Geomorphology 107 (2009) 32–40

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Impacts of sea-level rise on the Moroccan coastal zone: Quantifying coastal erosion and flooding in the Tangier Bay

Maria Snoussi [a,*], Tachfine Ouchani [a], Abdou Khouakhi [a], Isabelle Niang-Diop [b]

[a] University Mohamed V, Faculty of Sciences, Department of Earth Sciences, Avenue Ibn Battota, B.P. 1014, Rabat, Morocco
[b] University Cheikh Anta Diop, Dakar Fann, Senegal

ARTICLE INFO

Article history:
Received 23 February 2006
Received in revised form 1 June 2006
Accepted 17 July 2006
Available online 14 November 2008

Keywords:
Moroccan coastal zone
Sea-level rise
Impact assessment
Inundation
Erosion
Adaptation

ABSTRACT

As part of a broad assessment of climate change impacts in Morocco, an assessment of vulnerability and adaptation of coastal zones to sea-level rise was conducted. Tangier Bay which is the most important socio-economic pole in Northern Morocco represents one of the cases studies. Using a GIS-based inundation analysis and an erosion modelling approach, the potential physical vulnerability to accelerated sea-level rise was investigated, and the most vulnerable socio-economic sectors were assessed. Results indicate that 10% and 24% of the area will be at risk of flooding respectively for minimum (4 m) and maximum (11 m) inundation levels. The most severely impacted sectors are expected to be the coastal defences and the port, the urban area, tourist coastal infrastructures, the railway, and the industrial area. Shoreline erosion would affect nearly 20% and 45% of the total beach areas respectively in 2050 and 2100. Potential response strategies and adaptation options identified include: sand dune fixation, beach nourishment and building of seawalls to protect the urban and industrial areas of high value. It was also recommended that an Integrated Coastal Zone Management Plan for the region, including upgrading awareness, building regulation and urban growth planning should be the most appropriate tool to ensure a long-term sustainable development, while addressing the vulnerability of the coast to future sea-level rise.

1. Introduction

The coastal zone of Morocco, which is nearly 3500 km long, bordering the Mediterranean Sea and the Atlantic Ocean, forms one of the main socio-economic centres of the country. More than 60% of the population lives in coastal cities which also host about 90% of the industries. Beaches and coastal resorts constitute a large percentage of the Gross Domestic Product (GDP). However, due to diverse human pressures, many coastal areas already experience acute environmental problems such as coastal erosion, pollution, degradation of dunes and saline intrusion in coastal aquifers and rivers. Accelerated sea-level rise will intensify the stress on these areas causing flooding of coastal lowlands, erosion of sandy beaches and destruction of coastal wetlands. Sea-level rise (SLR) is therefore one of the key problems that should be taken into consideration in climate change impact assessments for Morocco.

The overall objective of this work is to assess quantitatively the vulnerability to sea-level rise of the Tangier coast, located on the Strait of Gibraltar and one of the most important socio-economic poles of Northern Morocco. The specific objectives of this paper are: (1) to determine areas at risk of flooding and erosion, (2) to assess the most vulnerable socioeconomic sectors at risk, and (3) to identify the most appropriate response options for the areas at risk.

2. Description of the study area

Tangier bay is located at the entrance of the Mediterranean Sea on the African side of the Strait of Gibraltar (Fig. 1). It has a concave coast, limited to the West by the port area and to the South by gentle hills dissected by small rivers. The city of Tangier is developed on the south-western part of the bay.

2.1. Physical setting

Morphologically, the study area can be divided in three units: a relatively low area, corresponding to the lower reaches of the rivers and to the coastal strip, surrounded by two high areas, which belong to the Rif Mountains. The dominant shore types of the area are sandy and shingle beaches; however in the eastern part of the bay, the coastline is limited by high rocky cliffs. The inner shelf is covered by calcareous sand, followed by fine sand and gravels (Fig. 2). One of the main features of the shelf is rocky outcrops in many places in the bay.

* Corresponding author. Tel.: +212 61401532; fax: +212 37771957.
E-mail addresses: snoussi@fsr.ac.ma (M. Snoussi), Tachfineouchani@yahoo.fr (T. Ouchani), isabelleniang@yahoo.fr (I. Niang-Diop).

