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Coastal development and risks of flooding in Morocco: The cases of Tahaddart and Saidia coasts

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ABSTRACT

Coastal areas provide a large array of ecosystems services, contributing to the economic welfare of local communities. However, they are more and more submitted to both human pressures and natural forcing. Climate change creates additional risks and is expected to intensify the loss and degradation of coastal low lying-areas. The aim of this paper is to assess the risk of flooding due to sea-level rise and storm-surges for two Moroccan coasts: Tahaddart, a relatively underdeveloped coast and Saidia which has experienced intense urbanization over the last decade. Their risk assessment was compared to that carried out on the even more developed coast of Tetouan. The main findings of this study are: (i) the high level of risk that threatens these coasts is due to their low elevation and the value of the exposed assets; (ii) there is a positive relationship between the coastal risk and the build-up rate: the more a coastal area is artificialized, the more its risk index is high; and (iii) Coastal risk assessment is a useful tool that can help decision makers and coastal managers in the development of adaptation strategies and management plans to protect coastal ecosystems and make them resilient in the face of climate change.

1. Introduction

Coastal zones are the most important areas for the socio-economic development of coastal countries (Nicholls et al., 2007). They provide many essential ecosystem services (Millennium Ecosystem Assessment (MEA), 2005), but are also highly vulnerable to global change, including climate change, because of their geographical, climatic and socioeconomic characteristics. Indeed, their position at the land-ocean interface, especially when it comes to densely populated and highly urbanized lowlands, makes them hot spots for coastal risks (IPCC et al., 2007). According to World Population Prospects (2015), the world's population is growing by more than one billion people in the next 15 years, reaching 9.7 in 2050 and 11.2 billion people in 2100. Thanks to their natural and ecological landscapes, their socio-economic assets and cultural resources, coastal areas are attracting more and more people and activities (Neumann et al., 2015).

However, coastal ecosystems already experience multiple anthropogenic pressures from residential and tourism development, over-exploitation of coastal resources including fish, sand and forests. The pressure that is most dangerously threatening coastal areas is the increasing "artificialization" of the shorelines that makes them less resilient and more vulnerable to the unavoidable impacts of climate change and sea-level rise (Pons and Rullan, 2014). At the global level, Dilley et al. (2005) showed that about 3.8 million Km^2 and 790 million people are relatively highly exposed to at least (Drought and Geophysical), while about 0.5 million Km^2 and 105 million people are exposed to (Drought, Hydro, and Geophysical). As the rate of the coastal population increases continuously, it is expected that by 2020, 75% of the world's population (*i.e.* 7.1 trillion) will live at 20 Km from the shoreline (Nicholls et al., 2007; Anfuso and Nachite, 2011). This growth, which inevitably leads to an increase in coastal settlement and economic activities, will certainly heighten exposure and vulnerability to future global change. Projected climate change will very likely disrupt ecological systems (Torresan et al., 2009) and alter the environmental conditions along most of the world's coastlines. Sea-level rise induced by climate change is obviously one of the main threat to coastal areas (Cramer et al., 2018). With the likely increase in the frequency and intensity of storm surges, it will severely impact coastal areas through notably submersion, flooding and coastal erosion (Snoussi et al., 2008, 2009; El Mrini et al., 2012; IPCC et al., 2014a; 2014b; Aouiche et al., 2016; Hakkou et al., 2018). Bird (1985) reported that 70% of coastal areas are eroded. Mentaschi et al. (2018) estimated at about 28,000 Km^2 the global area affected by coastal erosion from 1984 to 2015.

Coastal population and coastal ecosystems are therefore at risk from the combined climate and non-climate related hazards (Gallopın, 2006;

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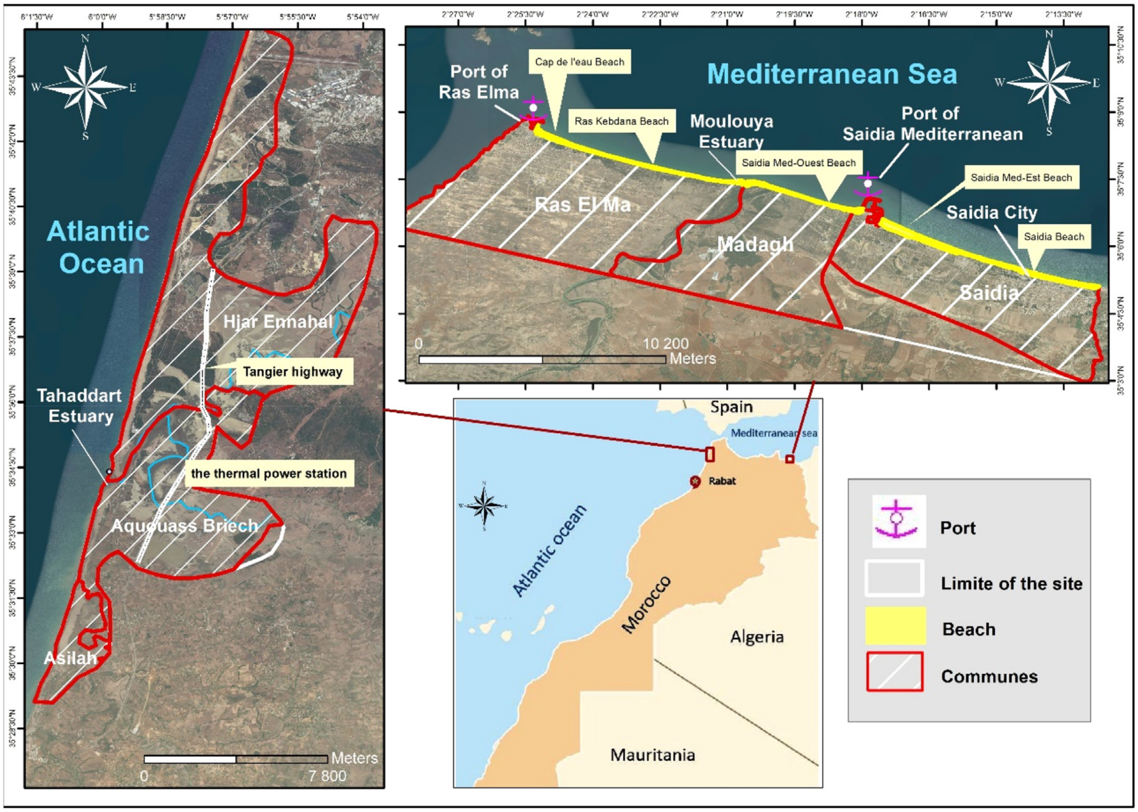

Fig. 1. Location of the selected study-sites.

Torresan et al., 2008; IPCC et al., 2014b; Cramer et al., 2018). This is why identifying those risks and highlighting the most critical coastal regions are essential and helpful for coastal managers and decision makers to proactively define adaptation measures.

Several vulnerability and risk assessment methods, based on multiple physical and socioeconomic variables, have been developed and improved during the last decades. Since the Gornitz Coastal Vulnerability Index (CVI) (Gornitz et al., 1991, 1994), other approaches based on GIS (Mocenni et al., 2009) or on dynamic models (Hinkel and Klein, 2009) have been developed. Nevertheless, index-based tools are particularly suitable to make a first risk assessment of different coastal areas to climate-induced hazards, according to the available data and information (Torresan et al., 2009; Ramieri et al., 2011; Satta et al., 2016, 2017). These multi-criteria approaches provide spatial results showing the area's most at risk from coastal hazards (Bagdanavičiute et al., 2015; Ferreira Silva et al., 2017).

