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# The Nador barrier island system (Morocco): functioning, natural and man-induced controls, scenarios of future evolutions

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**Abstract:**
The Nador barrier island system located on the Eastern Mediterranean coast of Morocco is an ecosystem of scientific and socioeconomic interest. The study of all its components (water mass, sediment, microfauna) and physiographic domains, as well as its hinterland and the close continental shelf, was conducted using various disciplines and techniques: geomorphology and morphodynamics (field study and analysis of satellite images over a period of 34 years), morphostructural analysis, sedimentology, ecology and water quality. The results which are mostly new and unique allowed understanding of the mode of the genesis and functioning of this lagoon system and highlighted the spatial and temporal evolutions at a seasonal and millennium scales. These evolutions are related to anthropogenic as well as natural factors which can act independently or simultaneously. The analysis of the effects of natural factors impacts helped to predict seven possible scenarios of future evolutions of this ecosystem.
In addition to their scientific interest, the results obtained as well as the generated thematic maps and the Territorial Information System (SIT) maps, constitute an important database and a fundamental decision-making tool for an adequate management and development of the region. Furthermore, the approach adopted for this study is expected to be particularly useful as a support for decision-making in the framework of exploitation and management of coastal ecosystems in general and lagoon systems in particular.

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## 1. Introduction

The Nador barrier island system belongs to the Eastern Mediterranean coast. It is located in the northern extremity of the Bou Areg plain between Beni Ensar city to the Northwest and Kariat Arekmane village to the Southeast (figure 1). This ecosystem includes (1) an elongated barrier island composed of a Quaternary bedrock topped by a sandy spit of 25 km in length and 300 to 400 m in width, except in the Southeastern part where it reaches 1.7 km, (2) a lagoon of semi elliptical shape, having a surface of 115 $km^2$ and a maximum depth of 7.5-8 m in the central part and (3) a continental margin (mainland) displaying salt marshes and ten streams (oueds) of periodical flows. This ecosystem, which is of particular scientific, biological and socioeconomic interest (ranked SIBE), has been subjected to high anthropogenic pressure (figure 2) and to managements using engineered structures (LOUAYA & HAMOUMI, 2006, 2011). Therefore it generated numerous studies within the framework of fishing and aquaculture development programmes as well as academic researches (ERIMESCO, 1961; TESSON, 1977; BRETHES & TESSON, 1978; SAUBADE, 1979; TESSON & GENSOUS, 1978; GUILLEMIN & HOUZAY, 1982; IRZI, 2002; MAHJOUBI, 2001; INANI, 1995; ARID *et al*., 1995; LEFEBVRE *et al*., 1996; DAFIR, 1996; EL-ALAMI *et al*., 1998; RAHOUTI, 2004). However, most of these works focused especially on the lagoon and very little was done on the morphodynamics and evolution of the barrier island. Knowing that the barrier island system’s elements are interdependent and that the genesis and the evolution of this ecosystem are closely linked to the regional geological context, it was necessary to undertake a study which integrates at the same time all its physiographic domains and all its components (water mass, sediments, microfauna) as well as its hinterland and the close continental shelf. This multidisciplinary study focused on geomorphological and morphostructural analysis at the regional scale(LOUAYA & HAMOUMI, 2006 & 2010), geochemistry (BLOUNDI, 2005), morphodynamics, sedimentology, ecology and water quality. The aim of this paper is to understand the mode of genesis and functioning of the Nador barrier island system and to predict its future natural or human-induced evolution using the results presented at the Tangier CM² Conference (HAMOUMI, 2011; HAMOUMI *et al.*, 2011a; HAMOUMI *et al.,* 2011b; LOUAYA & HAMOUMI, 2011).

## 2. Geological and physical setting

The Nador barrier island system belongs to the subsiding Neogene basin of Nador-Melilla, which was created during the upper Miocene. The structural history of this coast is very complex. After the paroxysmal phases of the Alpine orogeny, it was subjected to alternating phases of compression and distension, accompanied by calco-alkaline volcanism of shoshonitic tendency, in a context of NNW-SSE convergence of the European and African plates during the Neogene and the Quaternary (GUILLEMIN & HOUZAY, 1982; HERNANDEZ, 1983).