0169-555X/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2006.07.043

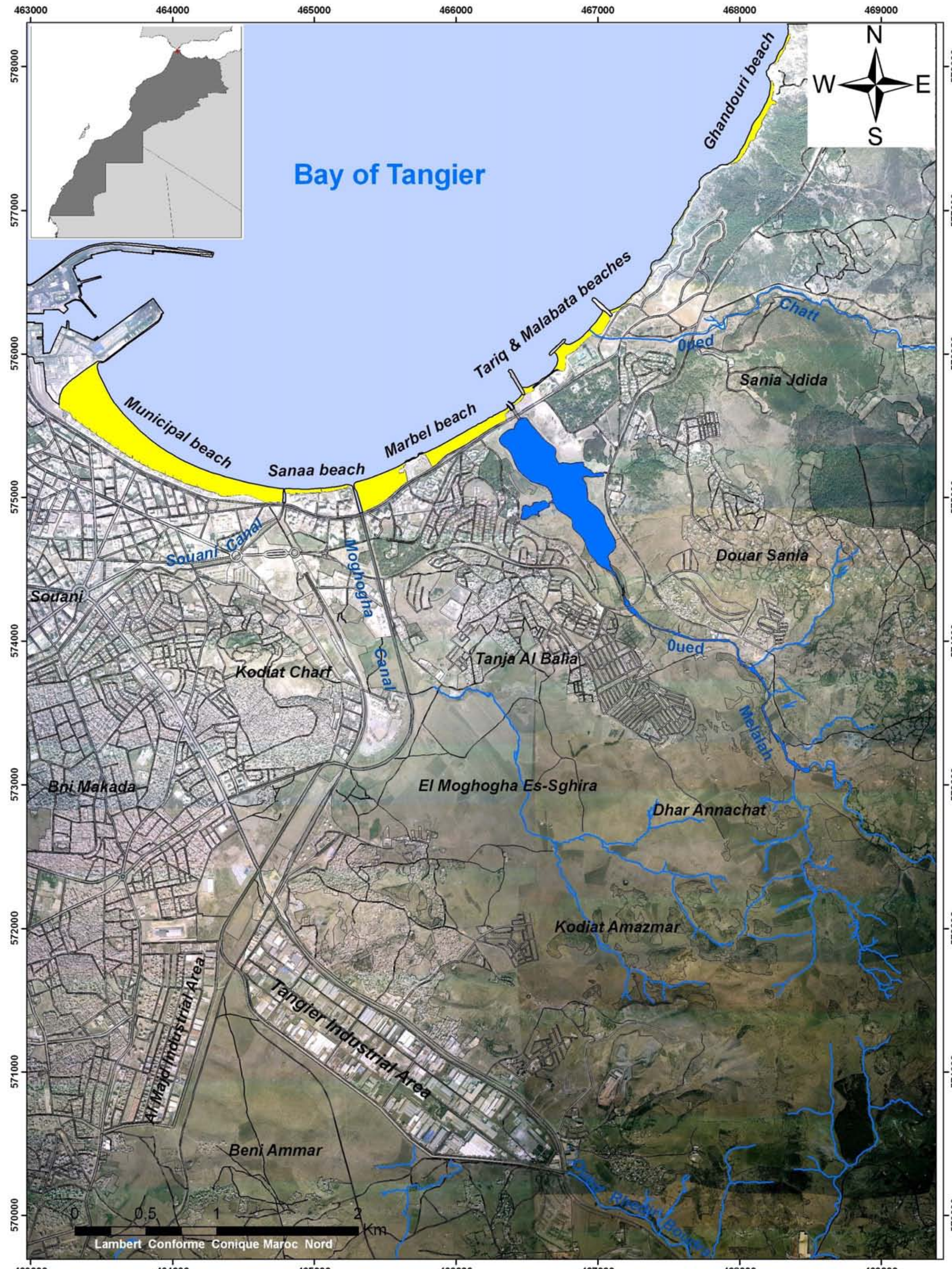

Fig. 1. Localisation of the study area.

2.2. Socio-economic background

According to the National Census of 2004, the population of the area is 431,303 inhabitants (RGPH, 2004), with an average growth rate of 2.3% per year. Population density increased from 336 to 525 inhabitants per km^2 between 1982 and 1994, while the national average rate is 37 inhabitants per km^2. Tangier is thus one of the most densely populated cities in Morocco. The city originally developed in the western part of the bay. However, due to rural migration and restricted space, uncontrolled urbanization extended not only to the southeast of the bay, but also on the hillslopes, which has initiated several problems of erosion and flooding.

The port of Tangier is the most important link between Morocco and Europe for travellers. For this reason, there is a dense network for transportation and communication. However, in spite of its large