In Morocco, the coastline, which stretches for almost 3500 Km along the Atlantic and the Mediterranean, and is home to 60% of the population and 90% of the industries, is highly exposed to coastal risks. Yet, there have been few multicriteria assessment studies of the vulnerability of coastal areas (Snoussi et al., 2008, 2009; Khouakhi et al., 2013; Raji et al., 2013; Tahri et al., 2017; Maanan et al., 2018). Regarding index-based risk assessment, only one study was conducted on the Tetouan coastline (Satta et al., 2016).

The main objective of this study is therefore to contribute to the identification of other coastal areas in Morocco at risk to climate and non-climate forcing. The rate of development of a coastal area being a determining indicator of risk exposure, we have selected two coastal sites but with a different development rate. The littoral of Tahaddart, poorly developed and the littoral of Saïdia which has undergone a recent fast development. We also completed the results with those we obtained earlier on the coast of Tetouan (Satta et al., 2016). The final outcomes are to help decision makers and coastal managers for the definition of adaptation and management strategies in the priority areas at risk.

2. Study sites and coastal development

The coastal areas selected for this study are Saidia-Ras Elma located on the eastern Mediterranean coast and Tahaddart littoral located on the Atlantic coast (Fig. 1).

2.1. The coast of Saïdia-Ras Elma

This littoral is a low-lying coastal zone stretching over 21 km long between Ras Elma Cape and Saïdia city. The coastline is straight and indented only by the Moulouya inlet. A large complex of secondary channels and salt marshes borders the Moulouya estuary on a flat area of 3000 ha. This wetland is classified as RAMSAR site and according to the national classification, it represents a Site of biological and ecological interest (SIBE) due to its role as a refuge or stop-over for many birds of national and international interest. Beaches are all sandy and backed in some parts by recent and ancient dunes. However, at many locations coastal dunes have been degraded or even completely removed over the years due to tourism and residential development, mining and recreational activities. It is worth remembering that the city of Saidia has long been a national tourist destination (Sbai and Lasgaa, 2012), but it became one of the fast growing touristic coast in the past decade in Morocco. It is usually a mass tourism which is not without having significant consequences on the environment.

From an administrative point of view, the area belongs to three communes: Saidia, Madagh and Ras Elma with a total population of 30,588 inhabitants (RGPH, 2014). However, this number is sometimes multiplied by 10 in the summer season, during which thousands of tourists, especially domestic, come to enjoy the beaches. For instance, the daily frequentation at the five beaches of the region is 800,000 for Saidia, 5000 for Saidia-MedEst, 100,000 for Saidia-MedOuest, 8000 for Ras Kebdana and 8000 person/day for Cap de l'eau, respectively

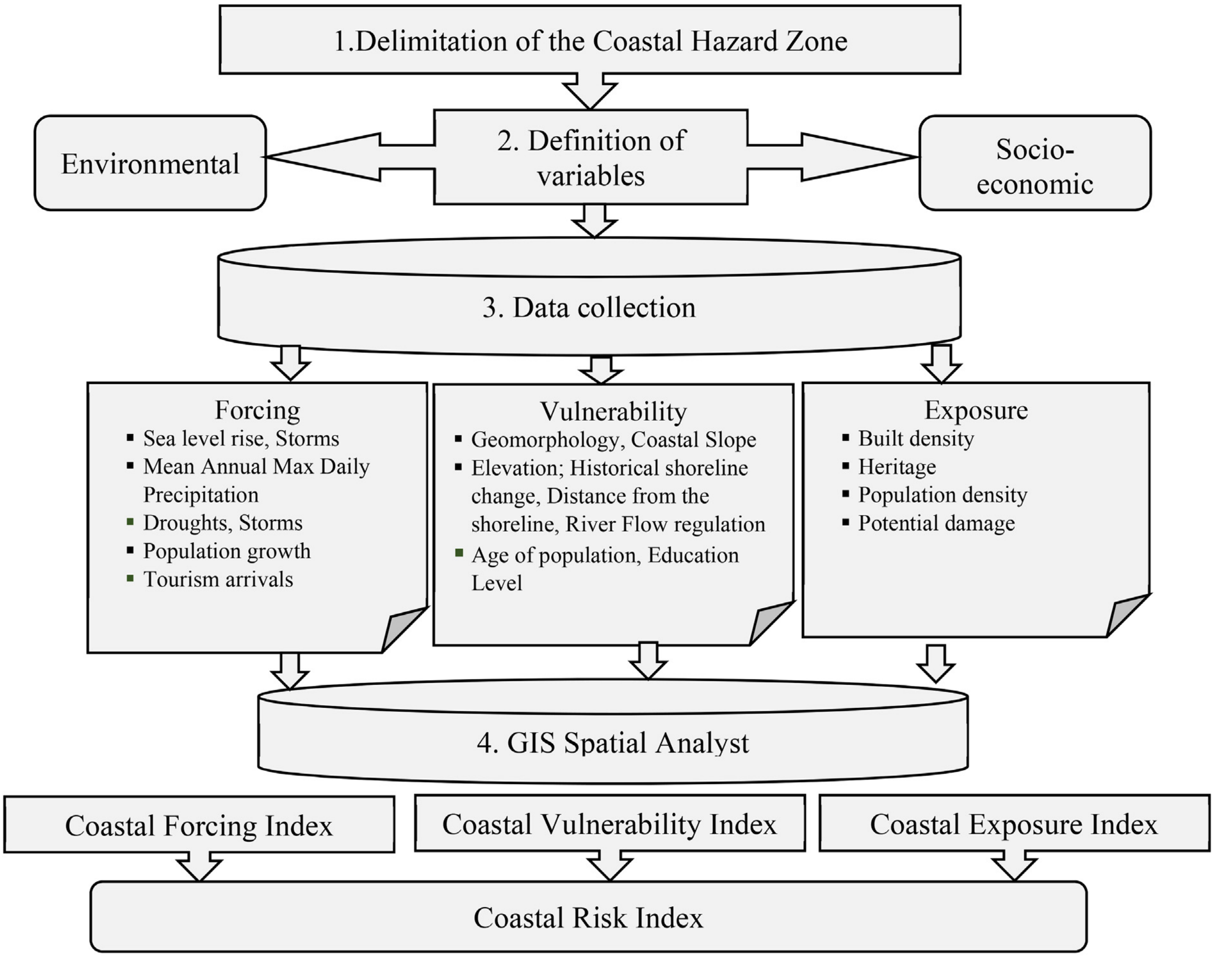

Fig. 2. Flow chart of the method used for the coastal risk index assessment.

(Fondation Mohammed VI pour la Protection de l'Environnement, 2017).

As regards to the socioeconomic sectors in the region, agriculture, fisheries and tourism are the main activities. Over recent decades, fisheries have been declining probably due to overfishing, while tourism has been expanding rapidly. Indeed, Saïdia was one of the five seaside resorts of the ambitious "Plan Azur", focused on the five-star luxury facilities, marina and golf course, and a flagship strategy of Morocco's tourism policy. This plan was not really a success, as the objectives, including job creation and improving the well-being of the local population, were far from being achieved.

