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COASTAL VULNERABILITY IN THE MEDITERRANEAN SECTOR BETWEEN FNIDEQ AND M'DIQ (NORTH OF MOROCCO)

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Abstract

This study assessed coastal vulnerability to erosion processes along a 24-km-long littoral with different levels of human occupation. An aerial photogrammetric flight and a Quickbird satellite image were used for mapping land uses and reconstructing coastal evolution from 1986 to 2003. Maximum erosion (-2.48 myr^{-1}) was recorded south of Marina Kabila port and maximum accretion (+2.25 myr^{-1}) south of Marina Smir port. Erosion/accretion rates have been divided into five categories and land uses have been mapped and divided into three categories. Coastal vulnerability has been assessed by combining coastal trend with land-use categories: 10% of the littoral recorded "very high" vulnerability, 29% recorded "high" vulnerability, and 61% of the investigated littoral presented "null" and "low" vulnerability. The "Imminent Collapse Zone", i.e. the littoral zone threatened by imminent erosion, presented mean values of 10.34 m, with maximum and minimum values of 15.3 and 7.6 m, respectively. Several human structures and activities are located within the imminent collapse zone and consequently will be threatened by severe erosion in near future.

Key words: GIS, satellite image, beach erosion, port, vulnerability, Morocco

1. Introduction. The variability of coastline position has a large range over time and space in response to a single or multiple factors. Over time-intervals lower than one year, the principal reasons for coastal erosion or accretion are

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essentially seasonal variability in wave energy and/or circulation in the nearshore zone and the impact of large individual storms and tsunamis. Over multiyear to decadal time frame, the most severe factors involved in coastal variability are sea level rise, increase in storm and wave energy, changes in coastal morphodynamics and long-term variations in the relationship between marine climate and sediment supply.

Despite causes and reasons for coastal erosion, littoral retreat is always reflected by inundation processes and/or beach, dune and cliff erosion. When the natural processes affect or threaten human activities or infrastructures they become a natural risk. In order to prevent the impact of natural hazards and associated economic and human losses, coastal managers need to know the intrinsic littoral vulnerability, using information on the physical and ecological coastal features, human occupation and present and future shoreline trends [1].

Vertical aerial photographs, satellite images, maps and charts are very useful tools for reconstructing coastline change at long (> 60 years) and medium (between 60 and 10 years) temporal scales [2, 3] and, further, they display coastal types distribution and dune fields evolution. Over the last two decades, airborne laser surveys or topographic "LIDAR" ("Light Detection and Ranging"), have been increasingly used in coastal morphological studies [4]. All previously analysed techniques are also common tools which give pertinent information for environmental mapping and classification, effects of storms, character of wave shoaling, land uses, etc. [5–7].

Using these techniques, vulnerability maps have been obtained for several coastal sectors around the world through the use of Geographical Information Systems (GIS), computer-assisted multivariate analysis and numerical models [8, 9]. "Flood Insurance Rate Maps" have been created by the USA government and "Coastal Zone Hazard Maps" have been prepared for coastal stretches affected by hurricane Hugo. In Spain, the Ebro delta vulnerability was evaluated over different time scales and a vulnerability assessment for a coastal sector located in Sicily (Italy) was presented by [10]. A GIS based coastal vulnerability index was developed for the Northern Ireland littoral [1] that took into account socio-economic activities [11], coastal erosion resistance and energy characteristics. Beach reduction at Rosario (Mexico) was combined with the probability of damage to landward structures, obtaining a vulnerability matrix. A GIS-based vulnerability assessment of coastal natural hazards for the state of Pará (Brazil) was carried out by [12].

Furthermore, [13] and [14] introduced new concepts on coastal management: coastal planners must be prepared for medium and long-term changes in land use, such as the replacement of a beach by a salt marsh.

This work presents a vulnerability map of the Mediterranean littoral between the coastal villages of Fnideq and M'Diq, in the northern part of Morocco. The vulnerability map was obtained through the spatial analysis of coastal erosion/accretion data and land uses. Erosion and accretion rates have been obtained for the 1986–2003 period through the use of aerial photographs and a Quickbird satellite image which was also used to map land use. Obtained data are very useful to local authorities to predict future shoreline behaviour in order to determine safe construction locations and elaborate land use plans [8].

