. 1*). It is distinguished by the presence of fragile cliffs and dunes that are rapidly retreating throughout the majority of the shoreline. A meandering waterway connects several estuaries that open up to the Atlantic Ocean in the study area. The northern section of the study area includes the Tahadart and Lokkous estuaries, while the southern section is home to the Moulay Bousselham, Sebou, and Bouregreg estuaries. These estuaries contribute significantly to local ecological functioning, providing habitats for various marine and bird species. They also serve as key areas for commercial and recreational activities, including fishing and tourism.

Due to its exposure to the Atlantic Ocean, the North Atlantic coastal zone becomes an appealing region that significantly influences both the natural and human environments. This interaction results in a moderate and humid climate, which creates favorable conditions for the region's development and promotes agricultural activities.

The topographical units of this study area are diverse but complementary. Between the estuaries are both coasts affected by silting and coasts affected by erosion along the entire northern Atlantic coastline, which has recently intensified under the effect of the predominant wind direction (south-west) and longshore drift (west-north-west direction).

The study area exhibits a wide temperature range, ranging from 4 to 40 degrees Celsius. Annual rainfall varies between 900 and 300 mm. As one moves further away from the beach, the influence of the oceans diminishes, revealing a more noticeable continental climate (*Fig. 2*). The prevailing wind direction is typically westerly, particularly during the summer season (Haddaoui et al., 2025b).

To assess physical vulnerability of northern Atlantic coasts of Morocco, we firstly estimated shoreline changes to highlight zones with high rates of erosion using a digital shoreline analysis system (DSAS). We then produced a coastal vulnerability map based on coastal forcing variables (*Table.1*), including the results of shoreline changes ESRI (2018). Since the influence of these variables is not similar, we adopted the Analytic Hierarchy Process (AHP) method to compare the importance of each variable. The AHP technique seems to be capable of organizing and analyzing complicated decisions (Saaty, 1980). The highly eroded coasts were superposed on the vulnerable areas to show how dependent the shoreline dynamics were on coastal forcing. The combined approach used for this study is depicted in the following flowchart (*Fig. 3*).