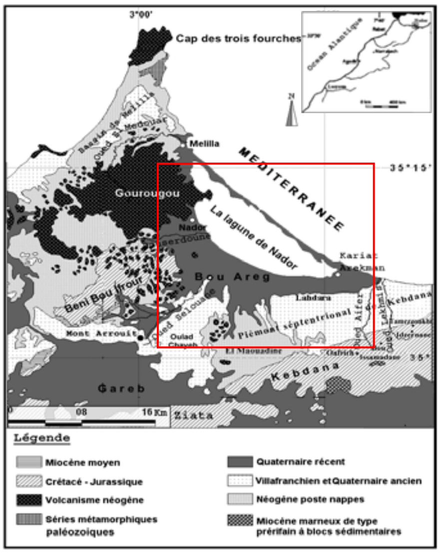



*Figure 1. Situation of the Nador barrier island system and regional geological framework after the geological 1/ 500000 scale map of Oujda.*


*Figure 2. Map of anthropogenic activities.*

The climate is of Mediterranean type, characterized by a low rainfall (150 to 450 mm/year), temperatures that range from 13°C during winter to 35°C during summer and winds of W and SW direction during winter and N and NE in summer. The coastal hydrodynamic regime is dominated by storm waves, swells from NE to ENE and W to NW which can reach 5 m in height and periods of 7 to 11 s (BRETHES & TESSON, 1978) and a littoral drift whose direction varies according to the seasons. The tide is semidiurnal with amplitudes varying from 13 cm outside the inlet to 3 cm inside the lagoon (HILMI, 2005). The intra lagoonal circulation is controlled by the currents (Mediterranean waters) entering through the inlet. According to ERIMESCO (1961) they circulate as a gyre, flowing along the barrier island towards the SE then towards the NW to leave the lagoon. But according to HILMI (2005), they flow towards the NW and dive at the lagoon ends depending on the wind direction. The circulation is also controlled by wind induced currents flowing along the barrier island that dive at the lagoon ends to fuel in-depth return currents (HILMI, 2005).

## 3. Materials and methods

The approach adopted in this work uses a very broad investigation program that involves various disciplines and techniques e.g. geomorphological study at regional scale and morphodynamic monitoring of the lagoon system during the period 1975-2005, based on field data and interpretation of satellite images that have been updated until 2010 (LOUAYA & HAMOUMI, 2006). In addition, the change detection using multi-temporal satellite images (Landsat MSS, 1975 and 1976; Landsat TM, 1986, 1988, 1993 and 2010, Landsat +ETM, 2000, 2005), was also applied using a 10 year scale period as well as over a period of 34 years. Sedimentological and ecological studies (HAMOUMI *et al.*, 2011a; HAMOUMI *et al.*, 2011 b), were conducted in parallel with the study of the water quality: physico-chemical parameters, nutrients and suspended matter of lagoonal waters (surface and bottom) and mouth stream waters (IOUZZI et al., 2005), according to a seasonal monitoring during the period 2003-2005 and a sampling strategy covering all lagoon domains and all areas likely to be affected by anthropogenic activities (figure 1, in HAMOUMI *et al.*, 2011a). The sedimentary and ecological environments were reconstructed for the present-day, using surface samples and sediments from the tops of the cores and for the period 1000 to 1200 years BP (estimated according to the datations proposed by MAHJOUBI, 2001), using the sediment samples from the bottom of the cores taken during the 2003 winter.

## 4 Ecosystem functioning

The correlation of hydrological and hydro chemical environments (IOUZZI et al., 2005) with reconstituted sedimentary and ecological environments, allowed to identify six dynamic zones in the lagoon (figure 3) and to understand their present-day functioning and its temporal evolution at a seasonal scale and for the period 1000 to 1200 years BP.

