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Comparative Study of Coastal Vulnerability in Morocco: In-depth Analysis of the Atlantic and Mediterranean Coasts through Machine Learning Models.

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Abstract

The Northern coast of the Sebou estuary on the Atlantic side is characterized by a relatively low topography, exposing the region to coastal change issues such as erosion and accretion. Utilized algorithms, including Random Forest, Decision Tree, and Support Vector Machine, demonstrated high performance with notable precision. The resulting mapping reveals that 20.07% of the coastline is moderately vulnerable, 10.35% is highly vulnerable, and 69.57% exhibits low vulnerability.

On the other hand, the Mediterranean coast, particularly the Tanger-Tetouan region, is generally associated with higher salinity compared to the Atlantic Ocean. Various models, such as Artificial Neural Networks, Decision Trees, Logistic Regression, Random Forest, and Support Vector Machine, are employed to assess coastal vulnerability. Results indicate that approximately 19.95% of the coastline is highly vulnerable, 20.92% is moderately vulnerable, and 59.1% shows low vulnerability. In summary, the low topography of the Atlantic coast makes it more susceptible to coastal change issues, while the Mediterranean coast is influenced by other factors, such as elevated salinity and specific Mediterranean climate conditions. Algorithm performances vary, but in both cases, certain models yield impressive results. Although vulnerability percentages differ between the two regions, both studies emphasize the importance of their respective approaches for coastal zone management and adaptation planning.

1. Introduction

Due to the combined effects of increasing urbanization and climate change in recent decades, coastal communities throughout the world are becoming far more vulnerable. Coastal risk management is becoming a top concern for governments and international organizations (Natesan et al. 2015).According to recent studies, more than 40% of people on Earth live within 100 kilometers of the coast, making these areas very susceptible to environmental changes and natural calamities.

Dynamic processes that take place in coastal zones provide diverse productive ecosystems that are essential to the human population zones (Houston 2013; Karim et al. 2018; Leet 1975).Climate change poses a serious threat to present and future generations ((Ormsby 2011; Park and Lee 2020). Coastal areas are still the most vulnerable to climate change, while having the most productive ecosystems on the planet.

Europe's shores are also being impacted by a variety of coastal pressures and hazards. Unchecked development, floods, and coastline erosion are issues that Morocco and other Mediterranean coastal nations like Spain, France, Italy, and Greece deal with. Popular tourist locations like the Costa del Sol in Spain and the Côte d'Azur in France are especially susceptible due to their dense population and reliance on coastal tourism for their economic existence (Saber M. Elsayed1 2018).

Furthermore, parts of northern Europe, such as the Netherlands and Belgium, are susceptible to floods due to their low elevation and ground subsidence (Marcet Llorens and Navarro-Pedreño 2023). Bangladesh, Indonesia, and the Philippines are among the countries affected by flooding and sea level rise. River deltas, including the Ganges-Brahmapoutre delta in Bangladesh and the Mekong delta in Vietnam, have additional

difficulties due to land sinking and deforestation (BRGM/RP 2009.Africa's coasts are among the world's most susceptible to coastal dangers due to their great geographical and environmental variety.

Many African countries, particularly those on the west coast, confront issues such as coastline erosion, sea-level rise, natural habitat loss, and marine ecosystem degradation. These dangers are compounded by variables such as rapid population increase, uncontrolled urbanization, and inadequate coastal protection infrastructure(COZ and HAMON 1964).

In North Africa, the Mediterranean beaches of Morocco, Algeria, Tunisia, and Libya face similar pressures, while local variations may exist. These regions suffer common difficulties, such as arable land loss, wetlands disappearance, soil salinization, and coastal ecosystem degradation as a result of increased urbanization and industry(Herdendorf 1982; Idrissi et al. 2004).

Morocco's coasts, both Atlantic and Mediterranean, have unique geological and environmental factors that determine coastal vulnerability(Khalfaoui et al. 2023). The Atlantic coast, which runs about 1,100 kilometers, is characterized by long, wide sandy beaches interlaced with rocky formations and sharp cliffs (El Mrini et al. 2013). This region experiences more dynamic ocean conditions, including higher tides and more frequent storms, which increases the risk of coastal erosion and floods, particularly in densely populated regions like Casablanca and Agadir.

On the other hand, Morocco's Mediterranean coast, some 500 kilometers long, has different topographical and geomorphological features. It is generally less exposed to ocean storms, but also faces unique challenges. Coastal plains are often densely populated and urbanized, increasing pressure on coastal ecosystems and making them more vulnerable to flooding from rising sea levels(Ennouali, Fannassi, Lahssini, et al. 2023).

Overall, sustainable coastal management in Africa(Snoussi, Haı¨da, and Imassi 2002), particularly Morocco, necessitates a comprehensive approach that considers environmental, socioeconomic, and cultural factors(Boruff, Emrich, and Cutter 2005). This necessitates strong collaboration among governments, local communities, international organizations, and researchers to produce successful coastal management policies and practices that are tailored to local situations.

Coastal risk management has become a global priority as a result of increased urbanization, climate change, and marine ecosystem degradation. Countries around the world, whether in Africa, Europe, Asia, or elsewhere, must take integrated and collaborative methods to preserving coastlines, protecting populations, and promoting environmental and socioeconomic sustainability(Gornitz and Kanciruk 1989). This includes investing in coastal protection infrastructure, restoring coastal ecosystems, creating coastal zone management rules, and raising public knowledge about coastal vulnerability issues(Rise and Klose 2004; Ward et al. 2011).

The repercussions, including erosion, flooding, and sea-level rise, necessitate an assessment of coastal vulnerability. Various methodologies, such as the Coastal Vulnerability Index (CVI) and Machine Learning (ML), are used to assess vulnerability based on physical, socioeconomic, and environmental aspects(Ennouali, Fannassi, Lahssini, et al. 2023; Fannassi et al. 2023).

Researchers all across the world have taken various techniques, including the use of GIS and multi-criteria methodologies for more accurate assessment. This problem is especially prominent in Morocco, which has both Atlantic and Mediterranean coasts. The comparative study of coastal vulnerability is thus critical for understanding the unique problems that different places face (Avci et al. 2023).

The focus on coastal research has increased, although gaps remain, particularly in Kénitra. This study proposes a novel approach based on automatic learning, including models such as SVM, LR, RF, DT, and ANN, to predict the côtière vulnerability in Tanger-Tétouan. This approach, which combines data and algorithms, aims to guide cooperative management and planning by providing valuable information to decision-makers and managers(Ennouali, Fannassi, Lahssini, et al. 2023).

Tangier and Tetouan are some of Morocco's most populous cities. They are situated at the confluence of the Mediterranean Sea and the Atlantic Ocean. The shore is rapidly urbanizing, with complex socioeconomic infrastructure and leisure activities (El Mrini et al., 2013). According to Moroccan research, low-lying coastal areas are especially vulnerable to sea-level rise, not only because of their low topography, but also because of their high environmental, socioeconomic, and tourism value (Fannassi et al. 2023; Snoussi, Khouakhi, and Raji 2011).

By focusing on eight criteria such as elevation, slope, geomorphology, and others, this methodology provides a holistic view of coastal vulnerability. Furthermore, it allows for the comparison of various machine learning models to gain a better knowledge (Mogaraju 2023)of the risks associated with distinct land uses.

The study emphasizes the significance of the ML technique for forecasting changes in coastal zones, emphasizing areas sensitive to various consequences. The findings can assist decision-makers alter coastal management strategies, thereby preserving these crucial ecosystems in the face of climate change and unrestrained urbanization(Fletcher et al. 2003).

During this study, researchers look at a variety of parameters, such as coastal erosion, sea level rise, coastal habitation, and other environmental and socioeconomic factors. They are able to model and predict future trends in coastal vulnerability in these regions by utilizing advanced automated learning techniques.

The findings of this study are critical for guiding coastal management policies in Morocco, providing valuable information on the most exposed areas and the necessary adaptation measures. Furthermore, this novel methodological approach could serve as a model for other regions facing similar challenges in terms of coastal vulnerability.

1–1. **Study area**

Tangier-Tetouan and Kenitra, two coastal regions of Morocco, are the areas studied in this research. Because of their geographical location and unique location and their unique coastal management problems, these two regions are particularly important. Located between latitudes 35°48 N and 35°24 N and longitudes 5°53 W and 5°0'W (Fig. 1 ;2). The area is distinct and incredibly dynamic at the coastal level because of its strategic location at the meeting point of the Atlantic seas and Mediterranean. Two of the most significant cities in the nation and vital crossroads for travel and trade are Tangier and Tetouan. and

important hubs for the travel industry are established there (Ennouali, Fannassi, Lahssini, et al. 2023; Fannassi et al. 2023). The coastlines of Tangier and Tetouan provide a diverse range of coastal scenery, from expansive sandy beaches to stunning rock formations.

