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Impact of Shoreline Retreat and Inundation due to Sea Level rise along the Coastline adjacent to the Guadiana Estuary, Portugal/Spain Border

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Resumo

A avaliação da regressão e inundação da linha de costa, na zona costeira do Guadiana (Portugal / Espanha) devido ao aumento do nível do mar, foi levada a cabo para identificar e cartografar zonas de risco. O Sistema de Informação Geográfica foi usado para visualizar e analisar impactes em zonas urbanizadas, redes de transportes e habitats.

A regressão da linha costeira em função da evolução da linha costeira actual e a um aumento do nível do mar acelerado, resultou em 3 cenários (SRES) nomeadamente, B1, A1B e A1F1 (38, 48 e 58 cm de aumento do nível do mar, respectivamente) e que mostrou uma grande variabilidade espacial. A zona costeira de Monte Gordo (Portugal) e toda a zona costeira de Ayamonte (Espanha) são susceptíveis a uma erosão severa. A extensão da erosão aumenta em função da subida do nível do mar. No entanto, o maior impacte para a regressão da linha costeira não são as alterações climáticas mas as intervenções antropogénicas, como a construção de estruturas para defesa da costa.

Uma primeira avaliação da regressão da linha costeira em função de uma hipotética tempestade, surge com os contornos de inundação devido ao aumento do nível do mar, que mostra que os danos causados na zonas urbanizadas será mais efectivo comparativamente aos danos causados nas dunas e sapal, que serão resilientes, dependendo fornecimento de sedimento.

No lado de Portugal da zona costeira do estuário do Guadiana, a vulnerabilidade de inundação devido a tempestades, surge com 3,0 e 4,9 m acima do nível médio do mar, demonstra um aumento de 2 a 4 vezes, respectivamente, relativo à zona de risco marcada pelo máximo de marés vivas (1,9 m do MSL). Um aumento de 2 a 3 vezes pode ser observado no lado de Espanha. No entanto, em termos de inundação total Espanha, será mais afectada.

A resposta a estes efeitos deve ser baseada no programa de Gestão Integrada da Zona Costeira através de intervenções de engenharia leve, estrategicamente planeadas, com o objectivo de mitigar os impactes negativos causados pela regressão da linha costeira devido ao aumento do nível do mar.

Abstract

The integrated impact assessment of shoreline retreat and inundation due to sea level rise over the coastal zone of the Guadiana estuary, Portugal/Spain border was carried out to identify and map hazard zones. Geographical Information System tools were used to visualize and analyse impacts on built-up area, transportation network and habitats.

The shoreline retreat with the present shoreline evolution rate and the accelerated sea level rise given by three SRES scenarios, namely, B1, A1B and A1FI (upper-bound values: 38, 48 and 59 cm rise in sea level, respectively) exhibit high spatial variability. The adjacent coastline of Monte Gordo tourist beach (Portugal) and the entire shoreline of Ayamonte municipality (Spain) are susceptible to severe erosion. The erosion extent increases gradually with the sea level rise. However, the main forcing of the shoreline retreat is not the climatic change but anthropogenic interventions including construction of coastal defense structures.

The first order assessment of shoreline retreat for a hypothetical storm surge with elevated flood contours due to sea level rise shows that the damage to the built-up area and urban habitat can be long lasting while the sandy dune and salt marsh habitats may have resilience depending on sediment supply.

The vulnerability of Portuguese side of the Guadiana estuary coastal zone for inundation due to storm surges of 3.0 and 4.9 m from mean sea level (1 and 2 m from the maximum spring high tide level, respectively) shows approximately two-fold and four-fold increase, respectively, relative to the hazard zone marked by the maximum spring high tide (1.9 m from MSL). Two- and three-fold respective increase can be seen in Spain side of the estuary. However, in terms of total area of inundation, Spanish side would severely affect.

The main response should be focused on Integrated Coastal Zone Management programme with strategically planned soft engineering interventions to mitigate the negative impacts of shoreline retreat due to sea level rise hazards.

Keywords: Shoreline retreat, inundation, storm-surges, sea-level rise, vulnerability, coastal zone management

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Chapter 1

1. Introduction

1.1 General Background

Climate change and the resultant sea-level rise due to global warming mainly due to human activities is now being a widely accepted phenomenon by scientists, economists, and political authorities (IPCC, 2007). Expected deleterious impacts may aggravate the environmental and social problems throughout the world. Especially, the coastal environment and its habitat are under immense risk. It is estimated that 400 million people live within 20m of sea level and within 20 km of a coast (Small et al., 2000). Thus, this population and their environment are directly exposed to the negative impacts of sea-level rise including permanent inundation of low lying regions, amplification of episodic flooding events, increased beach erosion and saline intrusion (Mclean et al., 2001). It is predicted that these effects may be intensified due to the acceleration of sea level rise over the course of 21st century (IPCC, 2001; Church et al., 2001). Therefore, prediction and mitigation of future sea level rise and resulting shoreline retreat and potential amplified inundation due to storm surges are among the most important tasks facing coastal scientists, engineers and managers in the context of intense human habitation and economic and social activities in the coastal zone.

1.2 Socio economic characteristics of the Portuguese coast and the Guadiana coastline

The coastline of mainland Portugal is 943 km (Santos, 2002). In national context, the occupation patterns of the Portuguese coast have altered in the last few decades due to rapid development with changing political and economical context. The average population density along the coastal belt of Portugal is about 215 inhabitants per km^2 while that of the Guadiana coastline is 250-500 inhabitants per $k\ m^2$. The significance of this value shows comparison with the national average of 125 inhabitants per k m^2. Economic activities of the coastal belt will contribute to the GDP by approximately 85% (INAG, 1994). The coastline of eastern Algarve shows 95% littoral population with respect to the inland population. Tourism industry where the coast is a powerful attractor represents 4.2% of GDP in 1997 and that of year 2000 has increased up to 8%. In addition, it is estimated that 9% of total employment opportunities are connected to tourism (Albuquerque and Godinho, 2001). The increased use of the coast for tourism and recreational activities has created serious ill effects which cannot mitigate by resource optimisation. Especially, in the Algarve region seasonal migrations resulting intense pressure on the coast is responsible for increased resident population density by a factor> 10. According to the recent studies the coast of Portugal has been altered by 30% for urban housing, industrial facilities, harbours and tourism infrastructures (INAG, 1994).

1.3 Vulnerability of Coastline for sea level rise

Especially, sandy beaches, salt marshes and estuarine areas can be ranked as “high” and “very high” vulnerable geomorphologic features for sea level rise (Thieler and Hammar-Klose, 1999). Estuaries are also susceptible to rapid changes due to accretion or erosion of sediments (Boski et. al, 2007). The erosion process can be aggravated by sea level rise whilst the coastal zone dominated by continuous accretion process the shoreline retreat due to sea level rise will be retarded. Salt marshes considered among the world’s most ecologically productive and economically valuable ecosystems are degrading rapidly with intense climatic and anthropogenic pressures (Costanza et al., 1997). These areas provide habitat and nursery ground for many commercially important fauna and flora. It can act as a sink in the event of storms, thus, buffering the coastal cities. In addition, it is a rich source of organic matter supplying to estuarine and marine environment while trapping contaminants entering from the catchment area (Turner, 1977; Patrick, 1994). It is understood that the rapid sea level rise is one of the main cause for their recent declining trends as the vertical accretion within the marsh area may not avoid the total submergence of vegetation (Kirwan and Murray, 2007).

1.4 Sea Level rise Scenarios

In the study of climate change, different scenarios have been used widely in many studies and it can be justified mainly for two reasons. Firstly, other than the global nature of the climate impacts there are significant indirect impacts that cannot be predicted or forecasted accurately enough at local or regional scale. Secondly, impacts and response of society and economic activity would be highly complex and make it difficult to forecast in long-term. Therefore, different scenarios which do not claim to likely reality but rather range of possible outcomes can be used as a decision making tool in mitigating the negative consequences of climate change impacts (Santos et al., 2002).

A set of scenarios was developed by Intergovernmental Panel on Climate Change (IPCC) to represent the range of driving forces and emissions. The scenarios presented in the Special Report on Emission Scenarios (SRES) are based on how the future world unfold and how such world contribute to the increase in greenhouse gas (GHG) emissions that are the product of very complex dynamic systems, determined by driving forces including demographic development, socio-economic development, and technological change (SRES: IPCC, 2000).

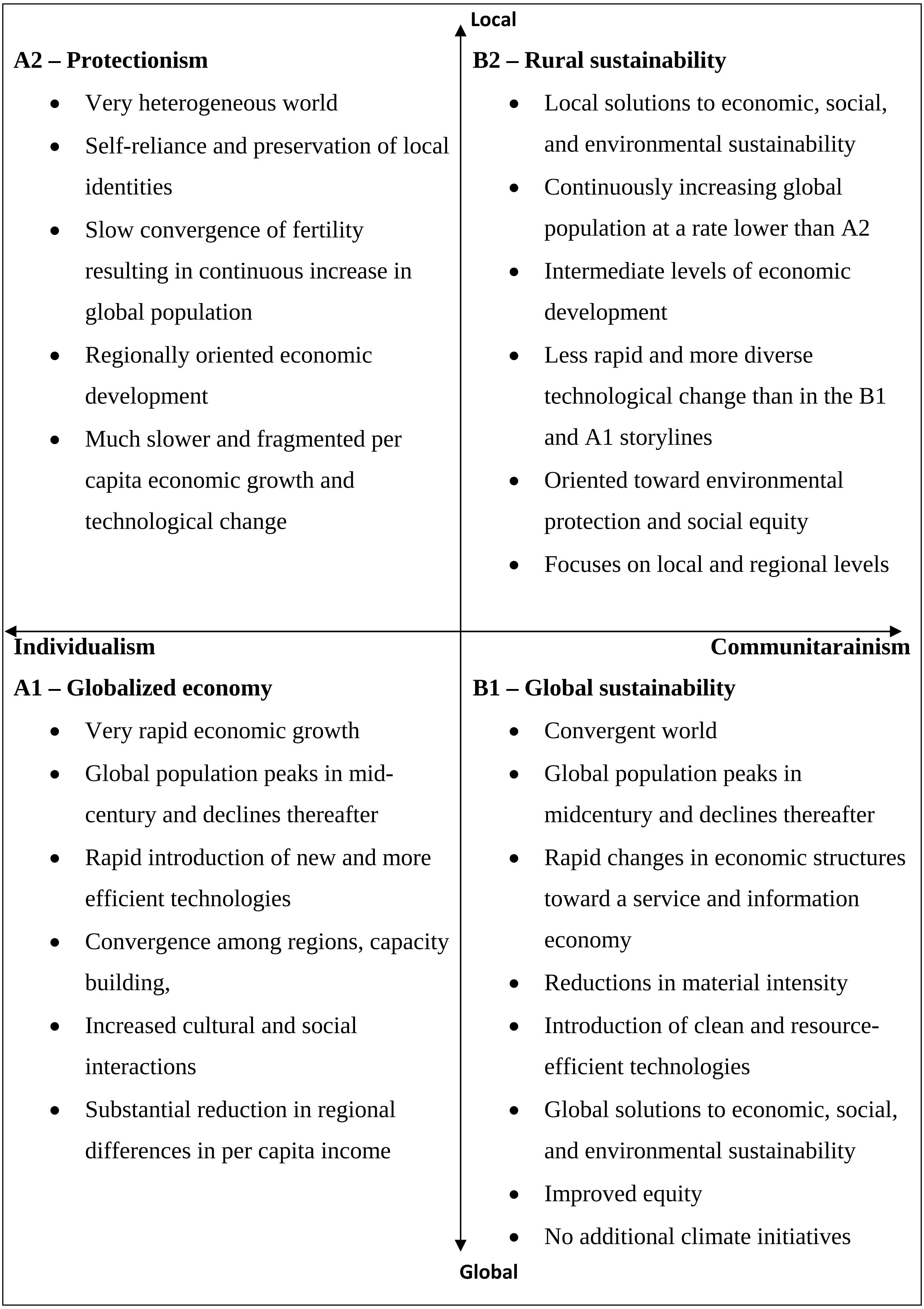
SRES scenarios consist of four different narrative storylines namely, A1, A2, B1 and B2 were developed to describe consistently the relationships between emission driving forces and their evolution and add context for the scenario quantification. Each storyline represents different demographic, social, economic, technological, and environmental developments. The A1 scenario is further classified as A1FI (fossil fuel intensive), A1B (balanced), and A1T (predominantly non-fossil fuel). All together SRES scenarios consists of six scenario groups and some share “harmonized” assumptions on global population, gross world product, and final energy. It is important to understand that feasibility of such future world should not be considered solely on the basis of an extrapolation of current economic, technological, and social trends.

Table 1: Projected globally averaged surface warming and sea level rise at the end of the 21st century based on the SRES scenarios (IPCC, 2007)

Case	Temperature Change (at 2090-2099 relative to 1980-1999)		Sea Level Rise (at 2090-2099 relative to 1980-1999)	
Scenario	Best Estimate ^{o}C	Likely Range ^{o}C	Range of sea level rise rate in mm/yr	Sea level rise range in m (5-95%)
B1	1.8	1.1-2.9	1.5-3.9	0.18-0.38
B2	2.4	1.4-3.8	2.1-5.6	0.20-0.43
A1B	2.8	1.7-4.4	2.1-6.0	0.21-0.48
A1T	2.4	1.4-3.8	1.7-4.7	0.20-0.45
A2	3.4	2.0-5.4	3.0-8.5	0.23-0.51
A1FI	4.0	2.4-6.4	3.0-9.7	0.26-0.59

Thus, table 1 shows projected rise in global average sea level under the SRES scenarios for the end of 21st century and the ranges given are 5 to 95% intervals characterising the spread of model results. It should be noted that, in the IPCC, 2007 sea level rise scenarios are excluding uncertainties in carbon cycle feedbacks. It is very important to understand all the average values of each projected range are very likely to exceed the 1961 to 2003 average rate of 1.8 ± 0.5 mm yr–1. The central estimate of the rate of sea level rise during 2090 to 2099 is 3.8 mm yr–1 under A1B, which exceeds the central estimate of 3.1 mm yr–1 for 1993 to 2003 which are based on the satellite altimetry data (IPCC, 2007).

1.5 Summary of SRES scenarios



A2 – Protectionism

- Very heterogeneous world
- Self-reliance and preservation of local identities
- Slow convergence of fertility resulting in continuous increase in global population
- Regionally oriented economic development
- Much slower and fragmented per capita economic growth and technological change

B2 – Rural sustainability

- Local solutions to economic, social, and environmental sustainability
- Continuously increasing global population at a rate lower than A2
- Intermediate levels of economic development
- Less rapid and more diverse technological change than in the B1 and A1 storylines
- Oriented toward environmental protection and social equity
- Focuses on local and regional levels

A1 – Globalized economy

- Very rapid economic growth
- Global population peaks in mid-century and declines thereafter
- Rapid introduction of new and more efficient technologies
- Convergence among regions, capacity building,
- Increased cultural and social interactions
- Substantial reduction in regional differences in per capita income

B1 – Global sustainability

- Convergent world
- Global population peaks in midcentury and declines thereafter
- Rapid changes in economic structures toward a service and information economy
- Reductions in material intensity
- Introduction of clean and resource-efficient technologies
- Global solutions to economic, social, and environmental sustainability
- Improved equity
- No additional climate initiatives

Figure 1: Summary of SRES scenarios (adopted from SRES: IPCC, 2000)

1.6 Aims and Objectives

The main objective of this study is to estimate the impact of shoreline retreat due to sea level rise along adjacent coastline of the Guadiana estuary and thereby, to identify the most vulnerable sectors at risk of this 15 km stretch of the coastline. Impact assessment due to shoreline retreat and resulting loss of land of different habitats are estimated based on the upper bound value of SRES B1, A1B and A1FI scenarios where the mean sea level rise by 0.38, 0.48 and 0.59m respectively by 2090-2099 (IPCC 2007). These impacts were compared with the shoreline retreat due to present shore line evolution which can be a consequence of present rate of sea level rise, shoreline accretion and erosion caused by long-shore and cross-shore sediment transportation, deficiency in sediment supply to coastal zone due to intense damming upstream of the Guadiana River and anthropogenic intervention including construction of jetties, groins, breakwaters and river training structures. Finally, it is intended to produce vulnerability maps to visualize the impacted zone which would help in planning mitigating measures for sustainable utilization and management of coastal zone resources. In addition to the above main objective, following objectives were achieved as an integrated study of coastal hazards due to sea level rise.

1. To carry out a first order assessment of impacts of instantaneous shoreline retreat due to hypothetical storm surges under elevated flood contours due to sea level rise.
2. To carry out a first order estimate of the maximum potential inundation area due to hypothetical storm surges under elevated flood contours due to sea level rise

Chapter 2

2. 0 Literature review

2.1 Evaluation of shoreline retreat

Prediction of shoreline response to the sea level rise and other coastal hazards including storm surges is among the demanding challenges for coastal scientists and coastal zone managers as it is identified that approximately 70% of world's sandy beaches are eroding (Bird, 1985). Even though, there are several recent attempts to predict the shoreline behaviour with respect to sea level changes, it has received less attention on the whole. This may be due to its inherited complex nature of the problem and both identification and characterization of critical parameters highly involve understanding of the temporal and special variability of the phenomenon (Cattaneo and Steel, 2003). Marine transgression resulting from relative sea level rise occurs typically, in an episodic and spatially heterogeneous fashion and storms too play a major role in driving the shoreline landward (Forbes et al., 2004). It is understood that the shoreline response for given sea level rise can be co-related to the local geomorphological and sedimentological characteristics including the geological framework, sediment supply and dispersal rates, sediment type, existing geomorphology, vegetation, lithification rates, abrasion, contemporary dynamics such as shoreface and nearshore circulation, and human intervention (Hays, 1967; Swift et al., 1976; Cooper and Pilkey, 2004). Storms also can cause significant geomorphological alteration, including shoreface sediment entrainment, beach, dune and cliff erosion; barrier overwash and modification of tidal inlets. For coherent coastal management plan with sound scientific basis, it is essential to understand the natural response to these environmental forcing that includes the trends in mean water level, variability in the frequency and severity of storm winds, storm surges, and waves, and variance in the seasonal duration and extent (Forbes et al., 2004). Furthermore, it is important to distinguish predictability of response due to meso time scale forcing such as relative sea level rise is higher than the micro time scale variability such as storms (Regnauld et al., 2004).

Even though the shoreline evolution accompanied with several processes explained above, many studies have used the simple Bruun Rule (1962) alone to predict the shoreline retreat due to relative sea level rise (Cooper and Pilkey, 2004). The Bruun Rule (eq. 1) uses the concept of equilibrium profile. As water level or wave conditions change the beach profile will respond to the changes so that there would be a new equilibrium profile. If the changes occur very slowly, the profile changes will maintain more or less same pace with the changed conditions giving an opportunity to apply static models independent of temporal variability. However, if the conditions are varying rapidly, a dynamic model should be used for prediction of profile change (CEM, 2002).

$$R = SGL/(h+B) \qquad (1)$$

Where R is shoreline retreat due to sea level rise by S above the mean sea level, G is the is inverse of overfill ratio, which describes the proportion of eroded material remaining in the active profile, L is the active profile width, from depth of closure (h) to the toe of the dune of which height is B. The depth of closure defines the most seaward limit of the active profile. There are two components of the Bruun Rule and they account for: 1) a retreat of shoreline R, which produces sediment yield (R*(h+B), and 2) an increase in the elevation of the equilibrium profile equal to the sea level rise, S and demand SL amount of sediment supply. Thus, the basic assumption of the Bruun Rule is that this sediment demand will be supplied by above sediment yield due to shoreline retreat and the result is the Bruun Rule and does not depend on the particular shape of beach profile. This equation is far from the actual natural beach profile. Hence, several attempts have been undertaken to for accurate predictions. Thus, it was modified considering the loss of sediment due to winnowing or canyon depositions in the offshore (Bruun, 1988). The main critique is that the Bruun Rule does not account for beach profile changes due to net long shore sediment transportation (Cooper and Pilkey, 2004; Cooper et al., 2005). However, it should be noted that Everts (1985) try to incorporate the unbalanced sediment flux into or out of the beach profile due to gradients in the net long-shore drift.