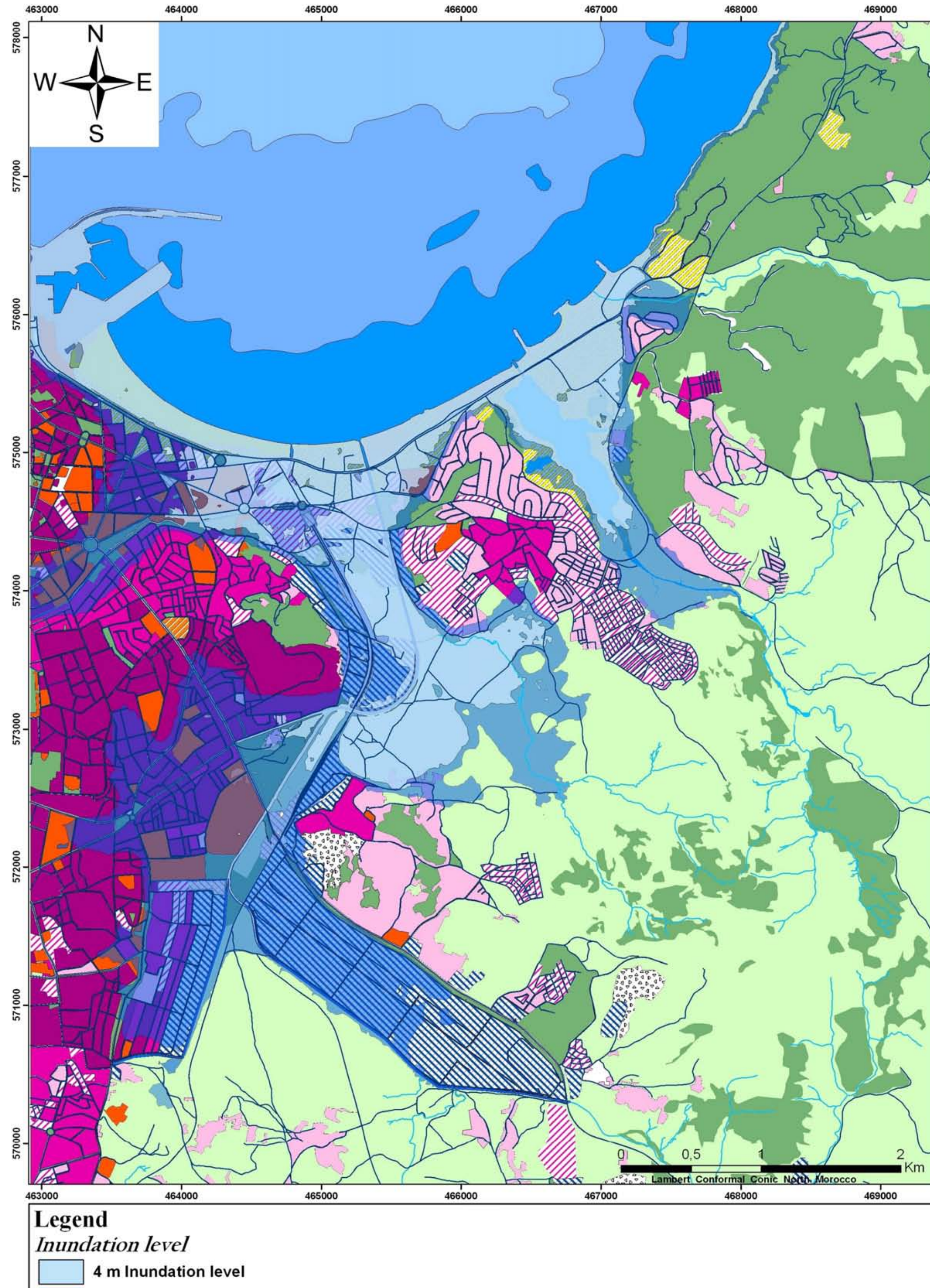

Fig. 2. Land use map.

dimensions and strategic location, the port handles only 5% of the national maritime import/export of goods, and contributes less than 0.8% to the national fishing activities.

The main contributors to the economy of the area are: agriculture, fisheries, industry, and tourism. The agricultural sector, together with fisheries, are the first providers of employment (44% of the active population), followed by trade and industry (14%); and the public sector (10%). Handicraft and informal trade constitute the remaining employments.

The land-use map (Fig. 2) shows that overall, cultivated lands are the most important areas (about 45%), followed by urban areas (21%) and

Table 1
Global mean sea-level rise scenarios using the IS92a greenhouse-gas emissions scenario and including the cooling effects of aerosols) (Warrick et al., 1996).

Scenarios	Sea-level rise (cm)	
	2050	2100
Low estimate (no acceleration)	7	20
Middle estimate	20	49
High estimate	39	86

natural vegetation (20%). The industrial infrastructures represent 6% and the tourist, public and private infrastructures cover 5% of the total area. Beaches, port area and coastal defences cover only 3% of the area.

2.3. Environmental problems

For more than half a century, the bay of Tangier has been subject to many environmental problems. The main anthropogenic drivers and pressures are: population growth, coastal urbanization, development of the city and extension of the port. While the extension of the port has boosted trade and economy in the region, it has also led to a significant erosion of the eastern beaches of the bay. According to numerous authors (LCHF, 1972; Long, 1998; El Arrim, 2001; El Moumni et al., 2002; Snoussi and Long, 2002; El Bouzidi, 2005), coastline retreat is estimated between 2 and 3 m per year in the eastern part of the bay. This retreat is aggravated by wind deflation which represents 30% of the total erosion (Charrouf, 1991).

The sand removed is transported to the West and accumulates mainly along the eastern mole of the port. The sedimentation rate is estimated at 5 m per year. As a consequence, while Tangier was the first seaside tourism destination in the 1970s in Morocco, erosion of the eastern beaches, where most of the tourist hotels exist, together with pollution of the coastal waters, have led to a drastic decline of the tourism industry since the 1990s. Indeed, the number of tourists has decreased by 30%, international nights have fallen by 53%, and tourism-related activities have also declined by 40% for transport and 25% for handicrafts (LCHF, 1972; Long, 1998).

Several actions have been undertaken by the authorities to protect the coastal resorts. The LCHF (1974) proposed a project with three phases: (i) construction of 2 groins and a breakwater, (ii) sand nourishment, and (iii) protection against aeolian erosion. However, due to lack of financial means and strong political will, only the first phase had been achieved between 1984 and 1985. Later on, Long et al. (1999) proposed beach nourishment to rehabilitate the coast, but the project has never been implemented. Now, sand has completely disappeared in front of the hotels, and the beaches are composed of gravels.

The coastal stretch of the bay, backed by the highlands, is now so heavily controlled by human infrastructure that it is no longer possible for the beaches and the wetlands to re-adapt to any new conditions. Indeed, human activities have reduced the natural coastal system's resilience, such that the potential for autonomous adaptation to SLR has decreased. In addition, the bay is a sand-deficient system, due to the very weak amount of sediment discharged by the few rivers that flow into the bay. This increases its vulnerability to flooding and erosion.

3. Methodology

The methodology used to assess the vulnerability to sea-level rise and adaptation of the area was based on the IPCC technical guidelines (Carter et al., 1994) and on the UNEP Handbook 'coastal zones' chapter (Klein and Nicholls, 1998). Two types of physical impact were considered in this study: land losses due to coastal erosion and to coastal inundation.

3.1. Sea-level scenarios

Over the last century, global sea-level change has typically been estimated from tide gauge measurements. Since long-term measurements are not available in Morocco, we used global data from satellite altimeters (Topex/Poseidon, since 1992 and Jason since 2001), which estimate the global sea-level rise at about 3 ± 0.4 mm per year for the period 1993–2004 (www.nasa.gov). Scenarios of future SLR used in this paper are based on the projections made by Warrick et al. (1996) and are shown in Table 1. They range from 20 to 86 cm by 2100 for the IS92a greenhouse-gas emissions scenario (which is the IPCC medium emission scenario), with a best estimate of 49 cm. Since land movements (subsidence/uplift) have not been quantified in the study area due to lack of data, these scenarios were provisionally considered as relative SLR scenarios.

3.2. Coastal topography and land use

An initial requirement for analysis of flooding impacts is the provision of spatial and topographic datasets. Elevation data were extracted from stereoscopic pairs of 1:10,000 aerial photographs (taken in 2005), using photogrammetric treatment. A Digital Elevation Model (DEM) was generated from the interpolation of the elevation data by Triangular Irregular Network (TIN), using the ARC/GIS software. In order to characterise the typology of future inundated areas, land-use classes were identified and mapped using GIS.