Following the rapid tourism development of the coast, multiple pressures are exerted on the coastal ecosystems, among which urbanization that progressed rapidly to the detriment of dunes and the Moulouya wetland (Snoussi et al., 2008, 2010; Boumeaza et al., 2010; Saddik et al., 2012). Tekken et al. (2009) showed that even in an unchanged climate, these developments would exceed the regions natural limits.

2.2. *The coast of Tahaddart*

Located in the north-west of Morocco on the Atlantic coast (Fig. 1), the Tahaddart littoral stretches over 27 km long. The site, which covers an area of 14,000 ha, extends on a tidal flat plain and constitutes a large wetland of high ecological value. Indeed, it is classified as RAMSAR site, since 2005 as well as SIBE. The ecological habitats mapped within the Ramsar delimitation are dominated by three major categories: marine/coastal, estuarine and lacustrine (Nachite et al., 2010; Achab, 2011; Rifai et al., 2018). The Tahaddart site is actually the junction of two adjacent watersheds, separated by a hill, whose rivers meet near the coast to form the Tahaddart estuary.

In terms of demography, the boundaries of the study area belong to three communes (Hjar Ennahl and Aquouas Briech and Asilah) with a total population of 45,043 inhabitants (RGPH, 2014). This site still has, largely, its original natural features, but the pressure of human activities is becoming increasingly apparent. The construction of the Tangier highway and the thermal power station on the coast, the damming of two wadis, and the extraction of the coastal sand, have all disrupted the natural functioning of the wetland and caused an erosion of sandy beaches that are very popular with tourists in summer (Amharak, 2006; Achab, 2011; Rifai et al., 2018).

However, the Tahaddart site remains much less developed than the Saidia coast, and it would be interesting to compare their vulnerabilities and the coastal risks induced by climate change they face.

3. Methodology

The assessment of coastal risks to climate change involves several concepts (vulnerability, exposure, adaptive capacity, resilience) that have been clearly defined and continuously updated in the different IPCC's assessment reports. The notion of risk in particular, has for long time been defined and used in the general framework of Disaster Risk Reduction (DRR); then, with the development of the concept of adaptation to climate change, risk is defined as a function of three factors: forcing, vulnerability and exposure (Romieu et al., 2010; IPCC et al., 2014a; 2014b; Satta et al., 2017).

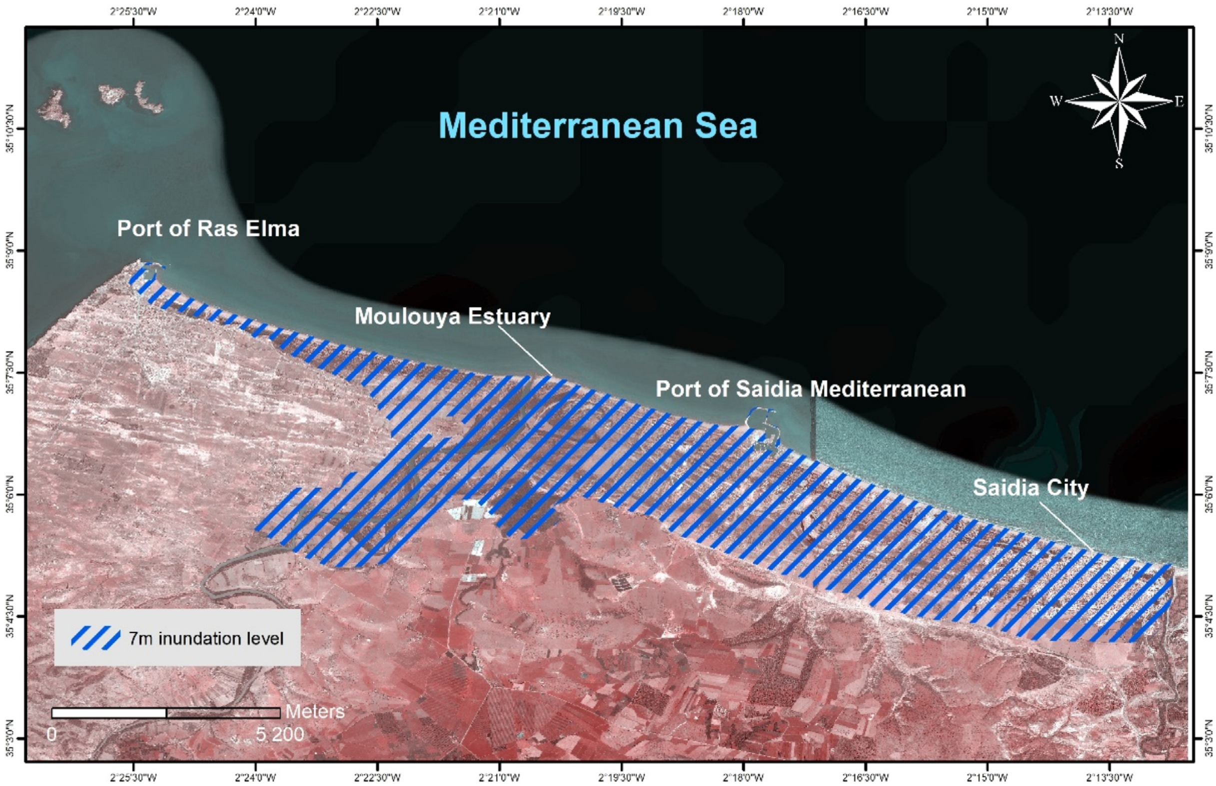

Fig. 3. Coastal Hazard zone for the coastal zone of Saidia-Ras-Elma.

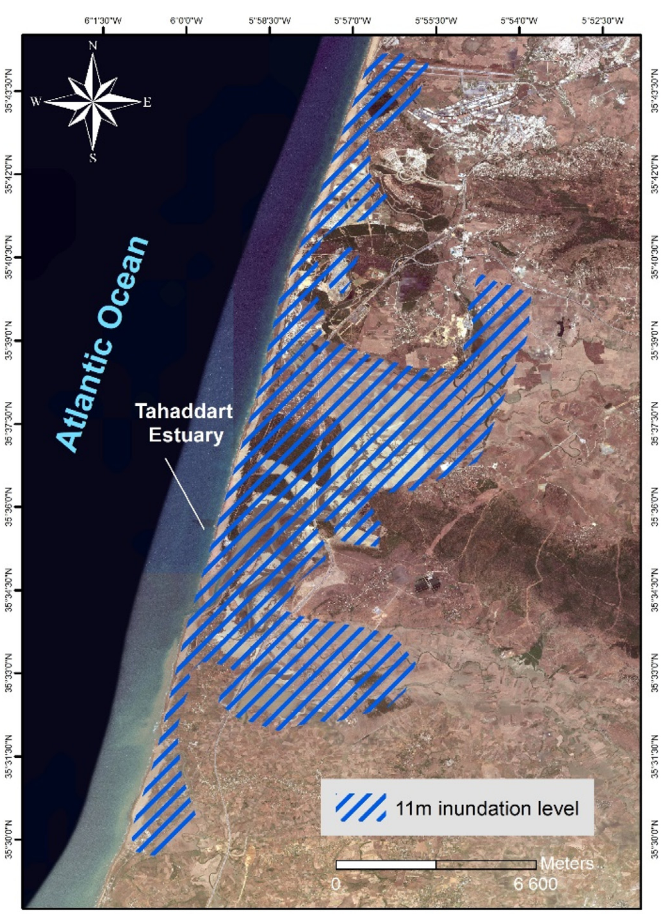

Fig. 4. Coastal Hazard zone for the coastal zone of Tahaddart.