The region faces several issues as a result of its strategic location and socioeconomic significance, including growing urbanization(Fannassi et al. 2023), pollution along the shore, and climate change-related risks including rising sea levels and coastal erosion. It begins with Tangier, which is situated on the African side of the Strait of Gibraltar, on Morocco's northwest coast, at the entrance to the Mediterranean Sea. Stretching over an approximate distance of 124 km, it is home to several urban and rural communities. Tangier can be divided into three morphological segments: a coastal plain bounded by two high sections of the Rif Mountains(Snoussi, Khouakhi, and Niang-diop 2009), and an exceptionally low area belonging to the lower reaches of rivers. The most prevalent shore types in the region are shingle and sand beaches. But a rocky cliff limits the shoreline in the eastern portion of the bay.Tangier is regarded as a densely populated metropolis. Because Tangier's port is regarded as a vital entry point for Morocco and Europe, there is a strong network for both communication and transportation.

Kenitra is situated on Morocco's Atlantic coast, along the Gharb's Atlantic coast, halfway between Sidi Taibi and Moulay Bousselham. Geographically speaking, it is located roughly between latitudes 34°11' and 34°18'5"N and longitudes 6°38' and 6°42'6"W(Hakkou et al. 2011; Hind et al. 2017). While not as well-known as Tangier-Tetouan, Kenitra too has comparable problems with managing its coast(Ennouali, Fannassi, Lahssini, et al. 2023). It is distinguished by the presence of a dune region that stretches from Moulay Bousselham to North Sebou. This region is 70 km long and 1 to 10 km wide, with an elon-gated shape parallel to the seashore, broken only by meanders and the Oued Sebou mouth. A stony cliff known as the "dead cliff" marks the western edge of the barrier beach. It is isolated from the water by a local reduction in sea level or sedimentation. This bluff overhangs the beach's live dunes, which may be overcome by recent marine sand eolian additions(Ennouali, Fannassi, Benmohammadi, et al. 2023).

An older dune, likely Rharbian, partially overlaps the sub-actual white dune at the top of the beach, which is stabilized by a deteriorated June grove. This has a dead cliff that dominates the entire area to the east, formed like a consolidated dune complex of the Soltanian era.The Gharb coastal area is situated between four topographic units: the alluvial plain of Gharb in the east, the dune complex in the west, the plateau of Maâmora in the south, and the plateau Rmel-Arbaoua in the north. The wadi Sebou, which passes through the towns of Mnasra and Kenitra, borders it to part of the south(Bryssine 1966; Du et al. 2019; Ennouali, Fannassi, Benmohammadi, et al. 2023).

This wadi forms in the 0.9% grade Gharb Plain and makes multiple meanders before emptying into the Atlantic Ocean near Mehdia (Ennouali, Fannassi, Benmohammadi, et al. 2023; Ennouali, Fannassi, Lahssini, et al. 2023; El Jihad, Peyrusaubes, and El Bouzidi 2014).

The region's Mediterranean climate has a seasonal impact; summers are hot and winters are mild, moderate, and stormy. Nonetheless, it is distinguished by observable temperature fluctuations between 4 and 40 degrees Celsius. The amount of rain that falls each year varies from 900 to 300 mm. Rainfall in the coastal region of Kenya averages 537 mm annually. The influence of the oceans diminishes as one moves

farther out from the coast, where the continental weather appears to be more noticeable. The majority of winds (56%) come from the west, which defines the yearly wind climate (summer regime). 25% of the time, there are regular east winds (winter regime). 19% of the time, the weather is calm. According to (Ennouali, Fannassi, Benmohammadi, et al. 2023; SOGREAH 2011), these winds have the capacity to produce 20 m3/year of wind transit toward the land.

The three municipalities under consideration have a combined population of about 97,000 people(HCP (Morocco High commission for Planning) 2014), up from 30,600 in 1971. Long swells are common in the coastal zone, with the surf zone—the 400–500 wide coastal strip—being the primary area affected(Khomsi et al. 2013).

The dominant swells originate from the northwest with typical periods of 10 to 15 s and 70% have a significant height (0.5 to 2 m). Off the coast of Bouknadel-Kenitra, storm swells come from the West-North-West (280◦N to 300◦N) and arrive relatively frontal to the coast, which induces the formation of sagittal currents that are crucial for the morphological evolution of the beaches and are also dangerous for swimming. West and South- West swells are infrequent, but quite energetic, especially in spring and autumn, when they play an evident role in regulating sediment transit between the North and the South (Mhammdi N.,Snoussi M 2014). The tide is semi-diurnal with a period of 12 h 25 min. The coastal water flows are vulnerable to tidal currents that travel at 20 to 30 cm/s and can play a major role in sand transport (Maria Snouss 2020).The main city of Kenitra is becoming more urbanized, putting strain on coastal ecosystems as a result of residential and commercial growth. Furthermore, the area is vulnerable to flooding, particularly during high tides and winter storms.

The study intends to comprehend the particular vulnerabilities associated with coastal management by concentrating on these two places. By utilizing sophisticated machine learning techniques and an array of geographical, ecological, and socio-economic data, scholars can furnish invaluable insights to steer coastal management strategy and judgment.

The goal of the study is to pinpoint the most vulnerable locations and forecast changes in coastal vulnerability in the future. Through these initiatives, coastal communities are better equipped to withstand the effects of urbanization and climate change.

2. Material and methods

2-2-Data sources and method

Following our analysis of the two zones—Tangier- Tetouan and Kenitra—a comprehensive survey was carried out to gather information from various sources (Table 1,2) so that we could evaluate these zones' susceptibility. We next used the technique shown in Fig. 3.

Table 1
Data used according to Tangier- Tetouan

Variables	Data source	period
Sea level rise	PSMSL (http://www.psmsl.org/)	—
Shoreline change rate	CoastSat (Satellite Imagery)	2021 2000
Coastal slope	DEM (USGS Earth explorer)	2021
Elevation	ANCFCC (USGS Earth explorer)	2021
Tidal range	Previous studies	—
Maximum wave height	(http://www.puertos.es/)	2000–2021
Geomorphology	FIELD KNOWLEDGE	2021
Natural habitat	Bibliographic research 'MED KEY HABITATS PROJECT'	2016

Table 2
Data used according to Kenitra

Variables	Data source	Period
Sea level rise	PSMSL(http://www.psmsl.org/)	2017
Shoreline change rate	Satellite Imagery (Landsat7 & Landsat 8) (https://earthexplorer.usgs.gov)	2002–2021
Coastal slope	DEM (https://earthexplorer.usgs.gov)	2022
Elevation	USGS Earth explorer (https://earthexplorer.usgs.gov) Resolution 12 m	2022
Tidal range	Other researches (Bibliographic research)	–
Mean wave height	Public Agency Puertos del Estado (Ceuta port station) (http://www.puertos.es/)	2002–2021
Geomorphology	Bibliographic research, Field trip	1989, 2019, 2021
Natural habitat	Regional Directorate for Water and Forests and the Fight against Desertification	2019

2-3-Data used

In the current study, eight variables were taken into account to create the CVI. The significance of each metric taken into account and how to create them for use in CVI assessment are explained in the section that follows.

2-3-1- Geomorphology

As per the Tanger-Titouan Zone. It describes the comparative rate of erosion of various beach relief types (such as sand, rocky, and cliff beaches); as a result, it's important to comprehend their stability and geographical distribution (Pantusa et al. 2018). In our case, six distinct geomorphological units have been cartographed. The most common are the high cliff, rocky beaches, and sandy beaches(Fannassi et al. 2023).

Notable in the Kenitra region. The coastal zones are also subject to a variety of natural forces, ranging from meteorological and marine hazards like storms to natural erosion phenomena.

Our study site's geomorphology demonstrates the relative erodibility of various reliefs (such as cliff, rocky beaches, and sandy) along the coast, necessitating an understanding of the resilience and geographic relief distribution (Pantusa et al. 2018).In our case, two separate geomorphological units were able to identify them as follows: (a) along the edge of dunes, falaises that are no taller than 10 m; and (b) on the east side of the cordon, a rocheuse falaise that overhangs the beach's living dunes and may have been elevated by more recent eolian contributions of marine sand.

A more ancient (perhaps rharbienne) one is partially obscured by the white sous-réelle at the top of the beach. She is bounded on the east by a dead falaise that dominates the entire Merjas coast and is shaped like a solidified from the Soltanienne era (Ennouali, Fannassi, Lahssini, et al. 2023; M’hamed Aberkan 1989) .

2-3-2- Elevation

From Tangier to Tetouan. It symbolizes the altimetry of a terrestrial area. According to Mukherjee et al. (2012), it is crucial to assessing vulnerability as it provides comprehensive details on mitigation. The National Agency for Land Conservation, Land registry and Mapping - ANCFCC (40 cm resolution) and the USGS Data Explorer (30 m resolution) provided the digital elevation model (DEM) data used in this survey(Fannassi et al. 2023) (Figure. 4).