3.3. Inundation level scenarios

One of the first consequences of a rise in sea level is an increased flood risk associated with storm surges, in low-lying coastal zones. Hoozemans et al. (1993) defined the risk zone as the land area between the coastline and the "maximum" design water level, which can be calculated from the Eq. (1):

$$\mathrm{Dft} = \mathrm{MHW} + S + \mathrm{Wf} + \mathrm{Pf} \tag{1}$$

where Dft is the inundation level, MHW the mean high water level, S the relative SLR, Wf the waves height and Pf the SLR due to a lowering of the barometric pressure. Data on tides and surges in Tangier bay come from different bibliographic sources (LCHF, 1972; Charrouf, 1991; L.P.E.E., 2002; SOGREAH/Amendis, 2004).

Two levels of inundation were considered:

(i) a minimum inundation level: calculated using the minimum value of MHW (1.71 m), the mean wave height (2.8 m) and the low hypothesis of SLR (0.07 m in 2050 and 0.20 m in 2100); and
(ii) a maximum inundation level: calculated using the maximum value of MHW (2.29 m), the storm wave height with return period of 1/100 years (8 m), and a high hypothesis of SLR (0.39 m in 2050 and 0.86 m in 2100). However, according to Sanchez-Arcilla and Jimenez (1997), sea-level rise will induce a decrease of the return period of water levels associated with storm surges, especially in a passive system or a sand-deficient one, which is the case of the Tangier coast.

Although at present, an in-depth knowledge of these processes, and of how waves are transferred to the coast, are lacking in the study area. The calculations using the Hoozemans et al. (1993) equation nevertheless allow us to estimate the preliminary extent of the area at risk of inundation. Results are presented in Table 2. As values are very close together, the levels 4 m as minimum and 11 m as maximum have been used for the calculations of the potential land loss by inundation.

Table 2
Minimum and maximum inundation levels in 2050 and 2100.

Scenarios	Minimum Inundation levels (m)		Maximum Inundation levels (m)	
	Without CC	Low estimate of SLR	Without CC	High estimate of SLR
2050	4.68	4.58	10.46	10.68
2100	4.83	4.71	10.61	11.15

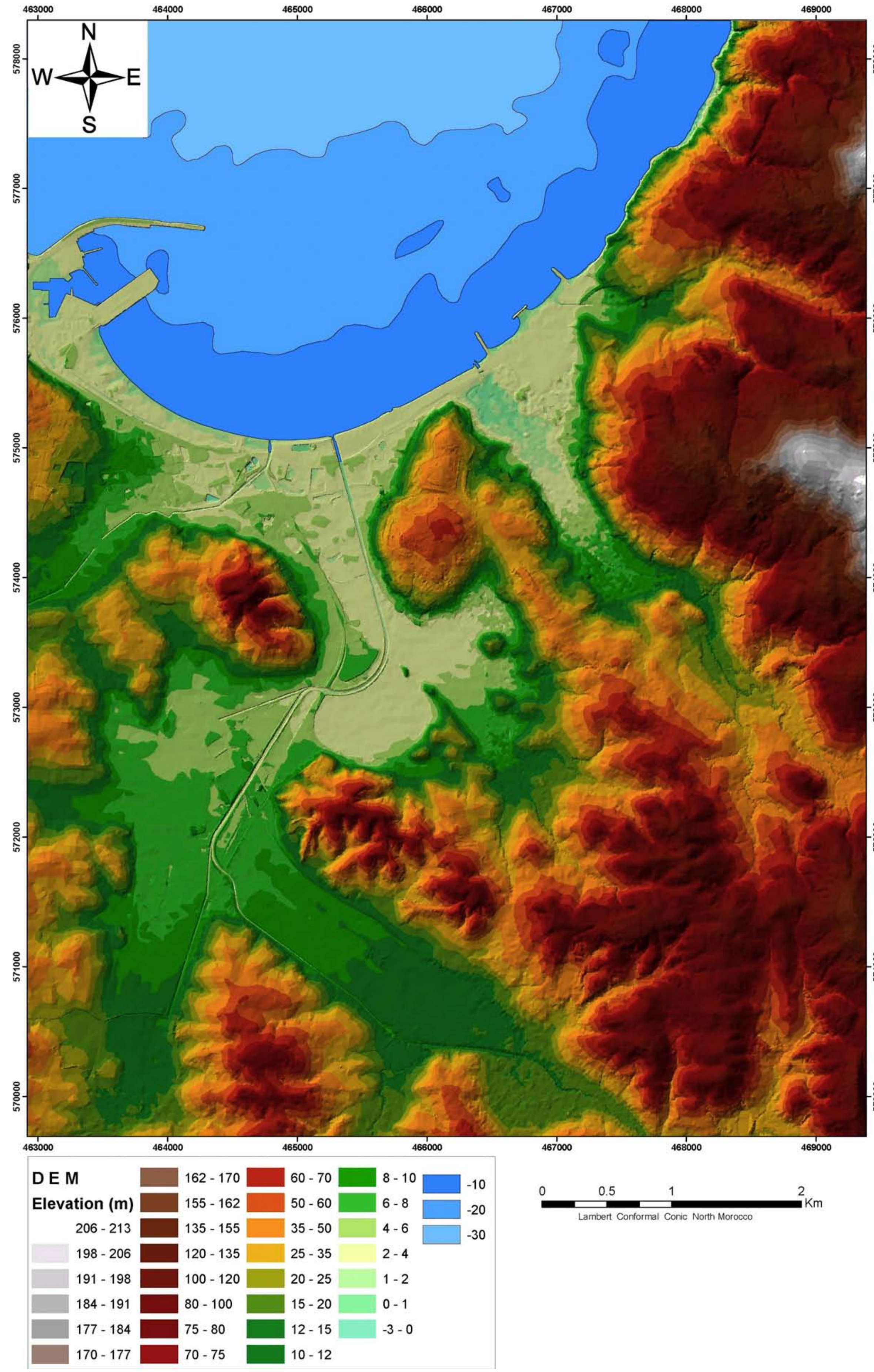

Fig. 3. DEM of the study area.