Another, shortcoming is that the Bruun Rule is originally derived for sandy beaches. However, without paying attention to the above criteria, there are some studies aimed for estimating shoreface erosion in mangrove swamps (eg. Ellison, 1993), and mud flats (eg. Kriby, 2000). However, some studies have taken measures to correct the Brunn Rule for the type of depositional features in the shoreline. Kont et al., (2003) used different values for the overfill ratio, For instance, for sandy beach it is 1.0; for gravel and pebble beach- 0.7; shingle rich loam - 0.4; and for limestone 0.1. Despite these modifications, the uncertainty in the upper limit of the active profile remains unresolved, creating difficulties to establish a realistic profile width (CEM, 2002). It was found that the Bruun Rule initially overestimated the profile response due to time lag between elevated water level and the profile response in which the depth of closure was used as the maximum depth of significant profile change and the upper limit as the natural vegetation line in the foredune (Hands 1983). In general, the shoreline retreat is about 50 to 200 folds of the sea level rise and larger factors would relate to the gentler and more energetic slopes in which the depth of closure is greater. Even though there are many critiques against the use of the Bruun Rule for assessing shoreline erosion due to sea level rise, still it is being widely used for many studies because there is no simple, viable quantitative alternative (Cooper and Pilkey, 2004)

Moreover, evidence from recent studies suggest that coastal beach response to the extreme events within micro time scale will not appear in the long term shoreline trend regardless of the severity of extreme event because beaches recover long term trend. Therefore, it can be assumed that impact of extreme events including storm surges will not be responsible for severe shoreline erosion in long term (Zhang et al., 2004). Similar conclusion have drawn by Fenster et al., (2001), which shows that storm surges will not directly control the shoreline erosion in long terms compared to shoreline response due to long term process such as sea level rise. However it is very important to assess the maximum potential risk zone due to such severe extreme events because still the vulnerability of such events for population, built-up area and vegetation are very high and economic loss also can be significant unless otherwise there is no proper management plan for recovery or adaptation.

It can be seen that there are four basic modelling approaches to estimate the shoreline erosion and predict the shoreline response (Roelwink and Broker, 1993). Accordingly, they are equilibrium profile models, empirical profile evolution models, processes based models and descriptive models. The processes based models can be further classified as research models incorporated with complete governing physics and practical models where the governing processes are simplified to certain degrees according the problem. However, most of above models are not fully sophisticated to represent the dynamic and highly three dimensional near-shore zone including the shoreline (Miller and Dean, 2004).

Edelman (1972) modified the Bruun Rule to accommodate the time dependent and larger water level increase assuming that the profile response in pace with such short term and high sea level rise. In this formulation, the active profile height is now dependent parameter of time. The integration of the derivative of sea level rise will lead to final shoreline retreat. The depth of closure (h) and active profile width (L) were substituted with breaking depth and surf zone width. Dean (1991) formulated a shoreline response model by using theoretical pre- and post- storm profile given by the equilibrium profile proposed by Bruun (1954) and Dean (1977). The solution was obtained by equating the eroded and deposited areas derive from the integration the areas of initial and final equilibrium profile. The solutions were obtained for steady state sea level rise and wave set-up distributed in the surf zone resulting from breaking waves. Even though, this wave set up acts similar to storm surge, it is evidenced that the impact is larger in case of storm surge than the wave set-up (CEM, 2002). The magnitude of the shoreline erosion response is showed to be determined by the maximum shoreline potential response, that would occur if the beach was allowed to respond completely to a new equilibrium; and the characteristic erosion time scale, which governs the exponential rate at which the profile responds toward new equilibrium (Kriebel and Deans 1993). The beach erosion derived from this closed loop model (Convolution method) is found to lag the erosion forcing in time and it is damped relative to the maximum potential resulting fraction of response that will take place actually. This is mainly because of the assumption that there is exponential erosion rate. It is understood by analysing the storm surge hydrograph and erosion response hydrograph that for short term hurricanes will cause maximum erosion near the end of storm and maximum erosion that would occur may be 20 to 40% from the erosion potential and that for long term surges is 40 to 90% (Kriebel and Dean 1993). A considerable improvement has been achieved in formulation of response of shoreline to storm surges considering a small wedge-shaped sand volume offshore of the breaking depth. The formulation is function of slope of the beach profile at the waterline, wave breaking depth, and surf zone length, dune or berm height and storm surge level. The surf zone length is included with offset which represents the length between the sloping beach face and virtual origin of the equilibrium profile. However, for most of the cases this offset can be negligible (CEM, 2002). It should be noted that the convolution model overestimate the post-storm beach recovery therefore, this solution in its original form may not be used for estimating the extent of recovery (Kriebel and Dean, 2003).

2.2 Inundation due to sea level rise

Even though the shoreline retreat due to erosion and inundation due to flooding are inter-related they describe different processes. While the erosion process meant to redistribute the sediment from onshore to offshore, the inundation will cause the drowning of land either temporarily or permanently (Zhang et al., 2004). Generally, inundation of the shoreface refers to the shoreline retreat (Cooper et al., 2005). However, there would be more inundation if there are inlets, river mouth and tidal creeks. Inundation changes the position of coastline and drowns natural habitats, built-up area and human settlements. Inundation can aggravate the coastal erosion by mobilizing sediment offshore. Inundation can be determined by using the sea level rise rate, sediment availability, slope and geomorphology of the shoreline. In the context that there is no other interference, the first order effect of sea level rise would be displacement of flood exceedance curves upward resulting increase of the risk zone. The degree of expansion would vary geographically as seen in the studies carried out in Netherland and Egypt (Nicholls, 2002).

There are several approaches to calculate the flood contours. Gornitz et al., (2002) estimated the maximum flood level adding the component of surge, mean high water and sea level rise for each decade between 2000 and 2090. Empirical approach developed by Hoozemans et al., (1993) was adopted to assess the vulnerability of flooding by Snoussi et al., (2007). Hoozemans et al (1993) is also similar to the approach used by Gornitz et al., (2002) but it contains the barometric set up which is the rise of sea level due to lowering the atmospheric pressure in a storm event. Recently, more accurate study has been carried out to assess the coastal flooding hazard in Veldelagrana spit of Cadiz, Spain (Benavente et al., 2006). Three components, namely; wind set-up, barometric set-up and wave set-up have been used to estimate the storm surge component. Pile up of water with storm wind effect over the near shore zone is called wind set-up and increased wave breaking height would result in water level increase in the surf zone called wave set-up.

2.3 Response of salt marsh land for inundation

In global scale, coastal wetland losses due to sea level rise may not have significant impact compared to the deterioration of such sensitive ecosystems due to anthropogenic pressure (Hoozemans, 1993). It is understood that the wetland loss due to sea level rise will be controlled mainly by the rate of rise rather than the total rise as they have capacity to respond to inundation (Cahoon et al., 1999). However, sea level rise would cause significant loss when the rate of sea level rise exceeds a defined threshold (Nicholls and Lowe, 2004). This threshold limit may be controlled by the vertical accretion rate. If the vertical accretion is not in pace with the sea level rise rate due to deficit in sediment supply with the forced intervention such as upstream damming, there would be loss of land area (Reed, 1990; Siams et al., 2001). Furthermore, the susceptibility of wetlands to long term sea level fluctuations shows dynamic and non-linear response (Nicholls et al., 1999). However in this context that marsh lands are already under stress due to the human intervention, impact of sea level rise would create significant additional stress on their healthy existence (Nicholls, 2003). It is possible to apply the simple mass balance equation to estimate the salt marsh elevation changes with the sea level rise. Thus salt marsh elevation relative to a potentially moving tidal frame of reference would be given by the algebraic sum of added thickness of externally derived elastic sediment, additional thickness of intrinsically-derived organic sediment, change in relative sea level and the elevation change due to autocompaction of the marsh deposit above a hard incompressible substrate (French, 2006). It is shown in one dimensional model analysis, under a constant rate of sea level rise, a marsh deep in the tidal frame will accrete at rates greater than the rate of sea level rise and accretion rate will declines. The platform gains elevation relative to sea level rise, until the platform reaches an equilibrium water depth where accretion rate is equals to sea level rise (Kirwan and Murray, 2007). In this regard, over the millennia the accretion in pre topic times was compatible with the sea level rise (Boski, et al., 2007).

2.4 Socio-economic classification of vulnerability due to sea level rise

The knowledge of impacts on the socio-economic sectors due to sea level rise hazards are limited owing to the very reason that there is not enough comprehensive studies directly focused to the above topic (Santos, 2002). Under the IPCC, Coastal Zone Management Subgroup developed a stepwise methodology to assess the vulnerability of sea level rise on Country-specific institutional, economic, technical and social implications (IPCC,1991). Assessment of the impacts of sea level rise and related coastal hazards have been very much focused on the loss of dry land and wetland due to erosion and inundation and then the interpretation these losses in terms of cost associated with it (Santos 2002). However, the cost assessment is in fact a demanding task which requires inputs from the atmospheric, oceanic, geologic, biologic, environmental, social, economic, aesthetic and cultural valuation of the system.

As a first order assessment, development of vulnerability indices has become common approach to overcome the problems due to insufficient data. However, such indices will not be used directly either in planning or decision making process (Feenstra, et al., 1998). Studies on vulnerability assessment in Portuguese coast have been carried out using AVVA technique (Aerial Videotape-assisted Vulnerability Analysis). This method requires oblique aerial video recording of the coast, archival research, limited ground truthing, and data analysis and processing (Letherman et al., 1995). The natural attributes in the hazard zone were classified accordingly: coastal geomorphology includes beaches, wetlands, cliffs, and artificially protected shorelines. Inland geomorphology is described by flatland, hilly land, mountainous land and wetlands. The shoreline evolution trend is represented by stable/ accretion or stabilized by protection works, tendency to erode, and erosion confirmed. Each attributes of Coastal geomorphology were classified further. The classification of socio-economic attributes are includes; coastal protection present, land use, population density, coastal development. This land use classification holds important under the present study as similar classification has been adopted. This includes urban/city, residential, industry, tourism, agriculture, forest, barren and shrub land.

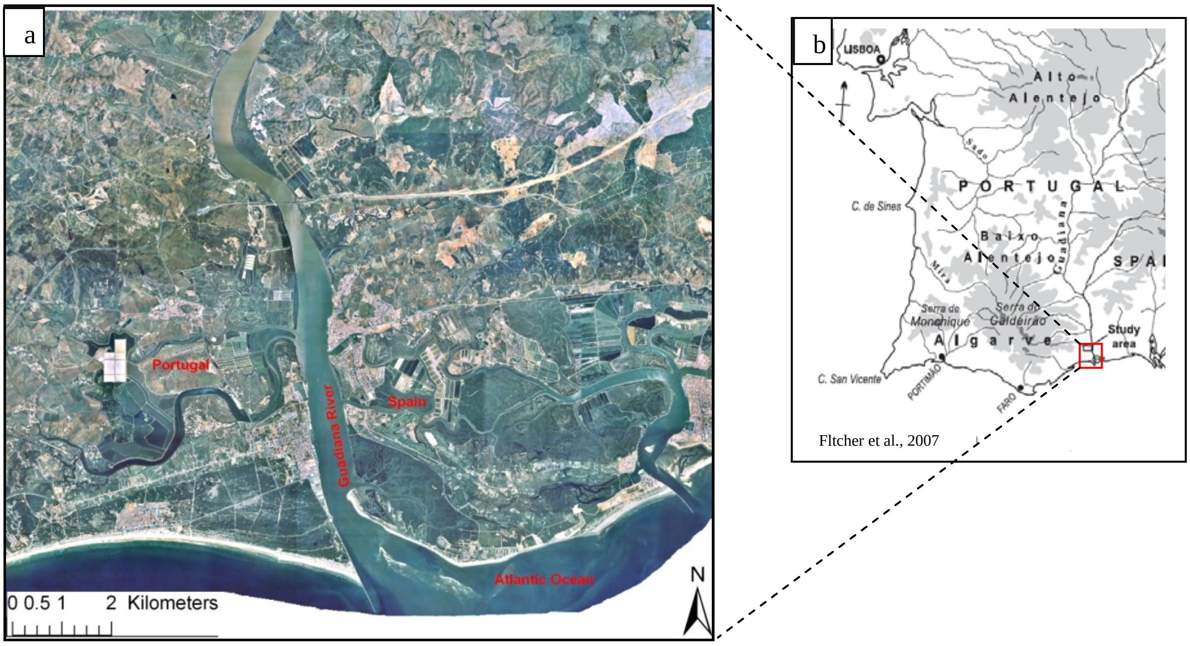
Vulnerability analysis by Snousi et al., (2007) has adopted accordingly, similar classification of loss due to shoreline erosion and inundation, including marsh lands and ports also. Flood risk on coastal population is usually assessed by in terms of number of people exposed to extreme floods. Nicholls, (2002) defined the flood risk zone as the area below the 1000 year storm surge ignoring the present flood protections available. However, it is estimated that even without sea level rise the number of people affected by coastal flooding would increase as the rapid migration of population to coastal zone (Nicholls, 2003). A dynamic analysis of flooding have been carried out using Nicholls, (2004) methodology where that examines the impact due to sea level rise on population assuming the coastal population growth is twice the national population growth reflecting the net coastal migration, and improving defence standards estimated using increase in per capita GDP as a measure of adaptive capacity (Nichols and Lowe, 2004). This study considers the SRES stabilization experiments which includes climate change and socio-economic scenarios.

Chapter 3

3.0 Study area

3.1 Administrative Boundaries

The Guadiana River is a transboundary river where the national border of Portugal and Spain runs the last 200 km of the river course. The Portuguese side of the adjacent coastline comprises three administrative divisions, namely, Monte Gordo, Vila Real de Santo Antonio and Castro Marim. The coastal stretch in the Spanish side is a part of Ayamonte municipality. Figure 1 shows the satellite image of the area (Year 2000) and figure 3 shows administrative boundaries (Municipal) of both countries. In addition, the administrative map shows the main urbanized areas belongs to both countries.



Fltcher et al., 2007

Figure 2: Study area a) Satellite image (2000) of the Guadiana estuary, Portugal/ Spain boarder and b) its location in the southwestern Iberian Peninsula

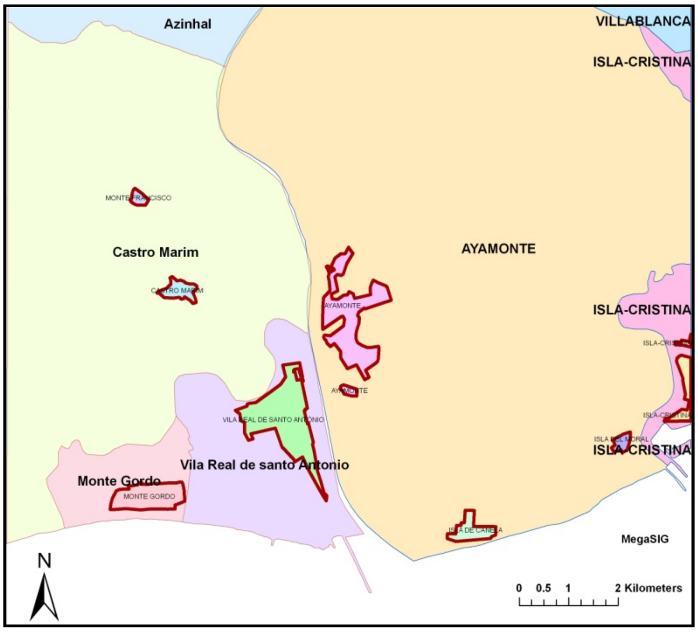


Figure 3: Administrative (Municipal) and urbanized area belongs to the study area Physiography (Source, MegaSIG project, 2002-2004)

The study area, the Guadiana estuary and adjacent coastline is located at the passive continental margin of south West Iberian Peninsula and The Guadiana River basin is one of the largest on this peninsula (Boski et al., 2007). Figure 4 shows the physiographic maps of the study area.

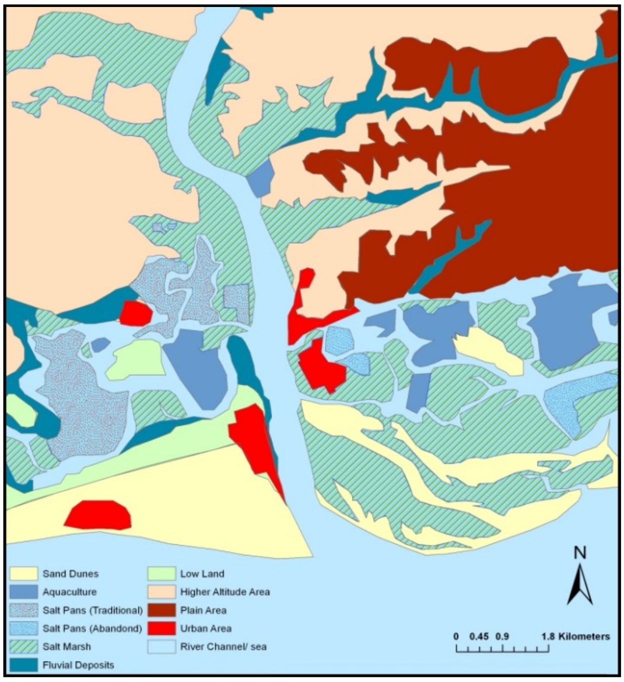


Figure 4: Physiographic maps of the study area (Source, MegaSIG project, 2002-2004)

The western side (Portugal) of the river is a large littoral spit with transverse progradation and separated from the mainland by a marsh. Aeolian dunes are developed at the seaward side of this spit and on the landward side of the spit, a salt marsh drains directly into the main estuarine channel. The eastern side (Spain) consist of an array of old barrier islands transformed into elongate spit and separated by salt marsh which drains directly to the sea through a feeder inlet via a high density tidal channel network (Morales, 1997). These inlets in the Huelva coast are result of the entrenchment of the fluvial system during the Pleistocence lowstand, followed by the Holocene transgression. The Guadiana River was able to cut a slightly wider valley in the seaward parts of its course across the Guadalquivir basin and this part is now nearly fully submerged after the transgression. The resulting small shallow embayment into the river mouth is dividing the river mouth in to well defined estuary, where fluvio-marine interactions are occurring and prograding salt marsh complex and barrier islands which are a wave-dominated fluvial delta. According to morphological studies, there are 12 different depositional facies in the system: fluvial delta, tidal inlet, flood tidal delta, washover, beach, dune, estuarine channel, lagoon, tidal creek, channel margin, tidal flat and salt marsh (Morales, 1997).

3.2 Hydrodynamic setting

The Guadiana estuary is semidiurnal mesotidal, with a mean tidal range of 2.0 m, ranging between maximum values of 3.8 m and a minimum of 0.5 m (Instituto Hidrogra´fico, 1998). The tidal wave moves from east to west along the coast, producing minor currents in the range of 0.3–0.4 m/s (Morales, 1997). The wave regime is characterised by waves of low to medium energy, including both Atlantic swell waves and local sea waves. As the southwesterly waves prevail with approximately 50% of occurrences from the west it can be considered as the dominat wave regime while southeasterly waves with 25% occurrence are more energetic (Costa, 1994). This can produce about 5.3m high waves with 100 year return period (Pires, 1998). The mean annual significant offshore wave height is about 0.92 m with an average period of 4.6 s, and peak average periods of 8 s (Costa, 1994).

The longshore sediment transportation is estimated between 100,000 and 300,000 m^3/year from west to east due to the prevailing onshore wave conditions (Gonzalez et al., 2001). The Guadiana River characterized by strong seasonal changes, will supply the estimated suspended sediment load of $57.9x10^4$ m^3/year and $43.96x1010^4$ m^3/year to the shelf between 1946 and 1990 (Morales (1995, 1997). Due to the off shore sediment transportation, sediment grains with a diameter of 2 mm (very coarse sand) will be remobilised down to a depth of about 5 m during fair-weather conditions, and 30 m during storms, while grains with a diameter of 0.032 mm (coarse silt) will be remobilised down to 10–15 m under fair-weather conditions, and 45–50 m during storms (Komar and Miller, 1973, 1975).

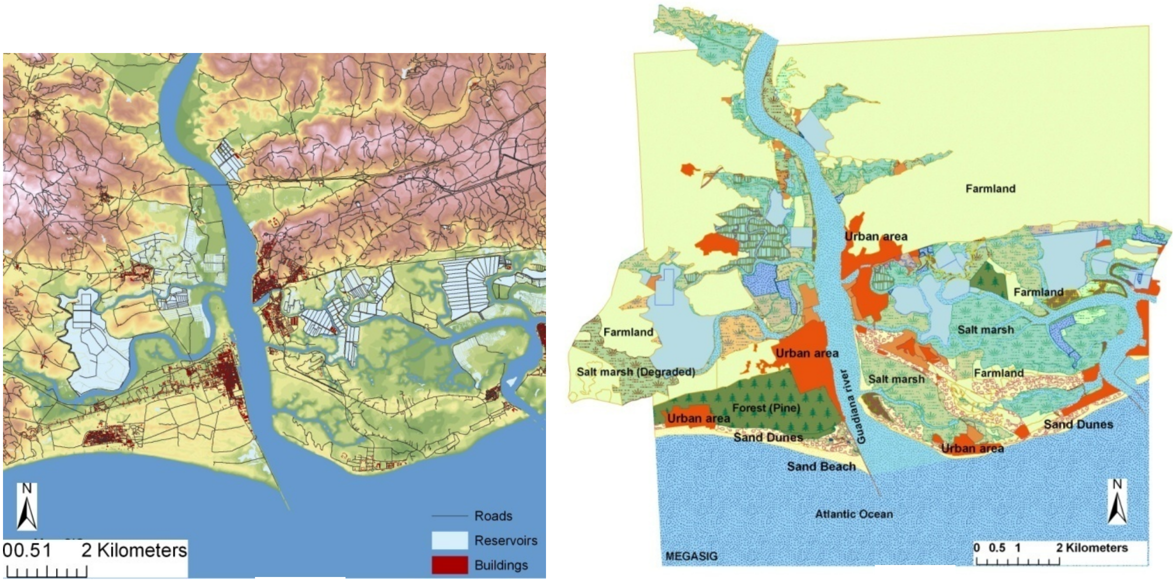
3.3 Fauna and flora

This estuarine system is very important for feeding and reproduction of several species including animals, birds, fishes, molluscs and crustaceans. More than, 2000ha of this area in Portugal side was declared as a “RAMSAR” convention protected area after and obtained a nature reserve status in 1975 (ICN, 2002). Saltmarshes are developed on the accreted sediments on both side of the infilled estuary (Boski, 2007). They are occupied by halophyte vegetation and are strongly influenced by tide variations and adapted to extreme conditions including high salinity and periodic flooding (ICN, 2002). Cereal cultivation using traditional practices were the main agricultural activity until mid 20th century while traditional and modern saltpans are main industrial activity in the area of concern. 434ha of Maritime Pine Pinus pinaster planted at the end of 19th century for fixing the dunes is the only forested area in the eastern coast of Algarve region (ICN 2002). Tourism is also main economic activity especially in Monte Gordo, Portugal and Isla de Canela, Spain.