**Fig. 1.** *Geographic location of the study area showing its main coastal components and geomorphological features*

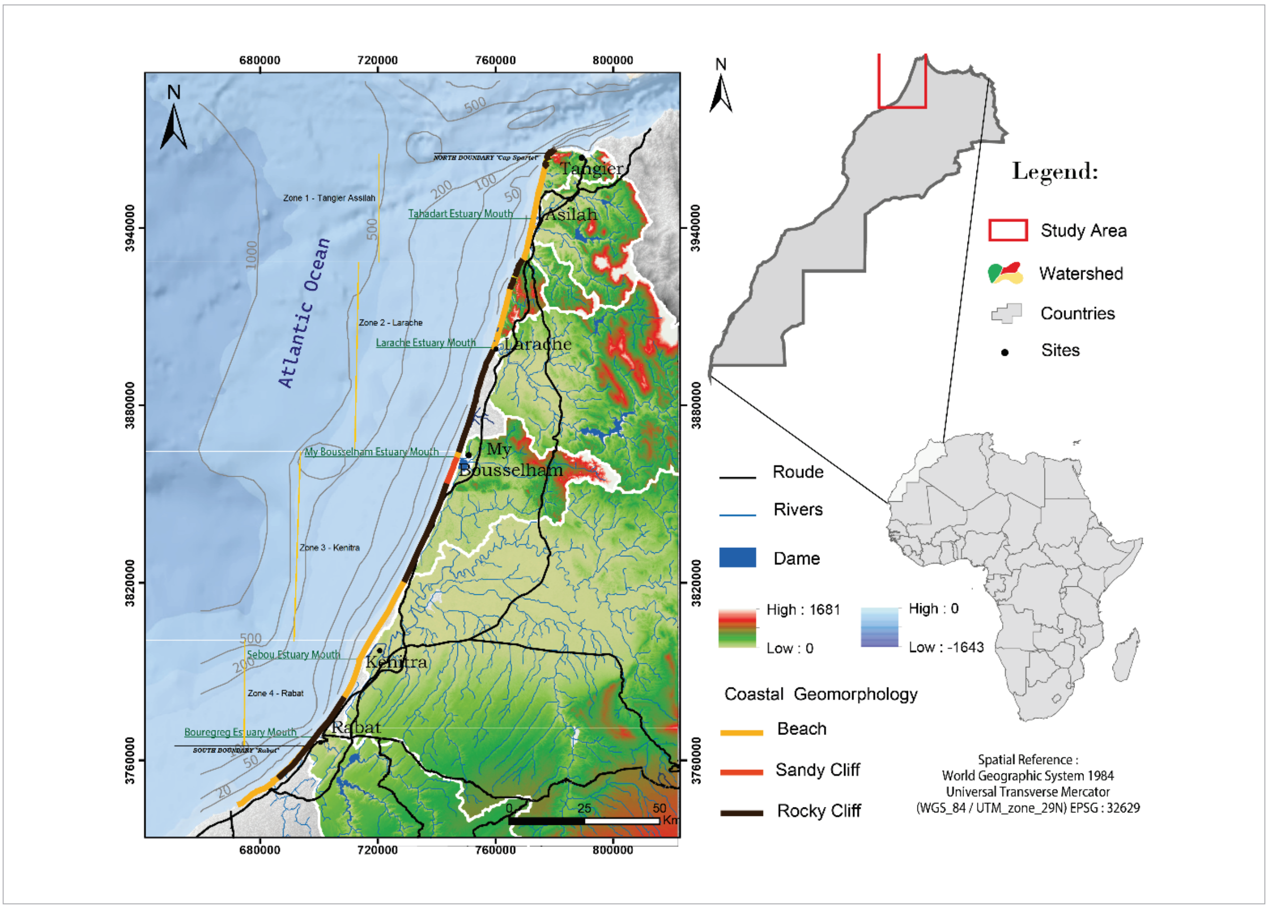
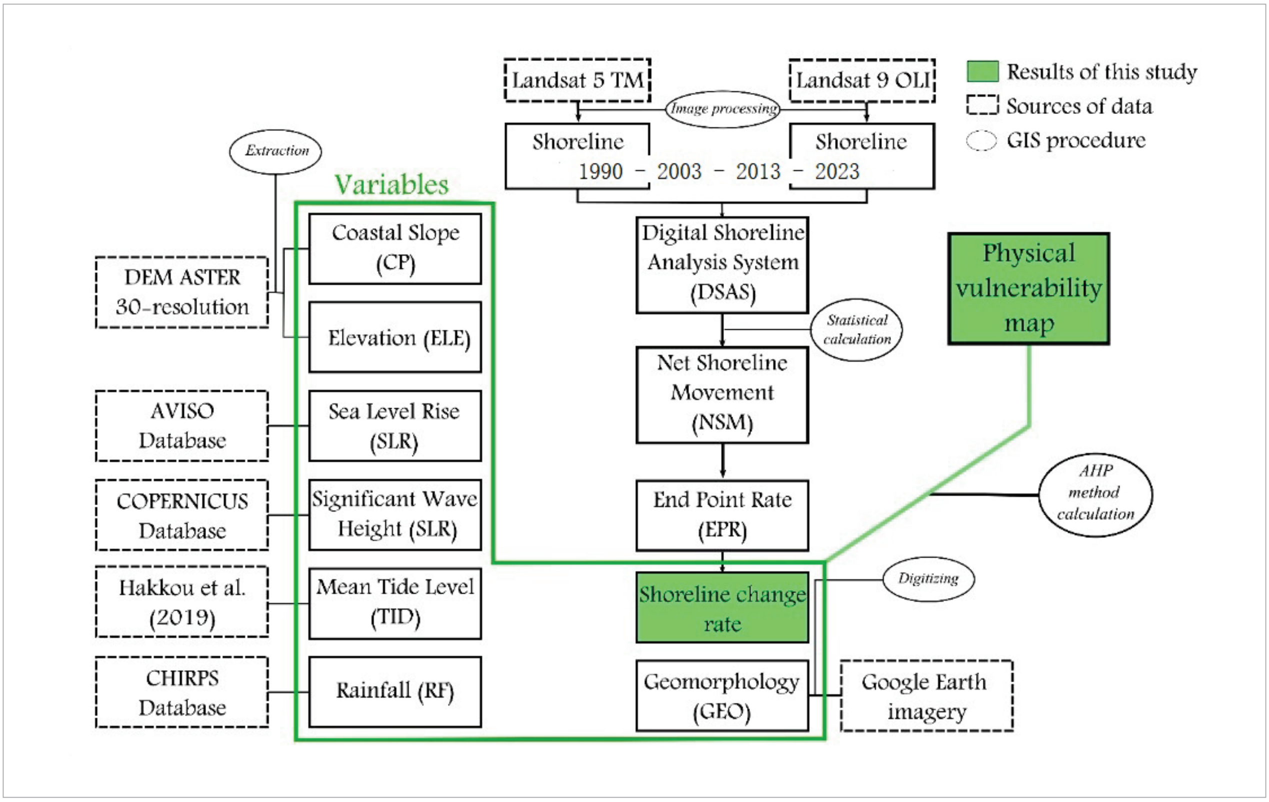


**Fig. 2.** *Climatic data of study area (1990–2023) **


*Data obtained from the Puertos del Estado buoy network (REDCOS), period 1990–2023*

**Fig. 3.** *Flowchart of the methodology used to discuss the problematic of this study*




## Datasets description

In this section, we describe the data used to evaluate shoreline changes and generate variables for coastal vulnerability mapping (*Table 1*).

For the analysis of historical shoreline changes spanning from 1990 to 2023, we employed publicly available Landsat data (*Table 2*). The shoreline for the year 1990 was mapped out using data from Landsat 5 TM, and the 2023 shoreline was charted with the aid of Landsat 9 OLI-2. Landsat datasets are highly valued and deemed a crucial tool for conducting coastal research on a regional scale (Klemas, 2011). The ability of Landsat imagery to offer multispectral resolution and cover multiple temporal points at short intervals enhances the detailed examination, quantification, and distinction between terrestrial and aquatic surfaces. This, in turn, furnishes essential information for the investigation of coastal dynamics (Gong, 2012; Kovalskyy and Roy, 2013).