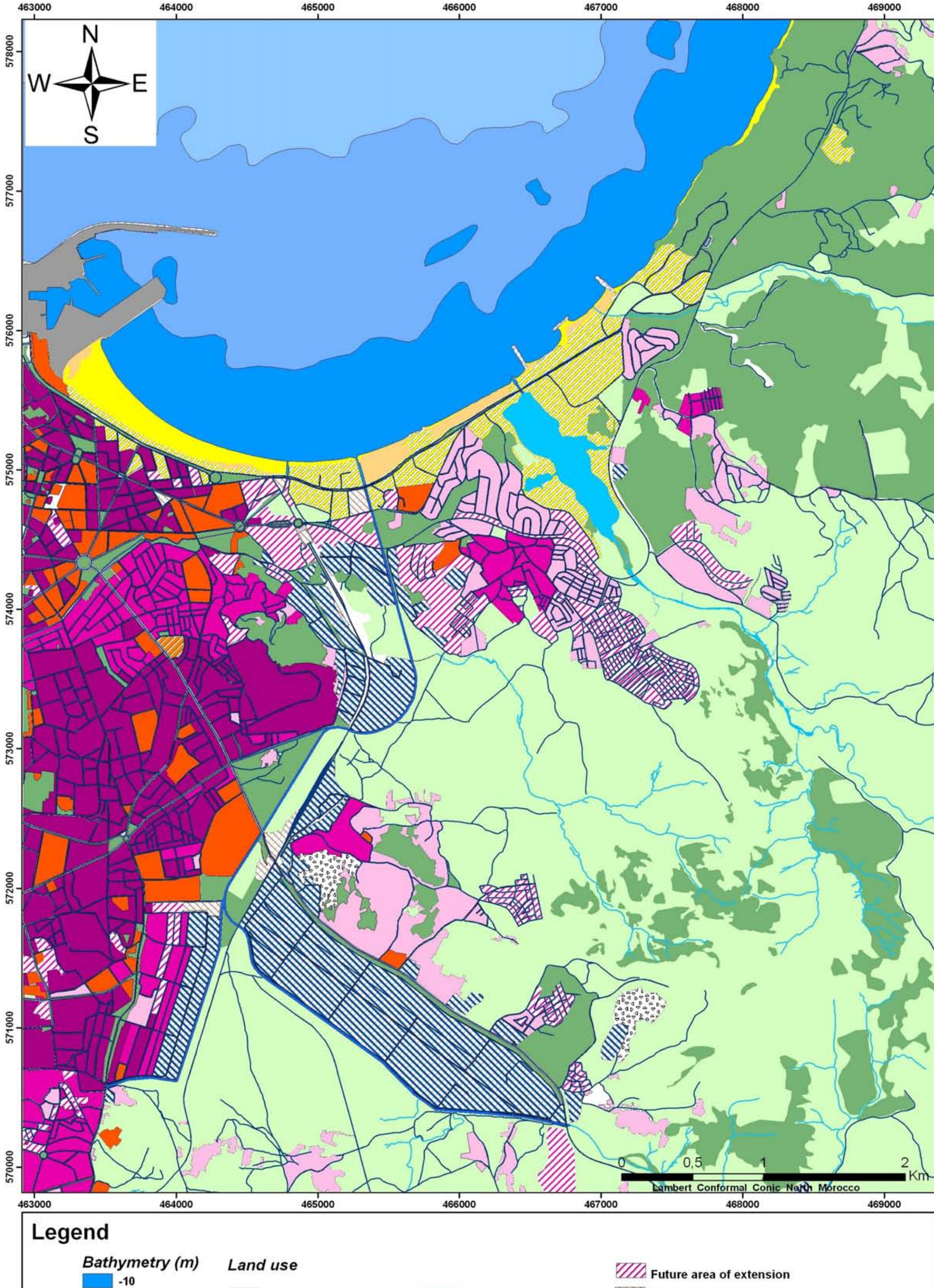

Fig. 4. Land area vulnerable to flooding with the minimum inundation level of 4 m and the maximum inundation level of 11 m.

Table 3
Potential land loss by inundation for 4 m and 11 m inundation levels scenarios.

Cartographic units		Areas/length	Inundated areas with the minimum level (4 m)	Inundated areas with the maximum level (11 m)
Roadways		264.64 (km)	8.0%	36%
Railways		9.83 (km)	0.5%	79.2%
Sandy beach		0.35 (km^2)	98.4%	99.9%
Shingle beach		0.16 (km^2)	95.8%	99.9%
Artificial lake		0.29 (km^2)	95.0%	99.7%
Canal for water diversion		0.17 (km^2)	49.4%	90.8%
Port		0.38 (km^2)	97.5%	99.9%
Coastal defences		0.04 (km^2)	89.6%	99.5%
Urban area	High density	3.36 (km^2)	1.45%	34.8%
	Middle density	1.66 (km^2)	0.2%	22.6%
	Weak density	2.45 (km^2)	1.0%	8.0%
	Ongoing planning	1.20 (km^2)	12.5%	27.2%
Tourist infrastructures		1.08 (km^2)	69.1%	84.5%
Public and private infrastructures		1.12 (km^2)	15.0%	62.0%
Industrial zone		2.39 (km^2)	8.1%	63.4%
Land cover		8.13 (km^2)	2.9%	10.3%
Agricultural area		18.33 (km^2)	6.3%	13.1%
Total area		41.11(km^2)	9.65%	23.85%

(In % of the total inundated areas). CC: climate change, SLR: sea-level rise.