2. Study area. The studied area consists of a 24-km-long coastal sector between the Moroccan villages of Fnideq and M'Diq (Fig. 1). The beaches consist of sand sediments, mainly composed of quartz. Dune ridges, fossil cliffs and a small, rocky shore platform (in Restinga zone) are also present along the studied littoral. Active cliffed sectors are only located north of Kendissa and are stable at the time scale of this study. No significant sedimentary inputs are derived from cliff retreat processes. Major watercourses flowing into the studied coast are the Rio Negro and Smir rivers and Fnideq Stream whose basins are 16, 74 and 10 km^2 respectively. Their fluvial inputs, are not significant especially after 1991, when a dam was emplaced in the Smir River, the most important sedimentary source.

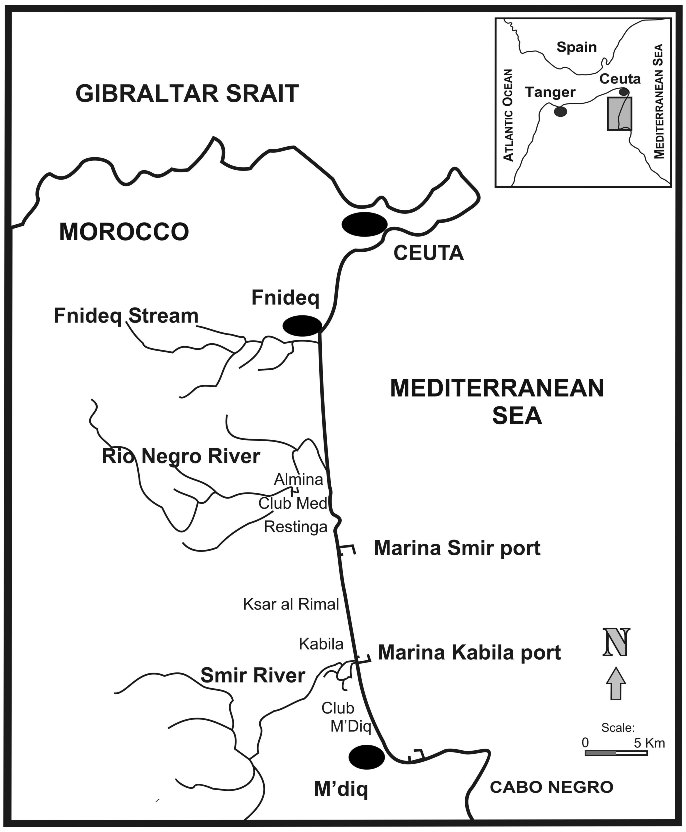

Fig. 1. Location map of the studied area

The area tidal characteristics are semidiurnal and microtidal ranging from a few centimetre neap tide to between 80 and 100 cm spring tide. Easterly wind "Chergui" prevails from May to October, whereas from October to February, westerly "Gharbi" winds are recorded. During the months of April and May there is equilibrium between ENE and WSW winds.

Due to littoral orientation, waves approach the coast from the first and second quadrants while waves associated with storm conditions come from the E and ENE. In M'Diq, highest recorded wave height from these approaching directions is 5.5 m with a period of 5 seconds and a recurrence period of 20 years. The main currents flow northwards but SSE during the summer season, with a maximum velocity of 0.68 m/s.

A sea level rise value for the investigated area of 2.5 mm yr^{-1} was proposed, with hypothetical sea level increase of 15 and 27.5 cm respectively by 2050 and 2100.

Coastal occupation has been growing over recent years because of the increasing tourist demand. In detail, coastal developments covered the 15.5% of the littoral area in 1969, the 27% and 48% respectively in 1986 and 1994, and the 80% and 90% respectively in 2004 and 2007. As a result, the littoral is nowadays very urbanized and tourist activities represent the main economic resource in the area. Human occupation mainly consists of the construction of tourist (i.e., Marina Smir and Marina Kabila) and fishing-devoted (i.e., M'Diq) ports, summer houses, hotels and a motorway which runs parallel to the coastline. The urbanization process considerably affected the coastal environment, essentially dune ridges and two lagoons of great ecological interest. The Protection Zone includes the seashore and a 6 m strip landward extended from the maximum limit which the water reaches, but a 100 m wide zone is proposed in the new Coastal Act, which has been waiting approval since 1996.

3. Methods. To obtain coastal erosion susceptibility maps, this work was based on interpretation and combination, using GIS tools, of land use distribution with medium-term evolution of the investigated littoral which shows homogeneous beach morphology and topography [15].

