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Climate risk assessment of the Tangier-Tetouan-Al Hoceima coastal Region (Morocco)

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Coastal zones occupy a prominent position in the sustainable management perspective of Tangier-Tetouan-Al Hoceima (TTA) region because they accommodate a majority of the region's population and contribute to the economic wellbeing of local communities. High demographic and economic pressures associated to climatic and environmental factors increase and intensify the vulnerability of these coastal areas. The latter are severely affected by climate change implications in the course of time, which lead to damage and loss in coastal low-lying zones. In practice, the risks related to climate change, as coastal risks, are frequently addressed, and assessing coastal risk in the context of climate change is a research priority. The aim of this work is to evaluate the flooding risk of TTA coasts, taking into account the inundation level related to the conditions of extreme wave (return period of 100-year) and extreme sea level rise. We firstly defined the coastal hazard zone that corresponds to the maximum inundation level of 13 m for the whole area. We then applied a Coastal Risk Index application at the Local Scale (CRI-LS) methodology to calculate forcing, vulnerability, exposure and risk indices using nineteen physical, environmental and socioeconomical variables. Findings show that coastal hazard zone of Tangier-Tetouan-Al Hoceima region is extremely exposed to coastal forcing. More than 50% of the hazard zones indicates highly vulnerable zones and highest exposure is generally focused on the most populated urban zones. In the light of this, the coastal risk mapping shows hotspot zones in terms of climate change-related coastal risks located at Tangier Bay, south of Tangier city, Fnideq and Martil coasts, Tetouan city and north of Ksar El Kbir city. This paper corresponds to a useful support that can help policy-makers in decision-making to quietly follow coastal planning and management processes and participate in preserving coastal areas for future generations, which support the sustainable development goals of Agenda 2030 started by the United Nations with the goal of eradicating all kinds of poverty.

KEYWORDS

coastal risk index, northern Morocco, climate change, climate coastal hotspots, coastal adaptation policies

1 Introduction

The world is experiencing many climate, environmental and social change challenges, and coastal communities are engaged in an ongoing effort to tackle the impacts of this change. Particularly that is the case of the coastal areas that are severely affected by climate change that results in an increase in sea level rise, coastal storms, flooding, and erosion. (IPCC, 2022). The last report of the Intergovernmental Panel on Climate Change (IPCC) states that "climate change is widespread, rapid and intensifying" and that humankind's role in the climate crisis is unequivocal. The compound effects of extreme weather events are on the rise. The observed impacts from slow-onset processes of sea-level rise and regional decreases in precipitation are attributed to human-induced climate change with high confidence (IPCC, 2022). One of the mid to long-term projections (2041-2100) for coastal areas is that approximately one billion people will be at risk from coastal-related climate hazards under all IPCC scenarios. Scenarios exacerbated by population growth in low-lying coastal dwellings. The same report summarizes the concept of risk in the context of climate change as the one that derives from the interactions between climate-related hazards, and the exposure and vulnerability of human beings and ecological systems. The new aspect of the concept of risk is the risk that can be a consequence of human response to climate change (IPCC, 2022). However, understanding how natural and human-induced drivers will contribute to rising vulnerability and risks in coastal areas, requires a broader use of future projections capturing the spatiotemporal dynamics that drive changes in the different vulnerability dimensions, including the socio-demographic and economic spheres (Furlan et al., 2021).

The World Bank study (2011) on "*Climate Change Adaptation and Resilience to Natural Disasters in Coastal Cities of North Africa*," concluded that with a temperature of 4°C, 2.1 million people in Morocco will be affected by flooding. There is a high vulnerability to sea level rise in the coming decades that is related to the high concentration of populations and activities in coastal areas, and increased risks due to an increase in global sea levels, storms, and local coastal erosion. In this regard, the World Bank has ranked Morocco's coastal GDP in the Top 10 countries at risk with increasing storm surges (Dasgupta et al., 2009).

The climate-related risks for coastal communities are therefore worrying for Morocco. The country is quickly developing, and its coastal areas are facing rapid population growth and urban development, particularly the region of Tangier-Tetouan-Al Hoceima (Ivčević et al., 2020).

Like most of the Moroccan coastal areas, the coastline of the Tangier-Tetouan-Al Hoceima (TTA) region concentrates major societal and economic issues: population, industry and logistics, resort and tourism, fishing, agriculture, etc. (Haut-Commissariat au Plan, 2018). It is home to a large amount of biodiversity and provides many ecosystem services. However, the shift of populations and activities from the hinterland to the coast, since the beginning of the century, has contributed to a strong 'artificialization' of the coasts, making them more exposed to various meteorological and marine hazards, and consequently more vulnerable and less resilient to coastal risks (Snoussi et al., 2008; Snoussi et al., 2009; Khouakhi et al., 2013; Satta et al., 2016; Aitali et al., 2020). Many coastal areas have already experienced a real estate boom and increased pressure on coastal dunes that are retreating or disappearing, exposing more and more property and people to flooding and coastal erosion (El Mrini et al., 2012; Kasmi et al., 2020; Flayou et al., 2021).

In this context of increasing anthropogenic pressures, climate change is expected to amplify the stresses on coastal areas, creating more and more assets exposed to hazards and thus posing a challenge for coastal decision-makers who are faced with the increasingly complex task of balancing development and the management of coastal risks, in particular submersion and coastal erosion (Cramer et al., 2018; Mastrocicco et al., 2021). One of the open questions is whether policymakers are aware of the gravity of these imminent risks in the coastal areas. Different coastal societies might not necessarily have the same risk perception level nor similar policy answers. The importance of local knowledge for sustainable disaster risk reduction and management is largely recognized by international policy, such as the Sendai Framework for Disaster Risk Reduction (United Nations, 2015). However, the extent to which this scientific knowledge is translated into concrete and practical measures, as well as the importance of risk awareness sessions, is still open to debate (Bwambale et al., 2020; Ivčević et al., 2021). To this end, public authorities have a growing demand for decision-making tools, such as coastal risk assessment, to help them prioritize hot spot areas. Different tools are suggested to assess coastal vulnerability and risk to climate change at different spatial and temporal scales and for different decision-making purposes (Mclaughlin and Cooper, 2010; ETC-CCA, 2011; Ramieri et al., 2011; Torresan et al., 2012; Gallina et al., 2020). More recently, a literature review of climate-related coastal risks in the Mediterranean in terms of methods, techniques and data platforms (Sarkar et al., 2022), showed that among the various types of techniques available, coastal risk assessment, coastal vulnerability assessment, and model-based and index-based approaches are the most preferred ones. However, despite the development of these many methods and tools, most of them cannot be easily applied because they require a lot of data, specialized knowledge and skills in using complex programs (Hinkel & Klein, 2009). Satta (2014), after the analysis of 26 existing methods, proposed an integrated approach to provide Mediterranean coastal managers with a coastal risk assessment tool that is simple, flexible, applicable at the local scale, and with lower costs, and therefore easier to use by managers with limited resources and data. This is why we have chosen to apply the Coastal Risk Index at the Local Scale (CRI-LS) proposed by Satta (2014) in this study, but with some considerations and improvements:

(i) The TTA region, which is a territorial authority with legal status, and administrative and financial autonomy, is characterized by strong territorial, bio-physical and socio-economic disparities, and is therefore subject to different degrees of climate change-related risks, requiring a global vision, equitable risk management and a coherent governance at the regional scale, even if adaptation measures will be carried out at a more local scale. This is why the coast of the whole TTA region has been considered in this study

(ii) The study was conducted as part of the ongoing development of the TTA Region Coastal Plan, which involves all coastal stakeholders. We believe that since the project is still in the formulation phase of the coastal plan, our results will have a much better chance of being considered in the plan implementation phase, since they integrate the needs of the local communities. Indeed, the vulnerability and risk assessment studies should be driven by bottom-up processes in which local stakeholders are involved.