Kenitra: The study extracts many morphological features using the numerical elevation model (DEM). With a resolution of 12*12 m, the DEM was obtained from the Shuttle Radar Topography (SRTM) mission images, as shown in Fig. 5a. With the use of DEM, the region of interest can be precisely delimited by automatically extracting the different relief factors. DEM elevation numerical models have facilitated the automatic extraction of morphological properties (surface, length, width, perimeter, shape, relief and slope) (Ennouali, Fannassi, Benmohammadi, et al. 2023; Ennouali, Fannassi, Lahssini, et al. 2023) (Figure .5).

2-3-3- Slope

Figure .4 shows that the Tangier-Tetouan zone has a slope ranging from 0% to 114%.

Kenitra reported that the slope values varied from 0 to 21% (Figure. 5b).

2-3-4- Shoreline change

In this study, we analyzed coastline changes in the Tangier-Tetouan and Kenitra regions using data from various sources. We retrieved data from Landsat 7 satellite photos at a resolution of 30 meters and CoastStat, a tool noted for its ease of use and effectiveness in coastal monitoring (Vos et al. 2019) for the Tangier-Tetouan coastline between 2000 and 2021. Coastal Dynamic Analysis System (DSAS) end-of-course rate (EPR) was used to evaluate the rate of coastal change. The coastal data for Kenitra for the years 2002 and 2021 were taken from Landsat 7 (30 meters resolution) and Landsat 8 (10 meters resolution) satellite pictures, respectively. The effect rate (EPR) produced by the DSAS was used to evaluate changes along the coast.Over a 19-year period, the total error, also known as the Global Shoreline Position Error (Ept), was computed. It showed system stability with an inaccuracy of roughly 2.25 meters year (Ennouali, Fannassi, Benmohammadi, et al. 2023).

We examined patterns in shoreline change from 2002 to 2021 using the EPR technique. The average rate of coastal accretion that we saw was closer to the shoreline, at + 1.32 meters per year, whereas the average rate of erosion that we observed was − 1.08 meters per year. At a rate of -4.37 meters per year, the erosion was particularly noticeable in the Mnasra and Siditaibi areas(Ennouali, Fannassi, Benmohammadi, et al. 2023).

Conversely, Benmansour, Moulay Bousselham, and the sections north of the mouth of the Sebou Wadi underwent a high accretion, with an average rate of + 5.25 meters per(Ennouali, Fannassi, Lahssini, et al. 2023).

2-3-5- Sea level rise (SLR)

Sea level variations in the Tangier region are crucial given the effects of climate change. We chose to anticipate a 2.5-millimeter annual growth in a pessimistic scenario. Sea level rise is definitely exposing coastal communities to more threats, which emphasizes the urgent need for preparation and adaptation(Fannassi et al. 2023). On the other hand, tidal gauges are used in Kenitra to monitor sea level, giving officials a clear and accurate picture of how the situation is changing. According to surveys, there is an average 3.2 millimeter increase annually(Ennouali, Fannassi, Benmohammadi, et al. 2023)., according to (Snoussi 2020). Higher sea elevation coastal locations are recognized in this context as being especially susceptible to the effects of climate change.

2-3-6- Natural habitat

The effects of coastal hazards, which can destroy coastal cities and deteriorate shorelines, are greatly reduced when natural ecosystems (such as coral reefs, coastal forests, and low dunes) are present (Maanan et al. 2018).

2-3-7- Wave height

In Tangier-Tetouan, our study estimated that the maximum wave height from 2000 to 2021 was 2.94 meters (Fannassi et al. 2023).At Kenitra, data collected at our study site indicate that the average maximum wave height along the coast was estimated at 1.73 meter's for the period 2000 to 2021 (Ennouali, Fannassi, Benmohammadi, et al. 2023)..

2-3-8- Tidal range

It conveys the difference between the highest and lowest tides of the year every year ((Maanan et al. 2018).. There is a clear trend in vulnerability assessments to label coastal regions with lower tidal beaches as severely vulnerable.

2-4-CVI calculations

Each characteristic was ranked using semi-quantitative values ranging from 1 to 5, in accordance with the CVI technique (Eq. 2). The maximum contribution of a parameter to coastal vulnerability is represented by a score of 5. Using this methodology in Tangier-Tetouan, the sensitivity of the research region was evaluated at this stage, with a total of 10033 points.

Similarly, in Kénitra, we also chose to use the CVI methodology, which yields 4013 points, to evaluate the vulnerability of a portion of the research region. Semi-quantitative evaluation ratings ranging from 1 to 5 were used to rate each variable, with 5 denoting the highest contribution to coastal vulnerability(Fannassi et al. 2023).

$$CVI = \sqrt{\mathrm{CV}\left(\mathrm{Productmean}\right)} = \sqrt{(x1 \times\ x2 \times\ x3 \times\ x4 \times\ x5 \times\ x6 \times\ x7 \times \ldots\ldots\ldots xn/n}$$

Where **xn** is the number of vulnerability variables.

This phase enabled us to map the coastal vulnerability of the region as shown in (Fig. 4).

2-5-Data pre-processing

As it prepares data for input into machine learning models, this phase is crucial.

2-5-1- Data preparation

The eight variables were constructed using ArcGIS software and a number of Python packages, including Numpy and Pandas. This phase creates a database that contains the coordinates of every point in X and Y as well as the values of every variable for each target class, which are Very Low Vulnerability (VL), Low Vulnerability (L), Moderate Vulnerability (M), High Vulnerability (H), and Very High Vulnerability (VH), respectively. The textual data source yields numerical data.

2-6-Machine learning models

The main models that were employed in this work are thoroughly described in this section.

2-6-1- Support vector machine (SVM)

Using this supervised machine-learning method, problems with regression or classification can be addressed. But it's mostly applied to challenges involving classification. It works well as a classifier construction method. By creating a decision border between two categories, it is intended to make it possible to predict labels using one or more feature vectors.

(Huang et al. 2018).

2-6-2- Logistic regression (LR)

Machine learning has embraced a strong statistical technique that is widely used for categorization and relationship predictions between an event occurring based on a dataset of independent factors (Pourghasemi et al. 2018).

2-6-3- Random forest (RF)

a commonly used supervised machine learning technique for a wide range of applications, including regression and classification (Mogaraju 2023).It is composed of an immense number of little decision trees, known as estimators, which produce their predictions. It does better than the competitors when it comes to categorization issues.

2-6-4- Decision Tree (DT)

Both regression and classification issues are often resolved by a supervised machine learning programme. It seeks to develop a training procedure that can identify the category or magnitude of the target variable using fundamental decision-making concepts learned from historical data. It is the most often used instrument for decision-making.. (Navada et al. 2011)

2-6-5- Artificial neural network (ANN)

A mathematical parable about the brain's capacity to recognize complex patterns. analogous to the way people handle data (Kumar et al. 2021)). Input, output, and one or more hidden layers make up the network's layers(Ennouali, Fannassi, Lahssini, et al. 2023; Fannassi et al. 2023).

2-7- Models Evaluation

A classifier's future accuracy can be predicted by estimating its current accuracy. Machine learning techniques generally include some variation or uncertainty because a training dataset can't always contain

all possible examples. The Tangier zone's 10033 points and Kenitra's 4013 points, which indicate high, moderate, and low susceptibility, make up the dataset utilized in this study. Model performance was assessed using thirty percent of the data using a range of metrics, such as F1 score, kappa index, accuracy, recall, and mean square error. Training was done with the remaining seventy percent. The equations for the previous measurements were explained by (Ennouali, Fannassi, Lahssini, et al. 2023; Fannassi et al. 2023).

3. Results and Discussion

3 – 1 Performance of the proposed models

The results of the machine learning models for Kénitra and Tanger-Titouan show significant differences in terms of performance. In Kénitra, all models show precision above 82%, with recall, F1 score and kappa values ranging from 0.72 to 0.99, and RMSEs close to zero, indicating excellent overall performance. The best-performing models in this area are SVM, DT and RF. In contrast, in Tangier-Titouan, model precision ranged from 0.66 to 0.99, recall from 0.62 to 0.99, F1 score from 0.63 to 0.99, and kappa from 0.60 to 0.99, with RMSEs ranging from 0.10 to 0.85. This greater variability suggests that the Tangier-Titouan data are more heterogeneous or contain more noise, making some models less effective. The best models in this area are also RF, DT and SVM, while logistic regression shows the lowest accuracy. These differences indicate that Kenitra's data are probably more homogeneous and better suited to the algorithms used, while Tangier-Titouan could benefit from more rigorous data pre-processing or the use of more sophisticated models to improve overall performance. So, although both areas show good performance overall, Kenitra shows a more stable and homogeneous performance, while Tangier-Titouan shows greater variability, potentially requiring further adjustments to optimize the performance of machine learning models.