The risk assessment methodology proposed in this paper is an index-based method commonly used in the literature and which has proven its usefulness as a decision tool for managers. The method is based on a set of environmental and socioeconomic indicators that best define the climate and non-climate forcing, the vulnerability and the exposure of the two studied sites. Data were then processed through spatial analysis under the software ArcGis 10.3.1. Data processing was done following 3 steps: (i) Thematic analysis through georeferencing and digitization (geological map, drought, distance from the shoreline …), using the Raster calculator tool; (ii) Spatial analysis using a supervised classification in order to obtain the land cover maps and derive other variables (coastal slope); and (iii) Reclassification of all the variables into the defined five classes.

Fig. 2 represent the flow-chart of the main steps used in this approach. The first step aims to determine the extent of the coastal hazard zone; the second step is devoted to identifying the available socio-economic and climatic variables, through the compilation of data and information, in order to build a useful database that will allow to determine the three sub-indices, namely the forcing index, the vulnerability index and the exposure index. The fourth and last step is a spatial analysis using geographic information systems in order to determine the Coastal Risk Index that integrate the three coastal sub-indices (forcing, vulnerability and exposure).

3.1. Delimitation of the coastal hazard zone (CHZ)

As defined in Satta (2014), the coastal hazard zone (CHZ) is the coastal zone prone to erosion and inundation hazards induced by the accelerated sea level rise and the extreme meteorological events and storm surges. Coastal lowlands, where population and activities are generally concentrated, are then particularly prone to flooding and erosion (Heberger et al., 2009; Nicholls et al., 2008; Ferreira Silva et al., 2017). The identification of the coastal hazard zone is therefore critical for an effective long-term coastal management, including protection and safety of the local populations and infrastructures.

Table 1
Variables chosen for the calculation of the CRI.

Variables	Description	Data Sources
Coastal Forcing		
Sea level rise	No data at local level. Regional data used Satellite altimetry data	AVISO database
Precipitation	Mean Annual Maximum daily precipitation	http://www.water.gov.ma/
Tourism arrivals	Number of tourists who travel to the study sites	http://www.tourisme.gov.ma/
Population growth	Annual population growth (%)	https://www.hcp.ma
Droughts	Significantly driest winters experienced by the Mediterranean regions during 1971–2010 relative to the period of 1902–2010.	NOAA Website
Storms	Average number of SWH above 95 percentile/year, which represents the number of events exceeding the long term (e.g. return period 100 years) 95 percentile of daily SWH	(www.puertos.es; Amharrak, 2006; Snoussi et al., 2008, 2009)
Coastal Vulnerability		
Geomorphology	Geomorphologic structure of the coastal zone.	Geological map (Sbai and Lasgaa, 2012; Taaouati, 2012; Rifai et al., 2014; Tahiri et al., 2018)
Coastal Slope	The slope of the coastal zone	GIS (Achab, 2011; Taaouati, 2012)
Historical Shoreline change	Percentage of eroded coast/Sediment budget.	(Salmon et al., 2010; Mouzouri and Irzi, 2011; Taaouati, 2012)
Elevation	Topography represent the value of du pixel in the selected area	GIS
Distance from the shoreline	Related to progression of the risk according to the shoreline	GIS
River flow regulation	Refers to the impact of dams on river flow	http://www.water.gov.ma/Google Earth
Education level	Percentage of population whose level is equal at least to the level 3 of the international standard	https://www.hcp.ma
Age of population	Population with age ≥ 65 years	https://www.hcp.ma
Coastal Exposure		
Land Cover	Land cover map	ESA MAP (Snoussi et al., 2010; Rifai et al., 2018)
Population density	It represents the number of people per Km^2	https://www.hcp.ma
Heritage	Presence or absence of historical monuments	Google Earth
Potential damage	It estimates the potential damage	Google Earth

Table 2
Variables ranking for CFI.

Coastal Forcing Index							
Variables		Scores					Weight %
		1	2	3	4	5	
H1	Sea level rise (mm)/y	< 1	1-1,6	1,7–2,4	2,5–3,2	> 3,2	30
H2	Mean annual max daily precipitation (mm/d)	< 16	16–32	33–64	65–128	> 128	20
H3	Population growth (%)	< 0,1	0,1–0,5	0,5 - 1	1,01 - 2	> 2	10
H4	Tourism arrivals (%)	< 0	0–1	1,01–5	5,01 - 10	> 10	10
H5	Droughts (Mm)	> 36	36–11	11– − 12	− 13– − 36	< -36	5
H6	Storms (cm)	< 50	50–150	151–250	251–350	> 350	25

Table 3
Variables ranking for CVI.

Variables		Scores					Weighting factor
		1	2	3	4	5	
V1	Geomorphology	Hard Rock shores	Soft Rock shores	Rivers, deltas, estuaries and cobble beaches	Sandy shores backed by bedrock or artificial frontage	Sandy shores and water plains	1
V2	Coastal slope	0–8	8–16	16–32	32–64	> 64	0,8
V3	Historical shoreline change	> 1	1–0.3	0.3- (− 0.3)	(-0.3) -(-1)	< (− 1.0)	0,8
V4	Elevation (m)	> 30	20–30	20–10	5–10	< 5	1
V5	Distance from the shoreline	> 4500	4500–2100	2099–900	899–300	< 300	0,4
V6	River flow regulation	No dams	/	Dams only in the minor tributaries	/	Dams in the largest tributaries	0,4
V7	Education Level (%)	> 60	60–44	43–28	27–10	< 10	0,5
V8	Age of population (%)	< 3	3–8,5	8,6–15	16–20	> 20	0,5

Saidia-Ras Elma and Tahaddart coasts, which both encompass wetlands and lowlands, are consequently highly exposed to the risks of flooding. To define the limits of the CHZ in these areas, and given the limited data available, we used an empirical approach based on the Hoozemans et al. (1993) equation:

$$Dft = MHW + St + Wf + Pf$$

where Dft is the inundation level, MHW the mean high-water level, St the relative sea-level rise, Wf the height of storm waves and Pf the sea-level rise, due to a lowering of the atmospheric pressure.

In Saïdia coast, the coastal flooding levels have already been calculated by Snoussi et al. (2008) using Hoozemans' equation. They estimated the maximum flood level, induced by a high estimate of sea level rise, and storm surges with a return period of 1 per 100 years to be

Table 4
Variables ranking for CEI (Adapted from Ferreira Silva et al., 2017).

Variables	Ranking for exposed variables				
	Very low 1	Low 2	Moderate 3	High 4	Very High 5
Population density (inhab/km^2)	< 1000	1000–1500	1500–2000	2000–2500	> 2500
Landcover	Bare areas	Shrub land, grasslands, Sparse vegetation	Forest and Water bodies	Agriculture	Urban area
Heritage	Absence	–	–	–	Presence
Potential damage	D1 (insignificant damage) for areas without habitats with ecological value, local paths or drainage ditches	D2 (marginal damage) for areas till shrubby vegetation or occupied by habitats in weak phytosanitary conditions	D3 (serious damage) for areas with coastal defense structure, areas with ecological value lower the previous with shrubby vegetation	D4 (critical damage) for discontinuous residential areas with equipment and services, and areas occupied high ecological values habitats	D5 (catastrophic damage) for consolidated urban areas and occupied by very high ecological value habitats

7.64 m.