(iii) Compared to previous application of the local scale index, the number of variables of the risk components have been increased to better describe the local climate change impacts and the lack of capacity to cope and adapt of the study area. Finally, we used the CRI-LS methodology to produce coastal risk map, a visual tool that provide a quick screening of risk hotspots. And here, we also improved the spatial resolution from 300-m- to 20-m- pixel size.

The main objective of this research is therefore to contribute to the identification of coastal areas at high risk to the combined climate and non-climate forcing in the TTA Region, considering their physical and social vulnerability. The final aim of this research is to provide decision-makers and coastal managers with climate risk maps that can help them define a sound coastal planning incorporating coastal adaptation. Considering how Moroccan territory administration is concerned, the potential study area choice benefits policymakers in deciding where flooding protection is necessary first and foremost (hotspot zones).

2 Materials and methods

2.1 Study area

Located at the crossroads of two maritime areas, the Atlantic and the Mediterranean, in the far northwest of Morocco, the region of Tangier-Tetouan-Al Hoceima (TTA) is the only one among the 12 administrative divisions of Morocco, which have two maritime facades. The coastline includes 51 municipalities, 34 of which have a maritime façade and 17 adjacent municipalities constitute the area of potential influence (Figure 1).

2.1.1 Physical setting

With approximately 447 km of coastline along the Atlantic Ocean, the Strait of Gibraltar, and the Mediterranean Sea, the coast of the TTA region has a specific geographical position and a geomorphological structure which make its landscape very rich and diverse, offering sites of great ecological value such as very steep coastal cliffs, creeks, coastal islets, bays, sandy beaches, coastal marshes, lagoons, etc.

Along the Mediterranean stretch, the region has a rugged coast with a succession of bays and capes. The shore is dominated by steep hills and cliffs (80%) isolating only beach pockets generally corresponding to the mouth of the rivers. This coastline is crossed by many rivers, the main ones being: Ghiss, Nekkor, Smir, Martil, Laou, and Amsa.

On the Atlantic side, the morphology is varied, ranging from low alluvial plains to beaches with or without dunes, sometimes preceding coastal marshes (Larache marsh, Tahaddart estuary

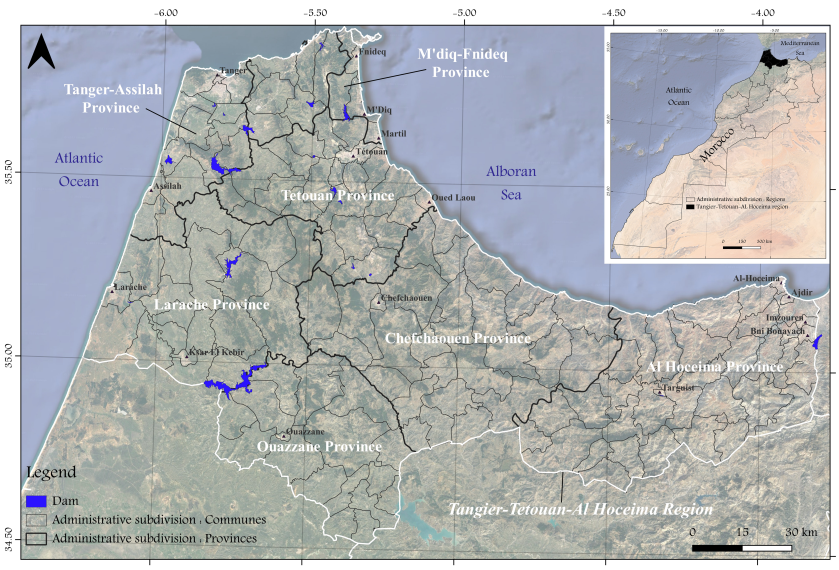

FIGURE 1
Geographical location of the TTA region and its administrative subdivisions. Background satellite imagery corresponds to google satellite of 2023, available as Basemap in QGIS v3.22.11 software.

complex), or rocky coasts or cliffs. This coastline is dominated by consolidated dunes forming alignments in the same direction as the coast itself. It is crossed by rivers, the main one being Oued Loukkos.

The coastline of the Strait of Gibraltar is rugged and dotted with rocks and beaches at the mouth of the wadis.

2.1.2 Climate

Overall, the region benefits from a Mediterranean-type climate with hot, dry summers and mild, wet winters. However, due to its geomorphological configuration, combining high Rif mountains and coastal plains, the TTA region is subject to very diverse climatic conditions. Indeed, the oceanic influence which characterizes the western basins of Loukkos and Tangier is gradually attenuated in the Mediterranean coastal basins, with an increasingly pronounced aridity from West to East. Between Larache and Oued Laou, rainfall can exceed 700 mm/year. While the eastern part of the region (particularly for the lower basins located between Jebha and Al Hoceima) receives barely 400 mm/year (CHIRPS data, https://www.chc.ucsb.edu/data/chirps).

Temperatures are generally mild, with an annual average of 17° C, but can vary from 0° C to 37° C depending on the season. However, it should be noted that in recent years, the region is subject to a higher occurrence of heat waves which further accentuates the negative impacts on people and natural resources (IPCC, 2022).

In terms of a marine climate, on the Mediterranean coast, the tides are microtidal, with a range that varies from 80-100 cm in spring to a few centimeters in neap tides (L.P.E.E, 1991). The intensity of tidal propagation, which comes from the Atlantic, gradually decreases to the east. The hydrodynamic conditions are characterized by dominant waves from the E to ENE, and a main longshore drift northward (El Mrini et al., 2012). The coastal area is very little fed with fluvial inputs, due to damming of the main watercourses, whose hydrological regime is typically Mediterranean with flash floods during the short-time high waters and an almost drying off in low waters (El Moutchou, 1995; Nachite et al., 2004; Anfuso et al., 2007; Niazi, 2007; El Mrini et al., 2012).

On the Atlantic side of the study area, the tides are classified as mesotidal with a maximum tidal range of about 3 m. Meteorological conditions generate W to NW swells. The strongest swells, of decadal frequency, can reach 7 to 9 m in amplitude during severe storms and are likely to mobilize sediments up to 100 m deep (Jaaidi and Cirac, 1987). The littoral drift is towards the south to SW (Taouati et al., 2011).

2.1.3 Hydrographic resources

The TTA region spans two hydrological domains: the Sebou basin and the Loukkos basin with an important hydrographic network. The renewable water potential is estimated at about 4 billion m^3/year as an average interannual supply, of which: 3,600 Mm^3/year of surface water and 460 Mm^3/year of groundwater (Agence du Bassin Hydraulique du Loukkos, 2018). Groundwater reserves remain quite modest given the dominance of impermeable geological formations in the region. The high intensity of rainfall during short periods, the predominance of clayey facies and the rugged relief, promote runoff and limit the importance of groundwater resources. During major storms, rivers experience sudden and violent floods, causing heavy damages, especially in highly urbanized areas. The city of Tetouan, for example, has experienced catastrophic flooding over the past 15 years. Only the limestone mountains, the plains, the alluvial valleys and a few small isolated basins benefit from the infiltration of rainwater, which forms modest underground reservoirs whose importance varies from one unit to another. Seventeen dams, two of which are currently under construction, are used to regulate rivers and reduce the risk of flooding, as well as to satisfy the needs for irrigation, drinking and industrial water and to face the negative effects of droughts.