3.4 Built up area and Land use/type

As shown in figure 5a, the human settlements of the Guadiana estuarine are concentrated in few urbanized localities. In Portuguese side, the built up area is mainly concentrated within Monte Gordo which is constructed on the coastal sand substratum, including beaches with high tourist attraction. The other main urban area is Vila Real de Santo Antonio which extends ca. 4.5 kms along the artificially elevated river banks. There are important roads and railway line connecting this town to the other parts of the region. Other roads are mainly connecting the urbanized area within the locality. In Spanish side of the river, Isla de Canela is located close to the coastline and it is also a tourist attraction area. It is estimated that approximately, more than one million tourists will be attracted to the littoral of Huelva province between May and September (Rodriguez-Ramirez, 2003). Isla de Moral and Isla de Cristina are other two cities and the later is showing rapid urbanization at present. However, large part of this area is out of the study area selected for the present study. Ayamonte which is the main city of the Spanish side located considerably above the coastline but part of this settlements lies within the low lying area of the river.

In Portuguese side, the land type is mainly the sand dunes and sand beaches. The upper part of the sand dune area is a forest of Pine trees planted to stabilize the dune area. There is no agricultural area within the low lying area of the west bank of the river. However, there is a vast area of salt marsh which is not much altered due to its status of a protected area. The coastline of the eastern side is also dominated by sandy dunes and salt marsh area is located behind these dunes and they are highly altered for urbanization and agricultural activities. Only the upper part of the salt marsh is considered as protected area in this region.



(a) (b)

Figure 5: a) Digital Elevation model of the coastal zone of the Guadiana estuary, Portugal/Spain Border, and built-up area map and b) a map of vegetation and land use/type (Source MegaSIG project)

3.5 Anthropogenic Pressure

A large scale changes in the shoreline and margins have been observed throughout the 20th century. For instance, intense damming along the upstream of the Guadiana River is one of the main forcing for changing the shoreline as it resulted in the significant reduction of average river discharge, altering the amount and type of sediment exported to the coastal zone (Gonzalez et al., 2001). There are more than 40 dams covering the 75% of Guadiana drainage area (Morales, 1997). This situation has been further aggravated by the inauguration of the Alqueva dam in February 2002, creating the largest artificial lake in Western Europe, and almost doubling the amount of water stored in dam lakes in the Guadiana River basin (Gonzalez et al., 2001). It can be seen that the tourism and rapid urbanization especially in the Spanish side of the coastline are exerting pressure on the natural systems such as sand dunes. The sea defence structures have created total or partial obstacle to longshore sediment drift. Jetties and groins in Vila Real de Santo Antonio and Huelva have cut of the sediment totally while the groyne in Isla Cristina avoids natural sediment transportation, partially.

3.6 Chronology of sea level rise

It can be identified that different overlapping processes had been dominant in shaping the coastline of Portugal since the Last Glacial Maximum until present. It can be seen that vertical sediment accretion is 7.6 mm/yr from 13000 to 7500 cal yr BP. During this period, sea level rise rate would be 7 mm/yr for the western part of the Gulf of Cadiz. Since 7500 cal yr BP, the average rate of the sediment accretion is about 0.9 mm/yr (Boski et al 2007). This rate is much lower than the present sea level rise rate of 1.5 mm/yr in this region proposed by Dias and Taborda, (1992). The eustatic sea level rise had been the decisive factor until mid Holocene and then the non- eustatic factors have become more important to determine the coastline evolution. Anthropogenic activities including deforestation, agricultural activities have contributed very much since the 15th century AD. Starting from 20th century, multiple damming of major rivers and sand mining from river beds have been critically affecting the sediment balance of Portugal coastal zone (Dias et al., 2000).

The study of mesoscale (ie. decadal) changes of recent relative mean sea level along the Portugal coast, deduced from tide gauge records of Lagos for 92 years indicates 1.5 mm/yr transgressive increase of mean sea level (Dias and Taborda 1988; 1992; Kol et al., 2002). These figures are consistent with the observed eustatic global rise in mean sea level during the 20th century. Further, it can be seen that the thermal expansion of the ocean is the prime responsible for the observed rise in sea level in Portugal and the isostatic and neotectonic components being negligible (Santos, 2002).

Chapter 4

4.0 Methodology

4.1 Assessment of shoreline retreat due to sea level rise

The methodology adopted to assess the shoreline retreat due to sea level rise was based on the methodology used for establishing the set back lines for coastal erosion hazards by Ferreira et al, (2006). The advantage of this methodology is that it will enable to incorporate the accretion and erosion processes present in the coastal zone as the present shoreline evolution rate (SER) is assumed to be dependent parameter of the present sea level rise rate, long-shore and cross-shore sediment transportation, impact of coastal structures and sediment supply with river run-off. The shoreline position by the end of 21st century was estimated using SER which is derived using recent aerial photographs of 1996 and 2005. Therefore, this would also account for the shoreline retreat due to recent anthropogenic intervention such as damming and construction of coastal structures including groins, breakwaters for coastal defence and jetties for river training at the Guadiana river mouth. The main assumption of this methodology is that for the period of projection (in this regard 100 years), there would not be significant changes in the processes that would account for the changes in the shore line evolution. This assumption is highly uncertain however, it is not possible to incorporate the possible changes in the coastal zone management plans. For instance, if there is sand nourishment or construction of jetties, breakwaters and dams to retain the water such intervention would alter SER directly by changing the sediment supply to the coastal zone from the river and by modification of long-shore and cross shore sediment transport due to change in the wave climate and the near-shore current field.

The total shoreline of 15 km was divided by 250m transects using ARCGIS tools (Figure 6). The shoreline change from 1996 to 2005 was calculated relative to the baseline (S_0) defined for 1996. The shoreward edge of the foredune vegetation line was used as the baseline because it is considered to be the best coastal feature that exhibits the transition between the wind and wave dominated domain rather compared to the short-term (tidal) or medium-term (seasonal) features (Ferreira et al, 2006). First, for each vertical aerial photograph the most shoreward edge of the foredune vegetation was established by careful analysis of photographs. Then shore line evolution was calculated for each transects using end-point rate method in which the distance of two shoreline averaged over the 10 year period. For realistic spatial prediction, 5- point moving average was applied thereby to smooth the shoreline changes.

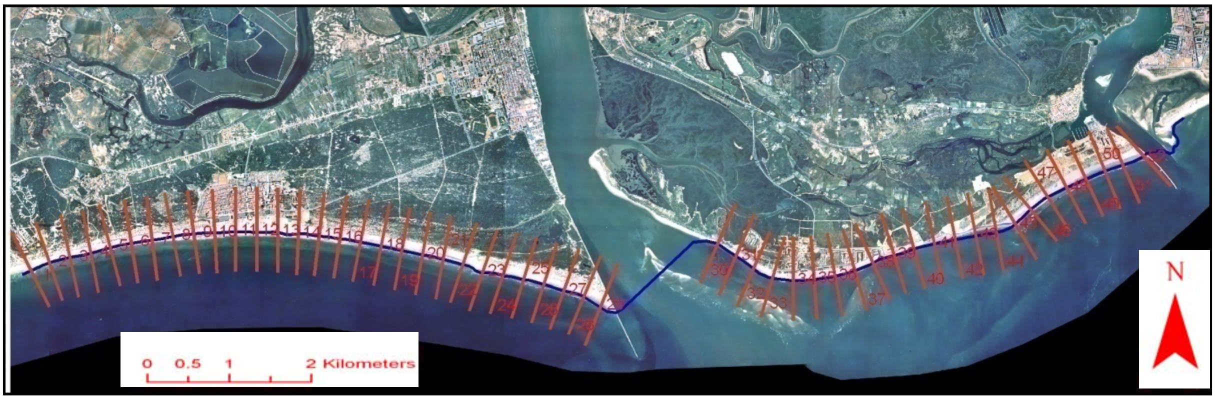


Figure 6: Transects along the coastline of the Guadiana Estuary

The shoreline by the end of 100 years with the constant SER rate was then predicted by super-positioning the shoreline evolution on the present shoreline position (S_P). In this present study, shoreline position derived from 2005 aerial photographs was used. Thus, new shoreline position can be given by:

$$S_{(100)} = S_P + SER*100 \tag{1}$$

However, it is unequivocally accepted that there would be acceleration in sea level rise during the 21st century (IPCC, 2001; 2007) and also the sea level rise rate given under each

SRES scenarios of sea level rise, are higher than the present rate of change. Therefore, it is required to incorporate the increase due to accelerated sea level rise. Thus adjustment corresponding to the shoreline retreat due to accelerated sea-level rise (ASLR) was estimated using the Bruun Rule (1962) for three scenarios considered in this present study and then results superimposed on the shoreline position derived based on the present SER. Thus, the final shoreline position would be more realistic than the projections solely based on Bruun Rule which is considered to be over prediction (CEM, 2002, Cooper and Pilky, 2004). Three scenarios of sea level rise namely B1, A1B and A1F were considered for estimating the ASLR. However only the upper bound limit of the AOGCM results, were used for these estimations thus the impact can be interpreted as worst case scenarios (IPCC, 2007). It should be noted that use of global values for each scenario can be justified as the isotatic and neotectonic components are negligible in this part of the sea (Santos, 2002). Adjustment for accelerated sea level rise (SLRa) can be formulated in terms of the present sea level rise rate (SLRp) and the expected sea level (SL100) at the end of considered period. The present sea level rise rate from 92 years of tide gauge data is estimated as 1.5 mm/yr. Even though this value agree with the global mean value form tide gauge records from 1961 to 2003, the satellite altimetry data analysis from 1993 to 2003 shows acceleration in sea level rise and global mean sea level rise rate during that period is 3.1 mm/yr. Therefore, in this present study also the above global mean value was used to accommodate the recent trends in sea level rise. Then the adjustment is given by:

$$SLRa = SL100 - SLRp \qquad (2)$$

Now, it is possible to apply Bruun rule (1962) to estimate the shoreline retreat (Ra) which is:

$$Ra = SLRa * L/(h+D) \qquad (3)$$

Where L is the horizontal distance between the upper and lower limits of the beach profile, h is the depth of closure of the active beach profile (measured below the mean sea level), and D is the dune elevation measured above the mean sea level.

Thus, final shoreline position at the end of 21st century can be given by for coastlines, under erosion or dynamic stability:

$$S100c = S100+Ra \quad (4)$$

For coastlines where the shoreline is experiencing accretion but the predicted erosion due to ASLR is greater than the seaward displacement can be estimated incorporating the accretion rate (SERa).

$$S100c = Sp +Ra - SERa*100 \quad (5)$$

If the accretion is greater than shoreline retreat due to ASLR, there would be net seaward movement of the present shoreline gaining more land. However, under the present study such seaward movement is not estimated. Parameters for the Bruun Rule were obtained from the literature and the Digital elevation model. The depth of closure, a useful engineering concept which defines the seaward limit of the effective profile fluctuation over long-term time scales was calculated using the empirical formula developed based on laboratory and field data by Hallermeier (1978, 1981). Wave data for this estimation were obtained from the preliminary report of the PROJECT INDIA (Pires, 1998). Based on the estimated depth of closure of 8m, the horizontal distance (L) between the upper (toe of dune) and lower limits (depth of closure) of the beach profile were derived from sea bathymetry contours of 1m interval developed from the digital elevation model (DEM) for the Guadiana near-shore zone. The beach slope too also derived from the same DEM. Granulometric data were obtained from the available literature of Gonzalez et al., (2004) and Dias et al., (2004) Finally, the shoreline retreat maps for each scenario were developed for the Guadiana coastal stretch using ARCGIS interface and overlaid on the land use and land cover maps and administrative maps. Finally, the loss of land of the Guadiana coastal zone on the both sides of the frontier was estimated. Further, the impacts on protected areas (with special attention to salt marshes), agricultural and industrial lands were estimated. Moreover, this methodology permitted the assessment of the impacts on the major constructed structures and transportation networks.

4.2 Shoreline retreat due to storm surges during maximum spring high tide situation

It is understood that under the sea level rise scenario, the impact due to storm surges would be much greater. Yet, even though there are some limitations of the available data including beach profiles extending from the surf zone to the dunes above the mean sea level, first order projections for the shoreline retreat due to hypothetical storm surges were developed using available data and validated digital elevation model used in the MegaSIG project. It should be highlighted; it is an inherited problem where the most of the coastal management programmes have to be undertaken with such deficit in the readily available data. Thus, the focus of the assessment of shoreline retreat due to storm surges under elevated flood contours with respect to sea level rise is to find out the order of magnitude of the maximum potential shoreline recession of the adjacent coastline of the Guadiana estuary.

In this context, Ferreira et al., (2006) method adopted to estimate the shoreline retreat due to accelerated sea level rise, storm surges under spring high water situation. The resulting shoreline was superpositioned on the overwash due to the same intensity storm to obtain the cumulative impact. This estimation would be the upper bound solution of the maximum potential risk zone of instantaneous shoreline retreat and overwash. The shoreline retreat due to storm surge under high tide situation was estimated using convolution model by Kriebel and Dean (1993). The main steps involved to access the instantaneous shoreline retreat are discussed below.

The convolution model is a simple analytical solution for time-dependent beach profile response to severe storms. It is understood that for a given initial beach geometry and sediment size, the peak water level and initial wave breaking height determines the maximum erosion potential if the beach is allowed to achieve equilibrium but with the assumption of exponential beach erosion rate, only fraction of the equilibrium erosion would occur. For short term storms the 20 – 40% of erosion potential of the storm would occur at the end of the storm and for long term storms that would be 40-90%.

The breaker depth of corresponding storm wave was estimated using the relationship given in the Shore Protection Manual (1984) where the breaker depth is 0.78 times the storm wave height. Based on this breaker depth, the length of the surf zone was estimated using the 1m interval contour maps derived from the DEM extent to the surf zone. The slope of the surf zone sea bathymetry and up to the toe of the dune and berm height were estimated using the same DEM. The maximum high water level and the storm surge with 100 year return period were used to estimate the rise of sea level which indicates the worst case scenario of 8 m rise of sea level during the 100 years. These results (R100) was superimposed on the shoreline retreat maps based on different scenarios of accelerated sea level rise to obtain the instantaneous shoreline retreat due to storm surges under high tide situation. Thus the 100 year shoreline position due to storm surges can be estimated as follows:

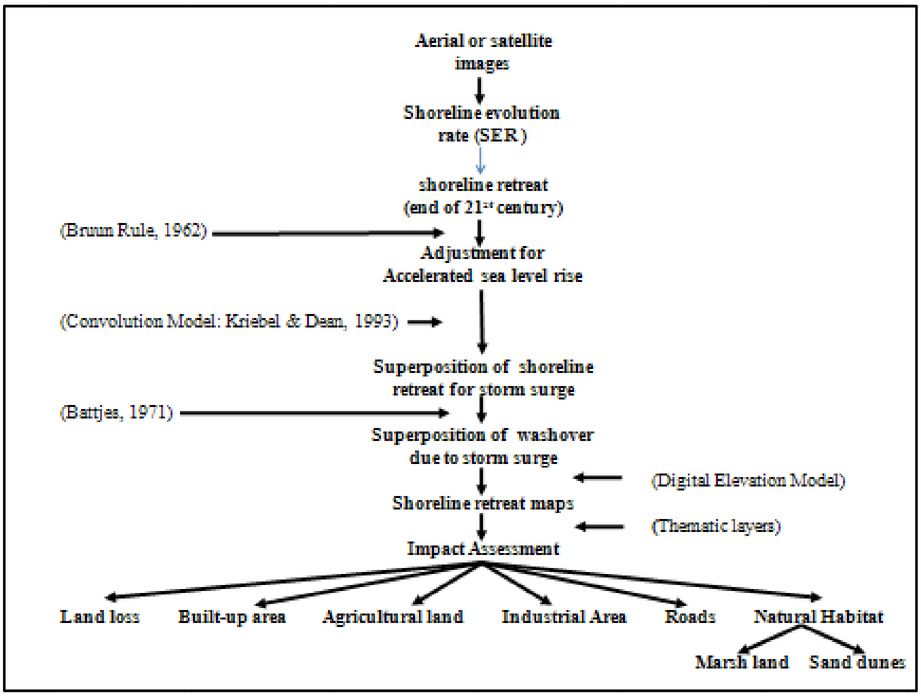
$$S100s = S100c + R100 \qquad (6)$$

$$R_{100} = I^{*}\{(W_b - h_b)/(B + h_b - I/2)\} \qquad (7)$$

$$hb = 0.78\ Hb \qquad (8)$$

where I is the storm surge height and mean high water level, Wb is the width of surf zone width, hb is the depth of wave breaking, Hb is the storm height and B is the dune/berm height. Finally, the maximum potential risk due to coastal hazards including accelerated sea level rise, amplified storm surges and overwash was calculated by adding the overwash component to the above results. The overwash component is estimated using Battjes (1971) formula.

$$R_{max} = (H_{S0}*L_0)^{0.5} R_s \tan b \qquad \textbf{(9)}$$

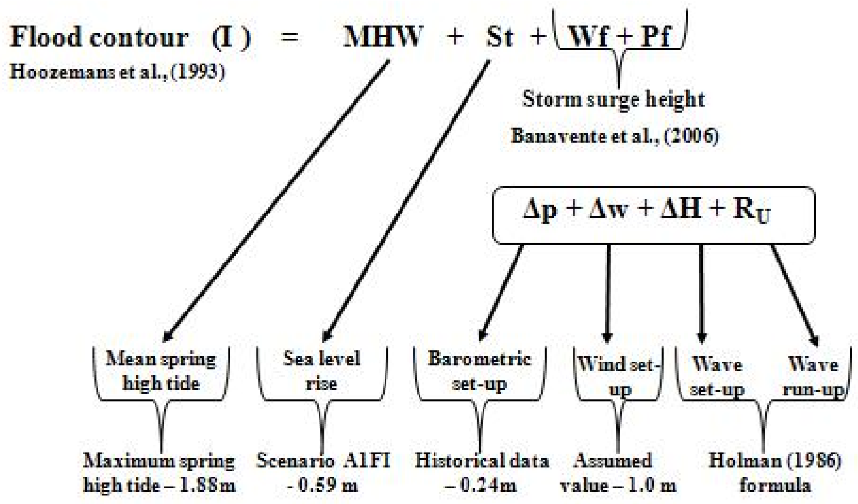


Box1: Impacts assessment steps due to shoreline retreat with sea level rise/storm surges

4.3 Inundation inside the estuary through the rivers and channels

The above methodology would not be used for total inundation areas including the inland inundation through the estuarine channel. To resolve this problem, approaches used by Hoozenans et al., (1993) and Banavente et al., (2006) were incorporated jointly. This method allows defining the inundation contours for sea level rise and using ARCGIS tools these inundation contours were overlaid on the DEM to derive the total inundation area and resulting secondary impacts. For this estimation three scenarios were selected to exhibit the low, medium and high risk zones.

$$I = MHW + St + Wf + Pf \qquad (10)$$



Note: Maximum spring high tide values were used to obtain the worst case
Flood contours were corrected for shoreline retreat using results of step 1

Box2: Steps of estimating the inundation due to sea level rise and storm surges.

Where the MHW is the mean high water level, St is the sea level rise, Wf is the storm height and Pf is the set-up due to lowering of the atmospheric pressure. The maximum spring high tide is 1.88 m above the mean sea level. According to the SRES scenarios B1, A1B and A1F, expected sea level rise is 38, 48 and 59 cm, respectively by the end of this century (upper bound values are based on the spread of Atmosphere-Ocean Global Circulation Model results- AOGCM). The storm-surge is due to the 0.24m barometric set up which is the average pressure drop in three historical events reported in the gulf of Cadiz affecting the coastal zone of the Guadiana estuary (4th December, 1987, 5th December, 1989 and 21st January 1996). Average wind set-up is assumed for this extreme case is 1.0m and wave set-up and wave run-up was the average value over the entire coastal stretch estimated using Holman (1986) formula.