3.4. Coastal erosion assessment

To predict coastal retreat due to SLR, the Bruun rule (Bruun, 1962, 1988), represented by the formula below is generally used:

$$R = SG[L/(b+h)] \tag{2}$$

where R is the coastal retreat due to sea-level rise, S is the SLR (the same as in Eq. (1)), G is the proportion of eroded materiel which remains in the active profile, L is the active profile width, b is the dune height, and h is the depth of closure.

There were some limitations in using the Bruun rule, including: (i) the offshore outcrops that reduce wave energy and thus erosion of the shore; and (ii) the value of the overfill ratio G is 1 for sandy beaches, but for the shingle beaches, it was assumed to be 0.5, according to bibliographic information on the coastline evolution of the bay (LCHF, 1972; Long et al., 1999; El Arrim, 2001; Snoussi and Long, 2002; El Moumni et al., 2002; El Bouzidi, 2005).

According to Nicholls et al. (1994), estimation of the high and low depths of closure was based on time scales of one year and 100 years respectively, giving low and high estimates of shoreline retreat. Depths of closure were referenced to a datum of 1 m above low water. Calculations were performed based on 'homogeneous' coastline segments. Five beaches have been defined based on the width of the active profile, which varies slightly along the coast of the study area.

3.5. Socio-economic impacts

Having determined the land losses due to coastal erosion and inundation, the impacts of these losses on the major socioeconomic sectors (tourism, agriculture, urbanization) as well as natural ecosystems at risk were estimated by overlaying the land-use map and inundation levels map. The cost of these impacts will be evaluated next.

4. Results

The DEM presented in Fig. 3, shows that the land with an elevation less than 4 m is limited to the coastal strip, the lower reaches of the rivers, and the artificial lake and canals. The land with an elevation between 4 and 10 m penetrates further upstream along the thalwegs. Projected flooded areas were calculated by combining the DEM with the minimum and maximum inundation levels maps.

4.1. Land losses due to inundation

The potential flooded areas with the minimum and maximum inundation levels are presented in Fig. 4. Loss estimates (Table 3) indicate that with the minimum inundation level of 4 m, about 10% of the total area would be at risk of inundation, these lands being occupied mainly by 1) beaches, the artificial lake, the port and the coastal defences, which will be almost completely flooded, 2) tourist infrastructures along the coast and 3) the canal for water diversion. With the maximum inundation level (11 m), about 24% of the coastal lands would be potentially inundated, which is two and a half times that of the minimum level. In addition to the areas flooded by the 4 m level, the 11 m inundation level would drown the urban and industrial areas. The most severely exposed zones are expected to be: the urban area (92.6%), the tourist infrastructures (84.5%), the railway (79%), and the industrial area (63.4%). The agricultural lands and natural vegetation would be relatively preserved, because they are located at higher altitudes. The less vulnerable areas to inundation would be the eastern part of the bay where the coastal cliffs fall directly to the sea.

However, land loss resulting from inundation is dependant upon sediment availability, as well as the potential for the coastal systems to migrate landwards. The Tangier coast, being a sand-deficient and heavily humanized system, will not be able to cope with the rise of the sea level, if no protective measures are undertaken. Indeed, potential loss of people living in the area at risk of flooding, as well as industrial infrastructures will have serious socioeconomic impacts in the region.

4.2. Land losses due to coastal erosion

The values of the parameters used in the Bruun (1962, 1988) equation are presented for each beach in Table 4. The coastal retreat (R) and the percentage of areas lost are presented in Table 5 for 2050, and Table 6 for 2100. In 2050, detailed calculations by sectors (Table 5) showed that with the low hypothesis of SLR, the most vulnerable beaches are Tarik and Marbel beaches. With the high hypothesis of SLR, these beaches would completely disappear. Sanaa beach would lose 84% of its area, and would be the second most vulnerable beach to erosion. The areas lost at Malabata sandy beach and Municipale beach would be respectively of 33% and 19.2%.

In 2100, estimates indicate (Table 6) that under middle hypothesis of SLR, almost all of the sandy beaches, except the Municipale and the Malabata beaches, are expected to be completely lost. In case of the high hypothesis of SLR, the situation will be worst and even the shingle beaches of Malabata and Marbel would be partially eroded (45.3% and 25.8% respectively).

Table 4
Values of the parameters used in the Bruun' equation.

Beach		L (m)	b (m)	h (m) h_1	h (m) h_{100}	G
Municipale		800	2	10	17.5	1
Sanaa		709	2.3	10	17.5	1
Marbel	Shingle beach	77.8	3	10	17.5	0.5
	Sandy beach	9.5				1
Tarik		547	3	10	17.5	1
Malabata	Shingle beach	25	2.8	10	17.5	0.5
	Sandy beach	13				1

L is the active profile width, b is the dune height, h is the depth of closure (h_1 for 1 year and h_{100} for 100 years) and G is the overfill ratio.

Table 5
Land loss due to coastal erosion in 2050 (*R*: retreat in m, *S*: surface in % of each beach).

Beach		Without climate change	With sea-level rise		
			Low estimate ($S=0.20$ m)	Middle estimate ($S=0.49$ m)	High estimate ($S=0.86$ m)
Municipale	*R* (m)	11.3	4.6	13.3	26
	S (%)	6.9	2.8	8.2	15.9
Sanaa	*R* (m)	9.8	4.0	11.5	22.5
	S (%)	36.7	15.1	43.1	84.4
Marbel Shingle beach	*R* (m)	4.6	1.9	5.4	10.5
	S (%)	4.7	2.1	6.0	11.7
Marbel Sandy beach	*R* (m)	4.2	1.7	4.9	9.5
	S (%)	61.6	25.1	71.9	>100
Tarik	*R* (m)	7.1	2.9	8.4	46.4
	S (%)	79	32.5	92.9	>100
Malabata Shingle beach	*R* (m)	3.5	1.4	4.2	8.1
	S (%)	8.9	3.7	10.5	20.6
Malabata Sandy beach	*R* (m)	3.5	1.4	4.1	7.9
	S (%)	14.5	5.9	16.9	33

Table 7 summarises the results for each hypothesis of SLR and each time horizon. It shows that in case of the low hypothesis of SLR, 3.6% and 10.3% of the beaches will be lost respectively in 2050 and 2100. However, with the high SLR scenario, the land loss will be 5.6 and 4.3 times higher, respectively in 2050 and in 2100, than with the low hypothesis.