3 – 2 Comparison of model results

In both studies, different machine learning models such as DT, SVM, RF, LR, and ANN were used to map and predict coastal vulnerability, and the results were integrated into GIS software to generate vulnerability maps. In Tangier-Titouan, the final map shows that, according to the RF and DT models, 33% of the area is very weakly vulnerable, 26% weakly vulnerable, 21% moderately vulnerable, 13% strongly vulnerable, and 7% very strongly vulnerable. According to the SVM, the percentages are slightly different, with 32% very low vulnerability, 28% low vulnerability, 19% moderate vulnerability, 15% high vulnerability, and 6% very high vulnerability (Fig. 6). The ANN model shows a similar distribution, with 33% very low vulnerability, 26% low vulnerability, 21% moderate vulnerability, 15% high vulnerability and 5% very high vulnerability. Finally, the LR model shows 32% very low vulnerability, 33% low vulnerability, 20% moderate vulnerability, 9% high vulnerability, and 6% very high vulnerability. Notable differences in vulnerability classes are attributed to variables such as slope, coastal elevation, relative sea-level rise, geomorphology, natural habitats and tidal range (Fig. 4).

For the Sidi Taibi and Moulay Bousselham region, the DT, RF, SVM, and ANN models gave accuracies of 99%, 99%, 88%, and 83% (Fig. 7). respectively, while LR gave the lowest accuracy at 82%. According to the results, RF and DT classify 44.21% of the area as very weakly vulnerable, 25.46% weakly vulnerable, 20.44%

moderately vulnerable, 8.96% strongly vulnerable, and 0.93% extremely vulnerable. The SVM classifies 44.33% as very low vulnerability, 26% low vulnerability, 20.23% moderate vulnerability, 9.02% high vulnerability, and 0.44% extremely vulnerable. The ANN model presents a classification where 37% of the area is very low vulnerability, 19.2% low vulnerability, 25.34% moderate vulnerability, 10.7% high vulnerability, and 7.76% very high vulnerability. For LR, the classifications are 48% very slightly vulnerable, 21.3% slightly vulnerable, 21.1% moderately vulnerable, 8.6% highly vulnerable, and 1% extremely vulnerable (Fig. 5). Vulnerability assessment in these two areas considered physical and human factors, including exposure to climate change, sensitivity and adaptive capacity, with features such as sea-level rise, geomorphology, slope and shoreline change directly influencing vulnerability. The model results show a vulnerability almost identical to that indicated by the CVI method after its generalization along the coastline, confirming the robustness and reliability of the models used.

In contrast to Tangier-Titouan, Sidi Taibi-Moulay Bousselham's models have higher percentages of very low and low vulnerability, indicating that the two regions have distinct vulnerability distributions. The DT, RF, and SVM models exhibit strong performance in both locations; however, Sidi Taibi-Moulay Bousselham has a greater overall accuracy, with DT and RF model accuracies reaching 99%, while Tangier-Titouan accuracies exhibit more noteworthy variability.

These discrepancies can be linked to the two locations' differing physical attributes and environmental factors, which affect coastal vulnerability. These factors include slope, coastal elevation, and geomorphology. While results from Tangier-Titouan demonstrate greater variability and variance in model sensitivity to data, Sidi Taibi-Moulay Bousselham results reveal more consistent model performance and more accurate vulnerability classification. These variations highlight how crucial it is to contextualize machine learning models to the unique features of each location in order to produce predictions that are accurate and trustworthy.

The combined effects of sedimentation and coastal erosion under a Mediterranean climate characterized by contrasting seasons have strongly shaped the present-day morphology of the Kenitra study area. This region is characterized by the presence of both unconsolidated and consolidated dune systems, intersected by the Sebou River and its estuary, which play a key role in coastal sediment dynamics.

Coastal vulnerability was assessed using eight main variables, including coastal slope, elevation, geomorphology, and exposure to climatic forcing. The results indicate that areas of **high vulnerability** are mainly concentrated around the Sebou estuary, a transitional hydrodynamic and sedimentary environment that strongly influences sediment distribution and the morphological configuration of adjacent beaches.

Photographic and cartographic analyses reveal contrasting shoreline evolution north and south of the estuary. To the north, Chlihat Beach has exhibited continuous accretion since at least 1969, with accelerated progradation following the construction of dams. Between 1969 and 2002, shoreline progradation ranged from + 1 m/year to + 2.4 m/year near the dam, and from + 0.5 m/year to + 1 m/year further north. This accretion is primarily attributed to the cumulative impacts of dams and river training structures along the Sebou River, which have significantly altered sediment transport processes. Since the

construction of the Al Wahda Dam, sediment inputs have decreased by more than 95%, although these values vary depending on hydrological cycles, including periods of drought and increased precipitation.

Overall, most of the Kenitra coastline is classified as having **low to moderate vulnerability**. However, rapid population growth and increasing urbanization exert growing pressure on this coastal zone, thereby intensifying both natural and anthropogenic risks. The coastal fringe is exposed to several hazards, including coastal erosion, flooding, and marine submersion. The Sebou coastal plain, due to its low elevation, dense hydrographic network, and soil characteristics, is particularly susceptible to erosion and flooding.

In addition, the Kenitra coastline is vulnerable to industrial and technological threats associated with human activities. Sea-level rise is expected to exacerbate coastal erosion processes, with sandy beaches retreating by an average of 10 to 15 meters, potentially threatening urban infrastructure. Progressive salinization of estuaries and coastal aquifers also represents a major concern, affecting ecosystems, water resources, agriculture, and the local economy. The combination of these factors highlights the urgent need for **integrated and sustainable coastal zone management** to mitigate risks and enhance the resilience of local communities.

Declarations

Ethics Approval

This manuscript has not been published previously and is not under consideration for publication elsewhere.

Consent to Participate

All authors have read and approved the final manuscript and agree to participate in this study.

Consent for Publication

All authors consent to the publication of this manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Use of Artificial Intelligence Tools

During the preparation of this work, the authors used ChatGPT to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Code Availability

The code used in this study is available from the corresponding author upon reasonable request.

Data Availability

The data used in this study are available from the corresponding author upon reasonable request.

Author Contribution

ZE: Conceptualization, Investigation, Writing – review & editing.TE: Methodology, Data analysis.KW: Visualization, Writing – review & editing.YF: Investigation, Methodology, Conceptualization.AB: Conceptualization, Supervision, Writing – review & editing.AYM: Supervision, Validation, Writing – review & editing.