2.1.4 Socio-economic background

The coastline of the TTA Region is home to 2,479,578 inhabitants in 2020, 75% of whom live in urban areas. The average annual growth rate of the region increased at a rate of 1.47% between 2004 and 2014. The prefectures of M'diq-Fnideq and Tangier-Assilah recorded the highest growth rates, while the province of Al Hoceima recorded the lowest rate. The population density is on average 600 inhabitants per km^2 (three times the regional density) but can exceed 7000 inhabitants per km^2 in coastal cities such as Tangier and Tetouan (Haut-Commissariat au Plan, 2018).

The main contributors to the economy of the coastal area are port activities, trade, and services, fishing, tourism, and agriculture. The economies of Tetouan and M'diq-Fnideq are heavily dependent on trade and services, while the economy of Chefchaouen is more dependent on agriculture and fishing. In Tangier-Assilah, in addition to trade and services, the industry is an important component of the economy. 80% of the permanent industrial workforce and 92% of foreign trade is located in the major cities of the Tangier-Tetouan region along the coast (Haut-Commissariat au Plan, 2018).

Over the past two decades, the region's population has continually migrated to the coastal plains because of the natural, economic, and logistical resource potential they offer. The high demand for space and resources has resulted in extensive urban encroachment on natural and agricultural lands to meet all these needs. For example, a diachronic analysis of the Tangier coastline between 1995 and 2018 (Wahbi et al., 2019), showed that over the 23 years covered by the study, the built-up area has tripled in the coastal strip of 10 km from the shoreline. In the prefecture of Mdiq-Fnideq, the orographic constraint imposed a first extension on low-lying areas, which then continues on the hills around the two towns. Urbanization often encroaches on soils of great ecological value, such as wetlands, dunes, forests…, but also by occupying areas prone to flooding or landslides. On the Atlantic coast of the TTA region, the analysis of LULC changes in Tahaddart coast (Aitali et al., 2020) showed a decrease in almost all the land use units between 1999 and 2019 except the built-up area, which shows a sharp increase. These changes are linked to the fact that the Tangier-Asilah prefecture, has experienced significant development in the last decade (Chattou, 2011), explaining the increase in the built-up area, to the detriment of the cultivated lands and the natural habitats (Rifai et al., 2018).

2.1.5 Environmental issues

Among the many pressures on the TTA coast, it seems that it is land pressure that dominates all along the coast, especially on the seafront, where linear urbanization is often carried out to the detriment of the coastal dunes, real beach regeneration reservoirs, the disappearance of which directly exposes the infrastructure to storm surges and other climate hazards.

In the bay of Tangier, while the extension of the port has boosted trade and economy in the region, it has also led to a significant erosion of the eastern beaches of the Bay of Tangier. According to numerous authors (El Arrim, 2001; Snoussi & Long, 2002; Bouzidi et al., 2004; Sedrati and Anthony, 2009), coastline retreat is estimated between 2 and 3 m per year in the eastern part of the bay.

Tetouan coast, which relies heavily on tourism, is also experiencing a strong retreat. Indeed, more than 95% of the dunes have been destroyed by residential and hotel infrastructure (Bello et al., 2006). In addition to coastal developments, the construction of dams on Smir and Martil, and of marinas (M'diq, Smir Marina and Kabila) have completely disrupted the coastal sedimentary budget, leading to severe coastal erosion. The historical shoreline changes, between 1958 and 2011 (Niazi, 2007; Snoussi et al., 2008; El Mrini, 2011; El Mrini et al., 2012) showed an overall erosive trend of the shoreline. Eroded beaches represent 70 to 86% of the coastline. Flayou et al. (2021) estimated the beach retreat to be between 20 and 24 m between 2004 and 2016, *i.e.*, an average annual rate of 1.83 m/year. In the eastern part of the study area, Khouakhi et al. (2013) estimated that about 60% of the Al Hoceima bay coastline showed an erosive trend between 1958 and 2013.

On the Atlantic coast of the TTA Region, the high wave energy beaches also show an erosive trend. For example, Charf el Akab beach retreated by approximately 70 m between 1985 and 1992 (in Taouati et al., 2011). Amharak (2006) estimated the rate of erosion north of the Tahaddart estuary at 1.94 m/year, presumably due in part to sand mining and dam construction.

2.2 Methodology

The analysis performed in this research consists on the application of a multi-scale coastal risk index (MS-CRI) to the TTA region (Figure 2), based on the index-based approach developed by Satta (2014). This approach, as proposed by other indices in the scientific literature (Davidson and Lambert, 2001; Peduzzi et al., 2009), considers Risk (R) as a function of three factors: hazards, vulnerability and exposure as described in the simplified equation (1):

$$R = F{*}V{*}E \tag{1}$$

In fact, the MS-CRI combines information on the potential effect of climate change on coastal hazards with physical, environmental, and socio-economic features (Greco and Martino, 2016; Satta et al., 2016; Satta et al., 2017; Torresan et al., 2020; Furlan et al., 2021), provides a simple numerical basis to identify the coastal areas where risks may be relatively high and displays these hotspots on geographic maps. This tool can easily be integrated into overall coastal management and adaptation strategies to support the implementation of the ICZM Protocol (Satta et al., 2016), and contribute both to coastal communities' protection and biodiversity conservation.

2.2.1 Multi-scale coastal risk index application at the local scale

This research proposes the application of the MS-CRI at the local scale of TTA region (CRI-LS) to define the coastal hazard zone and provide a wider spatial perspective of risk and vulnerability in 2100 at the local scale. The "hotspots", as well as the areas of relatively lower risk, emerge from the product of the different

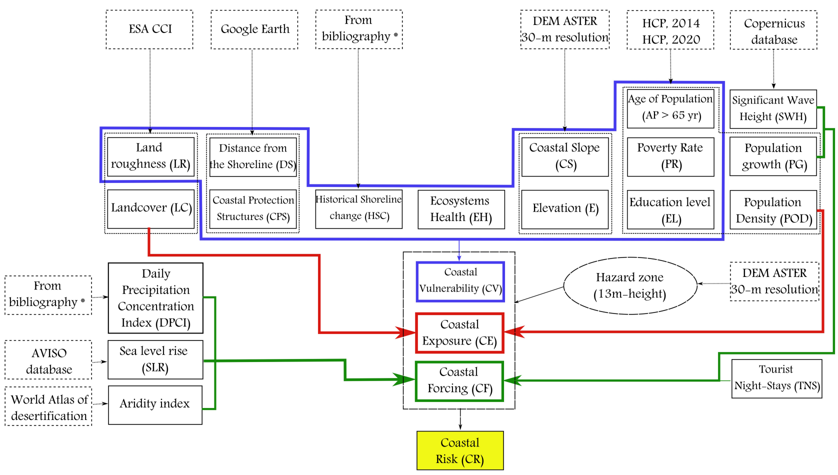

FIGURE 2
Flowchart illustrating the materials and method used to calculate the coastal risk index. *Bibliography used to produce both HSC and DPCI is mentioned in (Table 2).

10.3389/fmars.2023.1176350

coastal risks components factors aggregated into the three sub-indices: the forcing index, dealing with climate and not climate drivers, the vulnerability index, dealing with the susceptibility and resilience of the coastal areas and local communities, and the exposure index, dealing with the human and environmental assets that could be adversely affected.

The process for implementing the CRI-LS methodology, is articulated around the following 5 steps: delineation of the coastal hazard zones; data collection and variables choice; assignation of scores and weights to risk variables; creation of raster spatial data; calculation of the sub-indexes and the final index.

