Estuarine margins vulnerability to floods for different sea level rise and human occupation scenarios

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ABSTRACT

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Sea level rise (SLR) is increasing the risk of flooding in marginal low-lying estuarine areas. High water levels in estuaries are associated with the simultaneous occurrence of various phenomena ranging from high tidal levels to large fresh-water discharges. The intense and diverse human occupation of some of these marginal areas increases the flood vulnerability, endangering human lives and causing heavy economic and environmental losses. This issue becomes even more relevant since the European Floods Directive establishes mandatory guidelines to all member states regarding flood risk assessment, integrating flood maps with territorial characteristics. The present study aims to assess the vulnerability to floods of a specific area in Tagus estuary, by integrating hydrodynamic modelling results with land use cartography. Results suggest that about 16.1% of the estuarine marginal fringe could be flooded for the 2050 scenario, rising up to 23.7% for the 2100 scenario. Moreover, industrial and urban areas will be the most affected sites. Considering future development scenarios planned for that site, the results point to an increasing vulnerability of urban areas and therefore to the relevance of this knowledge in future planning and management guidelines as well as measures to adapt to SLR. The uncertainties and implications of the study are also discussed, and future research topics are indicated.

ADDITIONAL INDEX WORDS: *Future development scenarios, land use, climate change, Tagus estuary*

INTRODUCTION

Coastal and low lying areas around the world have high population densities and concentrate significant socio-economic values (McGranahan, *et al.*, 2007) and ecosystems services (Barbier *et al.*, 2011). These areas are specially exposed to sea level rise (SLR) which encouraged various studies regarding coastal vulnerability, natural, social and economic implications and adaptation measures (*e.g.* Nicholls and De la Vega Leinert, 2008; Tol *et al.*, 2008; Oliver-Smith, 2009; Anthoff *et al.*, 2010; March and Smith, 2012; among others).

Estuaries are especially sensitive to changes since these areas undergo different interactions between multiple forcing factors and ecological systems. High water levels in estuaries are associated with the simultaneous occurrence of various phenomena, such as high tidal levels, storm surge conditions, large fresh-water discharges, insufficient drainage conditions and flash floods in small watersheds tributaries. At the same time estuaries are ecologically important areas and anthropic factors such as dense occupation of the estuarine fringe, land reclamation or salt marsh degradation add complexity to the systems (*e.g.* Townend and Pethick, 2002; Gedan *et al.*, 2009).

To face the challenge of SLR, coastal communities and managers demand answers about the vulnerability of these systems in order to design adaptation measures and reduce possible consequences (*e.g.* Tribia and Moser, 2008). To pursue this challenge, land use information can help support vulnerability studies to SLR since this information, in a broad way, points out social and territorial vulnerabilities and help managers to foresee possible impacts (*e.g.* Snoussi *et al.*, 2008; Storch and Downes, 2011).

In Portugal, an overall assessment has been done to better understand the consequences of climate change, among which the possible effects of SLR were analysed (Santos *et al*., 2002; Santos and Miranda, 2006). Ferreira *et al.*, 2008 analysed the implications of SLR along the Portuguese coast, but few studies address SLR implications in estuaries at a local level.

This fact might be justified, among other aspects, by methodological and data limitations (e.g. Kattle, 2012) that hamper accurate and reliable assessments. This is a critical question especially considering managerial judgments.

This paper addresses flood vulnerability in a specific estuarine area at a local level, for two different SLR scenarios (2050 and 2100) and future land use development prospective.

STUDY AREA

The study area is located in Tagus estuary in the western Portuguese coast (Figure 1a). This estuary is under the influence of a semi-diurnal tide, being a high mesotidal system with a mean