### 4.1 Present-day period

Zone I corresponds to the inlet, having a depth of 4 m and subject to a high hydrodynamic regime dominated by meteorological and tidal currents. The values of its physico-chemical parameters, dissolved oxygen and nutrients indicate a strong Mediterranean influence and non-polluted water mass. The sediment supplies consist of brown, very well to well sorted medium marine sands, very rich in bioclasts and shells of bivalves and gastropods. They are composed of: quartz, feldspar, calcite (51.74%), the clay mineral suite: illite - kaolinite - smectite - chlorite and the accessory minerals: gypsum, halite, pyrite, aragonite and dolomite. This zone coincides with the ecological environment III characterized by: (1) an Ostracods association of high biodiversity and moderate density, where *Cyprideis* (>60%) prevails on *Loxoconcha* (10-20%), and (2) a foraminiferal association where peritidal species (36 to 48%) represented by *Ammonia tepida*, *Bolivinidae* and *Rotaliina* that predominate on the Miliolidae everywhere except in the sampling station 37 where the Miliolidae are dominant.

Zone II corresponds to the outer lagoon margin of depths varying between 0 and 2.7 m and submitted to tidal and meteorological currents entering by the inlet and storm surges, except in the areas sheltered by the spit’s hooks which are the seat of confinement. Its physico-chemical parameters and dissolved oxygen and nutrient contents indicate a strong Mediterranean influence and non-polluted water mass. Sediment supplies from the Mediterranean Sea and barrier island are composed of clays and brown sands with high content of bioclasts and shells of bivalves and gastropods. Sands are fine to medium and well sorted except in the sheltered areas where they are fine and moderately sorted. They consist of: quartz, feldspar, calcite (43%), the clay mineral suite: illite - kaolinite - chlorite – smectite) and the accessory minerals: gypsum, halite, pyrite, aragonite and dolomite. This zone is also characterized by the ecological environment III.

Zone III corresponds to the central part of the lagoon with depths varying from 3 to 7.5 m, its southern margin is under continental influence and its northern margin as well as its NW and SW corners are under marine influence, but its central part, characterized by weak circulation, can be the seat of a weak confinement especially during summer. Nutrient and dissolved oxygen contents indicate a slight impact of pollution which decreases as one moves away from the continental margin. The sediments consist of dark grey to green silty clays, sandy clays and clays with bioclasts and shells of molluscs and bivalves. Sands generally of medium size and poorly sorted are composed of: quartz, calcite (5.3-26.5%), feldspar, the clay mineral suite kaolinite - illite - smectite - chlorite and the accessory minerals pyrite, dolomite. This zone is also characterized by the ecological environment III.

Zone IV corresponds to the NW (Beni Ensar) and SE (Kariat Arekmane) corners under continental influence, highly confined and whose depths ranging from 0 to 1.20 m may reach 4 m. The water mass is characterized by high salinity which can reach 40.9 g/l, high pH values around 8.57, dissolved oxygen content lower than 6.8 g/l and high concentrations of: ammonium (1.46 µmol/l), nitrates (7.59 µmol/l), nitrites (7.99 µmol/) and phosphorus (9.97µmol/l). The sediments are composed of dark brown sandy clays, gravelly sandy clays and clays with significant organic matter content, bioclasts, shells of gastropods and bivalves and plant debris. In the NW corner (Beni Ensar) fed by the Gourougou massif, and the "Mont Atalayoune", mineralogical constituents are: feldspar (abundant), quartz, calcite (5.3%), the clay mineral suite smectite (largely dominant) - kaolinite - illite and the accessory minerals gypsum, halite, aragonite, dolomite, and hematite. In the SE corner (Kariat Arekmane) fed by the Kebdana massif and the Bou Areg plain, the mineralogical constituents are quartz, feldspar, calcite (26.5%), the clay mineral suite kaolinite (dominant) - smectite - illite-chlorite and accessory minerals gypsum and halite. This zone coincides with the ecological environment II characterized by (1) an Ostracods association of low density and generally moderate biodiversity where *Loxoconcha* (>50%) prevails on *Cyprideis* (20-30%), and (2) a foraminiferal association dominated by the peritidal group where the Nonionidae family (*Ammonia tepida* followed by *Nonion depressulum*), reaches a percentage of 60% and includes marine epifaunal species (Miliolidae and Bolivinidae).