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Figures

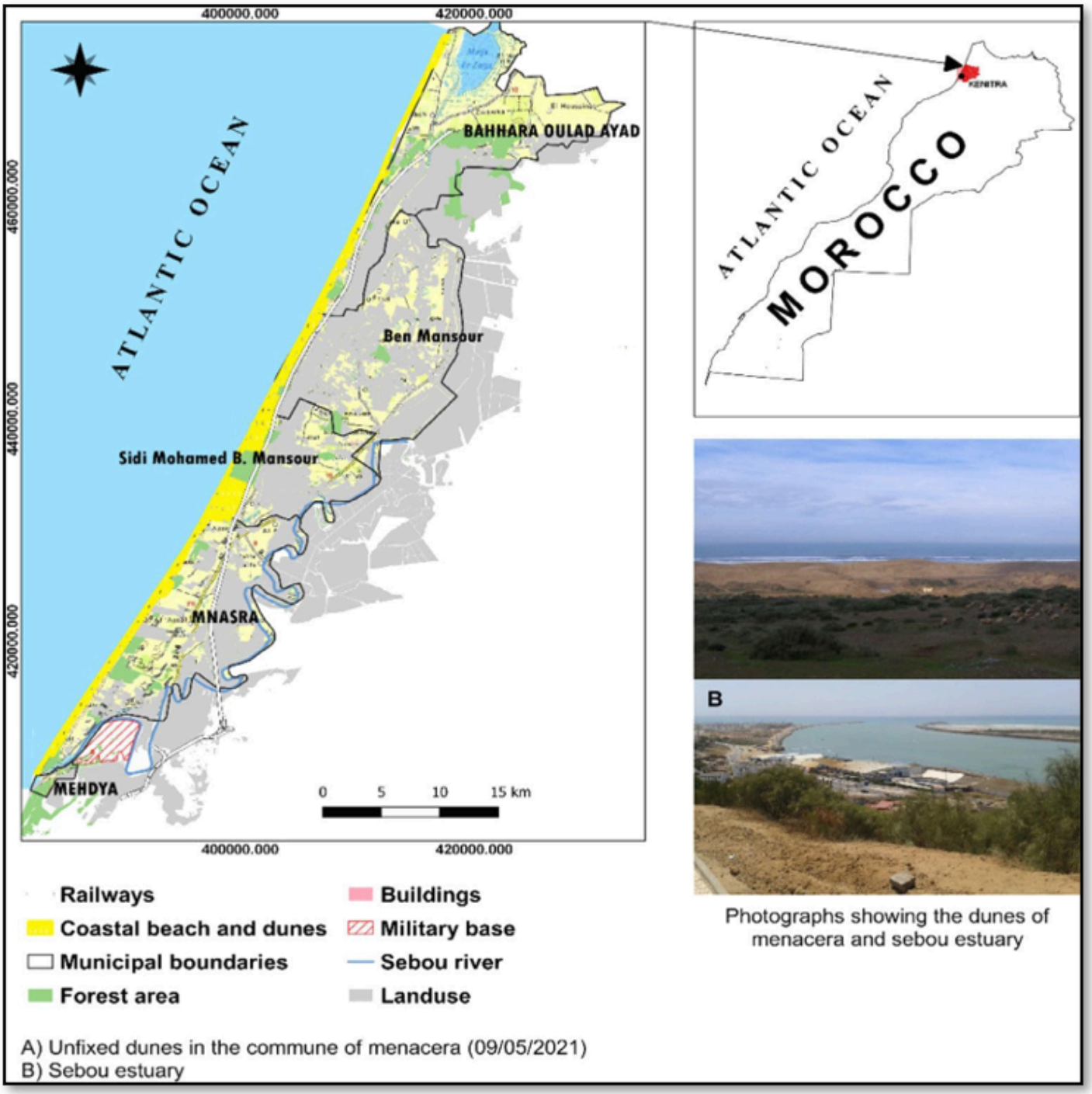


Figure 1

Geographical location of the study area Kenitra

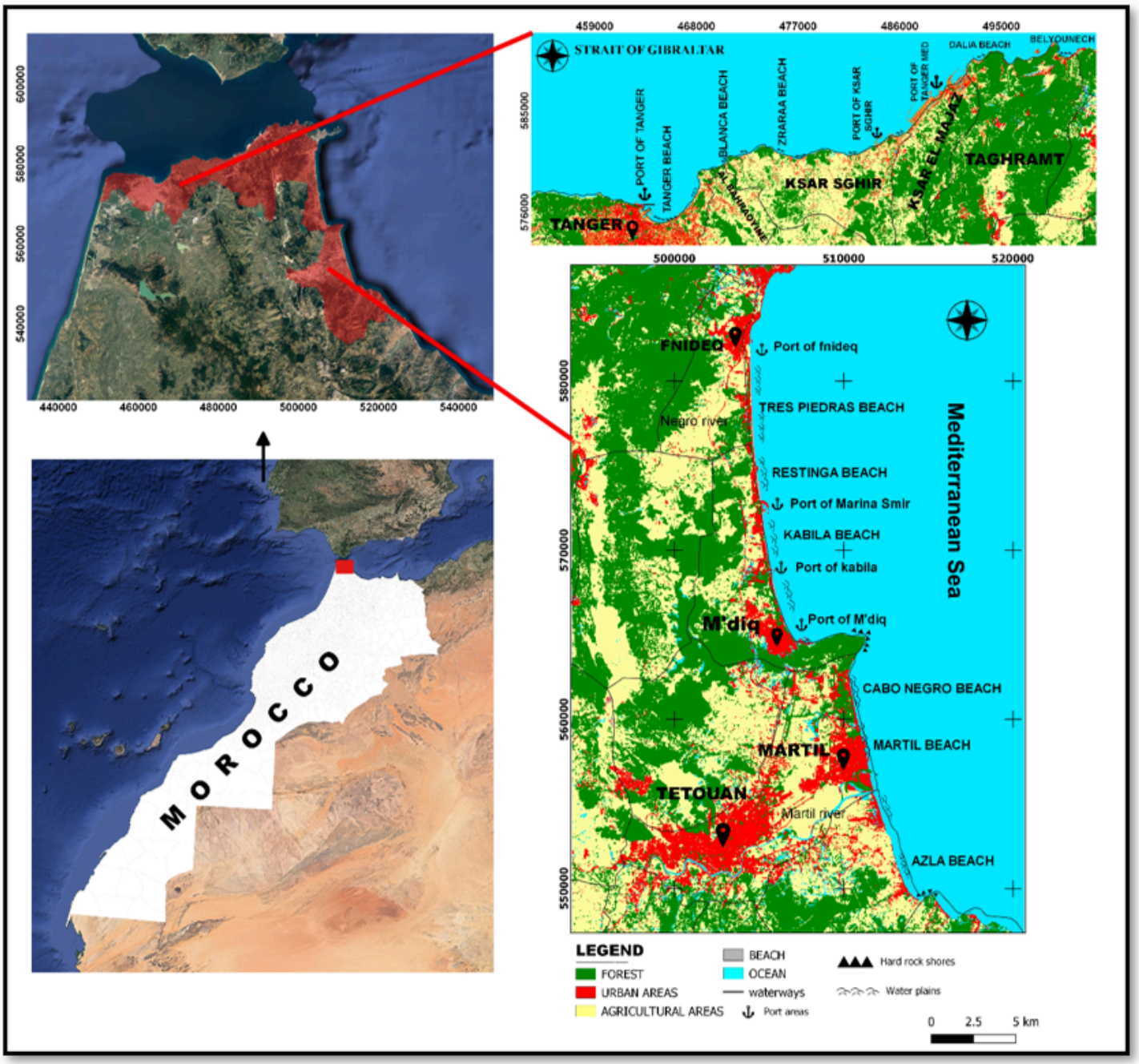


Figure 2

Geographical location of the study area Tangier to Tetouan

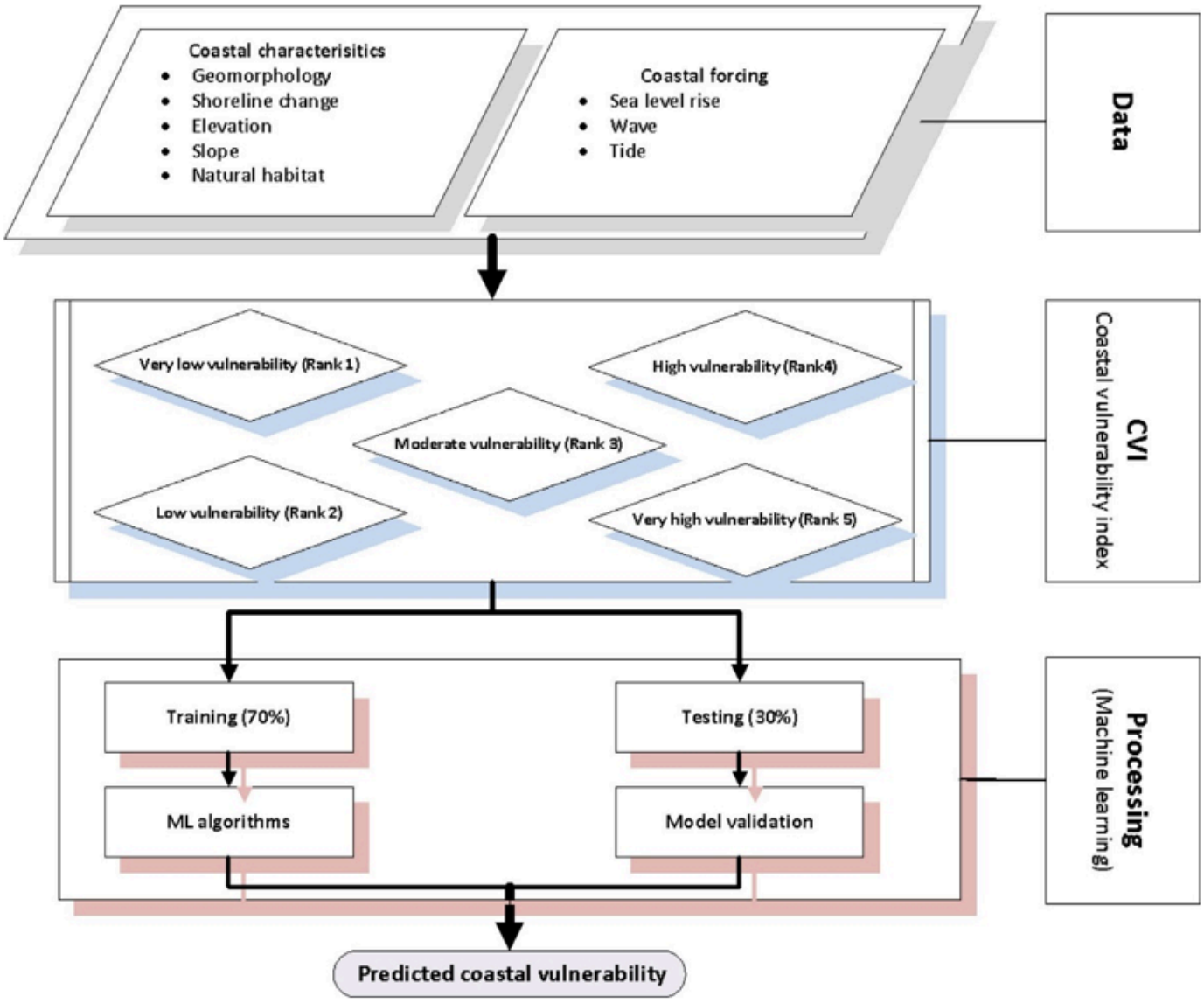


Figure 3

Methodology of work(Ennouali, Fannassi, Lahssini, et al. 2023).