Satellite imagery constituted the basic cartography used over GIS projects within the present study. Land uses and human activities were mapped on the satellite image within littoral zone extending from shoreline to a landward distance of 3 km. Information on land uses was complemented by accurate field observations on occupation degree and type.

Concerning the analysis of coastal evolution, it was carried out following the "end point rate" method using the 1986 photogrammetric flight (scale 1:20 000) and 2003 Quickbird satellite image (spatial resolution: 60 cm).

The analysis of coastal evolution followed the methods described by [16]. The 1986 photos were scanned, geo-referenced and geometrically rectified to solve aerial photographs distortion problems. Ground Control Points (GCP^s) for photo registration was obtained from the multispectral Quickbird image of 2003 and all information was presented in Gauss-Boaga Coordinates (zone 30, datum WGS84). Taking into account the smooth topography of the studied area, a 1st degree polynomial transformation was applied in the registration process. The number of GCP^s used varied from one photograph to another (ranging from 9 to 15 units) and their position has been located in unequivocal places.

Photographic distortion error was reduced and controlled in the geo-referenced documents by visual estimations comparing the registered photo with the base map (the satellite image), and through the root mean square error (RMSE). Being a microtidal environment, the shoreline position was defined as "the water line at the time of the photo" (page. 690, [17]). Because it was not possible to determine tide level position at the moment of the photo and to reduce errors in determining shoreline position because monthly and seasonal variations, [15] used topographic profiles surveyed in studied littoral during two years (2003–2005) to calculate foreshore slope and variations in shoreline positions. As a result [15] recommended, for the characterization of medium-term coastal evolution, to reject shoreline variations lower than 3.66 m. No storm conditions, which can give rise to run-up processes and unrealistic sea level position, were observed in the photographs and satellite image. Furthermore, aerial photographs and satellite image were respectively taken in May 1986 and June 2003, thus damping seasonal fluctuations.

Last, vulnerability matrix was the result of spatial union between accretion/retreat rate and land use layers [10]. The "Spatial Analyst" extension of the ArcGIS 9.1® software has been used to carry out all the spatial analysis procedures. The used methods included "intersection" and "union" operations between geographical layers containing different kinds of information.

4. Results. ***4.1. Coastal evolution.*** Coastline erosion/accretion rates for the 1986–2003 period was presented in Fig. 2. Considering the magnitude of shoreline movements because of monthly to seasonal variations (3.66 m) and the studied interval (17 years), coastline variations lower than 0.21 m yr^{-1} were not considered as representative. It is important to state that the aforementioned value (0.21 m yr^{-1}) was generally much smaller than the recorded erosion/accretion values, this indicating the prevalence of continuous, severe erosion/accretion processes during the studied interval.

The recorded general erosion confirmed the results obtained by [15] for the 1986–1994 and 1994–2003 intervals. Similar results were also obtained by other authors who studied the 1958–1986, 1986-1997 and 1997–2003 periods: erosion was recorded with mean values of 1.7, 1.3 and 2 m yr^{-1} respectively, and accretion was observed south of Marina Smir port (considering the 1958–2003 period, the 70% of the littoral recorded erosion). Thus, it is possible to state that the investigated littoral recorded continuous erosion from 1958 to 2003, obtained results excluding the existence of erosive and accretionary cycles, which could lead to misleading results because the use of the "end point rate" method to asses medium-term coastal evolution. In detail, coastal sector between Fnideq village and Club Med (Fig. 2) recorded high erosion rates, with mean and maximum values respectively of 0.76 and 1.36 m yr^{-1}. The littoral sector between the Club Med and Marina Smir port recorded mean erosion rate of 0.63 m yr^{-1}, with a maximum erosion value of 1.13 m yr^{-1}.

Erosion prevailed in central part of the coastal sector between Marina Smir and Marina Kabila ports, and important accretion was recorded southern of Marina Smir port (Fig. 2). Very important erosion was recorded in the southern part of studied littoral, between Marina Kabila port and Club M'Diq, with mean and maximum values respectively of 1.8 and 2.46 m yr^{-1}, as well as between Club M'Diq and M'Diq village, with maximum and minimum values respectively of 1.5 and 1.0 m yr^{-1}.