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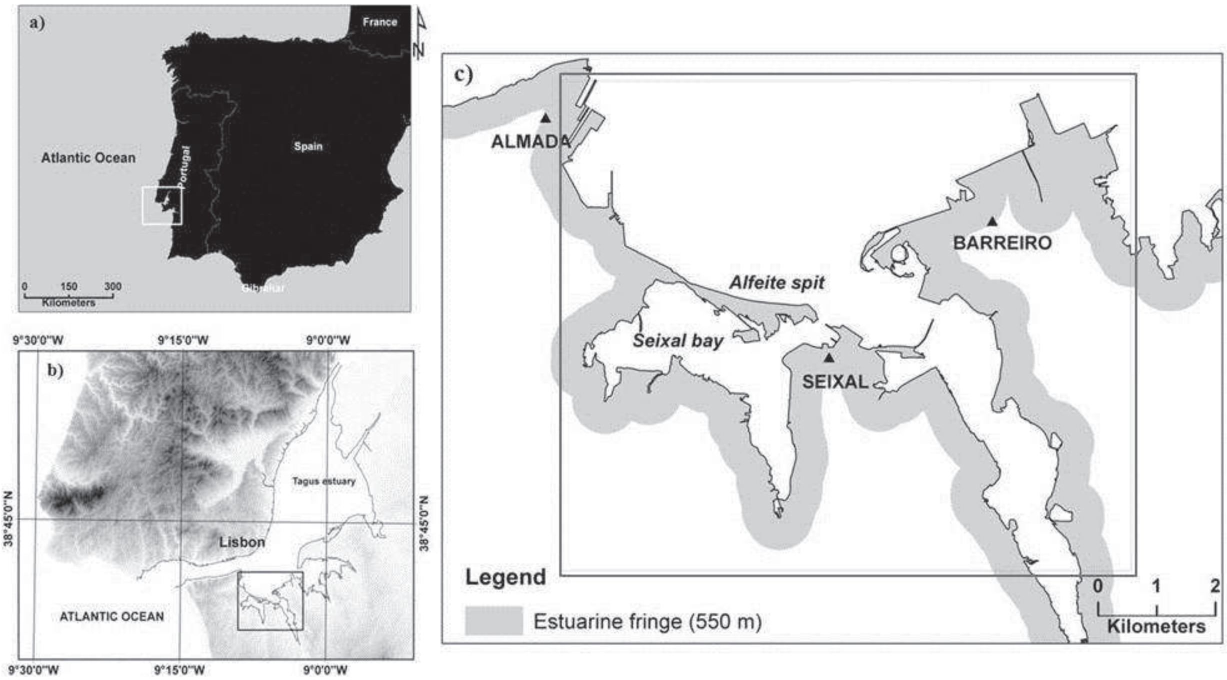

Figure 1. a) Location of the Tagus estuary, b) location of the study area and c) detail of the study area.

spring range of 3.2 m and a neap range of 1.5 m at Lisbon (Portela and Neves, 1994) being strongly ebb-dominated (Fortunato *et al.*, 1999). The main fluvial source to the estuary is the Tagus river, which has an average discharge of about 370 $m^3.s^{-1}$ (Neves, 2010).

Due to its particular morphology (Figure 1b), characterized by an extensive interior shallow region and a deep narrow channel, the tidal range varies along the estuary (Fortunato *et al.*, 1999) and ocean waves are limited to propagate into the channel (Freire, 2003). The orientation of the inner estuary (NNE-SSW and ENE-WSW) to the prevailing winds, north quadrant, promotes the local generation of waves, whose action provides the maintenance of beaches and sandbanks particularly along the left margin (Freire and Andrade, 1999)

The inner estuary is characterized by an extensive intertidal zone covering about 43% of the total area (Nogueira Mendes *et al.*, 2012). This factor contributes to important intertidal habitats development as saltmarshes more developed in the left margin (Caçador *et al.*, 2007; Nogueira Mendes *et al.*, 2012).

As one of the largest estuaries in Europe, with an area of 320 km^2, since the 19th century the estuary shows an important port expansion, urban and industrial development that promoted the explosion of human occupation of the marginal zone (Taborda *et al.*, 2009). The surrounding estuary covers eighteen municipalities, two of which are part of the study area. Recent data (INE, 2011) demonstrate that population in the Lisboa metropolitan region grew up to about 2.8 million inhabitants.

The anthropogenic occupation of the estuarine waterfront is diverse (Rilo *et al.*, 2012a): urban areas, industrial and airport facilities predominate in the northern margin, while in the southern margin urban areas, industrial, harbors and associated facilities prevail. The most extensive and important agricultural areas are located primarily in the NE region of left margin (Rilo *et al.*, 2012a).