Chapter 5

5.0 Results

5. 1The characteristics of Shoreline Evolution Rate (SER)

The shoreline evolution rate of a particular coastline depends on several factors including the sea level rise, the wave climate with the resulting cross- and long-shore currents, the sediment supply from rivers and inland sources, the wind which deriving aeolian sand movement and the anthropogenic interventions. Anthropogenic interventions include construction of coastal defence structures preventing natural sediment transportation along the coast, sand extraction, and obstructing bed load and suspended sediment transport by constructing the river diversion or storage structures such as dams and barrages. The adjacent coastline of the Guadiana estuary is affected by above natural and human forcings to different degrees. Thus, the shoreline evolution and shoreline evolution rate in this coastline must show high temporal and spatial variations. Figure 6 shows the present annual shoreline line evolution rate (SER) estimated from the shoreline positions deduced from the aerial photographs of 1996 and 2005. Five distinct zones can be seen along the coastline based on the SER. Aerial photographs (Datum: Intern_1924_Transverse_Mercator_Megasig) of the analysed Coastline was defined by easting coordinates (X axis of the figure 7) from 258000 to 272000 m. The Portugal coastline from 258000 to 260000 m and from 262000 to 266000 m show high accretion rate ranging from 0 to 4.3 m/yr and 0 to 3.8 m/yr, respectively. The coastal stretch from 260000 to 262000 m is dynamically stable showing no net shoreline erosion considered in this region. This region overlaps with the Monte Gordo tourist beach where the tourist infrastructures and other residential buildings and roads were constructed on the sand dune after removal of the vegetation and coastline is held by shore perpendicular groin constructed downstream of this coastline. The river training structure constructed at the west bank of the

Guadiana river mouth and extending 2000 m to the Atlantic Ocean and the above mentioned coastal defence structure are responsible for holding long shore sediment drift which resulted in the second accretion site in the Portuguese side of the Guadiana coast. This intervention has resulted in creation of 1-2 km of new beach and shows that the natural vegetation of foredunes is moving seaward presently as it is observed in Rodriguez-Ramirez et al., (2003).

Figure 7: The present shoreline evolution rate (SER) along the coastline of the Guadiana estuary and estimated based on aerial photographs of 1996 and 2005.

The negative consequences of this engineering construction can be seen further downstream of the coastline, especially the coastal stretch defined by 266000-270000 m is experiencing severe erosion. The maximum SER at this stretch is 4.8 m/yr. The main affected area is eastern side of another traditional tourist village, Isla de Canela. Western part of this region is eroding slower than the eastern side. This can be expected as it is reported that the touristic beach in Isla de Canela is frequently renourished artificially to maintain its tourist attractiveness.

The coastal stretch west of the Carreras inlet (270000-272100 m) can be seen as slowly accreting zone much close to dynamic stability. The average SER is ranging from +0.5 to -1.0 m/yr. The slow accretion is also result of the jetties constructed on both sides of this inlet.

There is a high risk that the present shoreline evolution trend will be further aggravated due to accelerated sea level rise causing severe erosion of stretches currently under erosion while other parts also will be exposed to the erosion processes. An attempt was made to estimate the possible changes in the shoreline evolution due to accelerated sea level rise. As the present SER contains the influence of present sea level rise trend, it is required to isolate the potential shoreline changes attributed to accelerated sea level rise. In this regard, the use of the Bruun Rule was adopted as the Guadiana coastline is sandy beach. Moreover, the comments of Pilkey and Cooper, (2004) regarding the use of above theory were considered. Since the Bruun Rule is not account for accretion and erosion processes, the shoreline predictions may not be realistic. This problem has been addressed by incorporating the SER with the Bruun Rule predictions. Thus the results may be close to reality. However, still it should be highlighted that it is not possible to incorporate the future trend in human intervention to the estimate the shoreline retreat realistically. In spite of these remarks, it may be useful to estimate the future shoreline trend for better management of the coastal zone.

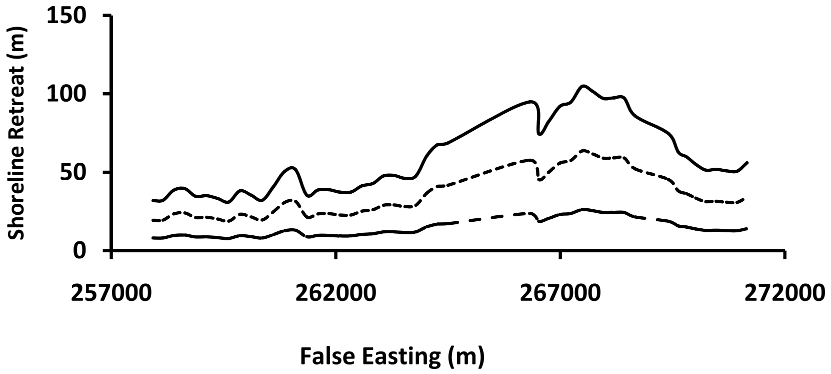


Figure 8: Additional shoreline retreat due to accelerated sea level rise based on the IPCC, 2007 sea level rise scenarios derived from SRES emission scenarios. —— A1FI scenario (A1 world, Fossil Fuel Intensive), ········ A1B scenario (A1 world, balanced energy sources) and- - - - - B1 scenario (B1 world)

Figure 8 shows the additional shoreline retreat due to accelerated sea level rise. The continuous line shows the additional shore line retreat trend along coastline for the upper bound value (59 cm) of SRES sea level rise scenarios A1FI and dotted line shows the trend for A1B scenario while dashed line is for B1 scenario where the sea level rise is 48 and 38 cm, respectively. It can be seen that the shoreline retreat due to accelerated sea level rise is almost constant for the Portuguese coastal stretch of the Guadiana estuary. In contrast, the additional shoreline retreat in the Spanish side is increasing steadily to maximum value of 95, 63 and 26 m for respective A1FI, A1B and B1 scenarios (figure 8). This observation can be explained using L (length of active beach profile), and B (dune height). According to the Bruun Rule, shoreline with low dune height will retreat more rapidly. Similarly, larger the active profile length, higher the shoreline retreat. For the Spanish side the active profile with increase to a peak and then reduce to the average total value and the dune height will decrease to a minimum value and then again increase. Due to the positive feedback of these parameters, the shoreline retreat will be very high and remarkably this location overlaps with the eastern part of the Isla de Canela where there is severe erosion occurring at present. Thus it is important to understand that B and L are important parameters in determining the shoreline retreat which is confirmed with the present analysis of additional shoreline retreat and the actual observations as reported in the literature (eg. Gonzales et al., 2001).

The additional shoreline retreat due to accelerated sea level rise would change the present SER. Figure 9a shows the resultant SER due to accelerated sea level rise based on the A1FI, A1B and B1 scenario, which present values along the coastline. However, the change in the SER along the Portuguese coastline is comparatively lower than the change in Spanish side, because of the rapid increase of shoreline retreat in eastern side of the coast due to changes in L and B. The resultant average value calculated using resultant SER values for each transect in the Portugal side is -1.12, -1.28 and -1.43 m/yr showing accretion on the whole for the three scenarios of A1FI, A1B and B1 respectively and that is for Spain side shows the total erosion case on the whole where SER is 2.28, 1.98 and 1.71 m/yr for above three scenarios. The maximum erosion rate in the Portuguese coastal belt is 0.71 m/yr for A1FI scenario and that for Spanish side is 5.83 m/yr for the same scenario. The maximum accretion rate for Spain coast of the Guadiana estuary is 1.58 m/yr for B1 scenario and that for Portugal is 4.23 m/yr for the same scenario. However, these figures show the high degree of spatial variability of the shoreline evolution rate along the Guadiana coastline.

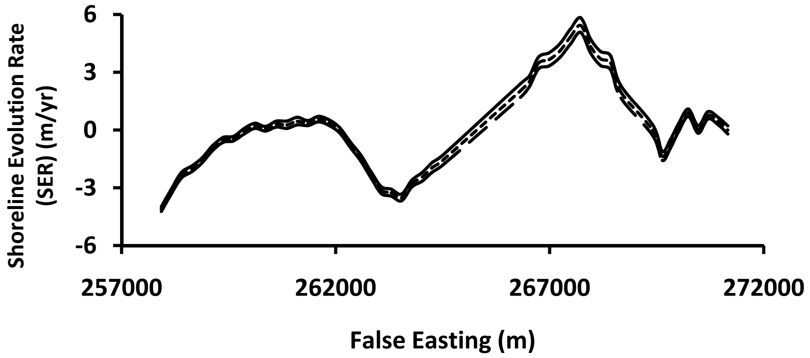


Figure 9a: Resultant shoreline evolution rate due to expected accelerated sea level rise driven by climatic change influence by the end of 21st century. –··– Present shore line evolution rate, –·–·- B1 scenario, ----- A1B scenario, and —— A1FI scenario.

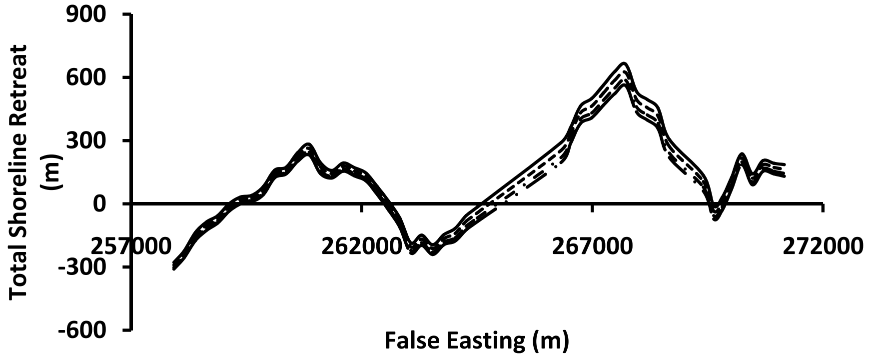


Figure 9b: Total shoreline retreat due to the present forcings and accelerated sea level rise. —— A1FI, ----- AIB, -·-·- B1 and –··– under the present SER indicates the corresponding scenarios.

As shown in figure 9b the total shoreline retreat is mainly dominated by the signal of present shoreline evolution rate projected to the end of 21st century. The contribution from the accelerated sea level rise for shoreline retreat would be negative for all the scenarios. The high accretion rate in Portuguese side of the Guadiana coastal belt would retard shoreline retreat reducing the negative impact of accelerated sea level rise on the coastal belt. The high erosion trend would be further increased along the Spanish coastline on the whole. In Portugal shoreline average accretion is 22 and 7 m for B1 and A1B scenarios respectively but for A1FI, erosion processes starts slowly. Thus, the sea level rise by 59 cm would result in shoreline erosion by 9 m. However the shoreline in the Spanish side of the estuary is on average under erosion and severity would increase with the rise of sea level for each scenario. The maximum length of shoreline erosion in the Portuguese side is 325 m and 662 m for Spanish side under A1FI scenario.

5.2 Estimation of permanent land loss due to shoreline retreat under present forcing and future accelerated sea level rise

The estimation of land loss based on the administrative divisions, land use and cover is important in the planning of integrated coastal zone management programmes. This classification would be useful to evaluate the social and economic impacts due to the anlysed coastal hazards. These results can be used to implement mitigating measures to minimize the negative consequences of such hazards. Figure 10 shows the total land loss from the coastal stretches of the Guadiana estuary belonging to Portugal and Spain for upper bound values of three SRES scenarios of sea level rise considered in this study. Furthermore, the loss of land due to accelerated sea level rise expected during this century is compared with shoreline retreat with present SER. Land loss due to present SER is estimated by assuming there is no significant intervention to the coastal zone during this century.

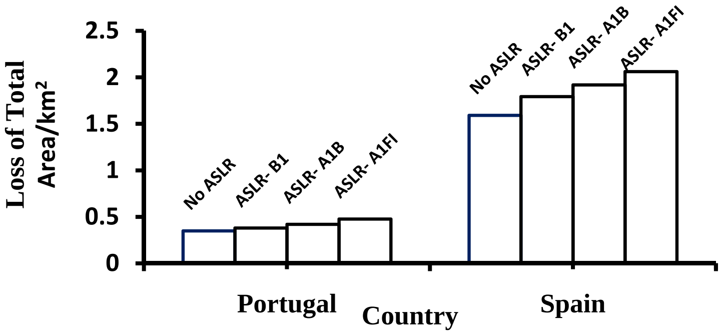


Figure 10: Total land loss from the coastal zone of the Guadiana estuary belongs to Portugal and Spain

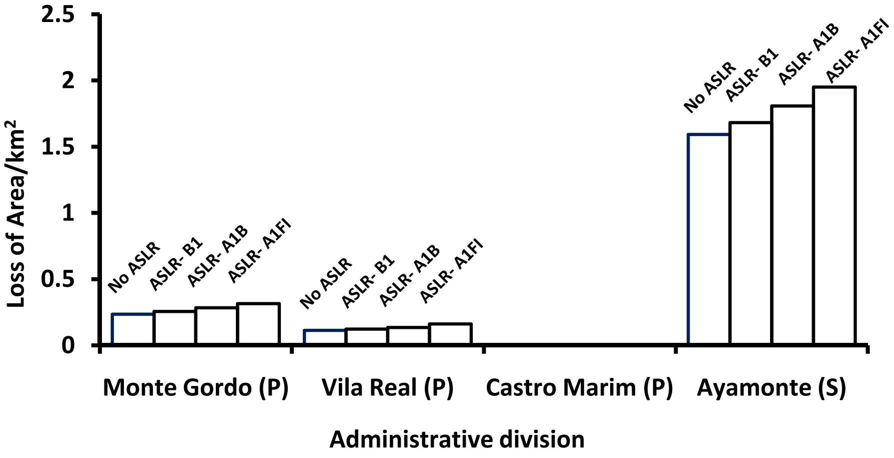


Figure 11: Land loss from the coastal zone of the Guadiana estuary belongs to Portugal and Spain and their classification based on the administrative division (Municipality)

Impact on land due to shoreline retreat was calculated using GIS tools corresponding to each scenario. Thus, the total land loss from Portuguese coastal stretch under the preset SER is 0.35 km^2 and that would increase by 9%, 20% 37% with the rise of sea level by 38, 48 and 59 cm, respectively by the end of 21st century (Table 2). The linear trend of increasing the total land loss for every 10 cm increment of the sea level corresponds to the approximately constant slope in the coastal zone. The average coastal zone slope is 0.044 for the Portuguese stretch of the Guadiana estuary, but the land loss is very much on the Spanish side almost 5 times that of the Portuguese side. The total land loss is 1.59 km^2 in this region would increase by 6%, 14% and 22% for sea level rise for B1, A1B and A1FI scenarios respectively (Table 3). This is approximately 10 cm increment for each case starting from the sea level rise expected by 2100 year with the present SER. The increasing trend is linear but the slower in rate than the Portuguese side.

Table 2: Comparison of land loss from the coastal zone of the Guadiana estuary belongs to Portugal and Spain and their classification based on the administrative division.

Country	Loss of Land according to Administrative Division (km^2)	Scenario			
		Present SER No ASLR	B1 SLR= 38cm	A1B SLR=48cm	A1FI SLR=59cm
Portugal	Monte Gordo	0.23	0.25 (9%)	0.28 (21%)	31 (34%)
	Vila Real	0.11	0.12 (9%)	0.13 (20%)	0.16 (43%)
	Castro Marim	0	0	0	0
	Sub Total	0.35	0.38 (9%)	0.42 (20%)	0.48 (37%)
Spain	Ayamonte	1.59	1.68 (6%)	1.81 (14%)	1.95 (22%)
Total land loss in the coastline of the Guadiana estuary		1.94	2.06 (6%)	2.23 (15%)	2.43 (25%)

According to the table 2 and figure 11, even though accretion is characteristic in the Portuguese coast presently, there would be shoreline retreat resulting land loss in Monte Gordo by the end of 21st century and the land loss from the tourist beach of Monte Gordo is o.23 km^2 under the present SER. The land loss in Vila Real do Santo Antonio is half the Monte Gordo municipality while there is no land loss from Castro Marim municipality under four scenarios (No accelerated sea level rise, B1, A1B and A1FI). The coastal stretch belongs to Castro Marim is also experiencing high accretion rate. Therefore the negative consequences of accelerated sea level rise would be off set. The eastern part of the Guadiana estuary in the Spanish side belongs to the Ayamonte municipality where the land loss will affect mainly the tourist village of Isla Canela and the coastal stretch up to Isla Cristina.

In terms of socio-economic aspects, the impact on existing road infrastructure, residential and other infrastructure buildings is a principal issue of a integrated coastal zone management plan. Loss of roads due to sea level rise hazards would be critical as it would affect not only to the area in the vicinity of hazard zone but there is risk to isolate some part of hazard zone from the rest of the country, creating much pressure on the economy and possibly requiring costly protective interventions. Thus the present study was focused on assessing the impact on transportation network (Roads) and infrastructures (Buildings). The estimation was based on the data and maps produced for the MegaSIG project (2002-2004). Therefore, the loss of road length and the number of buildings affected have to be updated for the present condition and which is out of the present scope of study.

Table 3: comparison of impact on the transportation and other infrastructures within the coastal zone of the Guadiana estuary belongs to Portugal and Spain

Impact on Infrastructures	Country	Scenario			
		Present SER No ASLR	B1 SLR= 38cm	A1B SLR=48cm	A1FI SLR=59cm
Loss of road length (km)	Portugal	0.13	0.17 (33%)	0.20 (21%)	0.35 (180%)
	Spain	11.9	12.4 (4%)	13.0 (10%)	13.8 (16%)
No of buildings loss	Portugal	26	27 (4%)	29 (12%)	35 (34%)
	Spain	112	115 (3%)	120 (7%)	124 (11%)

However, the impact on roads is very much less in the Portuguese side of the estuary as it is seen that the impact is only on two road segments loosing the approximately 0.35 km for the worst case of accelerated sea level rise under A1FI scenario (Table 4). This loss would be from the access roads to the Monte Gordo beach therefore, the loss would not be critical in terms of social and economic aspects. The impact on the recreational activities is also not significant as it would not cut off the access to beach severely.

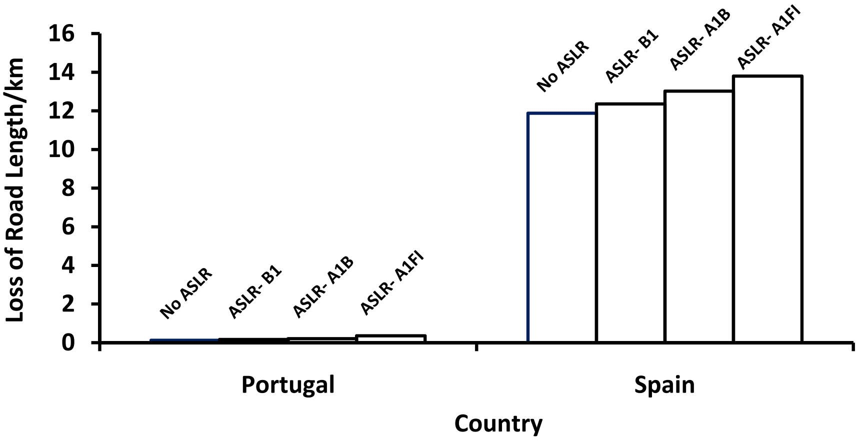


Figure 12: Impact on the transportation and other infrastructures within the coastal zone of the Guadiana estuary belongs to Portugal and Spain

The loss of road length on the Spanish side of the estuary is very significant corresponding 12 to 14 km for the sea level rise scenarios under present rate and accelerated rate. The loss of road length is mainly from the tourist village of Isla Canela and further eastward the loss is much more severe. This loss would impact existing socio-economic establishment detrimentally isolating the large part of the village from rest of the country. In terms of recreational activities, the access to beach would cut off critically. if there is no large-scale sand nourishment project to augment this negative impact of sea level rise, there may not be a tourist beach left in the area. This loss has to be assessed in the perspective that without sand nourishment project to hold on the coastline for much required tourist attraction, the main occupation and means of income of the local population will be lost. As seen in the figure 12, the increase in loss of the road length is approximately linear. For every 10 cm increase of the sea level, there would be approximately 5% increase in the loss of road length.

The number of affected buildings in both east and west part of the estuary also shows similar characteristics. Total number of buildings affected in the west is 26, 27, 29 and 35 and on Spain side that is 112, 115, 120 and 124 respectively for sea level rise with present rate and three SRES sea level rise scenarios considered in this study.

5.3 Impact on the land use type and cover

The assessment of impact on different habitat due to coastal hazard related to sea level rise is very important in terms of environmental point of view. In this present study land cover types considered is urban, sand dunes, marsh land agricultural land, barren or waste land, forest (Pinewood) and industrial (salt pans) area. In addition, loss of land was classified based on the designated protected area according to the regulations in force in Portugal and Spain. Figure 13a and 13b shows this classification. It should be noted that both parts of the estuary do not have all the habitat types considered in this study. For example there is no pinewood forest area in Spain side while there is no waste land in the Portuguese segment of the Guadiana estuary.