As for Tahaddart coast, we used the same approach with data on waves and storm surges collected from the Spanish station based off shore Tahaddart coast (http://www.puertos.es) and from literature (LCHF, 1972; Snoussi et al., 2009). The maximum flooding level is estimated to be 11.15 m.

For both sites, we used 7 m as setback line for the coastal hazard zones for Saïdia (Fig. 3) and 11.15 m for Tahaddart (Fig. 4).

3.2. Choice and definition of variables

The number of the variables used in the calculation of a coastal risk index are different from one study to another (Bagdanavičiute et al., 2015; Satta et al., 2016). The choice of relevant variables, when not limited by the availability of data, is crucial for the development of a sound risk index (McLaughlin and Cooper, 2010). They should, as far as possible, reflect environmental and socioeconomic drivers as well as climatic and anthropogenic forcing, which best describe forcing, vulnerability and exposure.

In this study, despite the data availability constraint, 20 variables were selected from which 6 for the forcing sub-index, 8 for the vulnerability sub-index and 4 for the exposure sub-index. (Table 1).

3.2.1. Scoring and assignation of weights to risk variables

The assignation of scores was performed using a 1–5 scale, 5 being the most important score and 1 the least important score. Regarding the weighting, the method proposed by Torresan et al. (2012) and used in Satta et al. (2016) was also applied in this study, in order to be able to compare the sites studied in this paper with Tetouan site studied in Satta et al. paper. A weight of 100% was assigned to variable judged to have higher influence on the final risk, while, a weight of 0% was assigned to variable judged to have no influence on the final risk (Torresan et al., 2012). The ranking was based mainly on expert judgments but also on stakeholder's perception, expressed during workshops organized by the ministry of environment and in which one of the authors participated.

3.3. Calculation of the coastal risk index

The coastal risk index (CRI) is the integration of the three sub-indices: Coastal Forcing Index (CFI), Coastal Vulnerability Index (CVI) and Coastal Exposure Index (CEI) described in the following sections.

3.3.1. Coastal forcing index (CFI)

As said before, sea level rise and storm surges caused by climate change are the main drivers of flooding and erosion in coastal areas (Ferreira Silva et al., 2017). To calculate the coastal forcing index (CFI), we used the formula of Satta et al. (2016) which incorporates, in addition to climatic forcing, non-climate variables such as tourism, population growth, and others (Table 2). The calculation of CFI is defined by equation (1).

$$\text{Coastal Forcing sub-index} = \{[\,\Sigma\,(Wv\,{*}Sv) - 1]\,/\,4\} \tag{1}$$

Where Wv is the weight of variables used, Sv is the score of the variables and which varies between 1 and 5. The results are presented in Table 2.

3.3.2. Coastal vulnerability index (CVI)

The term “vulnerability” is used by a wide range of scientific disciplines and decision-makers from different horizons (Zou and Thomalla, 2010). The Coastal Vulnerability Index (CVI) is the most common index for assessing coastal vulnerability caused by sea-level rise induced by climate change (Gornitz et al., 1991; Balica et al., 2012; Pantusa et al., 2018), and by socio-economic drivers mainly the excessive urbanization. In the literature, there are several definitions of

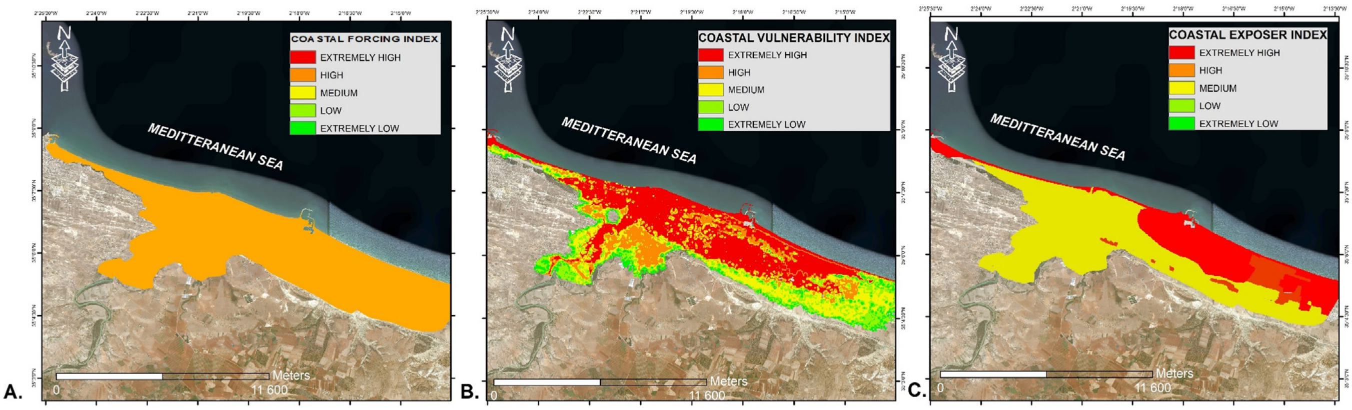

Fig. 5. Maps of Coastal Forcing (A), Coastal Vulnerability (B) and Coastal Exposure (C) of Saidia-Ras Elma coastal zone.

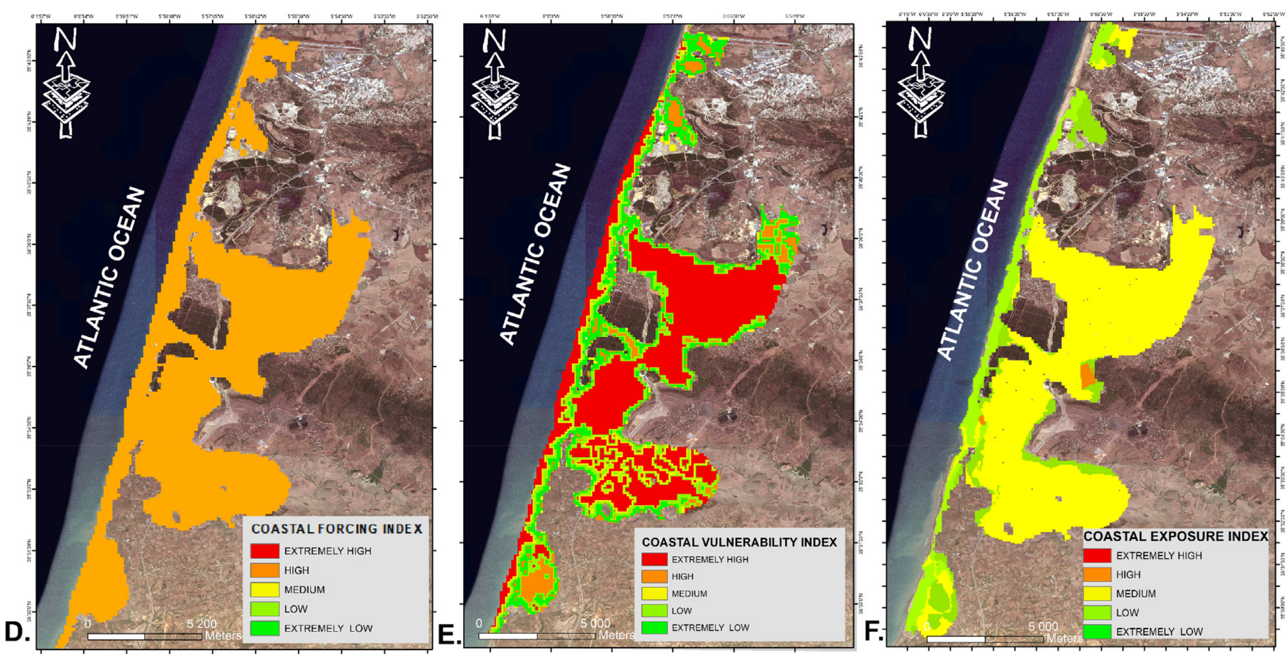

Fig. 6. Maps of Coastal Forcing (D), Coastal Vulnerability (E) and Coastal Exposure (F) of Tahaddart coastal zone.