Using GIS tools, recorded retreat and accretion rates were grouped into five categories (Table 1) including "strong erosion" ($>$ 1.75 m yr^{-1}), "moderate erosion" (between 1 and 1.75 m yr^{-1}), "low erosion" (between 0.25 and 1 m yr^{-1}), "stability" (between 0.25 m yr^{-1} of erosion and 0.25 m $yr^{-1}$of accretion) and "strong accretion" ($>$ 1.75 m yr^{-1}). Accretion values lower than 1.9 m yr^{-1} were not recorded hence "low" and "moderate accretion" categories were not created.

Table 1

Erosion/accretion and land use categories

Accretion/retreat rates	Very high capital land use (3)	High capital land use (2)	Low or no capital land use (1)
Strong erosion (−3)	−9	−6	−3
Moderate erosion (−2)	−6	−4	−2
Low erosion (−1)	−3	−2	−1
Stability (0)	0	0	0
Strong accretion (+2)	+6	+4	+2

4.2. Land use. Land use map includes tourist, agricultural, naturalistic and recreational activities, which were grouped in three different categories (Fig. 2 and Table 1) according to their economic value and density of urbanization.

Hotels, most important villages (i.e., Fnideq, Kendissa and M'Diq) and an urbanized area located south of Marina Kabila port, mapped as "restricted area" because property of the Royal Family of Morocco (hence with an important economic and political value), were included within the "very high capital land use" category (Fig. 2 and Table 1). The aforementioned villages, initially small communities devoted for agricultural and fishing activities, recorded a huge increase since the nineties because of immigration from hinterland and southern regions of Morocco [18]. Urbanizations (mapped as "residential areas" in Fig. 2), are composed of summerhouses essentially consisting of one- or two-storey isolated buildings

Fig. 2. Land use map, coastal evolution rates (m yr^{-1}) for the 1986–2003 period and vulnerability map of the studied littoral

Fig. 3. Last stages of a storm approaching from the East which stroke the studied littoral at the end of May 2006. Swash processes affected summerhouses at Almina (a), buildings under construction and residential area located between Ksar al Rimal and Kabila (b and c) and backshore at M'Diq village (d) where leisure facilities and a promenade are under construction

but four- and five-storey buildings have also been constructed with a consequent relevant impact on landscape. These developments, built in the 1980–1990 and (especially) 1990–2005 periods, have been classified within the "high capital land use" category (Fig. 2 and Table 1).

Last, agricultural-devoted areas, farms, and areas with no human activities, were included within the "natural and agricultural areas" mapped in Fig. 2. Areas devoted to camping activities ("camping areas") and protected areas ("natural protected areas") were also mapped. All previous classes were included within the "low or no capital land use" category (Fig. 2, Table 1). In detail, agricultural activities are carried out along the coastal plain and consist of traditional and intensive uses which include croplands especially for growing wheat (58.2%), forage (26%) and vegetables (15% [18]).

5. Discussion. ***5.1. Littoral dynamic.*** Taking into account the distribution of erosion/accretion areas along studied littoral (Fig. 2), it is possible to state that an offshore transport and, secondarily, a longshore northward directed transport prevail in investigated littoral. The first one produced general erosion along the investigated area, with most important values in the southern part that suffered the influence of Cabo Negro promontory. The second one produced accretion south of Marina Smir port, this way confirming local current measurements and impact of human structures on littoral transport [19, 20]. An opposite transport is also observed and responsible for small accretion north of Marina Kabila port. Sediment deposition in these areas is strongly related to port design and dimensions, in fact port structures work as fixed limits dividing the coast in littoral cells of different dimensions [15]. Probably, in the open sector between Fnideq village and Marina Smir port, free limits are formed, their determination being quite complex.

Other reasons for coastal erosion are the decrease of sediment supplies after the construction of a dam in Smir River and progressive and general urbanization of dune ridges (Fig. 3) which represented past barriers to flooding of low laying coastal areas as well as a natural reserve of sediments easily eroded under extreme wave conditions.

5.2. Littoral vulnerability. Information on coastal erosion/accretion and land use was combined obtaining several classes of coastal susceptibility to erosion/accretion processes (Fig. 2 and Table 1).

Concerning erosion/accretion rates, a value of "-3" was attributed to strong erosion (the negative sign indicating erosion), "-2" was related to moderate erosion, "-1" to low erosion, "0" to stability, and "$+2$" indicated strong accretion (the positive sign indicating accretion, Table 1). A value of 2 (and not 3) was attributed to strong accretion because we considered accretion-related problems less important than those related to erosion processes. Dealing with land use, a value of "3" was attributed to areas of very high capital use, "2" to areas of high capital use and "1" to areas of low or no capital use (Table 1).