The urban area in the Portugese side is classified as non priority urban habitat (MegaSIG, 2002-2004). However, the total area including the Monte Gordo urban area is within the sand dunes present in this area. The sand dune is highly altered in the vicinity of Monte Gordo tourist and recreational beach. The loss of urban area in west bank is not significant as the total loss from the entire urban habitat incuding Vila Real de Santo Antonio, is 0.06 km^2 for the worst case scenario, that is A1FI. However, the loss of land from sand dunes habitat is 0.35, 0.37, 0.41 and 0.45 respectively for cases of shoreline retreat under present SER and three SRES scenarios respectively (Table 4). There is land loss of 0.11, 0.13, 0.15 and 0.18

from the protected area belonging to the respective sand dune habitat loss given above. There is no impact on the agricultural and marsh land belongings to Portugal.

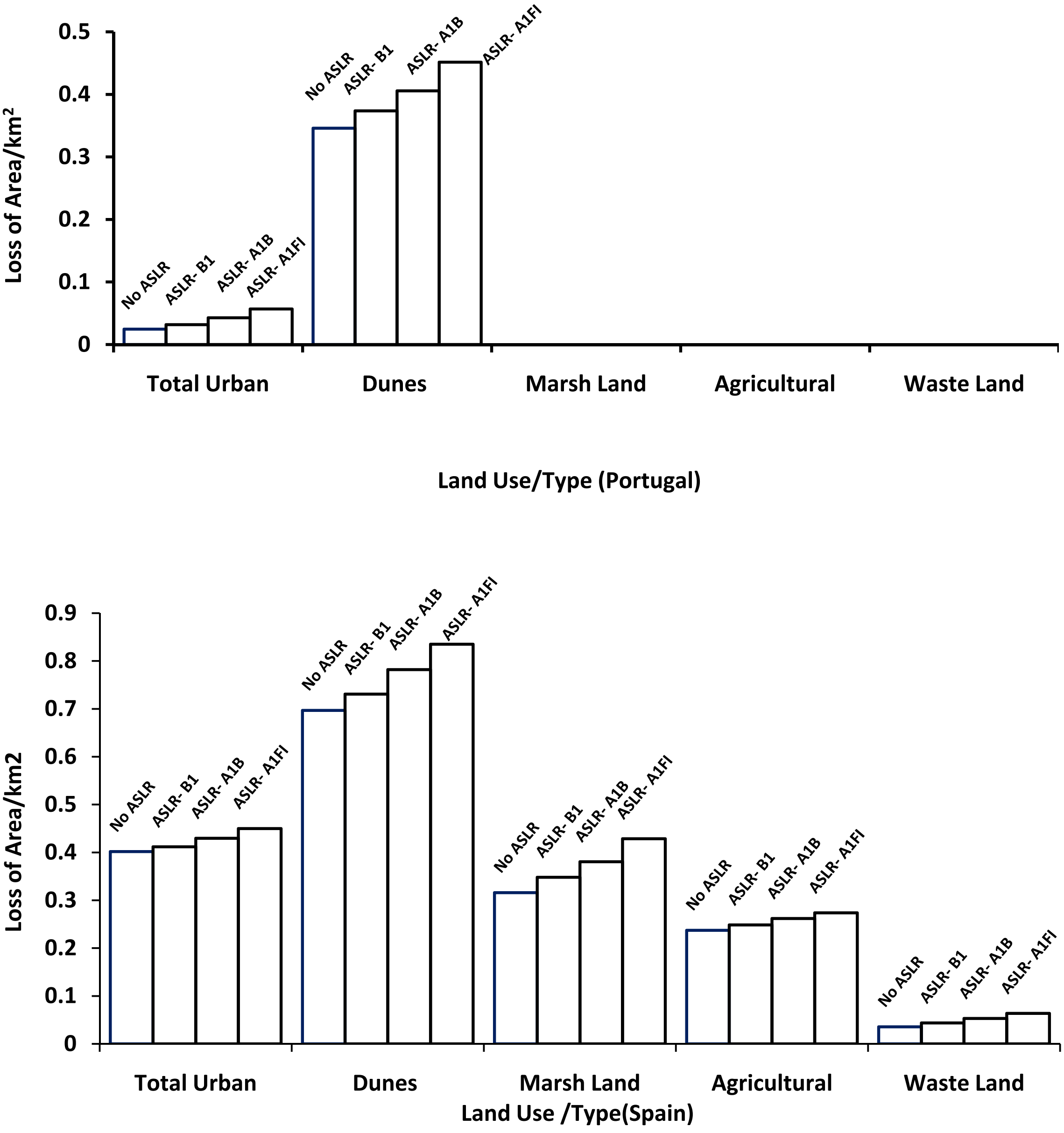


Figure 13: Impact on the habitat within the coastal zone of the Guadiana estuary belongs to (a) Portugal and (b) Spain. Classification based on land use/type

The impacts on different habitat in the Spain side are much more significant as it can be seen that most of the habitats are very vulnerable to sea level rise hazard (Figure 13 a and b). The urban habitat loss is mainly from the Isla Canela. The total loss of urban habitat would increase from 0.40 km^2 to 0.45 km^2 showing approximately 5% increase of area for each 10 cm increase of the sea level. The loss of sand dune is twofold as it is for Portuguese side of the coastal zone. However, increase of land loss is not constant for average increase of water level by 10 cm. the increase show slow exponential trend as the land loss increase is 5, 12 and 20% for 10 cm increase of the water level (Table 5).

Table 4: Comparison of the impact on the different habitat due to shoreline retreat due to present shoreline evolution and accelerated sea level rise on coastal zone of the Guadiana estuary belongs to Portugal and Spain (Percentage value given in bracket)

Country	Loss of Land according to the Land use/type (km^2)	Scenario			
		Present SER No ASLR	B1 SLR= 38cm	A1B SLR=48cm	A1FI SLR=59cm
Portugal	Total urban area	0.02	0.03 (29%)	0.04 (73%)	0.06 (131%)
	Sand dunes	0.35	0.37 (8%)	0.41 (17%)	0.45 (30%)
	Protected area	0.11	0.13 (19%)	0.15 (36%)	0.18 (64%)
Spain	Total urban area	0.40	0.41 (2%)	0.43 (7%)	0.45 (12%)
	Sand dunes	0.70	0.73 (5%)	0.78 (12%)	0.83 (20%)
	Marsh land	0.32	0.35 (10%)	0.38 (20%)	0.43 (36%)
	Agricultural land	0.24	0.25 (5%)	0.26 (10%)	0.27 (15%)
	Waste land	0.03	0.04 (22%)	0.05 (49%)	0.06 (78%)

From the environment point of view, the loss of land from marsh land or wetland areas would be very much deleterious to the healthy functioning of this much sensitive and dynamic, hence, more vulnerable ecosystem. However, it is expected that the land submerged with the rise of sea level would recover depending on the degree of vertical accretion within the estuaries. Further, it should be highlighted that wet land loss is mainly dependent on the rate of sea level rise rather than the rise of sea level. However, the present study was intended to delimit the maximum potential risk zone. Thus, the estimation would give upper bound solutions for the risk area. The total area loss from the marsh land is 0.32, 0.35, 0.38 and 0.43 and the increase of land loss for every 10 cm increase of water level is approximately 10%.

Permanent loss of agricultural land due to sea level rise is also significant as it would affect the economy of the people living in this area. On average, there would be 0.25 km^2 loss of land from the area. The land loss would increase by 5% for 10 cm rise of the water level. The loss of barren land is not that significant.

5.4 Cumulative Impact of accelerated sea level rise and storm surge during the maximum spring high tide situation

The temporary loss of land due to shoreline retreat due to storm surge is another issue considered in the present study of assessing the impact of sea level rise hazard. It is reported that the vulnerability of the sea level rise would be significant not mainly because of the sea level rise due to climate change forcing but the extreme episodic events such as storms surges with elevated flood contours respect to the sea level rise. However, it is important to understand that even though there is high potential in shoreline retreat due to storm surge event amplified by climate change forcing, in long term the shoreline evolution trend would not be determined by storm surges whilst the long term sea level rise and other sedimentary processes and wave climate and morphodynamic characteristics of the concerned coastal stretches. In this context, the following assessment of shoreline retreat due storm surges was undertaken. In addition, it should be noted that the following assessment is mainly based on the Digital Elevation Model validated for use in the MegaSIG project undertaken between Portugal and Spain. Thus the resolution of the DEM is with accepted accuracy for represent the coastal zone. However, caution have to be taken when using these results and further studies have to be undertaken to verify the values. That is the shoreline retreat extent should be validated from required no of actual beach profiles for the Guadiana estuary coastline.

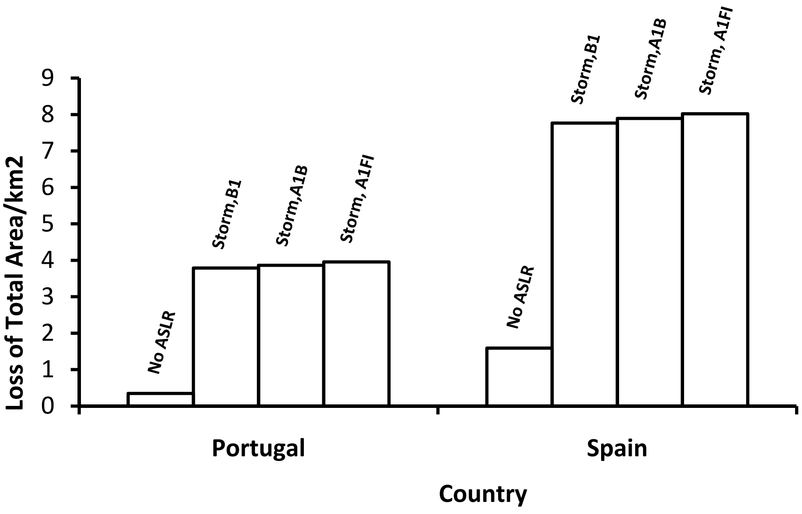


Figure 14: Total land loss from the coastal zone of the Guadiana estuary belongs to Portugal and Spain

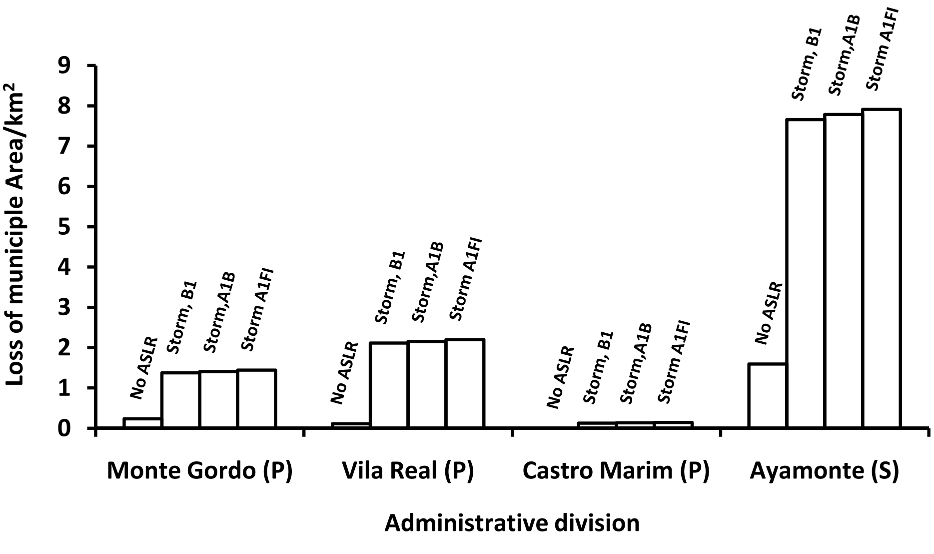


Figure 15: Land loss classification based on the administrative division of the coastal zone of the Guadiana estuary belongs to Portugal and Spain

Figure 14 and 15 show the maximum potential land loss due to cumulative effect of accelerated sea level rise, storm surge event during the maximum spring high tide situation in the coastline of Guadiana estuary belongs to both Portugal and Spain and the classification is based on the country and administrative division. The resultant sea level rise is 4.65, 4.75 and 4.86 m for three scenarios of B1, A1B and A1FI, respectively. The results are compared with the land loss due to land loss under the present rate of sea level rise that is the shoreline evolution with present SER. Accordingly, the land loss is very much significant for both parts of the coastal zone. The total land loss under this situation would be 3.61, 3.68 and 3.78 km^2 for B1, A1B and A1FI scenario (Table 5). The maximum potential land loss is approximately 9 folds compared to the long term sea level rise under present and accelerated sea level rise rate. With these conditions, all the municipal divisions would be affected and Vila Real de Santo Antonio would be the most vulnerable and then Monte Gordo where the loss of land on average is about 2.15 and 1.40 km^2 respectively.

Table 5: Land loss due to storm surge (classification based on the country and administrative division) from the coastal zone of the Guadiana estuary.

Country	Loss of Land according to Administrative Division (km^2)	Scenario			
		Present SER No ASLR	B1 SLR= 38cm	A1B SLR=48cm	A1FI SLR=59cm
Portugal	Monte Gordo	0.23	1.37	1.40	1.44
	Vila Real	0.11	2.11	2.15	2.20
	Castro Marim	0	0.13	0.13	0.14
	Sub Total	0.35	3.61	3.68	3.78
Spain	Ayamonte	1.59	7.65	7.78	7.91
Total loss from the coastline		1.94	11.26	11.46	11.69

The situation in the Spanish side of the coast is much worse than the Portuguese side. The total area loss is approximately 7.75 km^2. It can be seen that the total coastal stretch would be affected due average rise of sea level by 4.75 m. Thus, the total average area loss from the entire region is 11.5 km^2. Therefore, the Guadiana Estuary is highly vulnerable to storm surge and actual land loss would be 2 to 4 km^2 this value is based on the assumption that there would be 20 to 40% actual loss of land from the maximum potential for short duration storm surges. However, this figure has to be confirmed with hydrologic analysis of coastal flooding.

Table 6: Impact due to storm surge under elevated flood contours with climatic change driven sea level rise on the transportation and other infrastructures

Impact on Infrastructures	Country	Scenario			
		Present SER No ASLR	B1 SLR= 38cm	A1B SLR=48cm	A1FI SLR=59cm
Loss of road length (km)	Portugal	0.13	25.31	25.94	26.68
	Spain	11.9	33.96	34.24	34.49
No of buildings loss	Portugal	26	249	252	262
	Spain	112	243	245	248

The affected number of roads and their total length will also show the socio-economic vulnerability of this coastal zone for shoreline retreat due to episodic events. Here, the both sides of the estuary are equally vulnerable where the total road length loss is approximately 26 and 34 km (Figure, 16). Similarly, the number of building losses is significant especially evident in the Portugal coastal stretch where the total number of affected buildings is about 250 and that is a 10 fold increase of affected buildings compared to hazard only due to the accelerated sea level rise. The number of buildings affected in the Spanish side is also approximately same but the increase is two times relative to the damage caused by accelerated sea level rise (Table 6). There is no significant increase of road length for different sea level rise scenarios as compared to the surge level; the contribution from the accelerated sea level rise is negligible in a short term events such as storm-surge.

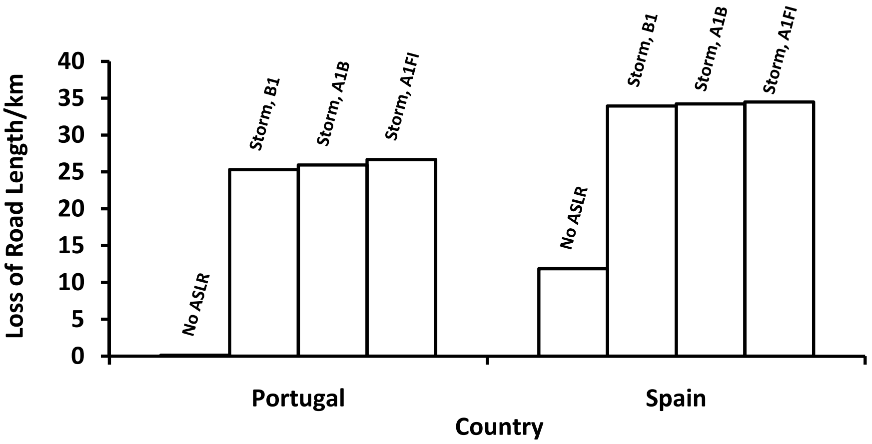


Figure 16: Impact due to storm surge under elevated flood contours with climatic change driven sea level rise on the transportation and other infrastructures within the coastal zone of the Guadiana estuary, Portugal/ Spain border

5.5 Impacts due to storm surge on coastal zone habitat

The present study further yields for estimating the land loss form coastal zone habitat due to shoreline retreat for the worst case where a hypothetical storm surge event occurring during the maximum spring high tide and under the elevated flood contours because of the accelerated sea level rise by the end of 21st century (Figure 17 a and 17 b). The analysis shows the vulnerability of each habitat type is extremely vulnerable for such event. It can be seen that 2.6 km^2 sand dune areas in the Portuguese coast would be affected due to storm surge with 100 year recurrence interval and that is about 7 times the vulnerability due to hazards caused by only accelerated sea level rise. Impact on the urban habitat can be visible mainly in the Monte Gordo municipal area and Vila Real de Santo Antonio. That for the Spanish side is very much significant as it would affect most of the urban areas namely Isla Canela, Isla Morad, Isla Moral and Isla Cristina, however the impact due to instantaneous shoreline retreat on Ayamonte municipality is not significant as it is located considerably upstream of the coastline. The total average urban area loss from the Spain coast is 0.82 km^2.

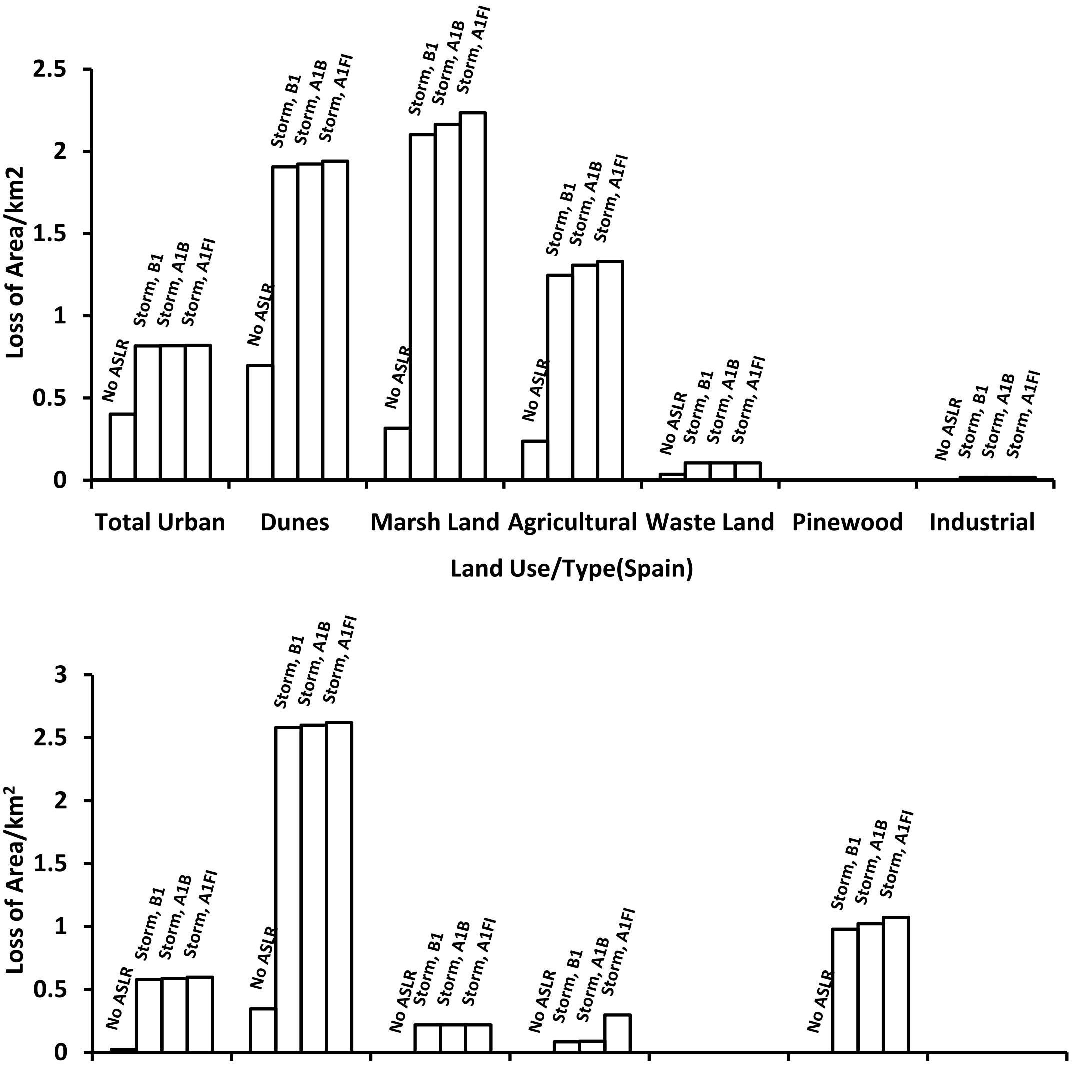


Figure 17: Impact on the habitat within the coastal zone of the Guadiana estuary belongs to (a) Spain and (b) Portugal. Classification based on land use/type

Under these circumstances there would be 0.22 km^2 marsh land loss in western part (Portugal side of the estuary). The agricultural area in the Portuguese side would be vulnerable only for the worst case scenario of sea level rise (i.e. A1FI). Loss of pinewood forest area is also very significant (approximately, 1.02 km^2). It should be noted that this forest area is the only forest area exists in the eastern Algarve. However, this is an artificially created forest for stabilizing sand dunes. More important aspect of the present findings is that the area loss from the protected area RAMSAR site is 3.05 km^2 (See table 17 for total classification of the loss due to storm surge and sea level rise).