This study was conducted in a restricted area (Figure 1c) located in the southeastern margin of the estuary, that was selected due to the data availability, past record of flood episodes (*e.g.* Freire, 2003), relatively diverse land use occupation, and prospective intention of land use change.

The territorial occupation of this area is associated to relevant industrial sites that were built in Seixal (steel industry) and Barreiro (chemical industry). Due to this important industrial presence urban areas grew nearby. These local industrial developments went into decline in the late 1990s and most of the facilities closed. At present, some management territorial plans indicate the intention of transforming a large part of these abandoned industrial sites into urban areas (includes residential, services and logistics facilities). The territory analysed in this paper is defined by the 550 m estuarine fringe, drawn inland from the highest astronomical tide line, according to the Portuguese law that regulates estuaries management plans (transposed law of the Water Framework Directive). This fringe corresponds to 22.7 km^2 (Figure 1c).

METHODS

Sea level rise scenarios

A wide range of global SLR projections are available, particularly when different approaches are considered in the estimations: process-based (*e.g.* IPCC, 2007) or semi-empirical models (*e.g.* Rahmstorf, 2007, 2010; Vermeer and Rahmstorf, 2009). The variability of the magnitude of mean SLR estimates for the 21st century and related uncertainties remain controversial issue of discussion. The discrepancies are related to the uncertainties associated with, among other factors, future of global temperature assessments, dynamic behaviour of ice sheets or the type of model used to do such estimates.

From data acquired at Portuguese margin Antunes and Taborda (2009) deduced a long-term average rate of SLR of 1.9 $mm.yr^{-1}$ for the 20th century. This finding is consistent with estimates for global mean SLR which allows us to admit that future local mean SLR scenarios can be supported by global estimates.

An overall assessment of mean SLR rise scenarios for 2050 and 2100 was performed based on literature review (IPCC, 2007; Rahmstorf, 2007; Horton *et al*., 2008; Vermeer and Rahmstorf, 2009). In this study the high end values of 50 cm for 2050 and 150 cm for 2100 were adopted to fulfil the management precautionary principle.

Modelling water elevations

Water elevations were simulated with the hydrodynamic model SELFE (Zhang and Baptista, 2008). SELFE solves the shallow water equations using an Eulerian-Lagrangian algorithm on a finite element framework. Herein, the depth-averaged version of the model (Zhang *et al*., 2011) was used and extensively calibrated against field data (Guerreiro *et al.,* 2012).

The model was forced at the ocean boundary by synthetic time series of elevation that mimic the combination of tides and storm surges with a 10-year return period. These time series were generated through the statistical analysis of surface water elevations measured at the Cascais tidal station, located outside the Tagus estuary. The methodology and its application to the Tagus estuary are described in detail in Fortunato *et al.* (in review) and Guerreiro *et al*., 2012 respectively. Maximum water levels throughout the estuary, for selected scenarios, were extracted from the model results.

Baseline conditions

The reference situation to assess the impacts of SLR in the study area was the highest astronomical tide line, drawn over 2007 ortophomaps (with 0.5 m spatial resolution) from the Instituto Geográfico Português (IGP). The adopted criteria to draw this line were based on biophysical, altimetry and legal aspects, described and discussed in detail in Rilo *et al*., 2012b.

To avoid inconsistencies, the elevation of this line was assessed based on water elevations obtained by the hydrodynamic model for a 2-year water level return period, considered representative of the present situation. The result obtained was 2.5 m relative to mean sea level, considered acceptable when compared with topographic survey data from 2010 of the estuarine margins.

Digital elevation model and land use information

An important requirement for the analysis of SLR impacts on the territory is the digital elevation model (DEM). In this study the DEM was based on the available topographic and bathymetric data, namely the supplied by the Tagus Basin Administrative Region Authority and Seixal Municipality, corresponding to surveys undertaken in 2010 and 2011.The DEM was created in ArcGIS software using natural neighbour interpolation technique with a spatial resolution of 30 m. Land use cartography of the study area was based on previous work (Freire *et al*., 2012). The cartography was performed in ArcGIS over 2007 orthophotomaps (0.5 m spatial resolution) based on a simple classification system inspired in Corine Land Cover (Caetano and Nunes, 2009). To keep data consistent the polygons were classified based on characteristics detected on a 1:10 000 scale and a topological relationship archive was constructed to avoid errors and assure quality control (Freire *et al*., 2012).