Zone V corresponds to the northern part of the inner lagoon margin (continental margin), between Oued Sidi Youssef and Taouima, ranging in depth from 0 to 3 m and fairly confined except during periods of fluvial discharges. It is submitted to continental influence and anthropogenic pollution which results in generally high pH that can reach 10.13, dissolved oxygen content of 6.8 to 7.2 g/l and nutrient contents that can reach 0.889 µmol/l of ammonium, 12.3 µmol/l of nitrates, 37.9 µmol/l of nitrite and 0.97 µmol/l of phosphates. It is fed by the Beni Oufrour and Gourougou massifs, the "Mont Atalayoune" and the Bou Areg plain. At the river mouths, the sediments are poorly sorted (clays, sands, gravels and pebbles) and rich in organic matter. The remaining areas consist of brown poorly sorted clayey fine sand, sandy clays, silt, clays with bioclasts, shells of bivalves and gastropods, plant debris and organic matter. The mineralogical components are quartz, feldspar, calcite (18.5%), the clay mineral suite smectite (largely dominant) - kaolinite - illite and the accessory minerals: gypsum, halite, aragonite and dolomite. This zone coincides with the ecological environment I characterized by (1) an Ostracods association of low density and relatively high biodiversity that shows nearby proportions of *Cyprideis* (40.1%) and *Loxoconcha* (37.7%), and (2) an association of foraminifera dominated by peritidal species, in particular *Ammonia tepida* (68%).

Zone VI corresponds to the southern part of the inner lagoon margin (continental margin) between Taouima and Oued Hali, ranging in depth from 0 to 3 m, fairly confined except during the periods of fluvial discharges and submitted to a significant pollution. It differs from the zone V only by (1) its mineralogical composition: quartz (abundant), calcite (28%), feldspar, the clay mineral suite: illite - kaolinite - smectite - chlorite and accessory minerals halite, dolomite and hematite, which indicates supplies from the Kebdana and Beni Oufrour massifs and the Bou Areg plain and (2) its ecological environment, which is of type II as the zone IV.

Seasonal control is expressed in winter by coarse (sand and gravels) flux and a lowering of the fauna biodiversity and density related to the effects of the turbidity and the desalinization induced by fluvial discharges in zones IV, V and VI. During summer, seasonal control is recorded by (1) the physico-chemical parameter’s changes, especially, in the areas submitted to confinement and continental influence, (2) the predominance of the clays decantation in the zones under continental influence, (3) a general increase of *Loxoconcha* and decrease of *Cyprideis*, (4) an evolution of the ecological environment III into the ecological environment II in the southern border of the zone III and (5) an increase of Rotalinidae, a decrease of Miliolinidae and a slight increase of the peritidal species in the zones V and VI.