Table 7: Impact on habitats due to storm surge with accelerated sea level rise and during a maximum spring high tide event

Country	Loss of Land according to the Land use/type (km^2)	Scenario			
		Present SER No ASLR	B1 SLR= 4.27+38cm	A1B SLR=4.27+48cm	A1FI SLR=4.27+59cm
Portugal	Total urban area	0.02	0.58	0.59	0.59
	Sand dunes	0.35	2.58	2.60	2.62
	Marsh Land	0	0.22	0.22	0.22
	Agricultural Land	0	0.08	0.09	0.30
	Pinewood	0	0.98	1.02	1.07
	Protected area	0.11	3.0	3.06	3.13
Spain	Total urban area	0.40	0.82	0.82	0.82
	Sand dunes	0.70	1.91	1.92	1.94
	Marsh land	0.32	2.10	2.16	2.23
	Agricultural land	0.24	1.25	1.31	1.33
	Industrial	0	0.02	0.02	0.02
	Protected area	0	0.91	0.97	1.02
	Waste land	0.03	0.10	0.10	0.10

As in all other cases the vulnerability of habitat for the analysed hypothetical storm surge event is extremely high. Sand dunes, marsh land and agricultural area would experience the worst impact under this situation and maximum potential loss of area for each habitat is about

1.92, 2.16 and 1.31 km^2, respectively (Table 7). Furthermore, significance of the marsh land loss should be highlighted as almost 1 km^2 of land loss is from designated protected area.

5.6 Hazard zone maps for shoreline retreat due to sea level rise.

Coastal erosion maps to support the visualization of hazard zone are the final outcome of the present study to assess the impact due to above sea level rise hazards with different severity. Figure 18 and 19 show the shoreline erosion maps under present sea level rise rate and three SRES scenarios namely, B1, A1B and A1FI. Figure 18 is overlaid on the digital elevation model and thematic layers of buildings and road network from MegaSIG project. This shows the potential areas, buildings and roads under threat for sea level rise hazards. Similarly figure 19 is the shoreline retreat map overlaid on the land use thematic layer. This identifies the different habitats at risk of losing area due coastal erosion hazards. However, the delimited area can be considered as the maximum potential area for above hazards. There are two reasons for this; 1) the models such as the Bruun Rule would predict most probably upper bound solution and, 2) the used scenario are the worst case scenarios. Especially, the sea level rise scenarios used are the upper bound (95%) values of solution envelop of AOGCM model. If the argument is excluded from the concept of scenarios, the maps can be considered as coastal hazard maps for 28-30 cm (under present rate of sea level rise), 38, 48, and 59 cm rise of sea level by the end of 21st century. Thus, these figures would cover the considerable range of possible sea level rise overlapping with the lower bound values of above scenarios. Therefore, these hazard maps would give comparatively good representation to the coastal hazards due to sea level rise.

Four hazard zone maps shown in the figures 18 and 19 have been given in annex 1, overlapping each scenario. This shows the increase of shoreline retreat for selected scenarios in this present study.

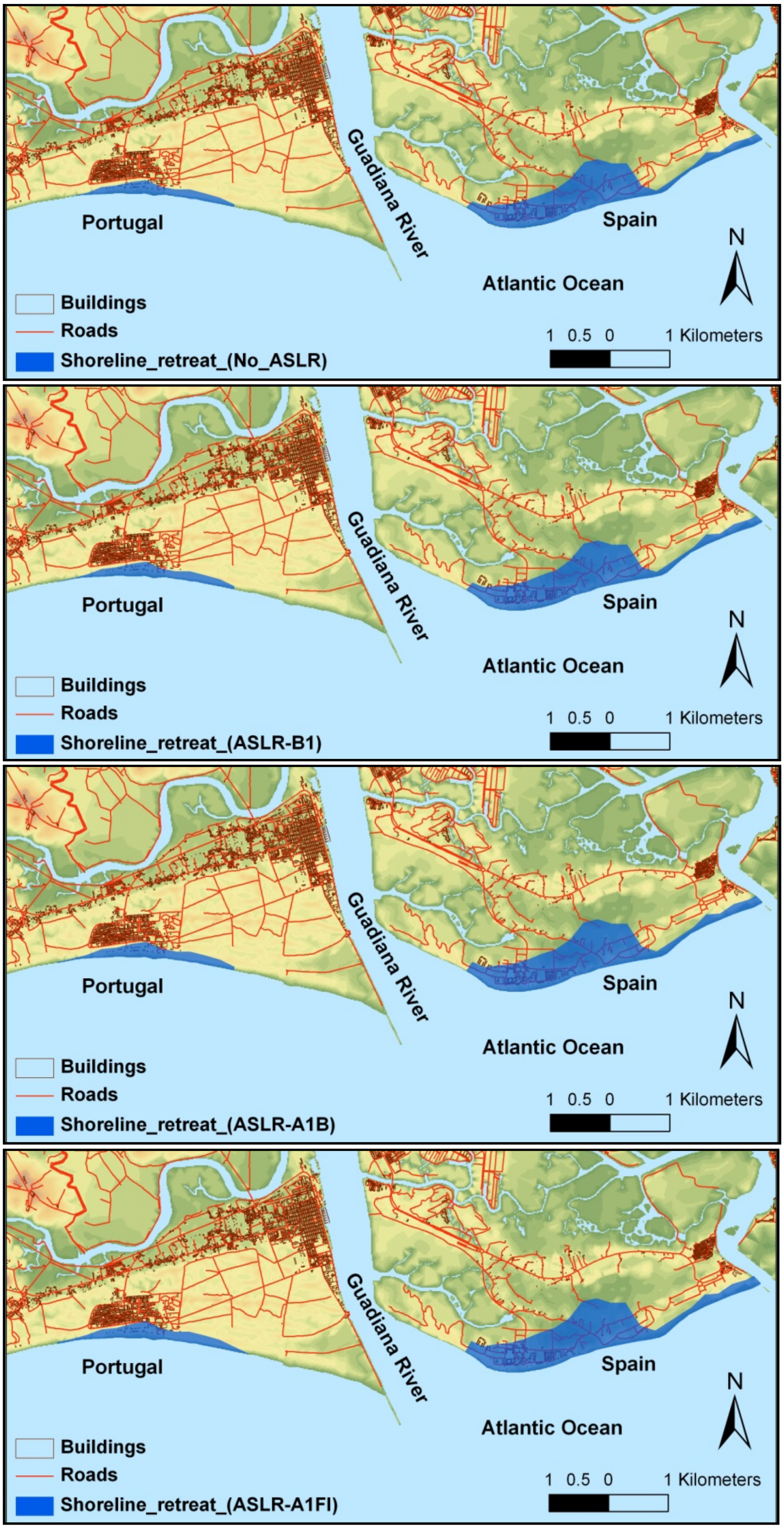


Figure 18: Hazard zone maps due to sea level rise for no ASLR, B1, A1B and A1FI scenarios overlaid on DEM and thematic layers of built-up area and transport network

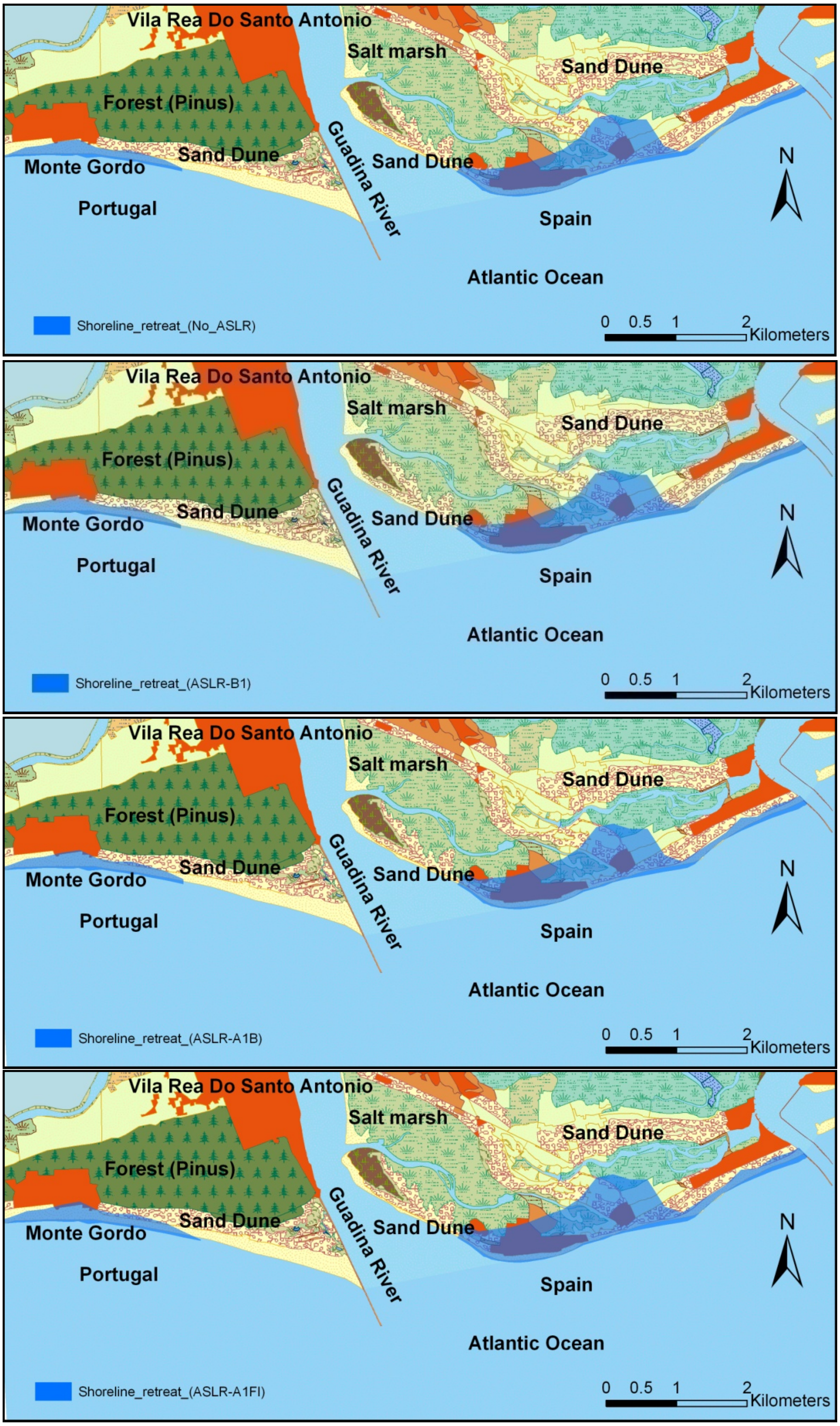


Figure 19: Hazard maps due to sea level rise for no ASLR, B1, A1B and A1FI scenarios overlaid on thematic layer of land use/type

5.7 Hazard maps for shoreline retreat for hypothetical storm surge

The coastal hazard maps are due to storm surge with a 100 year periodicity and with elevated flood contours by 38, 48 and 59 cm. It is assumed this storm would occur during the maximum spring high tide event (figure 20 and 21). They are overlaid on Digital Elevation model and thematic layers representing built-up area and road network (MegaSIG project).

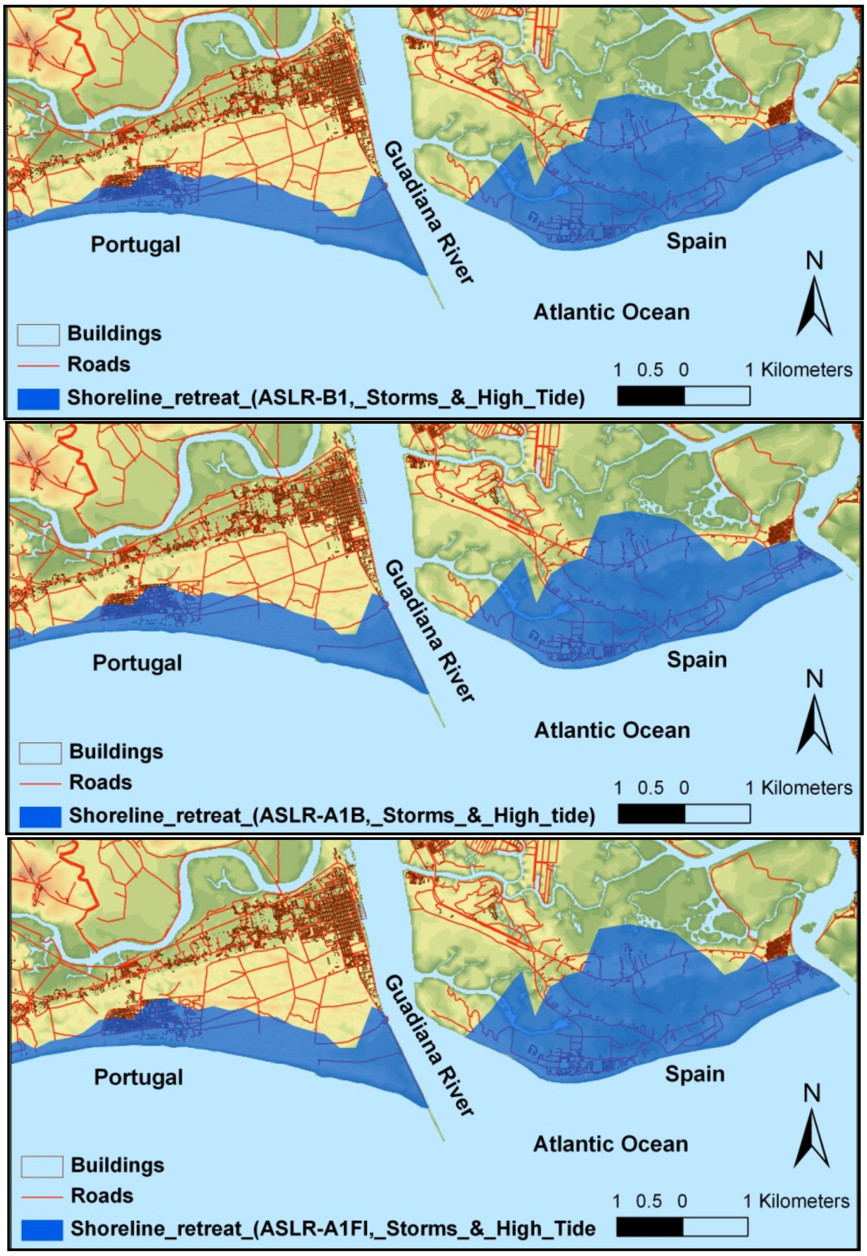


Figure 20: Hazard maps for a hypothetical storm surge and sea level rise under i) B1, ii) A1B and iii) A1FI scenarios. (Overlaid on DEM, and thematic layers built-up area and transport network)

These maps show the maximum potential area of flooding. However, the actual shoreline retreat and residual shoreline retreat in the longterm would be much lower compared to the maximum potential extent. For a short duration storm event, the actual retreat would be 20 to 40% of the maximum potential area as per the observations of Kriebel and Dean, (1993).

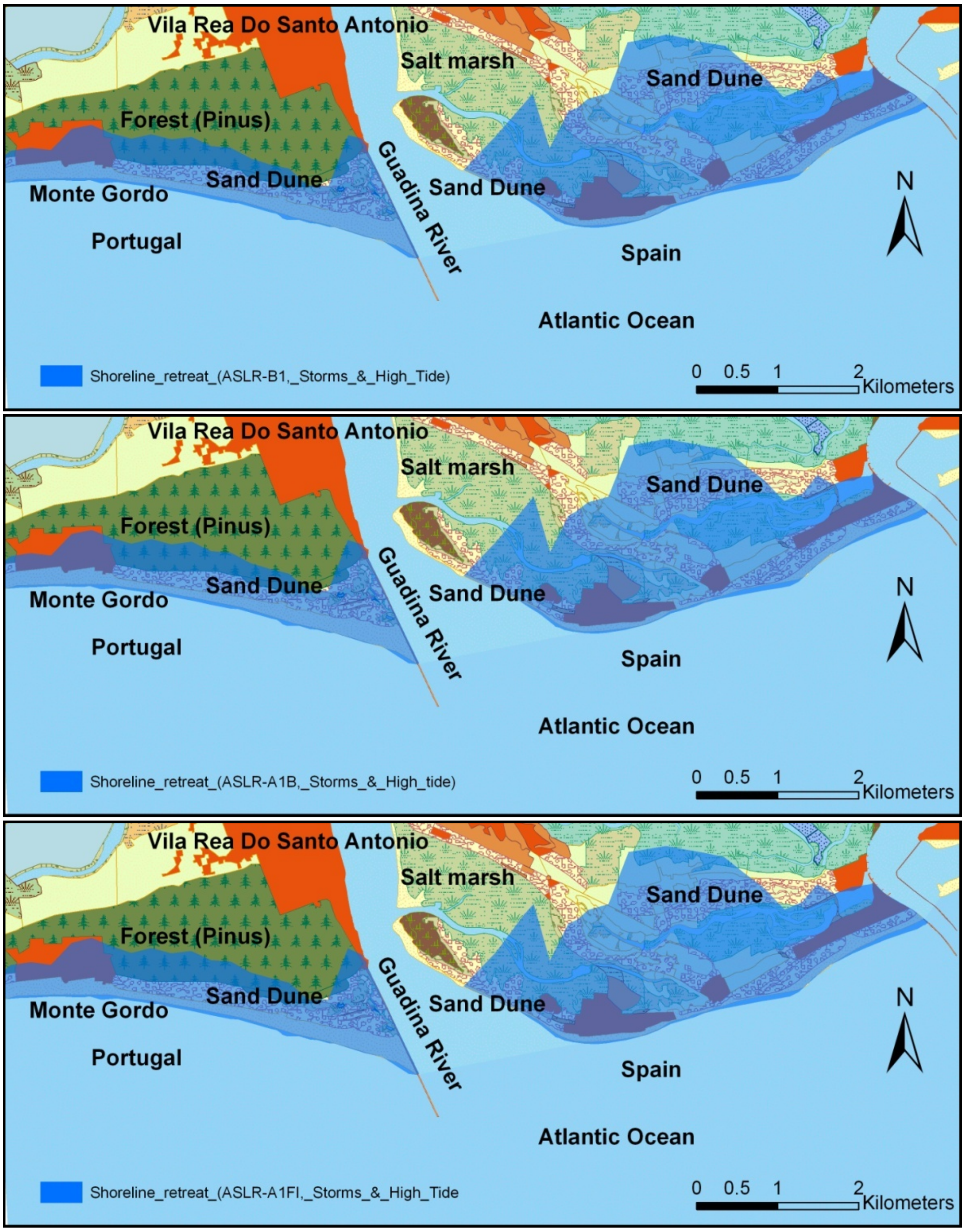


Figure 21: Hazard maps due to sea level rise for hypothetical storm surge and sea level rise under i) B1, ii) A1B and iii) A1FI scenarios. (Overlaid on thematic land use/type layers)

5.8 Inundation hazard due to storm surge and sea level rise

The shoreline retreat and inundation is closely related but represents two different phenomena. Shoreline retreat shows the redistribution of sand from the existing coastal stretch and inundation indicates the land submerged due to rise in water level. The results of the present inundation impact assessment represent three different cases; i) coastal flooding during the maximum spring high tide; ii) for storm surge with 100 year periodicity and elevated flood contours due to the worst case sea level rise scenario (i.e. 59 cm rise in the sea level by year 2090-2099) but from the mean sea level; and iii) same as the case (ii) but under the maximum spring high tide situation. Thus, the hazard maps represent sea level rise by 1.9, 3.0 and 4.9 m, respectively. The storm-surge is due to the 0.24m barometric set up which is the average pressure drop in three historical events reported in the Gulf of Cadiz affecting the coastal zone of the Guadiana estuary (4th December, 1987, 5th December, 1989 and 21st January 1996). Average wind set-up is assumed for this extreme case is 1.0m and wave set-up and wave run-up was the average value over the entire coastal stretch estimated using Holman (1986) formula.

The case (i) represents the maximum extent of existing frequent flood hazard zone under normal situation (i.e. no storm surge). The case (ii) represents the sea level rise by 1.1 m above the existing maximum extent of frequent flood hazard zone defined by case (i), and under storm surge and accelerated sea level rise. Similarly, case-iii represents 2 m rise of sea level relative to the case (i). In addition the coastal zone considered in this analysis is from the downstream of the Guadiana River where the suspension bridge linking the Spain and Portugal has been constructed. The aim was to assess any impact of that bridge. Thus, table 8 shows the potential inundating area under the above three cases. Case (i) is used to compare the increase of risk of inundating by approximately 1 and 2 m rise of water level from the maximum spring high tide situation.