Design of flood prone areas

In order to evaluate the possible impacts of SLR in the Tagus estuarine margins, namely in the study area, flood scenarios were built on the basis of hydrodynamic results for the high-end value of SLR in 2050 and 2100.

In the first step modelled water levels were imported into ArcGIS software. Then the results for the study area were extracted and spatially averaged. Finally the averaged value was used to extract a contour from the DEM. The contour represents a simplified way to determine the limit of flood prone areas.

In the second step the contours and land use cartography were overlapped. In order to obtain sizes and metric calculations, analysis and data management tools available in ArcGIS software were used.

The future occupation scenarios were assessed by research in

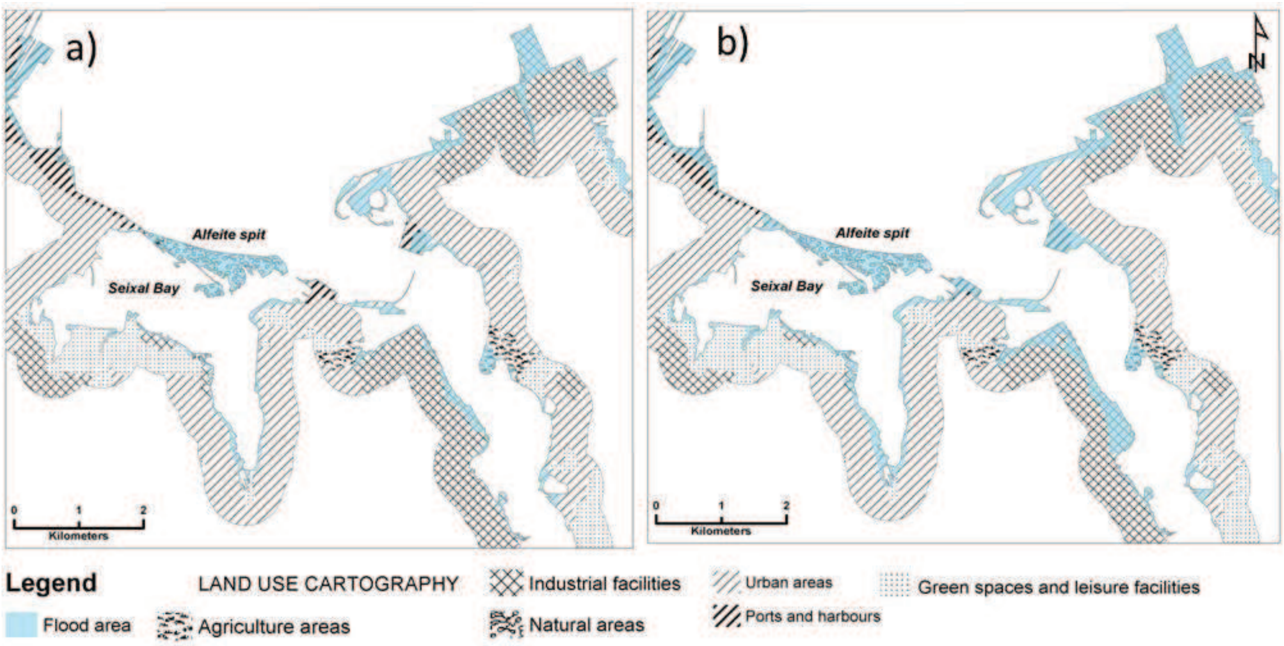

Figure 2. Flood scenarios overlapping land use cartography in the study area: a) 2050 flood scenario; b) 2100 flood scenario.