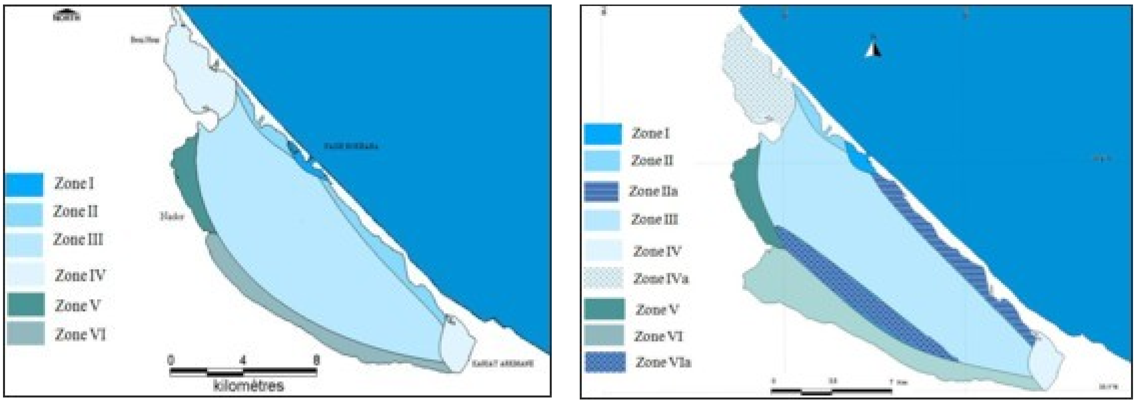
4.2 The period 1000-1200 years BP

Reconstructions for the period 1000 to 1200 years BP, show the existence of nine dynamic zones (I, II, IIa, III, IV, IVa, V, VI, VIa) in the lagoon (figure 3).

- Zones: I, II, III, IV, V and VI are the same as those identified for the present-day period, except that zone VI was located further inland, zone II was situated in the northern part of the barrier island and zone IV existed only in the SE corner.

- Zone IIa characterized by the ecological environment II occupied the southern part of the outer lagoon (lagoonal border of the barrier island).
- Zone IVa characterized by ecological environment II, with a significant marine influence occupied the NW corner
- Zone VIa characterized by ecological environment III under marine influence was situated at the margin of the central part of the lagoon.

Such organization was determined by the morphology and the size of the lagoon and the inlet location. The continental boundary of the lagoon was further inland and coincided with the present continental boundary of the Taouima salt marsh. Furthermore, the inlet N° 4 (in LOUAYA & HAMOUMI, 2006) occupied a different position; it was situated at the present location of the double tombolo (2.856W; 35.201N).




Present-day 1000-1200 years BP

*Figure 3. The dynamic zones of the Nador barrier island system.*

**5. Natural and man-induced control**

5.1 Natural factors

The ecosystem functioning is closely linked to the position and the size of the inlet and the morphology and the size of the lagoon. These characteristics that play an important role in the distribution of the dynamic zones during the present-day period as well as the period 1000-1200 years BP, are controlled by tectonics and climate. The results of the morphostructural study (LOUAYA & HAMOUMI, 2010), indicated that tectonics played a major role in the genesis and the evolution of the lagoonal system. It is the driving force for subsidence in the Bou Areg plain and the Nador lagoon and for a regional brittle structuring, including vertical and strike-slip faults of N-S, NE-SW, and NNE-SSW directions that controlled the opening and closing of some inlets (LOUAYA & HAMOUMI, 2006) and the fault of WNW-ESE direction, in the extension of the barrier island that affects the southern part of the "Cap des Trois Fourches". The lagoon is the result of the transformation of the upstream part of the present-day bay situated between the "Cap des Trois Fourches" and the "Cap de l'Eau" as demonstrated by: (1)