Overall, Tarik, Marbel and Sanaa are the most vulnerable beaches to coastal erosion. This vulnerability is not only linked to the sedimentary regime of the bay, which shows a net erosive trend in its eastern part over the last two decades, but also to the lack of sandy material. Indeed, since Tarik, Malabata and Marbel hotels have been built just a few meters from the coastline, the sandy dunes have been destroyed. Therefore, the eroded beaches will not be able to re-adjust their new profile to SLR. This assessment is of great concern because the tourism development of the region is based mainly on the beaches as economic resources. So this impact could have important socio-economic consequences.

5. Response strategies and adaptation

In spite of the large uncertainty regarding projected climate scenarios and empirical calculations, and given the potential impacts of SLR on various socio-economic sectors of Tangier bay, an anticipatory adaptation strategy must be developed. This should be

Table 6
Land loss due to coastal erosion in 2100 (*R*: retreat in m, *S*: surface in % of each beach).

Beach		Without climate change	With sea-level rise		
			Low estimate ($S=0.20$ m)	Middle estimate ($S=0.49$ m)	High estimate ($S=0.86$ m)
Municipale	*R* (m)	21.3	13.3	32.6	57.3
	S (%)	13.1	8.2	20.0	35.2
Sanaa	*R* (m)	18.4	11.5	28.2	49.5
	S (%)	69	43	>100	>100
Marbel Shingle beach	*R* (m)	8.6	5.4	13.2	23.2
	S (%)	9.6	6.0	14.7	25.8
Marbel Sandy beach	*R* (m)	7.8	4.9	12	21.1
	S (%)	>100	71.9	>100	>100
Tarik	*R* (m)	13.4	8.4	20.6	36.1
	S (%)	>100	92.9	>100	>100
Malabata Shingle beach	*R* (m)	6.6	4.2	10.2	17.9
	S (%)	16.8	10.5	25.8	45.3
Malabata Sandy beach	*R* (m)	6.5	4.1	10.0	17.5
	S (%)	27.0	16.9	41.5	72.8

Table 7
Total land loss due to coastal erosion in 2050 and 2100 (in % of the total beach areas).

Time horizon	Without climate change	With sea-level rise		
		Low hypothesis	Middle hypothesis	High hypothesis
2050	8.7	3.6	10.3	20.2
2100	16.6	10.3	25.4	44.6

based on a pro-active approach and 'no regrets' policy. However, it is clear that the vulnerability of Tangier to SLR will be mainly determined by the nature of ongoing development and the way the authorities manage its environment. In fact, coastal adaptation processes to climate change interact with existing management practices and can be considered multi-stage and iterative processes (Klein et al., 1999). Therefore, an integrated coastal zone management (ICZM) plan is the most appropriate and necessary tool for long-term sustainable development, which could tackle current and future vulnerabilities of the coastal area. This plan should actively involve the local communities, and include building regulations, urban growth planning, building institutional capacity and raising awareness (Snoussi and Tabet Aoul, 2000). Such plan should deal with both SLR and other impacts of climate change and/or human activities, and ensure that coastal development does not increase the vulnerability of the region. It requires the availability of a geographic database with relevant, detailed and accurate information, a monitoring system and a decision support system (El Raey et al., 1999).

Short-term adaptation measures are also necessary. The most suitable range or mixes of options that are recommended for the study area include:

1) Beach nourishment, including building artificial dunes as storm buffers and beach sand reservoirs. This option would be beneficial (e.g. for tourism) even in the absence of SLR;
2) Hard structures should be designed, as much as possible, to avoid adverse environmental impacts. Groins could be used with beach nourishment to trap sand in the eastern part of the bay. Breakwaters could reduce the energy of the north-eastern waves reaching the shoreline. Building of sea walls is a high cost option; it would be used only for settlements and industrial areas of high value and at direct risk of inundation.

6. Conclusion

Application of the IPCC methodology to assess the physical vulnerability of the Tangier coastal zone has allowed the quantification of areas at risk of coastal inundation and erosion due to accelerated sea-level rise. Even if accurate data on 'relative' SLR, as well as a knowledge of the hydrodynamics of the bay were lacking, results give a preliminary estimation of the areas at risk.

The DEM constituted a valuable tool with which flooding scenarios can be clearly visualized. Overlaying land-use map and inundation scenarios map allowed us to determine that the most vulnerable zones to inundation are the coastal defences and the port, the urban area, the tourist coastal infrastructures, the railway, and the industrial area; while the most sensitive zones to shoreline erosion are the Tarik, Marbel and Sanaa beaches. Urban settlements including tourist resorts and industrial areas would be the most affected economic assets, while agricultural lands are relatively preserved due to their high altitude. In fact, the total lands at risk of inundation are relatively small, due to the fact that the coastal fringe is relatively narrow and backed by uplands. The bay of Tangier seems less vulnerable than other low lying coastal zones in Morocco (Snoussi et al., in press). However, the high population density and vital economic sectors make the potential socioeconomic impacts of SLR on Tangier of particular concern.

It is recommended that adaptation measures should include ‘soft’ maintenance such as beach nourishment and sand dune restoration; and some ‘hard’ structures to reduce the wave energy and to protect the urbanized areas. More important are raising awareness and building regulations, in the context of an ICZM plan, for long-term development. These results should be completed by a detailed vulnerability assessment, including physical impacts on freshwater and biological resources, socio-economic impacts, and evaluation of adaptation options, using the combination of cost–benefit analysis with multi-criteria analysis.