2.2.2 Delineation of the coastal hazard zone

Identifying the coastal hazard zone is essential for efficient long-term coastal management, including the protection of both local populations and infrastructures (Satta, 2014). To do so, the estimation of the coastal hazard zone is based on an empirical approach of Hoozemans et al. (1993), taking into account the fact sea level rise 1.5 m in 2100. The later scenario was adopted as the upper limit for 2100 based on the precautionary principle. This claim is supported by the fact that sea levels can rise several tenths of a meter, during the 21st century, as sectors of Antarctica's marine-based ice sheets collapse (Satta et al., 2016 and reference therein). The value of 1.5 m was integrated in the Hoozemans equation and the results obtained for the study area are shown in Table 1. The Hoozemans equation also includes maximum flood level and storm surges with a 100-year return period (Table 1).

$$Dft = MHW + St + Wf + Pf \quad (2)$$

where:

Dft: inundation level; *MHW*: mean high-water level; *St:* relative sea level rise; *Wf*: height of storm waves; *Pf*: sea level rise resulting from a decrease in atmospheric pressure (negligeable in TTA region).

In fact, the inundation level is higher in the Atlantic and relatively lower in the Mediterranean because of the higher value of MHW (higher tidal range) (Table 1). Based on these calculations, the extent of the coastal hazard zone is the maximum inundation level of 13 m, owing to the large study area (Figure 3). Thus, the coastal hazard zone was defined using a digital elevation model with a spatial resolution of 30-m (NASA/METI/AIST/Japan Space Systems, and U.S./Japan ASTER Science Team). From a technical viewpoint, all pixels corresponding to an altitude of between 0 and 13m were extracted. We obtained a coastal hazard zone that covers an area of 520 km^2 (Figure 3).

2.2.3 Variables selection and ranking

In order to construct the coastal risk index map, a series of variables (Table 1) associated with a coastal spatial unit was used, based on the equation of risk that integrates coastal forcing, coastal vulnerability, and coastal exposure indexes. Each component of the risk equation, including the final outcome, was produced with a concept of multi-criteria decision-making (MCDM) theory following the approach described in section 2.2.1. using the geographic information systems (GIS) platform. The method is widely employed in research studies for regions with similar characteristics (e.g., Bagdanavičiute et al., 2015; Satta et al., 2016; Satta et al., 2017; Aitali et al., 2020).

The selection of relevant variables was conducted in order to further describe forcing, vulnerability, and exposure indices (Table 2), and according to data availability referring to the TTA coastal zones.

Once the variables were selected, a ranking score was defined for each variable class according to its relative importance (Table 3) and based on literature review. A scale ranging from 1 to 5 was applied, with 1 being the lowest importance and 5 being the highest. Secondly, the weighting of each variable based on expert opinions as well as on stakeholder consultation during regional workshops, was carried out. In fact, variables deemed to have a higher impact on the final risk were given a weight close to 100%, while variables deemed to have a lower impact were given a weight close to 0% (Torresan et al., 2012). This way of weighting was widely adopted to assess coastal risks associated with climate change at the regional (Torresan et al., 2012; Zhou et al., 2015; Satta et al., 2017) and local scales (Satta et al., 2016; Aitali et al., 2020), and as a metric for ranking risk mitigation strategies (Zhou et al., 2015).

The coastal sub-indices are calculated according to the equation:

$$CSI = \frac{\left(\sum_{i=1}^{n} x_i W_i\right)}{\left(\sum_{i=1}^{n} W_i\right)} \quad (3)$$

where:

CI = Coastal Sub-Index; n = number of variables; xi = scores related to variable i; Wi = weight related to variable i;

In order to convert the coastal sub-indices into the same standard scale ranging from 0 to 1, and facilitate the analysis of the values, a normalization procedure was applied to the variable xi as follows:

$$CSI' = \frac{\left(\sum_{i=1}^{n} x'_i W_i\right)}{\left(\sum_{i=1}^{n} W_i\right)} \qquad and\ x' = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (4)$$

where CSI'= normalized Coastal Sub-Index ranging from 0 to 1;

TABLE 1 Description of parameters used in Hoozemans equation to calculate maximum inundation levels for the main facades of the TTA region (Laboratoire Central d'Hydraulique de France (1974); Snoussi et al., 2008; El Mrini, 2011; Taouati et al., 2011; Khouakhi et al., 2013).

Location	MHW	Storm waves (return period)	Inundation levels (Dft)
Mediterranean (Tetouan):	0.96	6.20 (1/100yr)	8 m
Strait of Gibraltar (Tangier)	2.60	8.5 (1/100yr)	12.6 m
Atlantic (Larache)	3.70	7.8 (1/100yr)	13 m

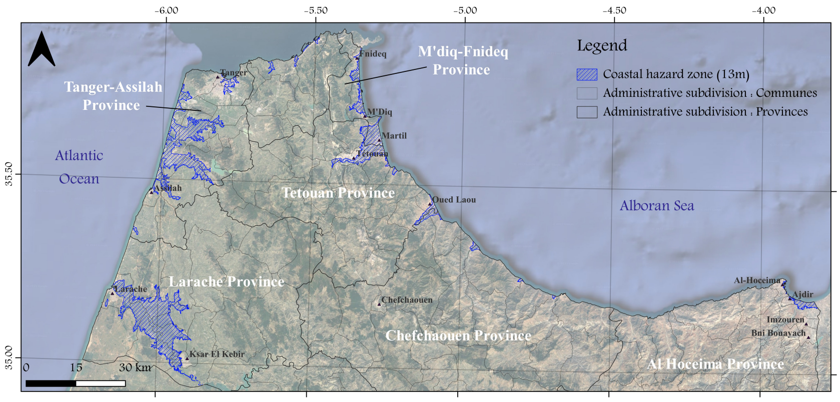

FIGURE 3
Coastal hazard zone (13m asl) for the TTA region. Background satellite imagery corresponds to google satellite of 2023, available as Basemap in QGIS v3.22.11 software.

TABLE 2 Description of variables used to create the coastal risk map and their sources.

Coastal risk components	Variables	Descriptions	Unit	Original Format of the dataset	Sources
Forcing	Aridity index (Ai)	Aridity is a measure of the "drought" of the climate expressed as the ratio of precipitation to evapotranspiration; the lower the ratio, the drier the climate. Ai less than 0.65 corresponds to an arid zone.	Mm	Raster	World Atlas of Desertification (EU Commission) https://wad.jrc.ec.europa.eu/geoportal
	Daily beach attendance	Number of people visiting and using the beach	x 10^3 Pers.	Shapefile (by province)	Ministère de la Transition énergétique et du Développement Durable (2022)
	Daily precipitation concentration index (DPCI)	Index used as a measure of concentration. A high DPCI value of precipitation indicates that precipitation is more concentrated on a few rainy days during the year. DPCI could also be used to estimate precipitation erosivity and aggressiveness (REF).	mm/day	Shapefile	Salhi et al. (2019)
	Population Growth (PG)	Annual population growth rate of communes crossed hazardous zone.	%	Shapefile (by commune)	Haut-Commissariat au Plan, (2020), https://www.hcp.ma/
	Sea level rise (SLR)	Measures the annual trend of sea level rise between 1993 and 2021. Accurate measurements for a limited period are available through satellite altimetry data.	mm/yr	Shapefile	https://www.aviso.altimetry.fr/?id=1599
	Significant Wave Height (SWH)	Represents the number of detected waves exceeding the 95 percentile of daily wave heights on average per year (MSHx95p), over a long-term period (e.g., 100 years)	Cm	Shapefile	https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-ocean-wave-indicators?tab=overview
	Tourist night-stays (TNS)	Rate of tourist arrivals to the study site	x 103 Pers.	Shapefile (by province)	TTA Region Statistical Yearbook (2018)
Vulnerability	Land roughness (LR)	Using Manning coefficients, it represents the resistance of the terrestrial surface to surface erosion	–	Raster	https://2016africalandcover20m.esrin.esa.int/
	Distance from the shoreline (DS)	Related to the progression of the risk according to the inland penetration	M	Shapefile (coastline)	Calculated using the GIS platform
	Coastal protection structures (CPS)	Percent of coastline with protective structures (Groin, breakwaters, seawall…)		Shapefile	Google Earthimagery