the geomorphological sequence composed of the Bou Areg plain, the lagoon and the close continental shelf, which is interrupted only by the barrier island (morphological discontinuity), (2) the semi elliptical shape of the lagoon and tighter curvature of its continental margin, (3) the perfect fitting between the SE and NW extremities of the lagoon and the coastline, and (4) the organization of the shelf isobaths in parallel arcs to the coastline (figure 4). The lagoonal system experienced afterward a complex evolution related to repeated periods of immersion/exposure of its barrier island and opening/closing of the inlets. 1000 to 1200 years ago, this ecosystem was a restricted lagoon with a narrow barrier island whose inlet (N° 4) was situated at the location of the present-day double tombolo. But according to the historical data (ERIMESCO, 1961), it would have evolved in the 14$^{th}$ century and by 1545 again in a lagoon with an inlet (N° 6, in LOUAYA & HAMOUMI, 2006) situated at the location of the "Tour Restinga" (2.787 W; 35.152 N). Moreover, the position of the inlet often varied, in addition to the two above mentioned inlets and inlet N° 5 (2.845 W; 35.194 N) opened by a storm surge in 1981. It was enlarged and artificially stabilized in 1993 and underwent transformation into a marina. Four relic inlets have been identified on the basis of geomorphological and morphostructural studies and historical data (Fig. 8 in LOUAYA & HAMOUMI, 2006). The inlets: N° 1 (2.913W; 35.249 N), N° 2 (2.900 W; 35.237 N) and N° 3 (2.874 W; 35.214 N), functioned respectively during the periods: 1910 to 1940, 1889 to 1907 and 1941 to 1979. The inlet N° 7 located between the SE extremity of the barrier island and the "Tour Restinga", whose functioning period cannot be precised in the current state of knowledge, but which probably could be the oldest one. Indeed, it consists of three curved end spits totalizing a length of 6.25 km, each spit is itself the result of the accretion of several hooks. Otherwise, it is in this part that the barrier island reaches its greatest width (1.7 km) and where recent deposits up to 10 m of altitude, display fixed dunes with an important vegetation. Climate controls seasonal fluctuations, fluvial regime, the hydrodynamic regime of the littoral and lagoonal circulation. Seasonal control is expressed by the changes in physico-chemical parameters, ecological environments as well as the nature and the amount of sediment supplies. Periods of drought combined with the silting or the closure of the inlet, have resulted in the lagoon depth decrease (1993) or its transformation into salt marshes (1755, 1907). The climate evolution over a period of 34 years resulted in the drying out of two water plans in the Kariat Arekman salt marsh (figure 5). The hydrodynamic regime dominated by meteorological currents is responsible for the inlets opening and closing. The inlet opening is favored by the characteristics of the barrier island which is narrow and straight. It was induced by storm surge and associated currents which created a breach in the most fragile part and the inlet closing was realized by littoral drift. Finally, the age of 3.000 years BP attributed to a soil level in the barrier island (IRZI, 2002), could be correlated with the sea level fall, identified by many authors

5.2 Anthropogenic pressure

Zones IV, V and VI of the lagoon are directly under the influence of an important anthropogenic pressure related to growing human activities in time and space farming, aquaculture, fishing, industry, tourism and urban development and the partially processed wastes of the treatment station (STEP). The induced pollution that affected the water quality (IOUZZI et al., 2005), has increased significantly since 1982 by comparison with the results of the previous work (INANI, 1995; LEFEBVRE *et al*., 1996; DAFIR, 1996). Its impact is expressed by: (1) a decrease in the percentage of *Loxoconcha* at the expense of *Cyprideis*, the disappearance of marine epifaunal foraminifera and an increase of Spiroloculinidae in the sampling stations subject to wastewater discharges from Oued Bouaroug and the pond treatment station (2) a decrease in the percentage of *Loxoconcha* at the expense of *Cyprideis* in the continental margin of the NW corner and (3) a decrease in the percentages of *Loxoconcha* (10.5%) and *Cyprideis* (62%) in the sampling stations subjected to high nutrient levels because of their closeness to the aquaculture cages. The pollution impact is also expressed by sediment contamination in organic and inorganic pollutants (BLOUNDI, 2005).

Moreover, the autodetection of changes over a period of 34 years (figure 5), showed a reduction of the NW extremity of the lagoon, linked to an artificial filling. It also highlighted important sedimentary imbalances in the barrier island related to the introduction of engineered structures. The great jetty of Beni Ensar harbor, located at the NW end of the lagoon and whose construction was completed in 1978, constitutes an obstacle for sedimentary flux from the North and causes wave refraction at the inlet N° 2. It is also at the origin of the barrier island littoral erosion that intensifies between the double tombolo and the "Tour Ristinga" and the filling of the inlet N° 3. The enlargement and construction of two jetties performed in the inlet N° 5 in 1993, induced a silting behind the NW jetty, erosion behind the SE jetty, the development of a flood delta and a shoreline accretion between the inlet and the double tombolo. Finally, the construction of the present artificial inlet launched in 2009, induced a shoreline accretion behind the West jetty, an erosion behind the East jetty and an accretion of the barrier island lagoonal border behind the East jetty and on either sides of the double tombolo

## 6. Scenarios of possible evolutions of the Nador barrier island system

The impact of anthropogenic factors on the lagoonal system is clearly established. If the pollution has been the centre of attention and has generated an action plan in the framework of the Marchica Med project, launched in 2009, the issue of the impacts of engineered structures still remains a serious problem. The sedimentary imbalances mentioned above could lead to the disappearance of the barrier island, if measures are not taken urgently. Furthermore, climate and tectonics play a key role in the control of temporal and spatial evolutions of the barrier island system and they can act independently or simultaneously.