Table 8: The maximum potential area for flooding defined by the flood contours for the coastal stretch of Guadiana estuary and percentage increase with respect to the maximum spring high tide is given in brackets

Inundation Scenario	Water level rise from Mean Sea Level (m)	Inundation Area (km^2)		
		Portugal	Spain	Total
Maximum Spring High Tide (Present hazard zone)	1.9	7.95	13.39	21.32
Storm surge of 100 year (without tide)	3.0	16.61 *(109%)*	24.87 *(85%)*	41.50 *(95%)*
Storm surge of 100 year (with maximum spring high tide)	4.9	23.20 *(192%)*	32.43 *(142%)*	55.63 *(161%)*

A 1 m rise of the sea level above the maximum spring tide level would be cause more than 100% increase of the maximum flood area for the west bank of the Guadiana River and 85% for the east bank. On the whole, increase of flood area is 95% . The increase of flooding area is approximately 200% and 142% for Portugal and Spain side of the estuary and total area risk for inundation increase by 160% for 2 m rise of sea level relative to the case (i) datum. Thus, it can be seen that, in terms of percentage increase of the flood hazard zone, the west margin (Portugal) of the estuary is under high risk. However, in terms of total area prone for inundation, the eastern margin (Spain) side of the estuary is more vulnerable. Further, according to the hazard zone maps, (Figure, 22 and 23) under the maximum spring high tide situation considered in the case (i), there is very little risk of inundating the built up area. Even though, it can be seen some part of the road segments are under threat, it can be assumed that they are elevated roads and above the flood level. However, there is further study is required to confirm this assumption.

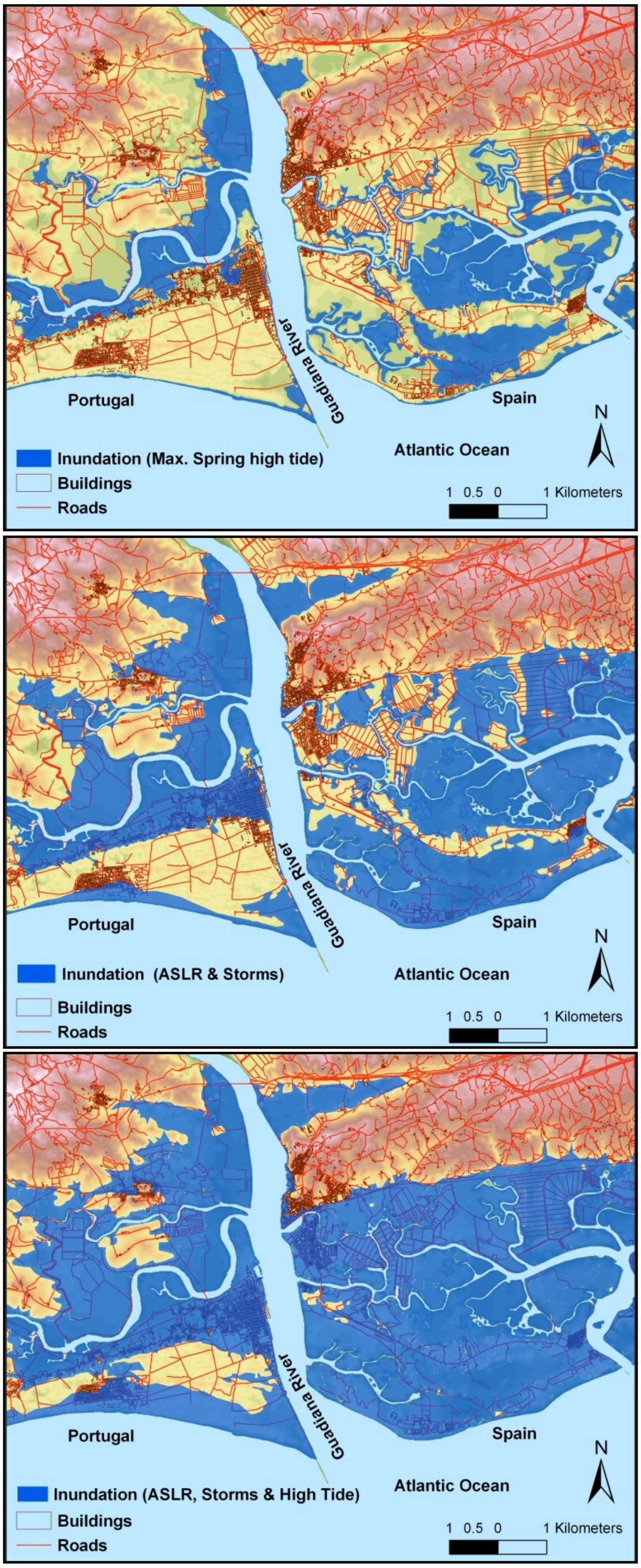


Figure 22: Maximum extent of potential inundating area under sea level rise by: a) 1.9 m, b) 3.0 m and, c) 4.9 m maps overlaid on DEM and layers of built-up area and roads

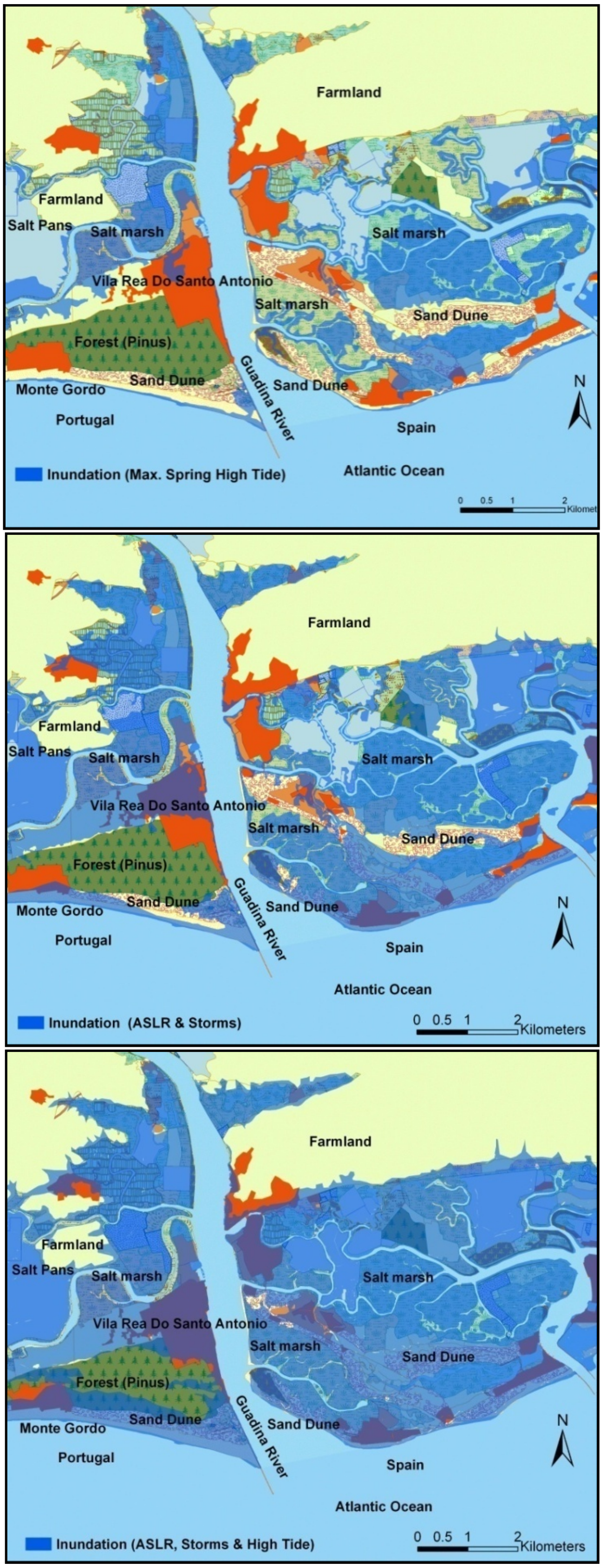


Figure 23: Maximum extent of potential inundating area under sea level rise by: a) 1.9 m, b) 3.0 m and, c) 4.9 m maps overlaid on thematic layer of land use/type

According to the hazard maps for extreme events of coastal flooding, a 5 m rise of the water level (Case iii) from mean sea level, the entire area of the Spanish side is under risk of coastal flooding. In the Portuguese side, considerable part of the sand dune would remain emerged above this extreme flood level. This is because the average sand dune height in this area is more than 5m and that is for Spanish side is 3.5 m. Under case (iii), the entire salt marsh areas of both Spain and Portugal side would be flooded.

However, it is important to notice that the forest area in Portuguese side also remains emerged from this extreme event which emphasise the importance of protecting the sand dune and forest area as their potential to protect the leeward side of sand dune. However, the inundation of leeward side of these sand dunes is possible because the water can channel through the estuary channels, but the damage would be less as the wave energy may have been already dissipated. Further, it can be seen that there may not be significant threat to the existing bridge linking the Portugal and Spain as the increase of flood area will not be enough to reach up to the piers of bridge at both ends even under the extreme case. The flood prone area close to this bridge seems to be almost same for all cases analysed in this study. However, this should be evaluated compared to the river runoff level. The probability of all these worst cases to take place together would be low, but the hazard can be considered as an event that takes place with low probability. Therefore, it may be important to study such extreme cases as a part of the preparedness programme.

Chapter 6

6.0 Discussion

6.1 The shoreline retreat due to sea level rise

The main focus of the present study is to assess the impact of coastal hazards related to sea level rise and to investigate the characteristics of the shoreline response to such hazards. Hazards considered in this present study are shoreline retreat under the present conditions including present sea level rise rate, intensification of vulnerability under the accelerated sea level rise and finally the shoreline response to the worst case of storm surge, where storm-surge occurs during the maximum spring high tide with the elevated flood contours due to sea level rise. Even though there are numerous examples of studies for analysing the vulnerability due to coastal hazards, there are few concerted attempts to project a realistic case of hazards incorporating several hazards. The present methodology yields such an integrated assessment, although the methodology was initially intended to delimit the set-back lines for coastal hazards. However, this methodology, developed by Ferreirra et al., 2006, can be adopted to assess the different coastal hazards related to sea level rise. The results would give much more realistic solutions compared to the recommended methodology in IPCC, (2001), in which the shoreline retreat is assessed solely based on the Bruun Rule (1962). The present methodology would also use the Bruun Rule for analysing shoreline retreat in sandy beaches. However, the over estimation by the Bruun rule will be reduced by incorporating the shoreline evolution process in the coastal zone. This can be accomplished by applying the shoreline evolution rate for the considered period. However, there are some limitations of the present method for estimating SER from the aerial photographs. As reported by Crowell et al., 1999, the best way is to use the SER derived from linear regression analysis undertaken for sufficient number of beach profiles. However, such accurate data and profiles are not available for this coastal zone. Therefore, the coastal beach profile was artificially created by using a validated Digital Elevation Model developed for MEGASIG project, which was undertaken as joint programme by Spain and Portugal. Thus, it is required to validate these results from such quality representative beach profiles. Furthermore, it is required to update the coastal hazards maps developed under this study. The main cause is that the present model is not capable of incorporating the human or natural alteration in the coastal zone (Belomo et al., 1999 cited in Ferreira et al., 2006).

6.2 Shoreline retreat due to storm-surge

Under sea level rise, storm surge will be amplified (Nicholls, 2002). In this case, the magnitude of the amplified flood due to storm surge is calculated linearly adding the sea level rise to the existing flood level. Moreover, the sensitivity of the flood recurrence interval is very significant, even for small increase of sea level rise, and it would occur without much alteration of the storm pattern (Gornitz et al., 2002). Even though, storm surges occur independent with the sea level rise, the flood contour defined by the storm surge with a certain return period will shift upward with the sea level rise (ie. Flood height due to Storm surge versus return period graph shifts up ward). If the return period was estimated for the same magnitude of flood height before sea level rise, the graph will indicate decrease of return period. Figure 24 shows an example of shifting the flood curve. In this hypothetical case, with the 10 cm increase of sea level, a flood with 100 year return period may be expected within 40 years. Therefore, the flood would be expected at least two times in next 100 years period. Thus, the recurrence interval increased twofold. Similar observation has made in several studies. For instance, for 20 cm rise in sea level, 10 year flood event will reduce to 6 months and 9 year event for Egypt and the Netherland, respectively (Nicholls, 2002). This indicates that there is an apparent increase of the frequency of flooding with a certain magnitude due to sea level rise. In this study, the considered recurrence interval of the storm is 100 years. Thus, the risk of shoreline retreat under storm surge with 100 year return period may be experienced several times during the this century.

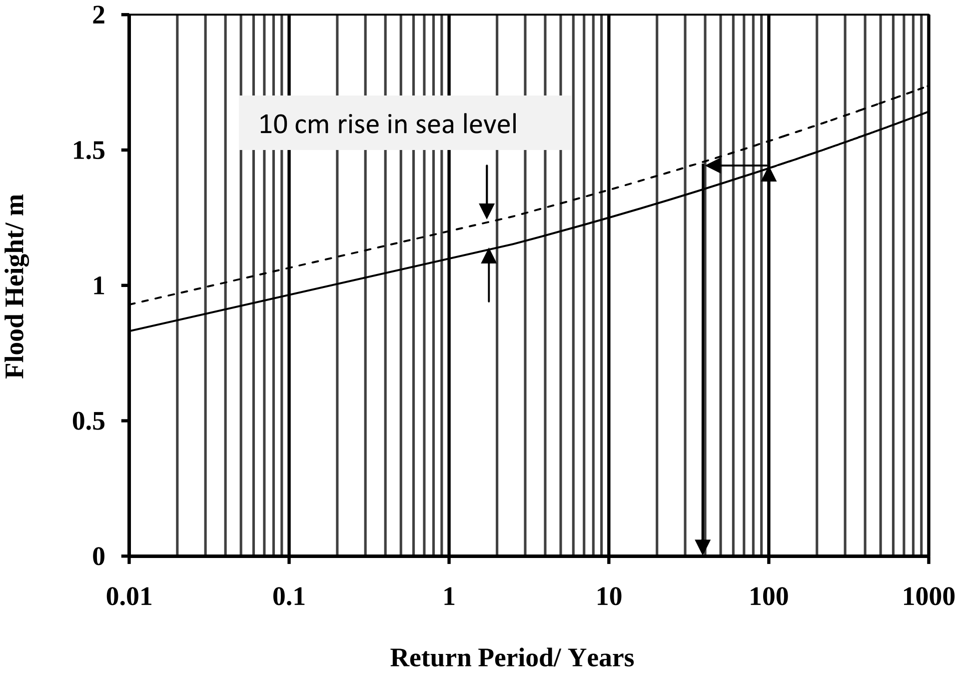


Figure 24: A hypothetical graph of flood height variation with the flood return period, "X" axis is in logarithmic scale

Estimating the shoreline erosion and consequent retreat due to storm surge can be achieved by several models, (eg. Hanson and Larson, 1998; Miller and Dean, 2004; Kribel and Dean, 1993). However the main limitation of all these models is that no model accommodates the long-shore drift. However, the model developed Kribel and Dean, (1993), is simple and easy to apply. The characteristic advantage in this regard is the efficiency of the model for computing the shoreline retreat. Thus it is possible to use this model for calibrating the hazard zone maps produced in the present study with sufficient number of profiles measured for each 5 to 10 years period. The frequency of updating these hazards maps has to be designed considering sand re-nourishment frequency and the engineering time scale, (Miller and Dean, 2004). The other advantage is that this model has been applied to several case studies of the

Portuguese coast successfully. Therefore, it is proven that this model would be suitable for the conditions of Portugal coast (Ferreira and Dias, 2000). In addition, it should be noted that the wave climate would be changed with a change of geomorphological features in the considered coastal stretch. Thus, it is necessary to refine the data and use more sophisticated methodology in updating the coastal hazards maps produced.

6.3 Hazard zone maps for coastal inundation

The delimited hazard zone map is based on the simple contour based method where the flood contour can be defined by using mathematical models, (eg. Hoozeman et al., 1993, Gonotz et al., 2002; Benevente et al., 2006). However, there are some limitations when applying projected sea level rise to simple digital elevation models. The main problem is the “concave up” profile of the coastal zone leading to overestimation of the land elevation. Thus, it underestimates the susceptibility of coastal areas for extreme flood events, (Titus and Richman, 2000). However, the present flood zone was established for each cause by careful observations of the water path through channels and along the steepest slope, where there is a possibility of flowing water to sink along this low lying slope. But, these results can be further improved by adapting hydrological methodologies such as HECGEO-HMS extension that can be used to work with ARCVIEW platform. In this regard, the concept of pour point and sink used in hydrologic analysis are important and the result would represent a very realistic estimation (Brown, 2006). In addition, the factors such as run-up velocity, beach and dune porosity, water percolation drag coefficients are also important in delimiting the flood hazard zones for a particular coastal zone but deficiency of such important data is characteristic of flood analysis, (Ferreira et al., 2006). Yet, it is important to carry out analysis utilizing maximum available data. As there is high degree of uncertainty in these assessment models, the order of magnitude of the affected area is also an important information for coastal zone management plan. Such plan would have to update with the availability of new set of data to better representation.

6.4 Impact of shoreline retreat due to sea level rise and storm surge

On the whole, impacts of sea level rise on the shoreline evolution are mainly due to the signal of the present shoreline evolution trend, compared to the contribution from accelerated sea level rise. On the other hand, it can be argued that the shoreline evolution trend has already accommodated the expected accelerated sea level rise rate. According to the previous studies, the sea level rise rate in this region is 1.5 mm/yr. However, this value represents the long term trend in sea level rise as it is based on the tide gauge data analysis at Lagos station from 1958 to 1994 (Dias and Taborda,1998). This value is comparable with the global average value based on long term data of tide gauge. Satellite altimetry analysis of sea level from 1994 to 2003 shows recent global average is approximately 3.1mm/year. Thus, using the same argument that the global average represents the long term sea level rise rate for this locality made using the tide gauge value at Lagos station, the recent sea level rise rate in this decade would be approximately 3.1 mm/yr for this region, and in agreement with the satellite altimetry data analysis. Sea level rise due to this rate would be about 30 cm at the end of 21st century. This value will be responsible for an average shoreline retreat by 62 m (Based on the Bruun Rule). However, the average shoreline retreat estimated from the SER is about 165 m by the end of 21st century. Thus, the contribution from other factors including sediment deficit due to cut off the longshore sediment transportation by coastal defence structures is significant. This can be proven further because the shoreline retreat curves would be the exactly the shape of present shoreline evolution trend in spite of accommodating the shoreline retreat due to accelerated sea level rise component. This may be because the accelerated sea level rise component would not be sufficient enough to show its dominance in determining the final shoreline position at the end of this century. Thus, it is possible that the shoreline evolution is highly influenced by the present sedimentary processes including cross-shore and long-shore sediment transport dynamics and the sediment supply to the coastal zone from the Guadiana river, where the river flux is highly reduced due to the construction of more than 48 dams upstream. This includes the Alqueva dam considered to be the largest dam in the western Europe (Dias et al., 2004). However, the main controlling factor of the shoreline retreat is the coastal engineering structures constructed along this coastal stretch. Especially at the river mouth there are two jetties constructed to avoid the sedimentation of navigating channel of the Guadiana river. The jetty constructed on the west bank is significant because it extends to the sea by 2000 m. The other jetty on the eastern side is completely submerged at present. There is another coast line defence structure (Groyne) just downstream of the Monte Gordo tourist beach constructed for holding the coastline of the Monte Gordo beach. At the eastern side, the Carreras inlet mouth is also protected with two training structures. The other artificial intervention is the sand nourishment at the Isla Canela tourist beach (Gonzalez, 2001) Coastal structure at the Isla Cristina is responsible for partial disruption for long shore sediment drift (Rodriguez-Ramirez, 2003). While the jetty at the west bank would virtually interupt the sediment transport completely at the beginning of the jetty and after mid 80's there is stabilization of the erosion processes even though still large part of the coastal stretch is still experiencing erosion trend (Dias et al., 2001a, Dias et al., 2001b). After partial infilling of sediment by the western side, some quantity of sand can move to the other side along a long path of the near-shore zone. This can be confirmed as the present rate of SER is also less than the rate of 1985 to 1994. Similar, observations have been made by Gornitz, et al., (2002) who claims that the sea level rise is an important factor determining the shoreline erosion, but human intervention such as trapping sediment supply in upstream reservoirs and disruption of long shore drift by coastal structures. Therefore, the shoreline erosion will be aggravated significantly by human intervention. Thus, the vulnerability and impacts of sea level rise is to be assessed in the context, that the human intervention also can cause significantly severe damage to the coastline comparative with the sea level rise hazard.