(Continued)

TABLE 2 Continued

Coastal risk components	Variables	Descriptions	Unit	Original Format of the dataset	Sources
	Historical shoreline changes (HSC)	Evolution of shoreline change that locates eroded coast/Sediment budget	M	Shapefile (by location)	El Mrini (2011); Niazi (2007); Taouati et al. (2011); Khouakhi et al. (2013)
	Ecosystem health (EH)	Expresses the contribution of the ecosystem as protection against storm surges, flooding, and other coastal hazards.	–	Shapefile	Agence Nationale des Eaux et Forêts, Google earth imagery
	Elevation (E)	Coastal unit surface (pixel) within a specific elevation class Xi	M	Raster	ASTER DEM, NASA/METI/AIST/ Japan Space Systems, and U.S./Japan ASTER Science Team.
	Coastal slope (CS)	In relation to the relative risk of shoreline retreat.	%	Raster	ASTER DEM, NASA/METI/AIST/ Japan Space Systems, and U.S./Japan ASTER Science Team.
	Education level (EL)	Persons with a level at least equal to level 3 of the international standard	%	Shapefile (by commune)	Haut-Commissariat au Plan (2014), https://www.hcp.ma/
	Poverty rate (PR)	Persons with a low quality of life (poor people)	%	Shapefile (by commune)	Haut-Commissariat au Plan (2014), https://www.hcp.ma/
	Age of population (AP)	Number of people over 65	%	Shapefile (by commune)	Haut-Commissariat au Plan (2014), https://www.hcp.ma/
Exposition	LandCover (LC)	Land surface covered by different types of physical coverage (classes) in various places	–	Raster	https://2016africalandcover20m.esrin.esa.int/
	Population density (PoD)	Number of inhabitants per km2 in each commune crossed the study area	Inhab./ km2	Shapefile (by commune)	Haut-Commissariat au Plan (2020), https://www.hcp.ma/

TABLE 3 Variable selection and ranking for the CRI-LS index.

Coastal risk components	Variables	Unit	Score					Weight (%)
			1	2	3	4	5	
Forcing	Aridity index (AI)	–	No	–	–	–	Yes	15
	Daily Beach Attendance (DBA)	x 10^3 pers.	< 1	1 – 5	5 – 10	10 – 20	> 20	10
	Daily precipitation concentration index (DPCI)	mm/yr	< 0.64	0.64 – 0.66	0.66 – 0.68	0.68 – 0.70	> 0.70	20
	Population Growth (PG)	%	≤ 0.1	0.1 – 0.5	0.5 – 1	1 – 2	> 2	10
	Sea level rise (SLR)	mm/y	< 1	1 – 1.6	1.7 – 2.4	2.5 – 3.2	> 3.2	10
	Significant Wave Height (SWH)	m	< 4.7	4.71 – 6.65	6.66 – 8.13	8.13 – 9.57	> 9.57	25
	Tourist Night-Stays (TNS)	x 10^3 pers.	< 50	50 – 100	100 – 500	500 – 1000	> 1000	10
Vulnerability	Land Roughness (LR)	Manning coefficient	> 0.06	0.06 – 0.04	0.04 – 0.03	0.03 – 0.02	< 0.02	10
		m	< 300	300 – 900	900 – 2100	2100 – 4500	> 4500	12

(Continued)

TABLE 3 Continued

Coastal risk components	Variables	Unit	Score					Weight (%)
			1	2	3	4	5	
	Distance from the shoreline (DS)							
	Coastal Protection Structures (CPS)	%	> 50	50 – 30	30 – 20	20 – 5	< 5	7
	Historical Shoreline Changes (HSC)	m/yr	> +2	+1 to +2	+1 to -1	-1 to -2	> -2	10
	Ecosystem Health (EH)	–	No detectable change	Slight signs of disturbance	moderate disturbance with a 50% loss of species	major disturbances	severe disturbance with loss of most species	13
	Elevation (E)	m	6 – 4.8	4.8 – 3.6	3.6 – 2.4	2.4 – 1.2	< 1.2	13
	Coastal Slope (CS)	%	< 1	1 – 2	2 – 3	3 – 4	> 4	9
	Education Level (EL)	%	> 25	25 – 15	15 – 5	5 – 0.5	< 0.5	10
	Poverty Rate (PR)	%	< 5	5 – 10	10 – 20	20 – 30	> 30	9
	Age of Population (AP)	Pers.	< 3	3 – 7	8 – 13	14 – 20	> 20	7
Exposition	LandCover (LC)	–	Barelands	Shrubland, grasslands, sparse vegetation	Forest and Water bodies	Cultivated areas	Urban areas	52
	Population Density (PoD)	hab/km^2	< 50	50 – 1000	1000 – 2000	2000 – 3000	> 3000	48

Considering that $x_{min} = 1$; $x_{max} = 5$ $and \sum_{i=1}^{n} W_i = 1$ the equation becomes:

$$CSI' = \frac{\left(\sum_{i=1}^{n} x_i W_i\right) - 1}{4} \quad (5)$$

The equations to be applied to the three groups of raster images describing the various components of the sub-indices are:

$$CF' = \frac{\left(\sum_{a=1}^{n_{CF}} x_a W_a\right) - 1}{4} \quad (6)$$

$$CV' = \frac{\left(\sum_{b=1}^{n_{CV}} x_b W_b\right) - 1}{4} \quad (7)$$

$$CE' = \frac{\left(\sum_{b=1}^{n_{CE}} x_c W_c\right) - 1}{4} \quad (8)$$

Where: CH', CV' and CE' are the normalized weighted coastal sub-indices; nCF = number of CF variables; nCV = number of CV variables; nCE = number of CE variables; Wa = weight associated with the CF variables; Wb = weight associated with the CV variables; Wc = weight associated with the CE variables.

As the three sub-indices were normalized it is feasible to combine them into an overall index, which is calculated from the multiplication of the values obtained for each sub-index, as follows (Satta et al., 2016):

$$CRI - LS = CF' * CV' * CE' \quad (8)$$

2.2.4 Construction of the coastal risk map

The next operational steps require the application of GIS tools to process the data and to move from the numerical to the spatial dimension. To do so, variables were converted to a raster format assigning the scores defined in Table 2 to the pixels. The raster pixels were resampled to a similar spatial resolution of 20 m in order to minimize errors caused by different image resolutions. The resolution value was chosen because it is the most accurate data resolution available in available datasets (Landcover). The Eq. (6), (7) and (8) were used to produce the maps of forcing, vulnerability, and exposure indices, and then the Eq. (8) to calculate the CRI-LS in the GIS platform. In the end, the resulting values of each index were classified into five qualitative classes from "very low" to "very high".

3 Results & interpretations

The coastal risk assessment led to highlight the levels of risk that may affect the coastline of TTA and hinterland areas. The assessment is based on factors that reflect the implication of climate change through the climatic and non-climatic forcing, environmental and socioeconomic issues. Using the CRI-LS method, the coastal risk, forcing, vulnerability, and exposure levels for each cell along the hazard zone are visualized in Figure 4.