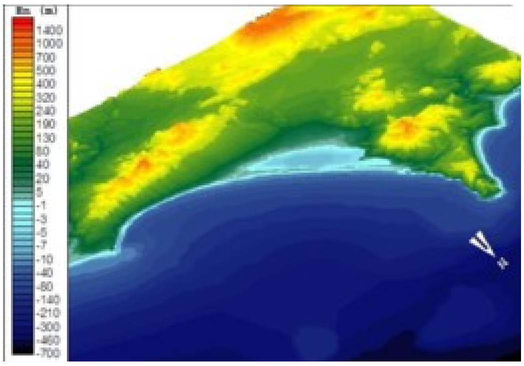



*Figure 4. 3D representation of the SRTM topographic and bathymetric data of the Nador barrier island system and the close continental shelf.*

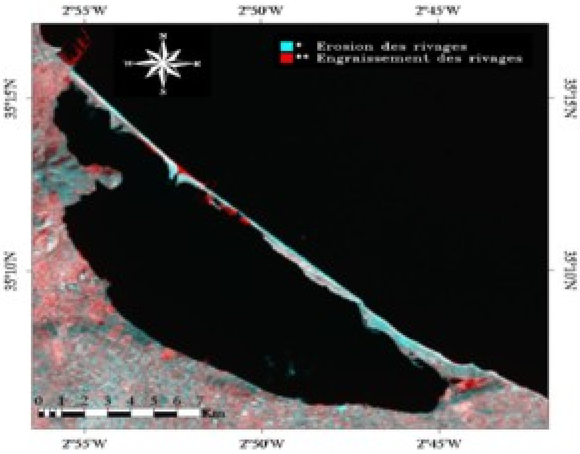



*Figure 5. Figure 5. Image of change detection between 1976 and 2010.*

Concerning the climate, evidence of global warming is well established. Thus, the inescapable hydrodynamic responses of sea level rise and droughts will accelerate the processes of flooding and erosion. The geodynamic context is at the origin of a strong destructive seismic activity in the Nador region which continues nowadays. The earthquakes in 1522, 1579, 1660, 1792, 1821, 1848, 1887 and 1915 and more recently 2005 and 2012, are the direct consequence of this context. Moreover, the volcanic activity that occurred in the region during the late Miocene - early Pliocene and again in the Quaternary and whose magmatic reservoir is probably superficial (GUILLEMIN & HOUZAY, 1982), could be reactivated at any time. However, these tectonic phenomena whose timing, movement type and magnitude are difficult to forecast, remain an unpredictable domain. Therefore, several evolution scenarios can be envisaged for the lagoonal system:

- an eustatic rise induced by climate change, coupled with a tectonic collapse which would induce the transformation of the lagoon into a bay and then into a continental shelf in the long term (figure 6A),
- an eustatic rise induced by climate change, coupled with a tectonic uplift would result in (1) the preservation of the lagoon in the case of a balance between tectonics and eustasy (figure 6B), (2) its transformation into a sebkha and then its vanishing if the tectonics are predominant on the eustatic rise (figure 6C) and (3) its transformation into a bay and then into a continental shelf if the eustasy is predominant on tectonics (figure 6A),

- a tectonic event that could induce (1) a reactivation of the Gourougou volcano and the filling of the lagoon with the eruption products (figure 6D), (2) the reactivation of the barrier island faults that would lead to the closure and/or the opening of inlets, (3) the uplift of the lagoonal basin which would induce its transformation into a sebkha then into a salt marsh (figure 6C) or (4) a collapse of the lagoon that would lead to its transformation into a bay then into a continental shelf (figure 6A).