To conduct a historical shoreline changes analysis for the period between 1990 and 2023, we utilized publicly accessible Landsat data (*Table 2*). The 1990 shoreline of the study area was extracted from Landsat 5 TM, while the 2023 shoreline was delineated using Landsat 9 OLI-2. Landsat data is considered an important and practical resource for regional coastal research (Klemas, 2011). The multispectral resolution capabilities and multitemporal coverage at brief time intervals provided by Landsat products enable more thorough observation, measurement, and differentiation of land and water surface features. Consequently, it provides crucial data for studying coastal dynamics (Gong, 2012; Kovalskyy and Roy, 2013).

On the other hand, a coastal vulnerability assessment was conducted along the study area using eight factors (*Table 1*), which could affect coastal resilience:

- Sea level rise (SLR), which reflects the annual trend of rising water levels between 1990 and 2023. The SLR values for the study area were obtained from satellite altimetry data (AVISO), which provide precise measurements for a limited duration;
- Significant wave height (SWH, metric MSHx95p), which represents the average number of waves detected per year that exceed the 95th of daily wave

percentile heights over a long-term period, typically spanning a century or more. The SWH values were acquired from Climate Copernicus data;

- Historical shoreline change (HSC), which resulted from the previous processing;
- Elevation (E), which refers to the height of the ground above sea level. The elevation data was extracted from the digital elevation model (DEM) obtained from ASTER data;
- Coastal slope (CS), which refers to the degree of steepness of the land surface where it meets the shoreline. The coastal slope was computed from the digital elevation model (DEM) obtained from ASTER data;
- Precipitation (Pr), which corresponds to the mean annual amount of precipitation over a period of 33 year, from 1990 to 2023. The precipitation data is obtained from CHRIPS (Climate Hazards Group InfraRed Precipitation with Station data) (de Sousa et al., 2020), which provides gridded rainfall estimates based on satellite and ground-based observations;
- Geomorphology (CG), which refers to the physical features and processes that shape the coastal environment. The geomorphology of the coastal zone was extracted from high-resolution imagery obtained from Google Earth;
- Mean tidal range (TID), which refers to the height difference between the average high and low tides over the span of a year. This range is determined by using daily tide gauge data, which captures the tide's height at regular intervals (Hakkou et al., 2019);

**Table 1.** *Variables used to generate the coastal physical vulnerability map and their sources*

| Variables | Unit | Spatial resolution* | Sources |
|---|---|---|---|
| Sea level rise (SLR) | mm/year | - | AVISO, (n.d.) |
| Significant wave height (SWH) | cm | - | CDS, (2023) |
| Historical shoreline change (HSC) | m | 30 m | USGS, (2023) |
| Elevation (E) | m | 30 m | LP DAAC, (2023) |
| Coastal slope (CS) | (°) | 30 m | LP DAAC, (2023) |
| Precipitation (Pr) | mm/year | 0.05° | de Sousa et al., (2020) |
| Coastal geomorphology (GEO) | - | - | Google LLC. (2023) |
| Mean tide level (TID) | m | - | Aangri et al., (2019) |

** 1 degree is equivalent to 111.1 km*

# Methodology

## Analysis hierarchy process (AHP) for coastal vulnerability mapping

The coastal vulnerability assessment was carried out in the study area using the AHP technique.

The AHP technique is a Multi-Criteria Decision-Making (MCDM) method that takes into account multiple qualitative criteria to solve complex decision-making problems. It involves decomposing the problem into hierarchical levels to establish priorities and make informed decisions (Saaty, 1980).

The AHP approach is based on expert opinions and stakeholder consultations for the identification of the most influential factors. Experts and stakeholders can provide insights into complex systems that may not be easily captured through quantitative analysis alone. This approach can be particularly useful when data is limited (e.g., Mimović et al., 2015; Vinogradova-Zinkevič et al., 2021; Agharroud et al., 2023), as was the case in our study. The following are the steps for AHP application:

- definition of the decision problem, which pertains to identify the location of hotspot areas where the vulnerability of coastal zones to climate change implications;
- definition of the criteria and sub-criteria to be assessed (see sections 3.1 and 3.2);
- creation of hierarchical structure that includes all criteria, sub-criteria and expected objective;
- determination of the relative importance of each sub-criteria and criteria based on expert opinion and literature reviews. To do so, a pairwise comparisons matrix (P) was created using a numerical scale of Saaty (*Table 2*).

$$P = \begin{bmatrix} Pii & \cdots & Pij \\ \vdots & \ddots & \vdots \\ Pji & \cdots & Pjj \end{bmatrix} \quad (1)$$

where Pij is the preference score of criterion i over criterion j using (*Table 3*).