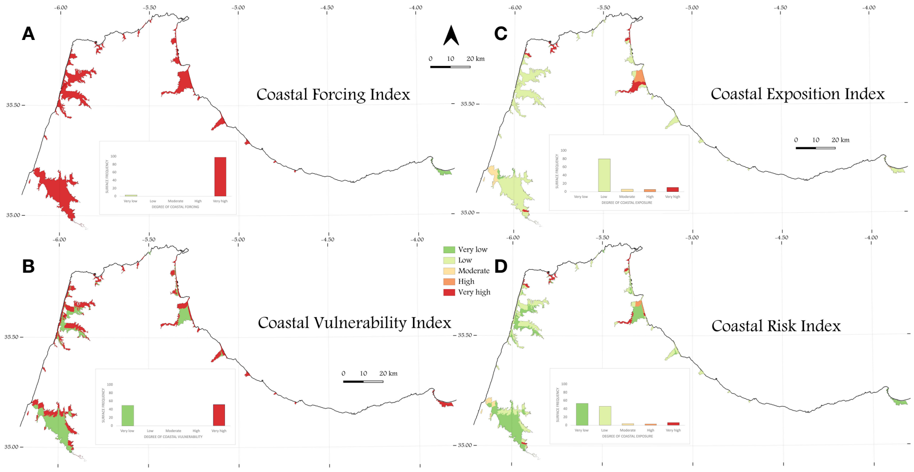

FIGURE 4
Result maps for coastal risk assessment of some selected coasts of the TTA region. **(A)** Coastal Forcing Index, **(B)** Coastal Vulnerability Index, **(C)** Coastal Exposure Index and **(D)** Coastal Risk Index.

3.1 Coastal forcing index

Seven climatic (Aridity index Ai, Daily precipitation concentration index DCPI, Sea Level Rise, Significant Wave Height SWH) and non-climatic (Daily Beach Attendence DBA, Population Growth, and Tourist night-stays TNS) variables were used to produce the coastal forcing index. Results indicate that, with the exception of the Al Hoceima site, which has a low coastal forcing, 97% of the study area is highly exposed to coastal forcing (Figure 4A). Due to long-term relative sea level changes brought on by sea level rise, coastal forcing is significant for most of the study area. In fact, the annual trend of the latter is greater than 2.9 mm/yr on the Atlantic coast, and increases to 3.3 mm/yr on the Mediterranean coast. A considerable amount of SHW is also linked to the sea level rise LR; along the Atlantic coast, it may reach 9.5 meters, whereas, along the Mediterranean coast, it may only reach 8 meters. This may explain the poor coastal forcing at the Al-Hoceima zone, as the SHW has a substantial amount of weight in comparison to other variables.

In addition, the population growth, associated with high anthropogenic activities in the coastal hazard zone's bordering cities, such as Tangier, Tetouan, Larache, and Assilah, also results in an increase in coastal forcing.

3.2 Coastal vulnerability index

To calculate the coastal vulnerability index, ten variables were combined including physical (LR, DS, HSC, E, and CS), environmental (CPS, and EH), and social (EL, PR, and AP) elements. A coastal hazard zone represents either very low or very high levels of vulnerability (Figure 4B), covering 48% and 52% of the total area, respectively. The coastal vulnerability map reveals that 'very high' vulnerabilities tend to be more concentrated nearby the coast, while 'very low' vulnerabilities tend to be farther from the coast.

The rise in vulnerability is solely due to physical variables. This claim is supported by the fact that: (1) the topographically low locations are those that seem to be more vulnerable; (2) the vulnerability rather decreases as the distance from the coast increases; and (3) the LR variable is crucial in determining vulnerability, particularly with regard to the risk of coastal flooding, because it varies according to the types of land cover (Satta et al., 2016).

Social vulnerability is also made evident in that high vulnerability zones extend over the cities and towns, which are relatively high in AP, EL, and PR. In addition, the vulnerability index may rise since there are not enough coastal protection structures along the TTA coastlines.

3.3 Coastal exposure index

This index reflects the level of exposure of the different stakes and assets located in the coastal hazard zone. Results show that 14% of the whole area corresponds to the highest exposure class (Figure 4C). The high exposure values are focused on the urbanized areas, which are characterized by high population density, such as Tangier, Tetouan, and Ksar El Kebir; along the coast of Fnideq and Martil (Figure 4C). In fact, all urban infrastructures, including buildings; highways, ports, marinas, and beach resorts, are concentrated in these cities. With the high population density, the potential damage related to the coastal hazard might be devastating. The rest of the area, 80% of the total area, has low exposure levels, with the exception of a few cells (6%), which consist of uninhabited or low-density territory.

3.4 Coastal risk hotspots

The coastal risk index was calculated from the three risk components discussed above. According to the coastal risk mapping, the low coastal risk class dominates the study area with 89% of the total, 3% exhibit a moderate risk, and 8% is at high risk related to climate change (Figure 4D). It appears to be a cumulative effect of important exposure and vulnerability levels leading to high-risk levels. These areas, which correspond to the hotspot zones in terms of climate change-related coastal risks, are associated with the low-lying areas of the Bay of Tangier, Martil coast, Tetouan and Fnideq cities, and the Atlantic coastline of Tangier. Zooming in on the most economically and demographically important areas (Figure 3) better visualizes the areas at coastal risk.

(1) At Larache province, most of the hazard zone shows low to very low-risk levels (Figure 5A), despite the presence of the Loukkos estuarine valley. This is probably due to the low population rate of this area, devoted mainly to extensive agriculture. The moderate coastal risk concerns the north of the city of Larache, where human and port activities are concentrated. The very high coastal risk is identified to the west and northwest of Ksar El Kbir city, where the population density is high and socio-economic indicators are lower;

(2) From Assilah to the south of Tangier, the majority of the coastal hazard zone exhibit low to extremely low-risk classes (Figure 5B), probably due to the low density of the population and human activities. The only place where the coastal risk is very high relates to the free zone of Tangier where many industries are concentrated, and where the standard of living of rural populations is low;

(3) The Bay of Tangier is one of the most at-risk areas on the TTA coast. Figure 5C shows that the hazard zone with the high coastal risk extends particularly over the urbanized zones, including the port of Tanger city. This area consists of a big number of economic companies with large investments that employ thousands of people. Another hot spot of coastal risk is located in the industrial zone south of Tangier. This is an area, which already regularly experiences continental flooding due to its low elevation and the density of urbanization (Figure 5C);

(4) Tetouan city has an exceptionally high coastal risk towards the south of the city along the Martil river and in related hillslopes (Figure 5D). On the seafront, the level of coastal risk is generally high to very high, except for the steep