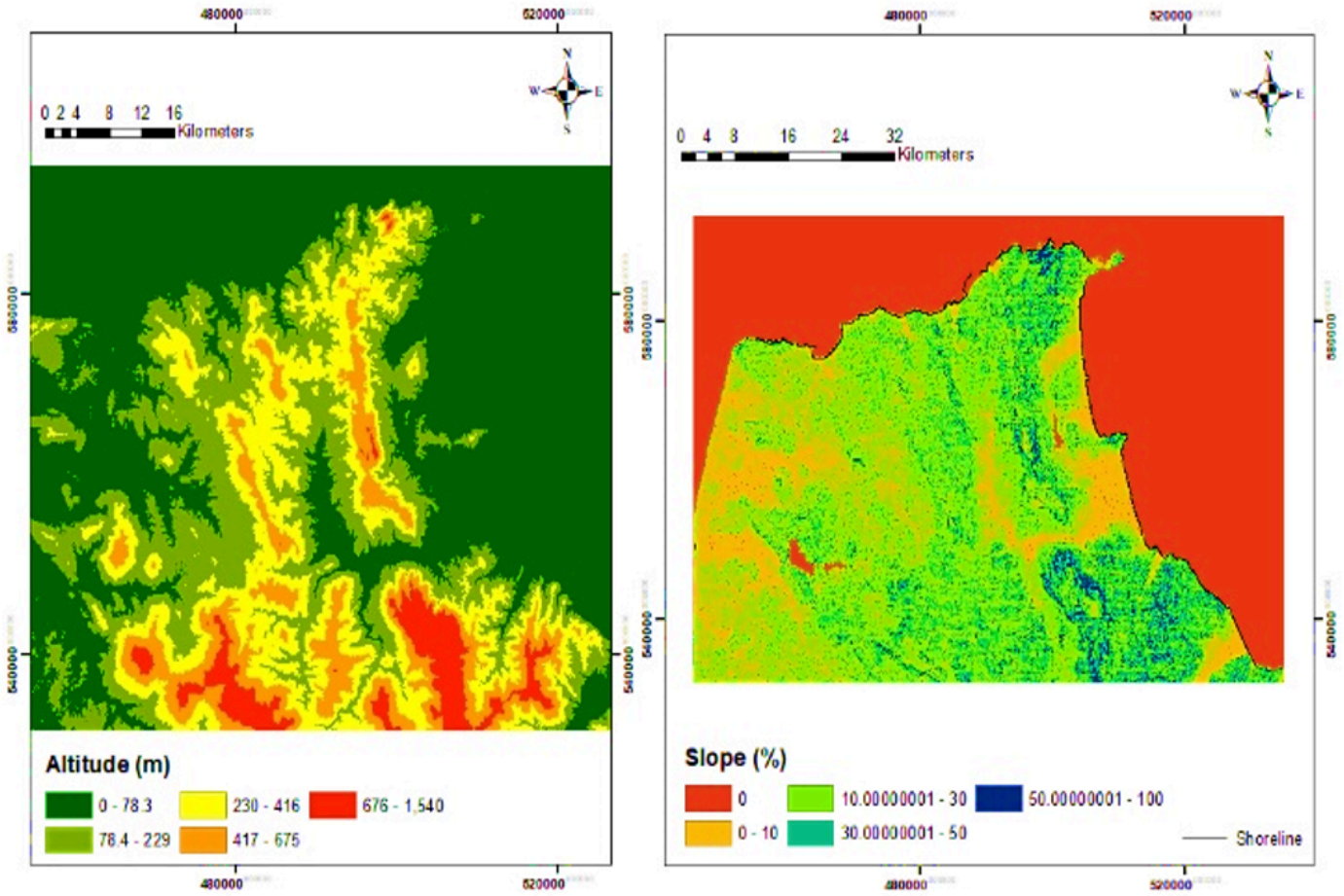


Figure 4

The maps of DEM (left photo), Slope maps (right photo) Tangier to Tetouan .

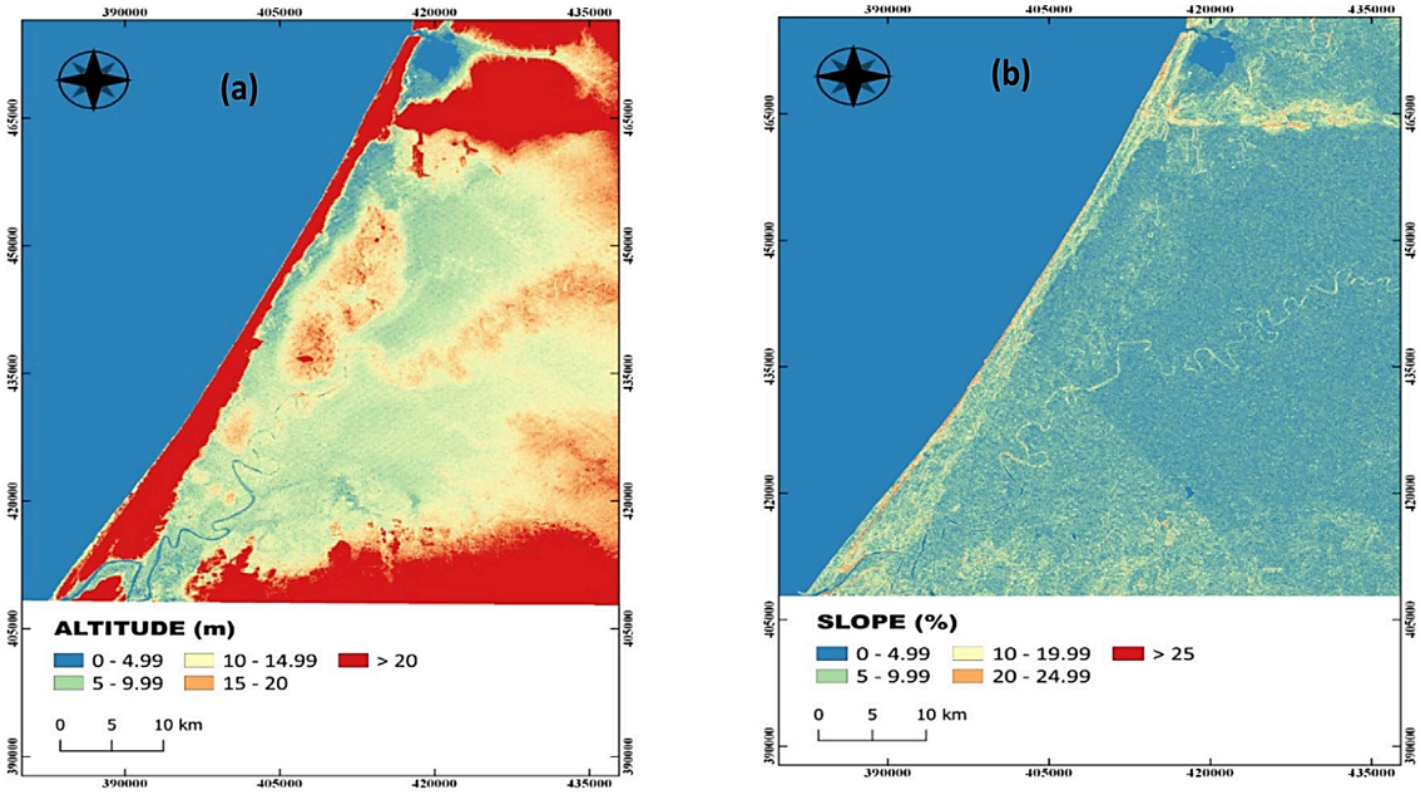


Figure 5

(a) DEM, and (b) Slope maps.