**Table 2.** *Fundamental AHP scale (Saaty, 1980)*

| Intensity of importance (Pxy value) | Value meaning |
|---|---|
| 1 | Equal importance of x on y |
| 3 | Moderate importance of x on y |
| 5 | High importance of x on y |
| 7 | Very high importance of x on y |
| 9 | Extreme importance of x on y |
| 2, 4, 6, 8 | Intermediate values |

- normalization of pairwise comparison matrix (*Eq. 2*) in order to compare each criterion to every other criterion in the same category and assigning a score to reflect the relative importance. The normalization allows establishing a common scale that preserves the original information and does not distort the value ranges.

$$\bar{P}ij = \frac{Pij}{\sum_{c=1}^{n} Pcj} \quad (2)$$

For this purpose, the input scores $P_{ij}$ and $P_{ji}$ must satisfy the constraint represented by the equation $P_{ij} * P_{ji} = 1$. Additionally, the sum of entries in column j should be equal to 1, which is denoted by $P_{cj}$.

- calculation of the criterion and sub-criterion weights ($W_i$) using the normalized pairwise comparison matrix as following *Eq.3*:

$$W_i = \frac{\sum_{l=1}^{n} \bar{P}ij}{N} \quad (3)$$

where N is the number of criteria or sub-criteria.

- Consistency analysis of the pairwise comparison scores to verify the reliability of the expert judgments. The consistency ratio (CR) is used to accomplish this task, using the following *Eq.4*:

$$CR = \frac{(\lambda\, max - N)}{RI(N-1)} \quad (4)$$

where $_{max}$ refers to the eigenvalue and RI corresponds to the random consistency index that depends on the number of criteria or sub-criteria (*Table 3*).

After determining and validating all criterion weights, the coastal vulnerability map (CV) by AHP approach was generated using these weights by following *Eq.5*:

$$CV = (\sum_{i=j=1}^{n} w_i . w_j) \quad (5)$$

where $w_i$ and $w_j$ are criteria or sub-criteria weights, respectivly.

**Table 3.** *Random consistency index for AHP method (Saaty, 1980)*

| Number of Criteria/variables | Random consistency index |
|---|---|
| 1 | 0 |
| 2 | 0 |
| 3 | 0.58 |
| 4 | 0.9 |
| 5 | 1.12 |
| 6 | 1.24 |
| 7 | 1.32 |
| 8 | 1.41 |

## Selection and relative importance of factors for mapping coastal vulnerability

To assess coastal vulnerability across the study area, we considered eight factors (as described in section “Datasets Description”, and (*Table 1*) that are related to coastal forcing. These factors encompass the physical processes that impact the dynamics of the ocean and coastlines, which are often influenced by climate change (e.g., Satta et al., 2016; Aitali et al., 2020).

We specifically selected the factors that are most relevant to increasing the vulnerability of physical assets and natural systems to damage or destruction from coastal hazards, taking into account data availability referring to the Moroccan north Atlantic coastal zones (Haddaoui et al., 2025b).

Based on literature review, the eight factors considered in this paper are the most factors used to assess the coastal vulnerability (e.g., Koroglu et al., 2019; Agharroud et al., 2023). AHP method is used as a tool to allows combining multiple qualitative factors to produce a comprehensive map of coastal vulnerability. As a result, (*Table 4*) summarizes ranking score calculated for each factor and factor class.

**Table 4.** *Ranking defined for each factor class and factor weights for AHP method*

| Factors (unit) | Class | Weight of class (%) | Coastal vulnerability factor contribution | Consistency ratio (CR) | Factor weights (CR = 0.04**) |
|---|---|---|---|---|---|
| SLR (mm/yr) | < 1 | 4 | Very low | 0.05 | 33% |
| | 1–1.6 | 7 | Low | | |
| | 1.6 –2.4 | 13 | Moderate | | |
| | 2.4–3.2 | 26 | High | | |
| | > 3.2 | 50 | Very high | | |
| SWH (cm) | < 4 | 3 | Very low | 0.03 | 23% |
| | 4–6.5 | 7 | Low | | |
| | 6.5–8 | 15 | Moderate | | |
| | 8–9.5 | 26 | High | | |
| | > 9.5 | 49 | Very high | | |
| HSC (m) | < –5 | 52 | Very high | 0.03 | 17% |
| | 4 | 28 | High | | |
| | –1–1 | 10 | Moderate | | |
| | –5 | 6 | Low | | |
| | > 5 | 4 | Very low | | |
| TID (m) | < 1 | 4 | Very low | 0.01 | 12% |
| | 1–2 | 6 | Low | | |
| | 2–4 | 15 | Moderate | | |
| | 4–6 | 32 | High | | |
| | > 6 | 43 | Very high | | |
| GEO | Estuary | 49 | Very high | 0.07 | 7% |
| | Rapidly receding sandy cliff | 26 | High | | |
| | Sandy coast | 15 | Moderate | | |
| | Dune cord | 7 | Low | | |
| | Rocky cliff | 3 | Very low | | |
| CS (°) | > 15 | 4 | Very low | 0.01 | 4% |
| | 10–15 | 6 | Low | | |
| | 5–10 | 15 | Moderate | | |
| | 2.5–5 | 32 | High | | |
| | < 2.5 | 43 | Very high | | |
| ELE (m) | > 12 | 4 | Very low | 0.01 | 3% |
| | 9–12 | 6 | Low | | |
| | 7–9 | 15 | Moderate | | |
| | 3–7 | 32 | High | | |
| | < 3 | 43 | Very high | | |
| RF (mm/year) | > 600 | 49 | Very high | 0.07 | 2% |
| | 550–600 | 26 | High | | |
| | 500 –550 | 15 | Moderate | | |
| | 450–500 | 7 | Low | | |
| | 400–450 | 3 | Very low | | |