CVI with slight differences and integration of physical and socio-economic parameters, to adapt the index to a specific coastal zone (Abuodha and Woodroffe, 2007; Kantamaneni et al., 2017). In this paper we used the weighted CVI developed by Bagdanavičiute et al., 2015 and expressed by equation (2):

$$CVI = \Sigma\,(Var_n * Fp_n) \,/\, n \quad (2)$$

where Var_n is the selected variables, Fp_n the weighting factor for each variable and n is the number of variables used.

The selected variables used to calculate the CVI were chosen based on data availability and because of their applicability to a local scale. They cover both environmental aspects (Geomorphology, elevation, coastal slope, shoreline changes, distance from the shoreline, river flow regulation), social variables (Education level, age of population) and protective measures (coastal protection structures). Table 3 represents the 8 variables, their scores and weighting factors. We assigned the highest weighting factor (1) to the physical variables (elevation and geomorphology), knowing that these parameters are the most critical in the extent of marine submersion and coastal erosion.

3.3.3. Coastal exposure index (CEI)

The uncontrolled increase in the 'artificialization' of the coasts, without considering the impacts of climate change, will very likely expose the infrastructures and the populations to coastal hazards such as flooding and erosion induced by sea-level rise and storm surges. Numerous studies have assessed the impact of future coastal hazards on coastal exposure (Hanson et al., 2011; Hallegatte et al., 2013; Neumann et al., 2015; Merkens et al., 2018), and showed that the increased exposure to coastal hazards is a critical issue for the sustainable development and management of the coastal areas.

The calculation of the coastal exposure index (CEI) applied by Ferreira Silva et al., 2017. The method assesses the value of exposed elements and integrates land use characteristics, population density and heritage monuments included in the study area. In this study, the used variables were adapted due to the constraint of data availability and the resulting equation is as follows:

$$CEI = \{[\,Dpop{*}\ LB\ {*}H\ {*}\ D]\ /4\}1/2 \quad (3)$$

where Dpop is the density of population expressed in number of people/Km^2; LB is the build land, derived from the land cover map in the study area; H represents the heritage index with the highest value assigned to presence and lowest value to absence of historical monuments; and D is the potential damage of assets in the study area. Five classes of damage have been proposed by Ferreira Silva et al., 2017 and considered in this

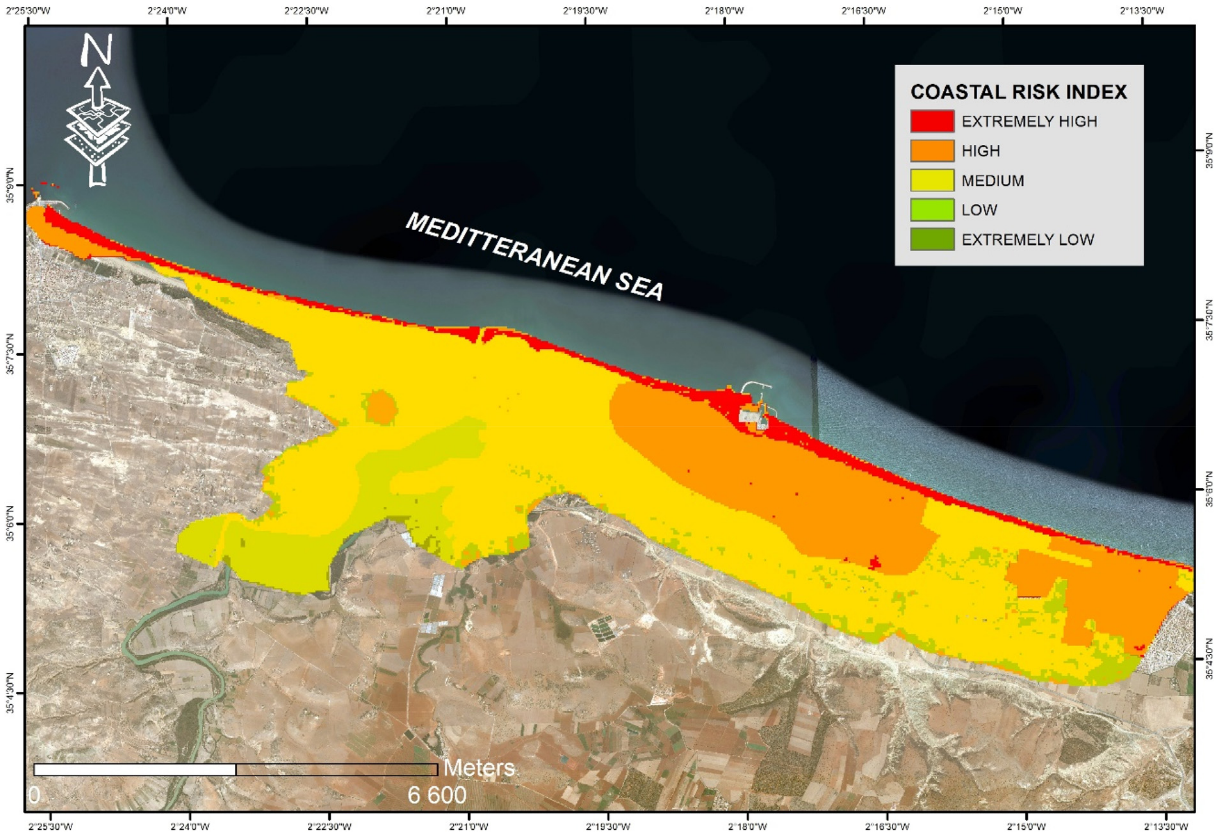

Fig. 7. Map of Coastal Risk Index of Saidia-Ras Elma Coastal zone.

study (Table 4).

3.3.4. Coastal risk index (CRI)

The coastal risk index is calculated by integrating the three factors of risk, namely forcing, vulnerability and exposure (IPCC et al., 2014b; 2014a; Satta et al., 2016), according to equation (4):

$$CRI = CFI * CVI * CEI \quad (4)$$

4. Results and discussion

The calculation of the three sub-indices (coastal forcing index, coastal vulnerability index and coastal exposure index) are presented on maps for the two studied sites: the Saidia-Ras Elma coast (Fig. 5) and Tahaddart coast (Fig. 6). The construction of maps was performed using the geographic information systems (GIS) and multicriteria analysis as used in previous studies (McLaughlin et al., 2002; Coelho et al., 2006; De Pippo et al., 2008; Özyurt and Erginj, 2009; Bagdanavičiute et al., 2015; Satta et al., 2015).