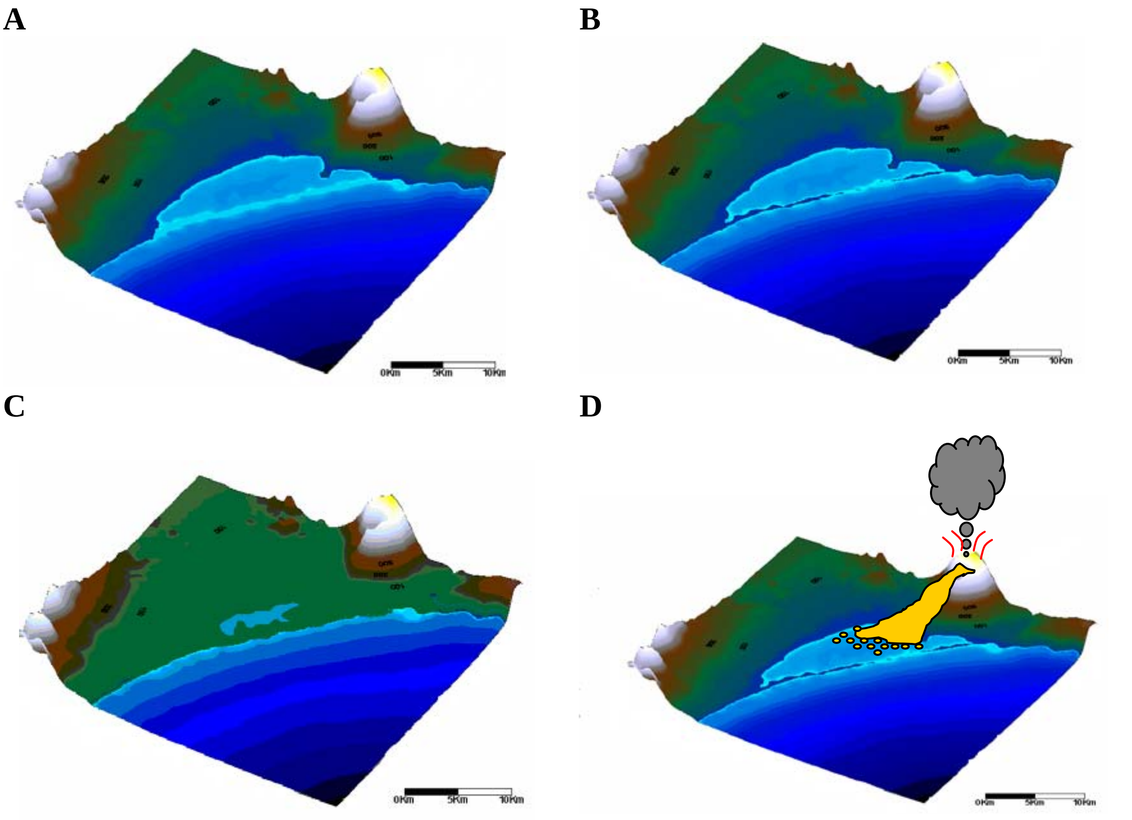



*Figure 6. Scenarios of possible evolutions of the Nador barrier island system.*

## 7. Conclusion

The results which are mostly new and unique, allowed to better understand the genesis of the Nador barrier island system and its functioning for present-day period and older period (1000 to 1200 years BP), as well as the natural factors which controlled its evolution (at seasonal and millennium scales) and the anthropogenic factors affecting its current balance. They also allowed to predict 7 possible scenarios of future evolutions of this ecosystem. In addition to its scientific interest, the approach adopted for this study that takes into account the evolution of morphostructural, geomorphological and sedimentological processes, the water quality as well as their impact on living resources, constitutes a practical tool for the exploitation and management of the coastal ecosystems in general and the lagoonal system in particular. Finally, all the results obtained as well as the numerous thematic and the Territorial Information System (SIT) maps constitute a large database and a fundamental decision-making tool for an adequate management and development of the region.

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