** Referred to the fig. 4*
*** Consistency ratio calculated based on a pairwise comparison matrix of eight variables used to define coastal vulnerability*

## Results and Discussion

### Shoreline changes analysis

oreline dynamics over an extended period, statistical analysis of endpoint rates is employed. Shoreline changes were calculated along the northern Atlantic coasts of Morocco spanning 33 years from 1990 to 2023. The shoreline change analysis shows that the erosion rates are typically falling within the range of 0 to 10 mm/year (*Fig. 4*). In the southern region of Rabat, erosion rates have been observed to exceed 10 mm/year (*Fig. 4*). Erosion hotspots were also identified in the estuaries of Moulay Bousselham and Assilah, where erosion rates can reach up to 5mm/year. Additionally, significant erosion rates have also been observed along coasts from Assilah to Larache, as well as in the southern coasts of Tangier. The rest of the study area is characterized by low erosion rates, which typically do not exceed 1 mm/year, with a few dispersed zones experiencing significantly higher erosion rates. Furthermore, (*Fig. 4*) shows that some coasts located near Assilah to the north, around Moulay Bousselham and the estuary of Kenitra and Tahaddart are in a state of accretion with a rate ranging from 0 to 5 mm/year.

Our findings show that the majority of the study area is experiencing shoreline retreat. This is relatively consistent with the previous studies that are focused on parts of our study area (e.g., Hakkou et al., 2011; Aangri et al., 2024; Moussaid et al., 2015; Hakkou et al., 2018; El Habti et al., 2022). However, the accuracy of our analysis in detecting the accretion in the north of Kenitra may be limited due to the spatial resolution of the input data and the large extent of the studied coastline (Gens, 2010; Ngowo et al., 2021). In fact, *Fig. 4* shows some pics of significant rates of accretion along the northern coast of Kenitra, consistent with the findings of the studies mentioned earlier. Accretion is also present in Tahaddart sector, especially at the estuary (Taaouati et al., 2015), but the accretion was not the dominant process; erosion was also a significant factor. The coasts close to Tahaddart in contrast underwent a high level of erosion that is consistent with the analysis results of El Habti et al. (2022).

As seen in the associated chart in (*Fig. 4*), some coasts along the study area exhibit very high erosion/accretion rates that reach up to 20 mm/year. However, these extreme values may not accurately reflect the long-term trend, likely due to technical limitations of the DSAS tool (USGS, 2018). DSAS uses a linear regression method to calculate shoreline change rates, which may not be appropriate for all types of shorelines, especially those with complex morphology or high curvature as the study area.

### Coastal vulnerability mapping

To assess coastal vulnerability in relation to the implications of climate change, a comprehensive map of coastal vulnerability was produced using eight forcing factors, which impact the dynamics of the coastal zone of the study area (*Fig. 5*). The results indicate that the southern 20-km coasts of Rabat are highly vulnerable to the implications of climate change (*Fig. 6*). The vulnerability is also evident in Kenitra due to the presence of the Sebou estuary. To the north, it can be observed that the coastal vulnerability is also high along the coasts of Moulay Bousselham (*Fig. 6*). The area is defined by the existence of an estuary, which serves as a nexus for both ecological and socioeconomic systems. This feature contributes to heightened susceptibility to climate change impacts on its coastal zones. In these sectors, the significant retreat of the shoreline, combined with the low topography and rapidly receding sandy cliff, and the high inundation level exacerbated by extreme wave conditions (with a return period of 100 years) and the potential for extreme sea level rise, increase the coastal vulnerability (*Fig. 5*).

At Larache zone, the coastal vulnerability varies from high to very high along its 40-km stretch (*Fig. 5*). The most susceptible zones appear to be primarily attributable to the significant wave height, as well as the increased risks posed by rising sea levels and fluctuations in rainfall patterns (*Fig. 5*).

Similar to the Larache zone, the coastline extending from Tangier to Tahaddart exhibits high to very high coastal vulnerability, with vulnerability tending to be lower toward Cap Spartel, north of Tangier. These coasts are at risk of experiencing the negative impacts of climate change due to both high trend of sea level rise and significant wave heigh that are characteristic of this coastline (*Fig. 5*). The combination of low topography and high levels of precipitation may increase its susceptibility to potential impacts of climate change.