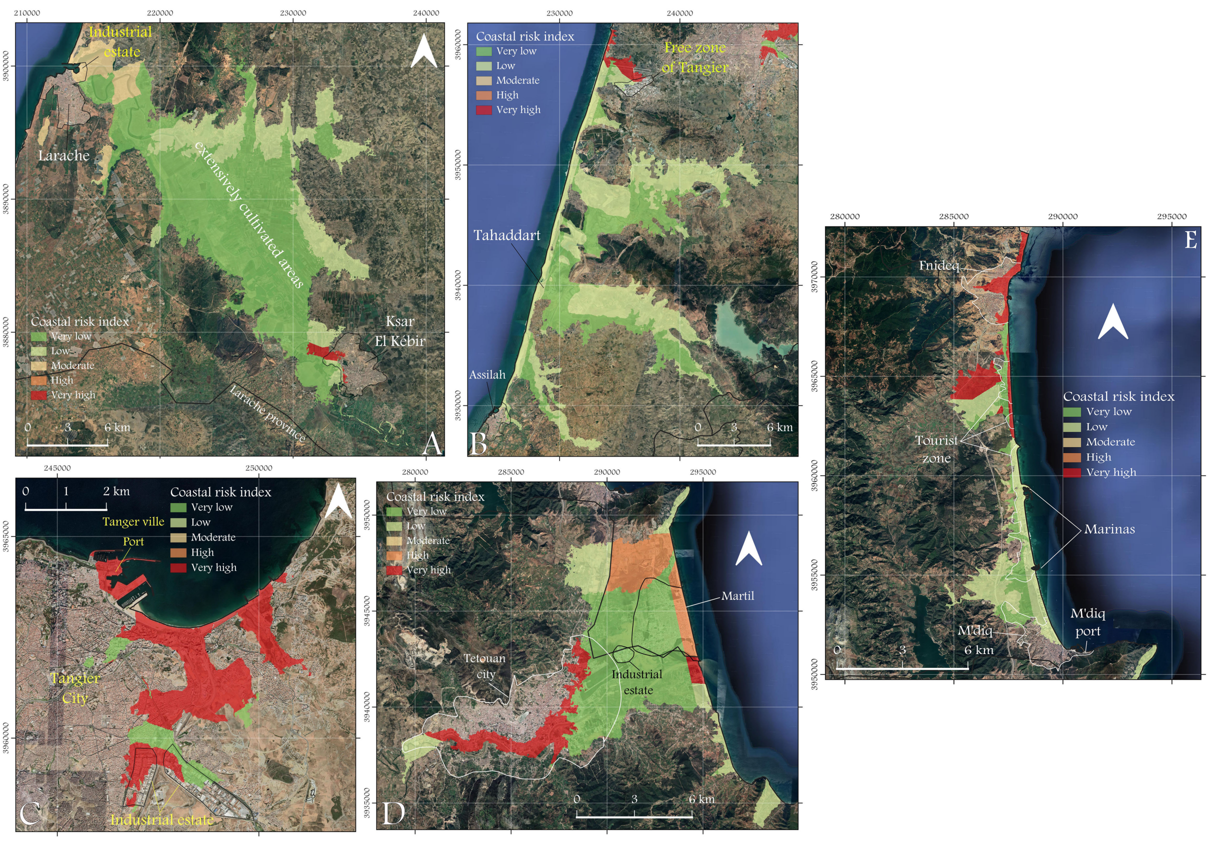

FIGURE 5
Maps focused on the most economically and demographically significant zones to define the hotspot locations in terms of coastal risk. **(A)** Larache, **(B)** Assilah-South of Tangier sector, **(C)** Bay of Tangier, **(D)** Tetouan, **(E)** Fnideq-M'diq.

coastline to the south. This coast is densely populated and highly urbanized, and has experienced a continuous retreat of the shoreline in recent years.;

(5) In Mdiq-Fnideq province, areas with very high coastal risk are concentrated in the urban area of Fnideq, including the port, and along the seafront, where several tourist resorts and infrastructure are located (Figure 3E). In some areas of the hinterland, coastal risk is also very high, due in part to the poverty and vulnerability of rural populations. M'diq is also known for its beach tourism. Yet, the coastal risk is low to moderate (Figure 5E), probably due to the higher standard of living of secondary residences here.

4 Discussion

The results of the coastal risk assessment in the TTA Region, performed using an index-based analysis, and visualized on risk maps, identified hot spot areas that require special attention in the development of the TTA Region's coastal plan.

For similar hazard conditions, a hot spot generally results from the combination or cumulative effect of high vulnerability and high exposure. These conditions are found in the Bay of Tangier and in the provinces of Tetouan and Mdiq-Fnideq. The factors that weighed most heavily in the assessment of risk in these hot spots are related to topography, population density and urbanization, and socio-economic indicators that reflect the resilience of the populations. The overall findings fully correspond to the existing literature in the region, as developed below.

In the Bay of Tangier, especially in its central part, the elevation is low, and the coastline is heavily urbanized with the largest agglomeration in the region, and one of the largest ports in Morocco. These assets of high economic value express the high exposure to coastal risks. In addition, the drastic reduction of sediment inputs by the few rivers flowing into the bay, the degradation of the lake's wetland (Snoussi et al., 2009), and the ineffectiveness of coastal erosion control structures (Sedrati and Anthony, 2009), make the area highly vulnerable to coastal hazards. According to Snoussi et al. (2009), 24% of the bay would be at risk of flooding with 11m inundation level scenario. The most exposed sectors are the urban area including the port, the coastal defenses, the tourist coastal infrastructures, and the industrial area. In addition, shoreline erosion would affect nearly 45% of the total beaches in 2100. These studies were based at that time only on the physical vulnerability component without considering the socio-economic or demographic parameters and therefore do not reflect all the aspects that can weigh in the assessment of coastal risks as this study has shown.

The Tetouan coast is also one of the Moroccan coasts that have been most rapidly and densely urbanized, mainly because of its tourist appeal. However, most of its beaches have an erosive trend, some of which might disappear in the next few decades (El Mrini et al., 2012; Flayou et al., 2021). Indeed, being a sand-deficient system, the coast will not be able to cope with the rise of the sea level, if no adaptation measures are undertaken. Satour et al. (2021) estimated the resilience index of this coast to flooding and showed that nearly 9000 households (18.4%) are in areas of very low to low resilience. Furthermore, Flayou et al. (2021) attempted a first assessment of the monetary losses that may be incurred by the tourism sector of the Tetouan coast, if the beaches were to disappear, which they estimated at 71.5 million US$ annually. This amount is largely underestimated because it does not take into account the evaluation of other ecosystem services provided by these beaches such as the protection of settlements and coastal infrastructures against marine submersion. Our findings are consistent with these previous results and support the fact that areas falling under very high and high risks are linked to a combination of high erosion rates with high capital land use.

Another factor that seems to influence coastal risks in the study area is related to the socio-economic disparities that characterize the TTA region, with significant gaps between urban areas and rural municipalities, particularly in terms of education and access to public services and employment (Haut-Commissariat au Plan, 2018). Some rural territories in the hinterland have a high rate of illiteracy and poverty, often resulting in a lack of risk perception and awareness. In this regard, based on a field survey in the Tetouan coast Ivčević et al. (2020), rightly advocate risk awareness as a predictor of precautionary behavior and readiness of inhabitants to protect themselves and their belongings from natural risks. This coastal risk analysis revealed that rural areas display higher vulnerability index than urban areas and therefore have higher level of risks. In fact, poor socio-economic conditions can sometimes shift areas with low physical exposure to high or very high-risk classes, because of low population capacity to cope with these risks. Hence the importance of combining several variables in order to integrate environmental, social and economic aspects, as was done through the use of the composite CRI in this study. But the most important challenge is that these scientific results are properly and effectively used in the coastal plan currently under development and which involves all stakeholders of the TTA Region. Therefore, it is worth mentioning the need for a continuous effort to bridge the communication gap between science, coastal planners, risk managers, and civil society (Ivčević et al., 2021).

4.1 Policy instruments for coastal risks

At the national level, Morocco has committed to reconciling environmental protection and socio-economic development over the past decades. Several laws and reforms were initiated at the national and regional levels. Regarding the coastal zones, the main legislative and regulatory framework for their protection and sustainable development is the Coastal Law (Law No. 81-12) (2015), which advocates, among other things, to fight against coastal erosion and to consider the limit of the non-constructible area. This law requires the development of regional coastal plans, by adopting an integrated management approach that considers the coastal ecosystem and climate change.