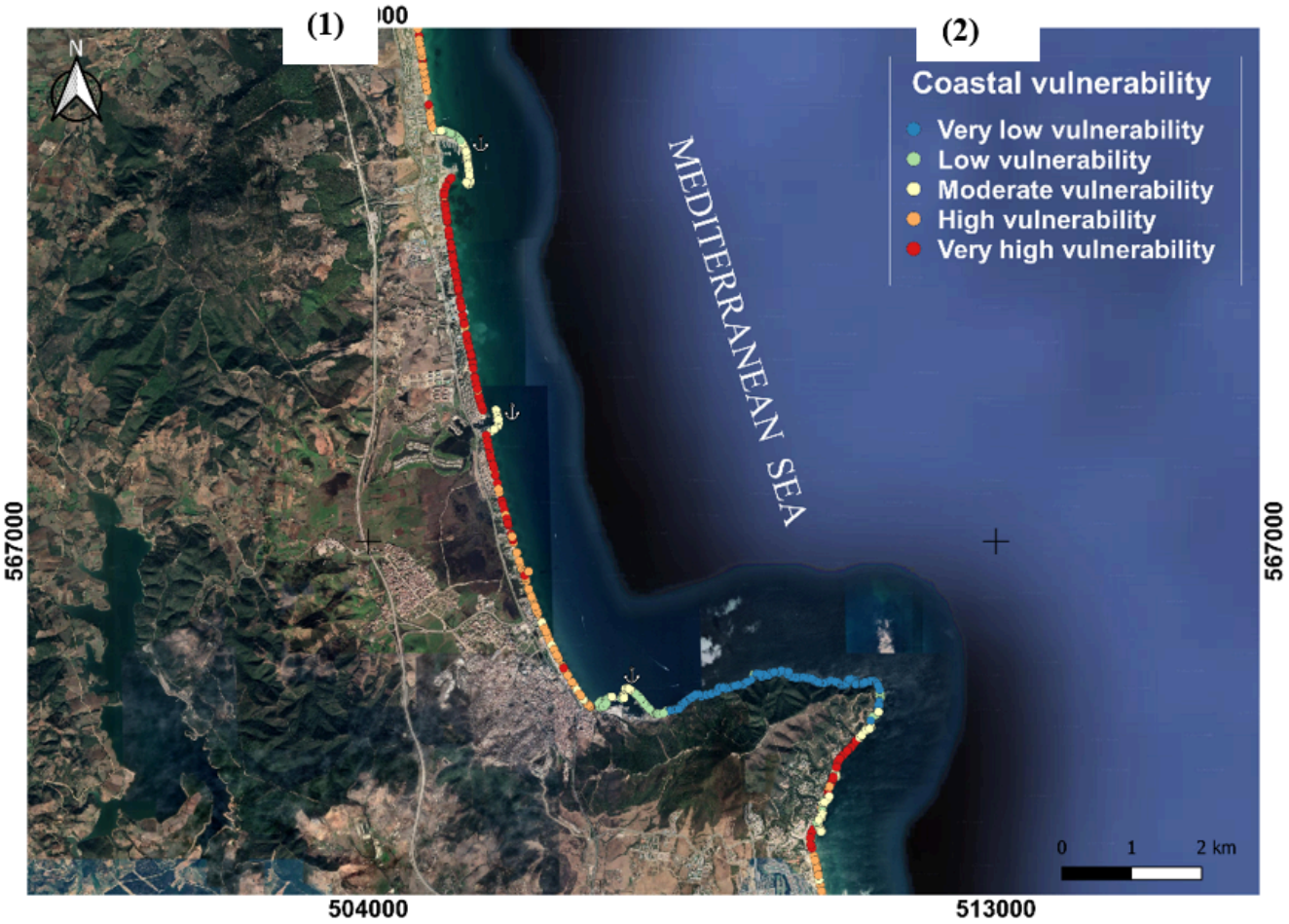


Figure 6

Fig.4.Coastal vulnerability points (10033points) in Tanger.

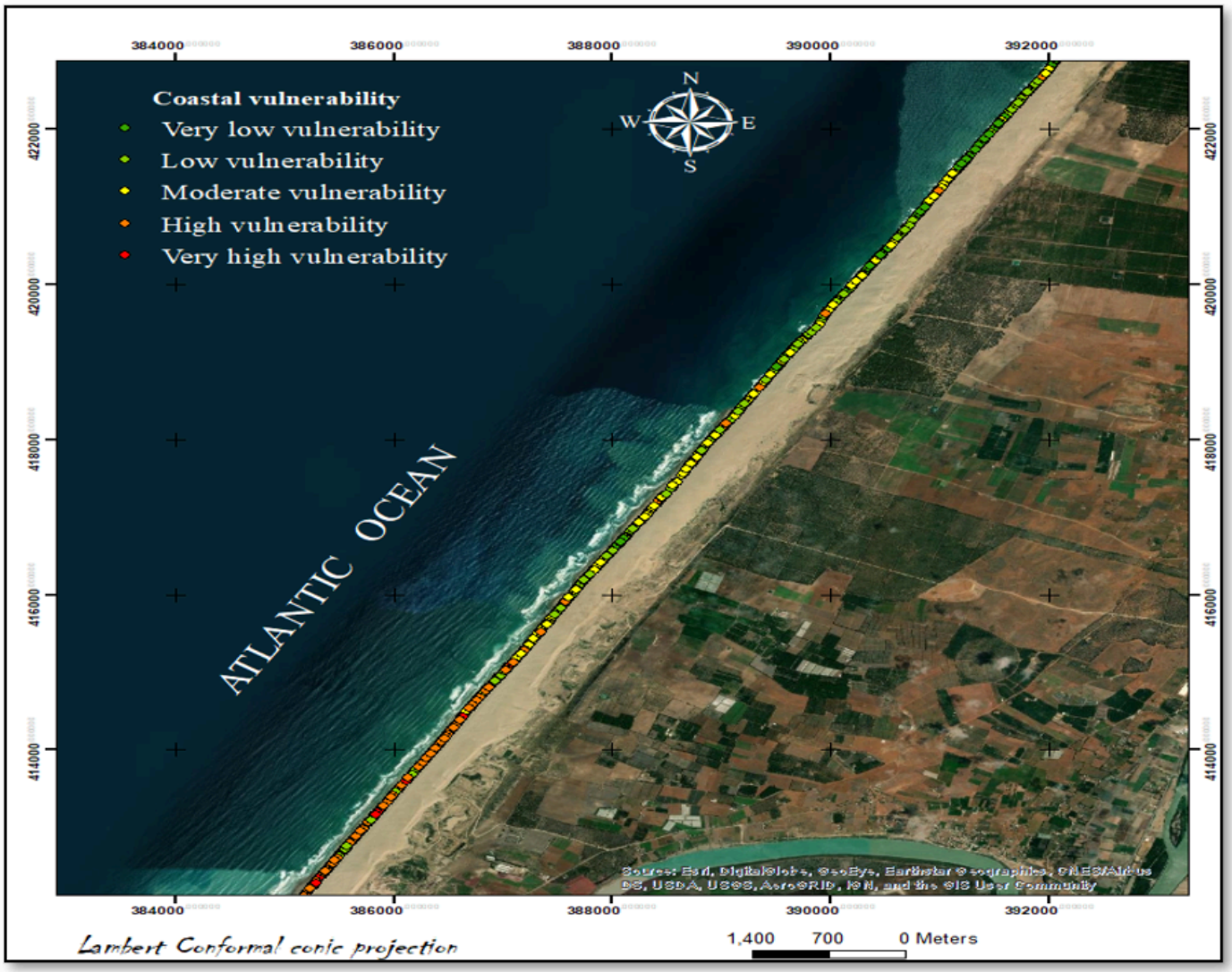


Figure 7

Fig. 5: Coastal vulnerability points by CVI including (4013points) in kenitra.