It can be observed that the estuary on the studied coastline is highly vulnerable to the effects of climate change. In fact, the latter can have a significant impact

**Fig. 4.** *Rates of shoreline changes for a period of 33 year (from 1990 to 2023) calculated, using endpoint rate (EPR), for each transect. Associated chart shows at what point the erosion/accretion was changed. Background satellite imagery is Google Satellite map, available as Basemap in QGIS v3.22.11*

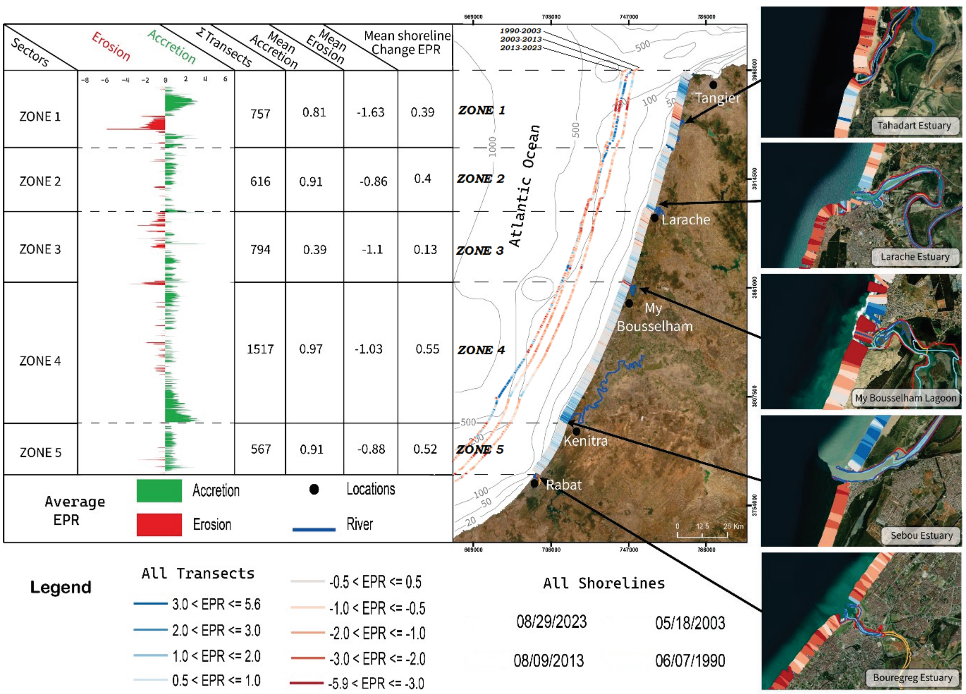



**Fig. 5.** *Spatial distribution of coastal vulnerability and the importance of various variables across the study area. Background satellite imagery is Google Satellite map, available as Basemap in QGIS v3.22.11*

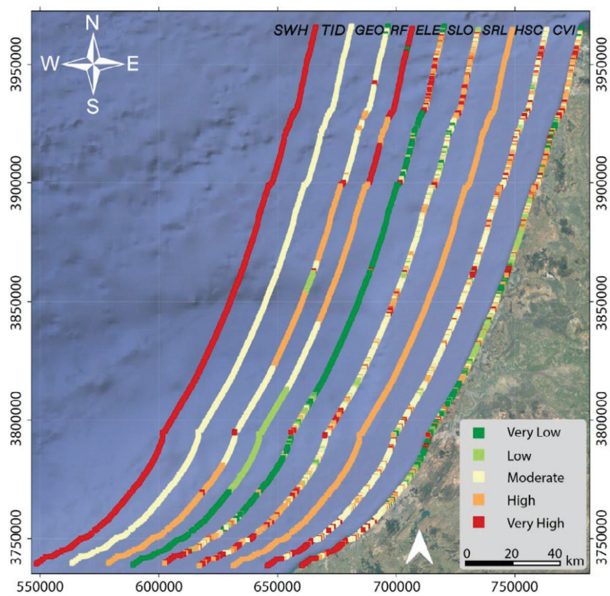
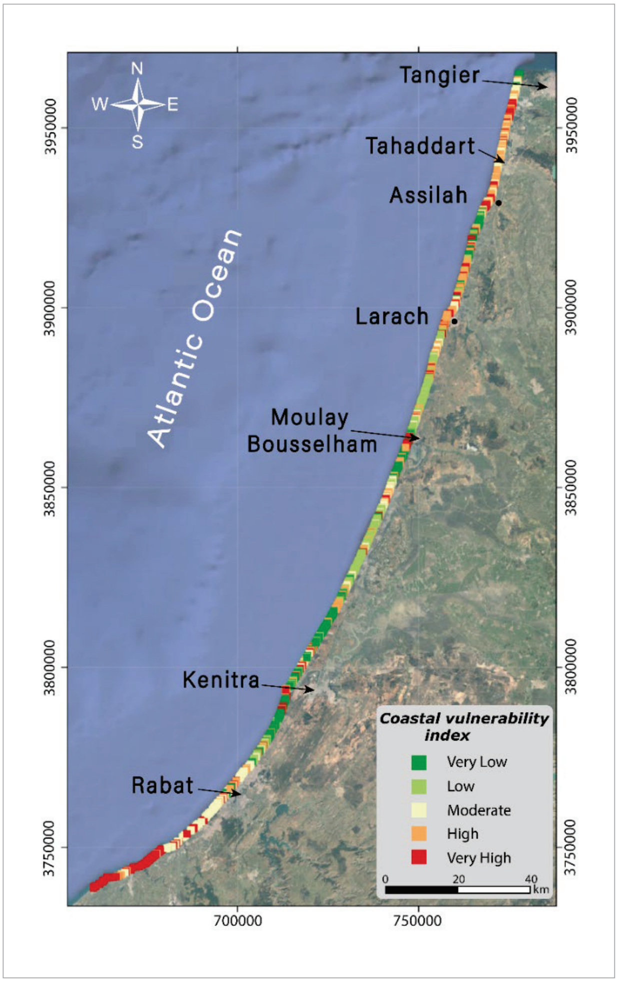