The impacts of shoreline retreat due to storm surge may not be significant in determining the long term trends of the shoreline. However, the vulnerability due to instantaneous shoreline retreat resulting from such extreme episodic events will remain to be highly critical for the socio-economic establishment. Therefore, the best approach for undertaking the risk of coastal flooding is not the construction of shore protection structures but adopting a well planned management strategy including proper evacuation plan and early warning systems. The long term trend would have to be accommodated by soft engineering interventions such as beach nourishments and sand by-passing (further explanation is given in the response and mitigation chapter).

The loss of salt marsh area by permanent inundation has to be considered in the context of two possibilities, as it is assumed that the coastal wetlands have a significant degree of resilience to coastal flooding. Vertical accretion and wetland migration are those positive responses of wetlands to the sea level rise (Nicholls and Lowe, 2004). The scope of the present study is not focused to access these responses quantitatively due to inherent constrains of the available data. By careful investigation of the flooding area and the availability of suitable land for such migration, it can be suggested that the vulnerability of permanent coastal flooding would be augmented by inland migration of the furthest landward boundary of the estuary. However, this problem would not arise for cases of inundation due to storm-surges as the impact is instantaneous. However, the vertical migration would retard because there is a severe retention of sediment with the construction of large number of reservoirs upstream of the Guadiana River. However, there is a need of detailed, quantitative analysis to assess the response of sea level rise on marsh land.

Chapter 7

7.0 Recommendations

7.1 Recommendations for Response, Adaptation and Mitigation

Response of people and different habitats to impacts due to sea level rise would have many aspects to consider as it is understood that the natural systems including coastal zone habitats show resilience to absorb the alteration to its natural processes and environment to a certain degree (Santos, 2002). In case of the coastal zone habitat, alterations such as sea level rise, storm surges and tsunamis would naturally absorb and adapt to the new system in the context that their processes including sediment supply to the coastal zone have not been disturbed. In this regard, intentional interventions are not required to offset the impact. This strategy is "Do Nothing". However, it is not the case for the coastline of the Guadiana estuary. There are several critical interventions to the natural processes. The main intervention can be recognized as the alteration to the sediment dynamics in this region. This has happened mainly because of two reasons; 1) construction of coastal defence structures such as groynes jetties and, 2) obstruction of sediment supply to the littoral of the Guadiana River with dams construction in the upstream of the river. Thus, relying on the natural resilience to counterbalance the deleterious impact of sea level rise would cause much more severe problems. Thus, this region requires intentional intervention to mitigate impacts including severe erosion.

Main responses can be identified in this type of coastal zone problems; 1) defend the coastline, 2) planned retreat allowing the shoreline to naturally migrate further inland and balance with the external forcing pressure by changing to a new equilibrium status (Cooper et al., 2005) and, 3) accommodation of the hazard. Under the planned retreat, all natural system effects are allowed to occur by complete pulling back from the coast. Manmade hard structures should be removed from the system to allow the natural processes to happen. Thus, it is intended to minimise the human impact to a virtual zero value. However, the strategy to accommodate the hazard also allows all the natural systems to take place but the human impacts are minimized by adjusting the human use of coastal zone (Cooper et al., 2005). However, it can be understand that the decision of adopting a particular method will be more polarized towards the socio-economic interests of mankind. Nevertheless, planned retreat can be seen as an environmental oriented approach. The feasibility of that approach is not possible for most of the cases, as some regions having socio-economic importance can not be allowed to retreating with the coastal hazards. Thus, the application of this methodology is also limited in global context. But for the coastal stretch belonging to the Guadiana estuary may not hold such economic significance, except income generated by tourism. This is especially the situation in the coastal stretch of the Guadiana Estuary in Portugal side. In this context, following adaptation strategies are proposed for analysis.

1) **Do Nothing**

   This method is not recommended as the coastline of the Guadiana Estuary is intensively altered due to human intervention. Therefore, the natural resilience may not counterbalance negative impacts of sea level rise hazards.

2) **Accommodation**

   a) It is recommended to implement Integrated Coastal Zone Management Plan incorporated with a Natural Disaster Management Plan. The later should address the following requirements: i) Early warning system, ii) Evacuation plan iii) Public awareness programme for smooth functioning of the natural disaster management plan.

b) Establishment of set-back lines for different activities are recommended with the intention of adjusting the human use of coastal zone. For instance, it is proposed to prohibit the construction of buildings but allow for recreational activities.

3) Retreat

  a) By removing jetties on Isla Cristina inlet and allowing the longshore sediment process to take place, is an possible option that can be considered under managed retreat plan.

  b) Relocation from high risk zone may be considered important to implement set-back line criterions. Especially, human settlements and infrastructures except tourism related constructions could be shifted further inland of Monte Gordo and Isla Canela beaches.

4) Protect

a) Soft engineering measures

  i) Sand nourishment projects would be necessary for Isla Canela and Monte Gordo tourist beaches. As the eastern side of Isla Canela coastline is severely eroding sand re-nourishment frequency has to be optimized.

  ii) Sand by-passing from the western side of the jetty at the Guadiana river mouth to eroding areas of Isla Canela and Monte Gordo beaches is also viable option.

  iii) Dune stabilization and reforestation of the dunes is a cost-effective mitigation technique to be considered for this coastline

b) Hard engineering measures

  i) It is necessary to avoid shore perpendicular structures. Shore parallel structures (off shore breakwaters) are option but it has to be designed so that it would not hinder the long shore sediment transportation seriously.

In this regard, spacing between two structures, height of the structure (above MSL) and length of the structures have to be designed so that it will not interrupt longshore drift by creating a “tombola” feature. The “salient” feature will not obstruct sediment transportation severely.

ii) Jetties, revetments, sea walls and groynes are not suitable to defence this low lying coastline.

Notes:

- It is recommended to consider hybrid approaches for mitigating the coastal hazards effectively (ie. Several approaches can be considered together in cost benefit analysis.
- Demarcating set-back lines has to be considered as it is important to protect the dune habitat and forest area on the Portuguese side of the coastal zone of the Guadiana estuary. These sand dunes are emerged under the worst case storm surge considered in this study. Thus, these protected lands would reduce the severity of storms resulting in less land loss.
- However, total planned retreat is not possible, as it is not possible to remove the jetty constructed over the west bank of the river mouth because it is important for navigation along the main river.
- Since the Guadiana River is a transboundary river, the management strategy would have to draw by focussing on transboundary issues. Sand by-passing from western side to eastern side of the river mouth may require an international agreement.
- However, if the natural long-shore drift is not altered by constructing the jetty over the west bank of the river mouth, the excess sand trapped within the west margin is actually intended to pass to the Spanish side naturally. In this context, out of the recommendations of this study is to propose an international agreement for allowing

natural sand movement to the downstream of coastline across transboundaries, similar to international laws for the fair allocation of water to the downstream of rivers (riparian right). However, the economic feasibility of such a sand bypassing project should be established.

7. 2 Recommendations for future studies

The present study to assess the sea level rise impacts has been undertaken with some limitations of technique used and available data for accurate estimation of some parameters. Thus, it is proposed to fill these limitations in the technique and data available. Most of these limitation and scarcity of some of the representative data have been discussed under the methodology and the discussion. The present study can be further improved by considering another important aspect of the number of people affected due to coastal flooding. Further, it would give better picture if this study can be extended to economic evaluation of the coast of flooding on the whole and based on different classification categories.

Furthermore, site characteristics such as grain size distribution over the beach along the coastline, wave breaking depth, surf zone length, depth of closure, active profile width, coastal slope and dune height have to be updated according to the every defined interval of time and the hazard zone maps have to be updated accordingly, It may be important to validate the profile generated by digital elevation models by carrying out topography and sea bathymetry survey with high resolution.

Chapter 8

8.0 Conclusions

Integrated assessment of the impact of the coastal hazards related to the sea level rise, shoreline retreat and inundation of the low lying area was applied to the transboundary fluvio-marine ecosystem of the Guadiana estuary and the adjacent sandy coastline fronted by sand dunes. This assessment was undertaken for several sea level rise scenarios as given in the SRES sea level rise forecasts of the IPCC, 2007 report. The cases considered for shoreline retreat assessment under present sea level rise rate, accelerated sea level rise rate and storm surge situation during the maximum spring high tide condition with elevated flood contours given by 38, 48 and 59 cm rise of sea level with respect to the B1, A1B and A1FI scenario.

The shoreline retreat projections for the end of 21st century indicate that the both coastlines are significantly vulnerable to sea level rise. The severity of shoreline erosion affects to a much higher degree in the eastern part of the analysed coastline. The average shoreline erosion in the western part is 0.4 km^2 and in eastern part is 1.85 km^2. The total area of erosion is 2.25 km^2 from entire coastline. These values corresponds a linear trend in increase of the land loss can be observed. On the whole, for each 10 cm increase in the sea level over this coastal stretch would account for 10% increase of land loss from this region due to accelerated sea level rise. The permanent impact on different habitats types is also an important aspect which was considered in this study. On the Portuguese side of the estuary, the total land loss represents the loss of sand dune habitats, including considerable loss from the designated natural reserve of Portugal. In the eastern side of the estuary, impact on the sand dunes, urban habitat and wetlands are more significant. The same applies to the infrastructures ie. about 12 km road length is lost in the Ayamonte municipal area. It has to be stressed that the resilience of the estuarine wetlands for sea level rise would be further diminished as this area is seriously affected by the decrease in sediment supply due to the sediment retention behind more than 40 dams located upstream of the Guadiana river.

Even though the shoreline erosion due to storm surges will not critically determine the long term trend of shoreline evolution as it is expected to attain the new state of equilibrium the vulnerability to such instantaneous even remains very significant, mainly in terms of the permanent loss and damage to the socio-economic establishment of this area. The impact on the built-up area and total urban area, for worst case storm surge is 0.60 and 0.82 km^2 in Portugal and Spain, respectively. Impact on agricultural area is also drastical as cultivated land loss from such habitat is 1.31 km^2. This would seriously affect to the local economy.

A 1m rise of sea level above the flood plain marked by maximum spring high tide, would lead to100% increase of the present flood plain of this area. Furthermore, it was shown that 2 m sea level rise over the same flood plain, due to extreme case storm surge would inundate almost entire area of this coast.

Some of the described hazards have been aggravated by the anthropogenic interventions, like for instance the “hard” coastal defences (jetties). Therefore, the response to hazards due to sea level rise has to be addressed with much caution. It is proposed to implement soft engineering measures such as beach nourishment, sand by-passing, and dune stabilization by reforestation wherever required. The coastal hazard zone maps produced in this study can be used for initial stage of drawing the management/intervention plan comprised in the Integrated Coastal Zone Management.

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Annexes

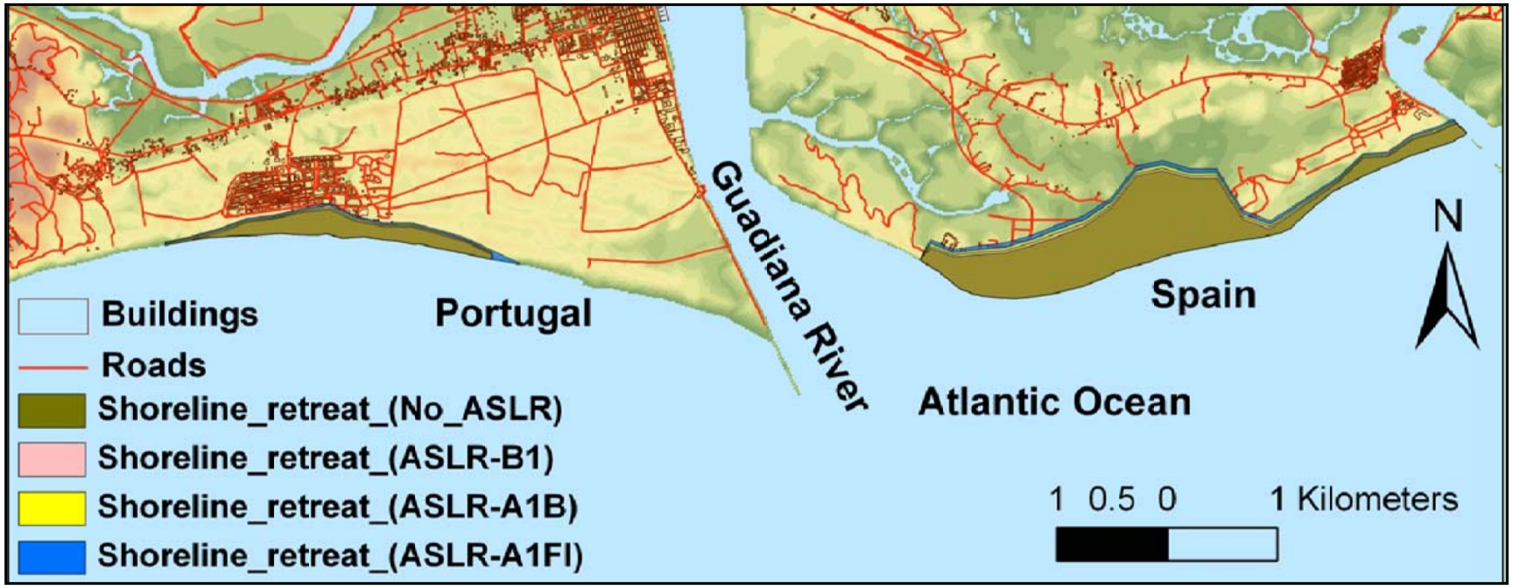

Figure 1A: Comparison of impact on roads and buildings due to permanent shoreline retreat due to sea level rise scenarios B1, A1B and A1FI and without accelerated sea level rise.

Figure 2A: Comparison of impact on land use/type due to permanent shoreline retreat due to sea level rise scenarios B1, A1B and A1FI and without accelerated sea level rise.

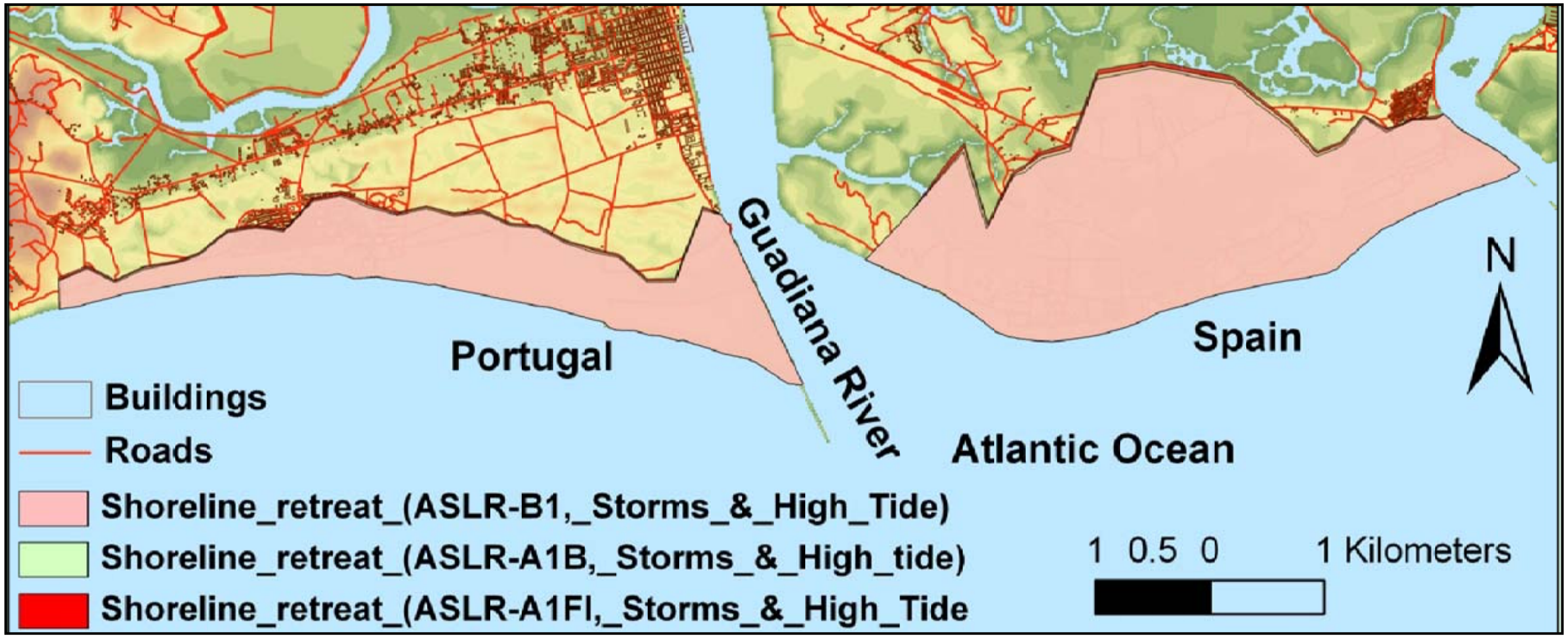

Figure 3A: Comparison of impact on roads and buildings due to instantaneous shoreline retreat for storm surge and sea level rise given by B1, A1B and A1FI scenarios of sea level rise.

Figure 4A: Comparison of impact on land use/type due to instantaneous shoreline retreat for storm surge and sea level rise given by B1, A1B and A1FI scenarios of sea level rise.

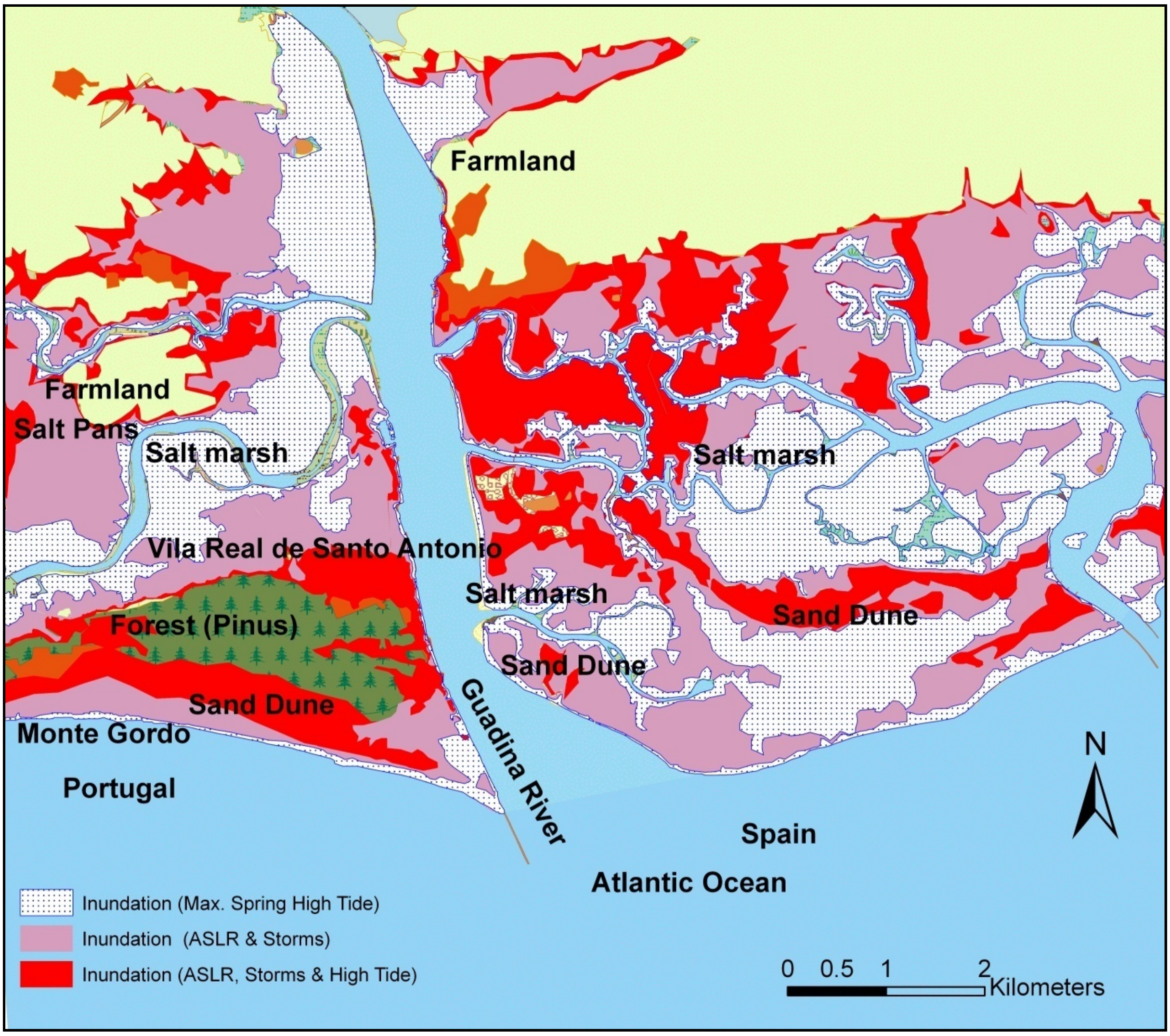

Figure 5A: Comparison of inundation extent due to i) the maximum spring high tide, ii) storm inundation and sea level rise, iii) storm inundation, sea level rise and maximum spring high tide of the Guadiana estuary.