Acknowledgments

This work was carried out as part of the “Vulnerability and Adaptation Assessment to Climate Change of Morocco's Coastal Zones” UNEP Project. This project was conducted by the Department of Environment and supported by GEF. We want to acknowledge suggestions from Agustin Sanchez-Arcilla and one anonymous reviewer which helped to improve this manuscript.

References

Bruun, P., 1962. Sea-level rise as a cause of shore erosion. Journal of Waterways and Harbors Division, 88 WWI, 117–130.
Bruun, P., 1988. The Bruun rule of erosion by sea-level rise: a discussion on large-scale two- and three-dimensional usages. Journal of Coastal Research 4, 627–648.
Carter, T.R., Parry, M.L., Harasawa, H., Nishioka, S., 1994. IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. University College of London/ Center for Global Environmental Research, London/Tsukuba, 59 p.
Charrouf, L., 1991. Problèmes d'ensablement des ports marocains sur la façade atlantique, vol. 1. La Houille Blanche, pp. 49–71.
El Arrim, A., 2001. Contribution à l'étude du littoral de la baie de Tanger (Rif nord occidental-Maroc). Approche sédimentologique, minéralogique, géochimique et impact de la dynamique sédimentaire. Thèse de doctorat national, Univ. Abdelmalek Essaadi, FST Tanger, 149 pp.
El Bouzidi, R., 2005. Evolution morpho-sédimentaire et variabilité spatio-temporelle du transit littoral dans la baie de Tanger (Maroc). Thèse Doctorat, Univ. Mohamed V-Agdal, Rabat, 198 pp.
El Moumni, B., El Arrim, A., Maâtouk, M., El Hatimi, I., Wahbi, M., Tribak, A.A., 2002. Erosion de la baie de Tanger. Ciesm Workshop Series N° 18, Monaco, pp. 43–47.
El Raey, M., Dewidar, Kh., El Hattab, M., 1999. Adaptation to the impacts of sea level rise in Egypt. Climate Research 12, 117–128.
Hoozemans, F.M.J., Marchand, M., Pennekamp, H.A., 1993. Sea level rise. A global vulnerability assessment. Delft Hydraulics, Delft / Rijkswaterstaat, The Hague, 184 pp.
Klein, R.J.T., Nicholls, R.J., 1998. Coastal Zones. In: Feenstra, J.F., Burton, I., Smith, J.B., Tol, R.S.J., (Eds.), 1998. Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies. UNEP/Institute for Environmental Studies, Nairobi/ Amsterdam, 35 pp.
Klein, R.J.T., Nicholls, R.J., Mimura, N., 1999. Coastal Adaptation to Climate Change: Can the IPCC Technical Guidelines be Applied? . Mitigation and Adaptation strategies for Global Change, vol. 4. Kluwer, Dordrecht, The Netherlands, pp. 239–252.
LCHF (Laboratoire Central d'Hydraulique de France), 1972. Baie de Tanger. Rapport des études sédimentologiques (65 pp.), et rapport de la mission hydrographique (56 p.).
LCHF (Laboratoire Central d'Hydraulique de France), 1974. Aménagement de la Baie de Tanger. Protection de la plage. Avant-projet détaillé et Présentation de la solution retenue.
Long, B., 1998. Rapport de visite de la plage de Tanger, 27 au 31 mars 1998. Rapport pour le Ministère de l'Equipement. Direction des Ports et du Domaine Maritime, Rabat. 20 pp.
Long, B., Bencheikh, L., Boczar-Karakiewicz, B., Merzouk, A., Romanczyk, W., 1999. Beach Protection at Tanger by Beach Nourishment (Gandori-harbour), pp. 637–652. Rapport pour le Ministère de l'Equipement. Direction des Ports et du Domaine Maritime, Rabat, 16 pp.
L.P.E.E. (Laboratoire Public d'Essai et d'Etude), 2002. Etudes océanographiques et maritimes du futur port de Oued Rmel, Rapport inédit, avril. 112 pp.
Nicholls, R.J., Leatherman, S.P., Dennis, K.C., Volonte, C.R., 1994. Impacts of sea-level rise: qualitative and quantitative assessments. Journal of Coastal Research 14 (4), 627–648 Special Issue.
RGPH (Recensement Général de la Population et de l'Habitat), 2004. Rapport général. Royaume du Maroc, Rabat.
Sanchez-Arcilla, A., Jimenez, J.A., 1997. Physical impact of climate change on deltaic coasts (I): an approach. Climate Change 35, 71–93.
SOGREAH (Société Grenobloise d'Etudes et d'Applications Hydrauliques) /Amendis, 2004. Etude d'Impact sur l'Environnement de la Station de Traitement des Eaux Usées et de l'Emissaire marin du port de Tanger. Rapport et Rapp. Annexe, Mai.
Snoussi, M., Long, B., 2002. Historique de l'évolution de la baie de Tanger et tentatives de réhabilitation. Ciesm Workshop Series N° 18, Monaco, pp. 43–47.
Snoussi, M., Tabet Aoul, E.H., 2000. Integrated coastal zone management programme, northwest African region case. Ocean & Coastal Management 43, 1033–1045.
Snoussi, M., Ouchani, T., Niazi, S., in press. Vulnerability assessment of the impact of sea-level rise and flooding on the Moroccan coast: The case of the Mediterranean eastern zone. Estuarine and Coastal Shelf Science.
Warrick, R.A., Le Provost, C., Meier, M.F., Oerlemans, J., Woodworth, P.L., 1996. Changes in sea level. In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), Climate Change 1995. The Science of Climate Change. Cambridge University Press, Cambridge, pp. 365–405.