**Fig. 6.** *Coastal vulnerability index (CVI) map*




on estuaries, which leads to changes in sedimentation regimes, salinity, temperature…, because of saltwater intrusion via sea level rise (Khojasteh et al., 2021 and references therein). Moreover, climate change effect may be reflected by frequent and intense storms, which can cause erosion, flooding and sedimentation (accretion) in estuaries, and so can alter the physical and biological processes that support estuarine ecosystems (e.g., Statham, 2012; Cabral et al., 2019; Dyer, 2021). Precipitation and ocean acidification could also have an impact on the estuaries and may increase their vulnerability. The changes in freshwater and seawater inputs affect the nature of water and the dynamic of the estuaries, which lead to estuary ecosystem perturbation (Agoubi, 2021).

On the other hand, several studies assess the coastal vulnerability along the Atlantic coasts of Morocco, including our study area (e.g., Maanan et al., 2018; Aitali et al., 2020; Agharroud et al., 2023). However, while these studies focus on a range of socioeconomic issues associated with the other physical characteristics that can influence coastal resilience, our study specifically surveys the coastal vulnerability to forcing factors related to climate change. Since we exclude the anthropogenic effect to assess vulnerability, the comparison of the results is no use.

## Hotspot zones and management practices

The results show the existence of multiple hotspot areas characterized by a high level of vulnerability. The coasts that are highly susceptible to the implications of climate change can be attributed to the significant shoreline retreat, which is further accelerated by the rise in sea level and the increase in wave height. Since the effect of the latter factors are relatively similar across the studied coastline, the specific vulnerability of each area depends largely on its unique morphology and topography. In particular, Loukouss, Moulay Bousselham and Bouregreg estuaries are especially susceptible to the impacts of climate change, and are therefore considered to be vulnerability hotspots. The coastline of Tangier and Rabat may be also referred as vulnerability hotspot, where both shoreline retreat and coastal vulnerability index are high (*Fig. 6*). In light of this, one can see that the vulnerability hotspot zones correspond to the main five estuaries situated along the investigated coastline. These estuaries are located in four urban communes and one rural commune (*Table.5*).

Once the vulnerability hotspots have been identified, measures to mitigate the implications of climate change on the coasts should be implemented, taking into account the complexity of the potential solutions with more practical guidance and advice (Toimil et al., 2020). To do so, Morocco has implemented several plans and strategies and constructed a variety of coastal defense structures, in order to improve protection and prevention measures and increase the resilience of its coasts in light of the ratification of the ICZM Protocol to the Barcelona Conventions (Panayiotis and Paraskevi, 2020; Agharroud et al., 2023). However, this could be not sufficient to mitigate the effect of climate change on coastal areas. In fact, several coastal defense structures that have been or will be built to protect the coasts are vulnerable to more severe hydrodynamic conditions in the future due to expected wave

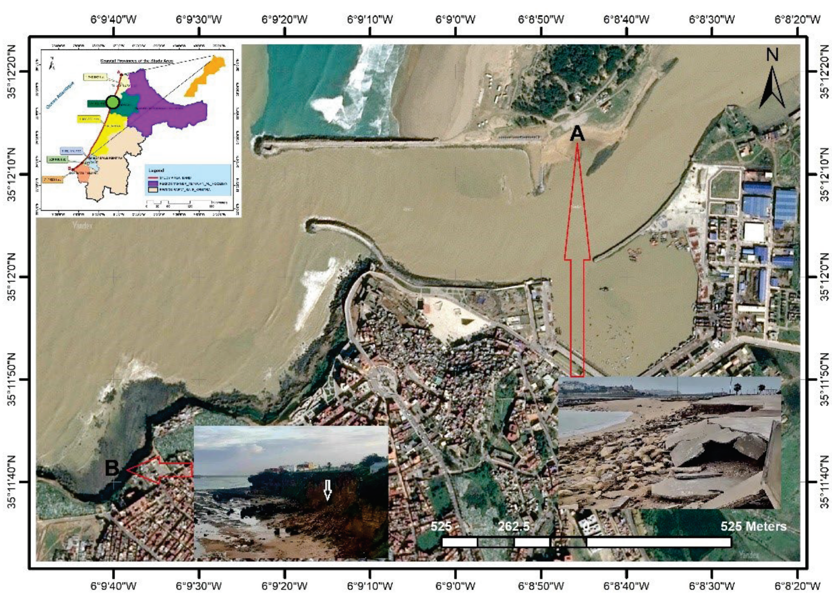
**Table 6.** *Shoreline change versus vulnerability level along the main estuary of the study area*