4.1. Coastal forcing index

Given the low extent and the straightness of the coastlines, the CFI is ranked 'high' for both sites (Figs. 7 and 8), but in details for Saidia, the climate forcing is weaker and the non-climatic variables (population and tourists) have a significant weight, whereas it is the opposite for Tahaddart, where the marine hazards are important and the human influence with less weight. So, at the end, the result is the same for the two sites. This is why the CFI is homogenous and high throughout their whole area (Fig. 5A) and (Fig. 6D).

Indeed, the marine-weather hazards from the Atlantic are stronger than those in the Mediterranean, and thus Tahaddart coast is more exposed to the marine hazards than Saidia. Offshore Tahaddart, the height of strong waves can exceed 4 m, with peaks of up to 8 m. The decadal swell has a significant height of 7.8 m (Amharak, 2006), while the coast of Saidia-Ras Elma is submitted to storm wave height of 6.20 m with a return period of 1 per 100 years (Snoussi et al., 2008). Another variable that weighs in the calculation is the population growth more important in Saidia than in Tahaddart.

4.2. Coastal vulnerability index

The map of Saidia-Ras Elma area (Fig. 5B) shows a rise in the indices from the hinterland to the coast, reflecting the impact of human activities and population density along the coastal strip. Furtheremore, Sbai and Lasgaa (2012), and Snoussi et al. (2008) have highlithed the high vulnerability of this coast to sea-level rise and storm surges, because of its low elevation and its high socio-economic characteristics. The Moulouya wetland and the surrounding lowlands and beaches are classified with very high (40%) to high (15%) vulnerability, due to the low elevation, the sandy type of the beaches and the flat salt marshes. In addition, previous study on Saidia shoreline changes (Boumeaza et al., 2010) showed that many parts of the coast are experiencing severe erosion and are therefore very vulnerable to future coastal hazards. In both sites, damming of the rivers has led to sediment abstraction and then coastal erosion. For instance, dams on the Moulouya rivers have trapped more than 95% of the sediment supply to the coast (Snoussi et al., 2002). Therefore, beaches are particularly vulnerable to the future sea level rise, as they are both sediment-deficient and highly developed. The low and extremely low vulnerability classes represent 15% and 20% respectively of the study area and are mainly located in the upper parts of the area, especially in the south-east.

As for the Tahaddart coast and its large tidal flats (Fig. 6E), almost the whole area (73%) is classified with high to very high vulnerability. The sandy coastal strip and some salt marshes with an elevation below the sea-level, fall in the extremely high vulnerability class. In addition,

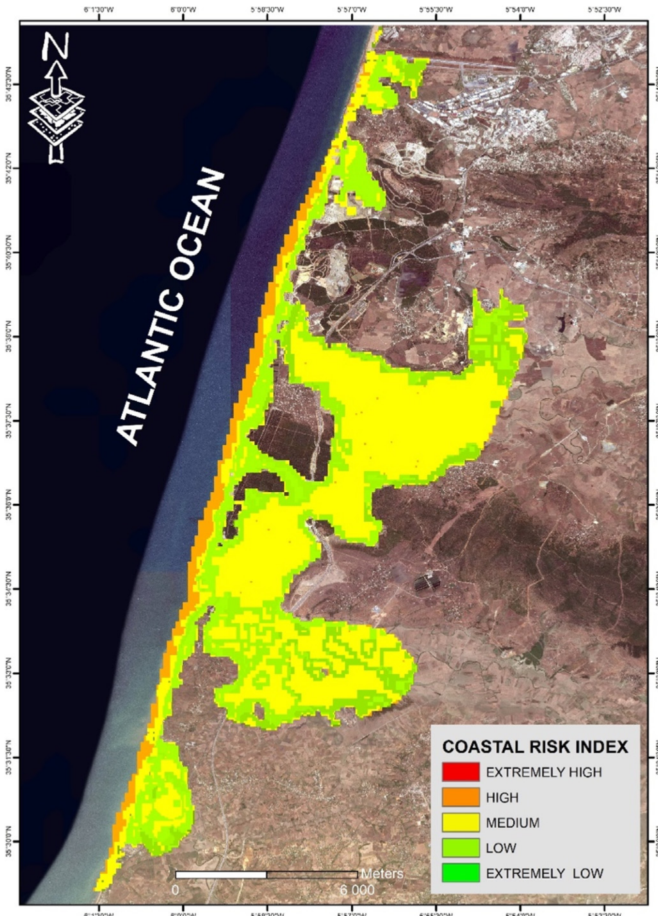

Fig. 8. Map of Coastal Risk Index of Tahaddart coastal zone.

the coastal plain is also at risk of fluvial floods. Rifai et al. (2018) showed that about 8% of the Tahaddart watershed area is prone to flood risk, of which 4% is high risk in the coastal plain. Regarding the shoreline changes, Amharak (2006) showed that due to the construction of Ibn Batttota dam on Mharhar Wadi and the illegal sand mining in the coast, the Tahaddart beaches have experienced a general erosive trend with an average annual rate of 1.94 m/year. Low and very low vulnerability classes cover only 16% of the area and are limited to the outer contours of the study area, where the elevation is slightly higher.

4.3. Coastal exposure index

For the Saidia-Ras Elma coast, the coastal exposure index map (Fig. 5C) shows that the urban agglomerations of Saidia and Ras-Elma have the highest exposure class. These cities concentrate all urban dwellings and equipment, including seaside resorts, roads, ports and marinas. The permanent population is dense: 8550 inhabitants/km^2 for the city of Saidia and 7580 inhabitants/km^2 for Ras Elma and the potential damage could be catastrophic. The rest of the study area, which includes the Moulouya wetland and agricultural lands, is classified with a medium exposure index.

As for the Tahaddart coast, almost the whole area is classified with a medium CEI (Fig. 6F). Indeed, there are only few buildings and farmlands. The area still contains some natural habitats and pristine areas, such as salt marshes and the water bodies, which are weakly exposed.

4.4. Coastal risk index

The risk index map was performed by multiplying the three sub-indices CVI, CFI and CEI values and integrating their pixels (Fig. 7) (Fig. 8). It is then expected that the highest values of CVI, CFI and CEI will led to the extremely highest risk index. This class represents 15% of Saidia-Ras Elma area and is displayed along the sandy beaches of the coast, reflecting their high vulnerability and exposure indices. The Mediterranea Saidia resort with its five stars hotels and the cities of Saidia and Ras Elma are all assigned a high-risk index, because of the high density of urbanization and population which made them highly vulnerable and highly exposed. This high-risk class represents 34% of the area. For the Moulouya wetland, despite its extremely high vulnerability index, it is ranked as medium risk index, due to its medium exposure index.

For Tahaddart coast (Fig. 8), except the coastal fringe, which is assigned a high-risk class (13%), due mainly to the extremely high vulnerability index, no area is ranked as extremely high-risk category. Medium coastal risk index is displayed throughout the whole area, with limited places with low and very low coastal risk index. This distribution is consistent with the vulnerability and exposure classes presented above, and reflects the low exposure of this study area, expressed mainly by a low rate of urbanization and low population density.