In terms of climate change policy, several initiatives addressing adaptation measures and building resilience in coastal areas have been taken in the last decade. In 2009, within the National Plan to Combat Global Warming, a wide range of adaptation tools have been integrated into sectoral adaptation strategies, such as coastal planning, water, agriculture, fisheries, forestry, biodiversity protection and tourism. In 2016, the country launched its National Adaptation Plan (NAP) process. Furthermore, according to the National Strategic Adaptation Plan, which constitutes a roadmap for the implementation of an adaptation policy coordinated at national and territorial level, climate risks are now factored in investment decisions and development planning. Following this framework, the TTA Region has launched its Regional Climate Plan (PCR) in 2020. Moreover, in its United Nations Development Assistance Framework (UNDAF) 2017-2021, Morocco has expressed a number of specific outcomes related to climate change adaptation that can be enhanced through collaboration with the United Nations system, including sustainable territorial planning and reinforced resilience to climate change and natural risks, especially for vulnerable populations.

In terms of coastal risk management, the operational plan for implementing the National Risk Management Strategy 2021-2031, identified two projects relating to coastal areas: (i) Studies and scenarios of marine flooding and coastal erosion and mitigation measures for priority territories; and (ii) Tsunami risk studies and scenarios for priority territories.

At the TTA Region level, in addition to legislative and institutional strengthening, several management actions have been undertaken to reduce coastal hazards and protect coastal infrastructure from erosion. The most representative example is that of the Bay of Tangier. Indeed, in 1987, two groins and a breakwater were implemented in front of the eastern beaches of the bay to protect seaside resort infrastructure and to prevent further erosion (Laboratoire Central d'Hydraulique de France, 1974; Long et al., 1999). Ten years later, these structures have proven not very effective in stopping coastal retreat. In fact, given the advanced stage of erosion, only an integrated management strategy involving a good understanding of beach, dune and nearshore dynamics, within an Integrated Coastal Zone Management framework (Sedrati and Anthony, 2007), can effectively combat erosion and prepare for the unavoidable effects of climate change.

4.2 Climate change adaptation options

Adaptation plays a key role in reducing exposure and vulnerability to climate change. In general, there is no single solution for coastal areas, but at least basic principles to respect, including 'low regret' or 'no regret' measures, and actions that focus on the long term rather than the short term (UNEP/MAP/PAP, 2015). Nature-based solutions (NbS) have proven to be the most appropriate to meet these principles, through restoration and improving the conservation of ecosystems such as coastal wetlands, coastal dunes, forests, and seagrass meadows (Kumar et al., 2020; EC, 2021, Moraes et al., 2022). In addition, NbS are expected to contribute to both adaptation and mitigation goals by protecting coastal environments from SLR and storms, and by storing substantial quantities of carbon (IPCC, 2022).

The coastline of the TTA Region, which is very diverse in terms of development, geomorphology, and biological diversity requires wider suite of adaptation measures either curative or preventive. The most appropriate solutions for the hotspots identified by the coastal risk analysis should combine hard structures such as seawalls, jetties, groins, and breakwaters to protect the most exposed coastal roads and settlements, with soft measures and NbS, including beach nourishment, and the fixation and revegetation of the coastal dunes. Coastal wetlands, like the Tahaddart tidal marshes or the Smir lagoon, provide a natural defense against coastal flooding and storm surges, and therefore should be restored and protected from urban expansion. The coastal defense structures built in the bay of Tangier to fight against beach erosion and protect the beachfront hotels will be exposed to more severe hydrodynamic conditions. Indeed, in shallow waters, with the rise in mean sea level and the potential intensification of offshore storms, the height of the waves will exceed the design values (Sergent et al., 2015; Almar et al., 2021; Bongarts Lebbe et al., 2021; Mohamed Rashidi et al., 2021). Most of the adaptation strategies proposed in the literature are based on coastal engineering and consist in: a) repairing the structures as they are b) reinforcing them c) demolishing and redesigning them d) accepting coastal realignment. According to Sergent et al. (2015), at very shallow depths (top of beach structures), if the mean water level rises by one meter, these structures will have to be raised by two to three meters to maintain the same crossing performance. In Tangier Bay, the breakwater and groyne will have to be either raised or reinforced, but this might be unsightly, or demolished and redesigned with the integration of softer measures like beach nourishment. However, this strategy might be costly and requires regular monitoring and maintenance.

4.3 Integrated coastal zone management: A proactive and effective process to implement adaptation

It is increasingly recognized that climate change challenges in coastal areas need to be addressed through integrated and ecosystem-based approaches, taking into consideration also other environmental and socioeconomic pressures (Cramer et al., 2018; IPCC, 2022). Moreover, the dynamic nature of climate risks means that a more proactive approach to adaptation planning is essential for coastal areas; otherwise, these risks could reach unacceptable levels (Nicholls et al., 2007; Rochette et al., 2010). The importance of anticipation, particularly in terms of providing knowledge and scientific data, essential at local scales, is also underlined, because of the many uncertainties on climate trends, which can constitute a major obstacle to the identification of coping strategies. Rochette et al. (2010) argued that beyond the conceptual convergences between the processes of ICZM and adaptation to climate change, synergies are possible at the operational level through common implementation tools, such as the setback zone.

At the national level, since the ratification of the ICZM Protocol to the Barcelona Conventions (Panayiotis and Paraskevi, 2020), Morocco has established a solid institutional, policy, and legal framework for ICZM, and hence has the capacity to effectively implement climate change adaptation strategies in coastal planning and management activities. In the TTA coast, the production of risk maps and the identification of hot spots on a regional scale will certainly help to i) better define the priority measures to be considered in the development phase of the coastal plan. The latter is a regulatory planning instrument, which must be based on robust scientific knowledge, provided that data are available, and on a participatory process; and ii) define a sound coastal planning integrating coastal adaptation measures during the implementation phase.

5 Conclusion

This research identifies hotspots and coastal areas at risk in the region of Tangier-Tetouan-Al Hoceima (TTA), Morocco. The main finding is that the coastal area of the TTA region is extremely exposed to coastal forcing, with more than 50% of the zone being highly vulnerable. This confirms that the TTA region is exposed to multiple and combined hazards, which in combination with high demographic and economic pressures intensify the vulnerability of the coastal areas. Compared to the previous study by Satta et al. (2016), we used the same Coastal Risk Index application at the Local Scale (CRI-LS) methodology, but we updated the vulnerability and exposure input data, we improved the spatial resolution from 300-m- to 20-m- pixel size, and we applied it to a whole TTA region.

The authors strongly recommend policy-makers to apply the outcomes of this research for current and future coastal planning and adaptation-related policies for the region of TTA. The process of preparation of the coastal plan of the TTA region is ongoing. It is a strategic document that reflects the vision of the region's coastal areas in the following twenty years and is elaborated by the regional stakeholders, the Regional Directorate of the Environment, and with the assistance of the UN Environment Programme/Mediterranean Action Plan (UNEP/MAP). Within this participatory process, more than sixty regional stakeholders are working on common objectives of sustainable development, to find ways how to mitigate the impact of climate change and to reduce coastal risks. In light of this process, the appearance of the present research is timely, so that the risk maps indeed can be applied in the new coastal plan of the TTA region. Since the coastal risk assessment identified hotspots in the region, this research facilitates the process of decision-making concerning the coastal adaptation to the ongoing processes of climate change, by making concrete decisions in coastal planning and management processes.

Although the human role in the climate crisis is unequivocal, the IPCC report (2021) gives us the power for change so it is important to know that we can still act and contribute to fighting the climate crisis and preventing the tipping points in our coastal areas.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

The research, analysis, and manuscript were shaped by all authors, who provided critical feedback. A final version of the manuscript was written by all authors after discussing the results. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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