| Estuary name | Shoreline change rate (m/yr) | Coastal vulnerability | Commune | Commune type |
|---|---|---|---|---|
| Bouregreg | −6.7 to −2.9 | Very high | Rabat | Urban |
| Sebou | −1.3 to 3.1 | High | Kénitra | Urban |
| Moulay Bousselham | −7.9 to −1.3 | Very high | Moulay Bousselham | Rural |
| Lokkous | −3.3 to 0.6 | High to very high | Larache | Urban |
| Tahaddart | −0.5 to 2.5 | High | Assilah | Urban |

height, mean sea level rise, and storm strengthening (e.g., Sergent et al., 2015; Almar et al., 2021). Due to the fact that the current vulnerability mapping took into consideration the inundation level, which is related to the conditions of extreme waves with return period of 100-year and extreme sea level rise (Snoussi et al., 2008), this may help to further decide the long-term adaptation measures during the development and the implementation phase of the coastal plan. In fact, it is worth to draw attention to the necessity of bridging the vulnerability assessment and adaptation theory and practice (Belrhaba et al., 2024; Chtioui et al., 2024).

Long-term adaptation along the study area is also crucial to lessen vulnerability to climate change. As is well-recognized, the Nature based-solutions (NbS) is the most effective approach to achieve this objective (Moraes et al., 2022). These solutions propose the conservation and protection of coastal ecosystems from negative implications of sea level rise and storms (e.g., Kumar et al., 2020; Moraes et al., 2022; IPCC, 2022). Therefore, adaptive capacity and mitigation of climate change can be enhanced through these solutions by leveraging nature-provided inherent resilience and ecosystem services (Welden et al., 2021). Due to the fact that NbS may not provide the necessary levels of protection since they are less known than conventional systems (Van der Nat et al., 2016), we support, in the interim, the implementation of both NbS and traditional engineered options, which may be more successful and affordable at the local and national scale (Toimil et al., 2020).

**Fig 7.** *Images depicting the collapse of a segment of the soft cliff along the southern edge of the Loukkos estuary (B) as well as on the right bank of estuary, (A) Larache, in February 2023*



### Limitations

In light of this study, we believe that policymakers will be able to make informed decisions regarding the coast regulations related to climate change implications. However, the finding of this study must be used with prudence. In fact, there are some technical limitations that could be improved to achieve enhanced decision-making. The initial part of our work is based on Landsat image time series, which have a spatial resolution of 30 m. These data prove to be the best open-source resource for conducting shoreline change analysis (McAllister et al., 2022). However, the low-resolution of Landsat data poses a limitation. It is possible that shoreline estimation will be subject to a significant amount of uncertainty, thereby affecting the accuracy of the final outcome.

On the other hand, the use of the AHP approach to assess coastal vulnerability poses some gaps that must be recognized. One can see that AHP approach largely relies on subjective evaluations and expert opinions, which can influence the reliability of the finding in terms of the selection of index variables (Roukounis and Tsihrintzis 2022). We believe that this aspect does not undermine the results since the interpretation and the meaning, weighting, and pairwise comparisons of the criteria are based on expert opinions, literature reviews as well as on stakeholder consultation. However, because the fact that the AHP approach could simplify the complicated decision issues (Giannakidou et al., 2020), which may lead to oversimplify the inherent complexities and interconnections within vulnerability analyses, thus insufficient knowledge of the system's intrinsic intricacies and interconnections.

## Conclusions

This study presents a detailed assessment of the physical vulnerability of Morocco's northern Atlantic coastline, highlighting key shoreline dynamics and climate-driven coastal hazards over the past three decades. The integration of shoreline change analysis with eight environmental forcing variables through the AHP-based Coastal Vulnerability Index (CVI) method allowed for the identification of high-risk zones, particularly around the estuarine systems of Bouregreg, Sebou, Moulay Bousselham, Lokkous, and Tahaddart. These areas exhibit a combination of accelerated shoreline retreat, low-lying geomorphology, and increased exposure to sea level rise and wave extremes.

The results underline the critical need to prioritize these hotspots in national coastal planning frameworks. In the face of escalating climate pressures, the study recommends a hybrid approach that combines nature-based solutions such as dune and wetland restoration with conventional infrastructure to enhance coastal resilience. Furthermore, long-term monitoring programs, the use of higher-resolution remote sensing data, and the integration of socio-economic vulnerability indicators are essential to refine adaptation strategies.

By bridging quantitative shoreline analysis with spatial multi-criteria assessment, this research provides a replicable framework for vulnerability mapping and supports evidence-based coastal risk management policies. It reinforces the urgency of implementing adaptive, ecosystem-based interventions to mitigate the escalating impacts of climate change on Morocco's coastal zones.

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