The two studied sites include both lowlands and high-ecological wetlands, but they differ in their degree of development, with Tahaddart still relatively underdeveloped, while Saidia has experienced intense urbanization over the last decade. The comparison with the Tetouan coast (Satta et al., 2016), which represents a site with a very advanced rate of development and artificialization (Fig. 9), allowed us to confirm that there is a positive relationship between the coastal risk and the build-up rate. The more a coastal area is artificialized, the more its CRI is high. Indeed, Tetouan and Saidia coasts have been identified as hotspots of coastal risk due to climate change in the Mediterranean region (Satta et al., 2015). The high level of risk that threatens these coasts is due on the one hand to the low elevation of the coastal plains and on the other hand to the high exposure values. For Tahaddart coast, despite its low elevation, its CRI is currently lower than these of Tetouan and Saïdia coasts. This is because Tahaddart is less developed and, except the thermal power plant, there are no other economic assets, nor human concentrations along this coast, which normally increase the exposure and vulnerability sub-indices. Therefore, the least developed coast of Tahaddart, that has still conserved its natural habitats and tidal flats, is currently at less risk of flooding and erosion and can remains so as long as it is protected from urbanization and unsustainable use of its natural resources. In addition, undeveloped and healthy wetlands provide a diverse array of ecosystem services to local population, including regulation. They particularly act as buffer and protect people and infrastructure from the destructive storm surges. Coastal dunes serve also as protective barriers from flooding and erosion and provide reservoirs of sand to replenish the beach zone. Therefore, in order to preserve these valuable ecosystems services, and make the coasts more resilient to future change, the protection of wetlands and dunes is mandatory.

5. Conclusion

The application of the index-based risk assessment methodology to two Moroccan coastal zones, namely Tahaddart and Saidia-Ras Elma, led to identifying and ranking the area's most at risk of flooding. The concept of risk, as defined by the IPCC in its 5th report (IPCC et al., 2014a), refers to forcing, vulnerability and exposure. We thus evaluated the indices of these three components, through an appropriate choice and weighting of environmental and socio-economic variables, which best reflect these factors. Even if very heterogenous, the integration of the three sub-indices CFI, CVI and CEI, allows to calculate the coastal risk index (CRI) and represent its distribution -as well as this of the CFI, CVI and CEI- on maps using the GIS. The results mainly reflect the topography and the nature of the land use. In other words, low and highly urbanized areas have the highest level of risk to flooding, while areas whose naturalness has been preserved, even vulnerable, are less at risk

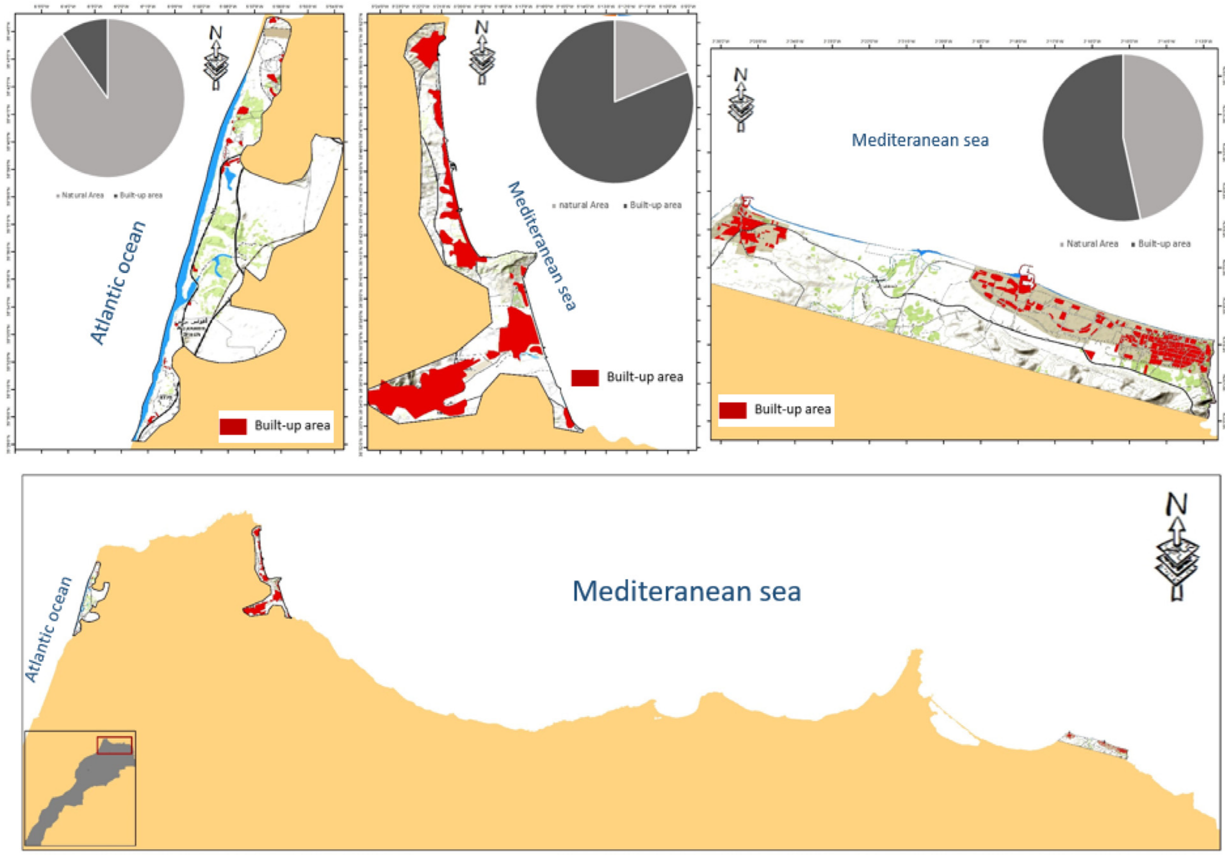

Fig. 9. Maps of the percentage of Built area.

of damage. The comparison with the highly developed coast of Tetouan, confirmed the relationship between coastal risk and rate of artificialization. Consequently, given the effects of present and future human encroachment on the coast, local authorities are faced with the increasingly complex task of balancing development and managing coastal risks - especially coastal erosion and flooding.

Although preliminary and perfectible, this study provides risk maps that can help decision-makers, on the one hand prioritize areas requiring urgent action to cope with climate change, and on the other hand to protect underdeveloped areas and those still pristine, from urbanization and the unsustainable use of natural resources including space. However, the lack of specific regulations for the coast, the lack of knowledge of the value of benefits provided by coastal ecosystems, combined with the poorly planned coastal development and the expected impacts of climate change, hinder effective decision-making about investments, conservation efforts, and management.

Among the possible and no-regrets measures that could help these coasts to cope with climate change and sea-level rise, we recommend nature-based solutions (especially for Tahaddart wetland) and soft measures such as the rehabilitation of coastal dunes, and beach nourishment of eroded coasts. For the already heavily developed coasts of Tetouan and Saïdia, adaptation options require hard structures such sea-wall and dikes to protect the high-value assets at the seashore. These should be combined with the soft solutions whenever possible. However, the most urgent and recommended measure, that could guarantee a long-term effect, is the implementation of the Integrated Coastal Zone Management (ICZM) plan, within which, urbanization and over-use of resources (including space) are strictly controlled.

Finally, with Morocco's high reliance on coastal tourism, coastal risks assessment highlights the urgent need for improved and integrated coastal management to reduce local pressures on the shorelines and preserve the benefits wetlands and dunes provide to the coastal community and the tourism sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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