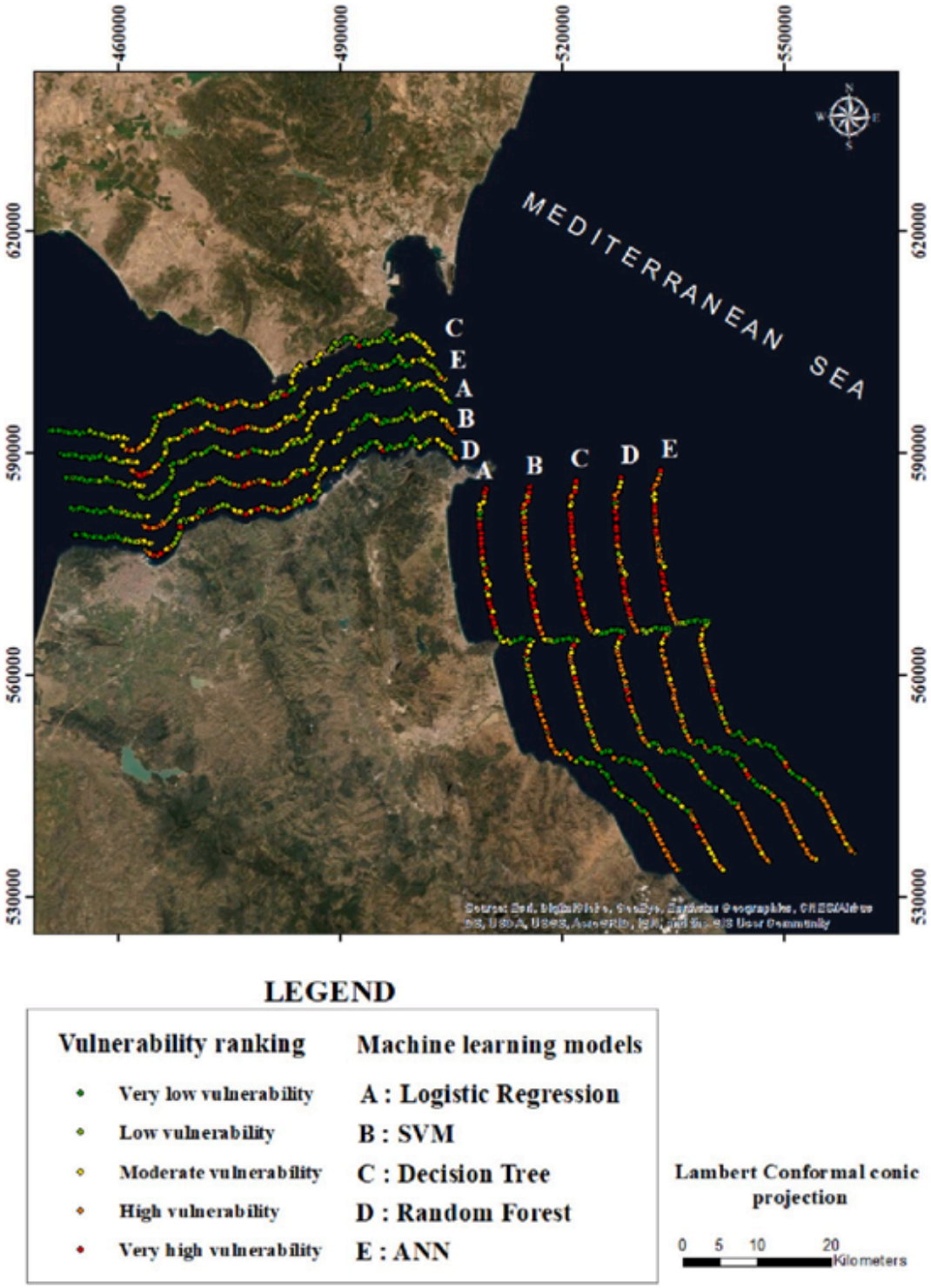


Figure 8

Fig. 6. Map of Coastal vulnerability using SVM, DT, LR, ANN and RF models.

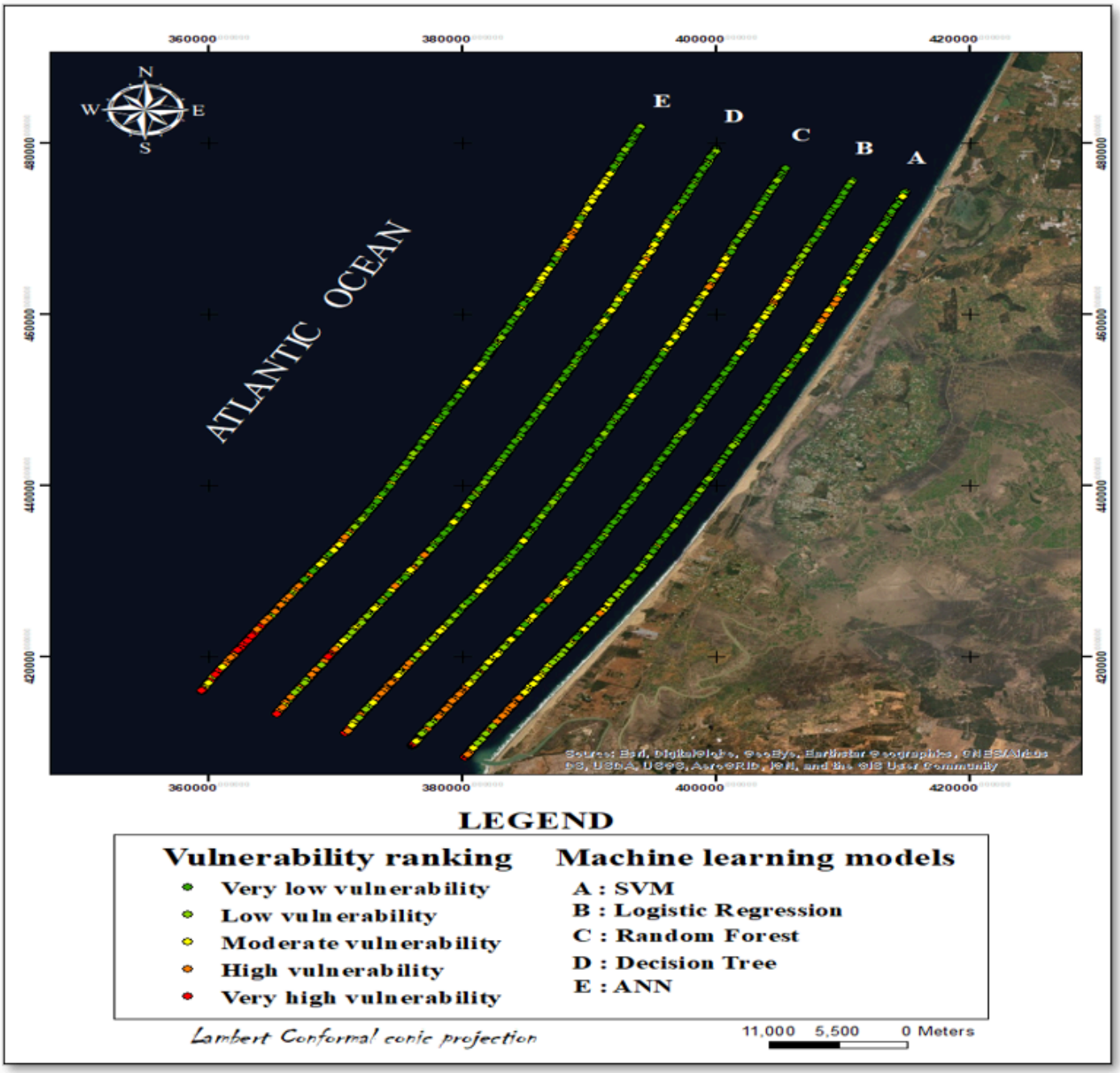
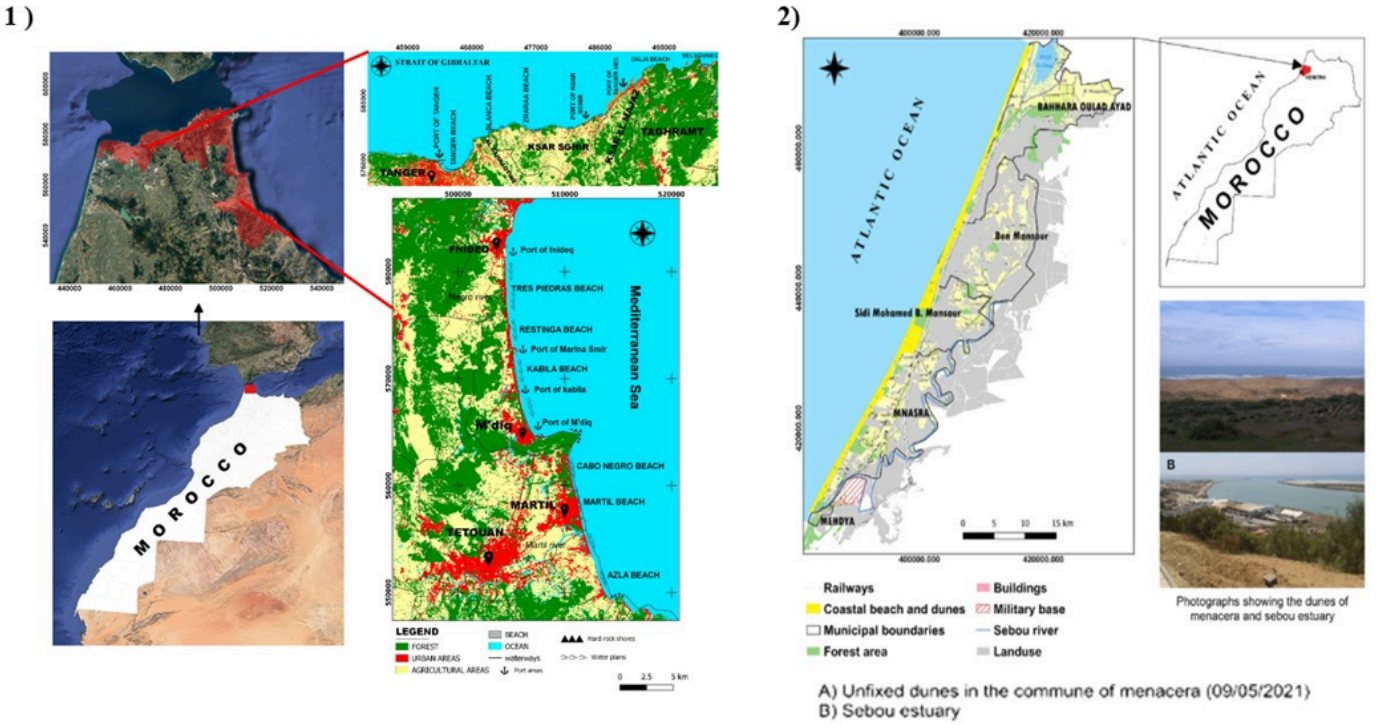


Figure 9

Fig. 7: Coastal vulnerability map using LR, SVM, RF, DT, and ANN.



1. Geographical location of the study area Tangier to Tetouan

2. Geographical location of the study area Kenitra

Figure 10

Unnumbered image in the Introduction section.