The obtained coastal vulnerability classes were characterised with a numerical value preceded by a positive or negative sign indicating vulnerability respectively because of accretion or erosion processes (Table 1). This way, a value of "9" indicated "very high vulnerability", "6" and "4" corresponded to "high vulnerability", "3" to "medium vulnerability", "1" and "2" to "low vulnerability" and "0" to "no vulnerability" because no changes were recorded.

Coastal vulnerability along the studied littoral was presented in Fig. 2 and percentages of littoral vulnerability were calculated using GIS outputs. High vulnerability, because of accretion, was recorded in 2% of littoral, south of Marina Smir port. As a result, aforementioned port, which is open to the south and this way stop longshore drift, suffers progressive infilling problems. Null and low vulnerability were respectively recorded in 7% and 54% of littoral. High vulnerability because of erosive processes, usually as a result of combination of moderate or high erosion rates with high capital land use, affected 27% of investigated littoral, i.e. Yasmin and Almina areas, the sector between Restinga and Marina Smir port, and the sector between Club M'Diq and M'Diq village (Fig. 2). Last, very high vulnerability, related to combination of very high capital use and high erosion rates, affected 10% of littoral, i.e. the area between Marina Kabila port and Club M'Diq.

Coastal retreat rates have been used to calculate the Imminent Collapse Zone (ICZ, [3]), i.e. the littoral zone threatened by imminent erosion, extending from shoreline landward with a width equivalent to five times the site erosion rate plus approximately 3.0 m (10 ft). Taking into account the maximum retreat rates, the ICZ presented mean values of 10.34 m, with maximum and minimum values respectively of 15.3 m (south of Marina Kabila port) and 7.6 m (between Marina Smir and Marina Kabila ports). Aforementioned values have been represented on satellite image from the water mark of maximum flooding: several human structures are very close or fall within the ICZ. It is interesting to notice that results on the position of ICZ were confirmed by field observations carried out in May 2006 during last stages of a storm approaching from the East (Fig. 3).

Last, it is interesting to notice that most vulnerable areas (because of erosion processes) and wider ICZ zones are not strictly linked to the presence of port structures. This is because the area records a net offshore transport and longshore transport homogeneously affects investigated littoral, which is rectilinear, and produces accretion when it interacts with port structures, only at very specific places. As a result erosion processes affect extensive areas but accretion takes place at very located places close to Marina Smir and Kabila ports.

6. Conclusions. Studied coastline, which experienced an increasing pressure from tourism and economic developments, is coming over recent decades under important erosion processes. As a result, 27% and 10% of the investigated littoral respectively record high and very high vulnerability because of very high and high capital land uses threaten by important erosion processes. High vulnerability because of accretion is only recorded in 2% of the littoral, upstream of Marina Smir port, and null and low vulnerability are respectively recorded in 7% and 54% of the littoral. Further, several human structures are very close or fall within the ICZ and will suffer important erosion in future years. According to previous results, there is a pressing need to present environmentally acceptable solutions to solve current and future shoreline problems.

Local planning staff must identify mitigation strategies from a regional, long-term perspective, this way providing a real foundation for cost-effective coastal erosion management. Sediments can be dredged in the wide beach formed in recent years south of Marina Smir port and inside the aforementioned port and used to nourish Restinga area which presents high vulnerability. Lower quantities of sediments can be also dredged north and inside of Marina Kabila port and used to nourish near eroding beaches. Permanent by-passing systems should be emplaced at those localities, i.e. Marina Smir and Marina Kabila, to prevent excessive sand accumulation processes. Further, the Authorities should support beach nourishment works (probably associated with the construction of small hard structures) to prevent future coastal damage at Club M'Diq, Smir lagoon, Almina and Yasmin sectors which present very high and high vulnerability and periodic erosion during severe storms, even though until recently, no damage has been recorded by the back beach structures. To this end, the Planning Administration should develop a program of marine geophysical investigations devoted to locating suitable marine sand deposits for nourishment purposes.

It is also important to regulate future development by restricting certain activities in specific, not urbanised, eroding sectors, i.e. at Tres Piedras and Kendissa. Abandonment and/or relocation are probably the best solutions in the previous sectors which present few, dispersed summer houses and an area devoted for camping activities.

Last, similar studies should be carried out in several sectors of the Atlantic and Mediterranean Moroccan littoral, which is recording increasing urbanization and development.

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