Table 1. Flood areas by occupation type for two SLR scenarios considering the marginal fringe of 22.7 km ^{2}

Occupation type	*Area (km²)*	*%*
2050 SLR scenario		
Agriculture parcel	0.1	0.5
Industrial facilities	1.1	4.6
Natural areas	0.7	3.2
Urban areas	0.9	4.0
Ports and harbours	0.5	2.3
Non-urban areas, green spaces and leisure facilities	0.3	1.5
Potencial flood prone area	3.7	16.1
2100 SLR scenario		
Agriculture parcel	0.2	0.7
Industrial facilities	1.8	7.8
Natural areas	0.7	3.3
Urban areas	1.4	6.0
Ports and harbours	0.8	3.7
Non-urban areas, green spaces and leisure facilities	0.5	2.2
Potential flood prone area	5.4	23.7

regional development plans (Ferreira, 2010; Santana, 2010). The information was summarized and georeferenced (with an average root mean square error of 3.06 m). The future time frame foreseen for the execution of these plans is diverse and ranges from 12 years to up to 18 years (Ferreira, 2010).

RESULTS AND DISCUSSION

The results show that the estuarine margins in the study area are vulnerable to inundation when SLR is considered (Figure 2 and Table 1). The results point out that about 16.1% of the estuarine marginal fringe will be vulnerable to flood for the 2050 scenario, rising up to 23.7% for the 2100 scenario. Urban and industrial areas are the most affected ones in both scenarios: 4.0% and 4.6% (2050) and 6.0% and 7.8% (2100), respectively. The effects of high water levels in urban areas can be exacerbated due to the drainage system behavior, which should be prepared for new baseline conditions.

In general, agriculture parcels and green spaces and leisure facilities would be the less affected sites, given their low representativeness at the study area. However, the Alfeite sand spit, an important recreational area that also contributes to the maintenance of Seixal bay ecosystem, will be totally flooded in both scenarios. Vargas *et al.*, 2008, analyzed the vulnerability of the Alfeite spit to inundation using a combination of hydrodynamic and morphodynamic models under SLR effects and predicted that in the worst case scenario almost all the spit would be flooded promoting the spit migration to south. This fact might represent a significant morphological change at the Seixal bay that can potentially modify the local hydrodynamic behavior leading to a significant change in natural habitats, namely sandy beaches and salt marshes (Figure 3).

The impact of SLR should consider not only natural forcing but also the dynamics of anthropogenic driven causes. A major concern in risk assessment is related with changes in land use. This effect was assessed by considering the development of two major plans that will change the land use of a large part of two industrial areas into urban parcels (includes residential, services and logistics facilities). With this potential change in land use typology the urban flood prone areas will increase from 4.0% to 7.4% for the 2050 scenario, and from 6.0% to 11.4% for the 2100 scenario. Simultaneously, the industrial flood prone areas will decrease from 4.6% to 1.2% for the 2050 scenario and from 7.8% to 2.4% for the 2100 scenario. The materialization of these plans will significantly increase the vulnerability of people and built structures, bringing new facts that should be considered in local strategies to cope and adapt to climate change.

SLR flood vulnerability assessment needs to consider the uncertainties that affect data and methodological approaches and therefore the results and conclusions taken from them. This issue was comprehensively discussed by Kettle (2012) and becomes more relevant since the conclusions and recommendations of SLR vulnerability studies are sometimes performed to inform stakeholders and national or local authorities. Uncertainty commonly rises from the lack of knowledge regarding the true value/behavior/characteristic of something. This can come from gaps of data, incompatibility of data from different sources, measurements errors, lack of representativeness or the intrinsic characteristics of methodological approaches, and is not always measurable.

In the present study the uncertainties were analyzed divided by levels (Table 2). Each level corresponds to a different stage in the followed methodology, and therefore has a specific set of uncertainty factors. Uncertainty factors range from the scientific discussion about the magnitude of SLR, the lack of high resolution topographic data on the study area or even the use of interpolation techniques to process the DEM to the lack of knowledge about future territorial dynamics suitable with SLR time frame predictions.

This synthesis reveals that conclusions on SLR vulnerability in Tagus estuary need to be framed by an appropriate understanding on the current uncertainties, but also brings to light the necessity to invest more in methodological improvements, quality data

Table 2. Major uncertainties factors in the current study. Based on Kettle (2012).

Level	Uncertainty Factors
SLR estimates	The use of global data to assess a local situation; different methods to forecast SLR trends.
Hydrodynamic modelling	Bathymetric data from different sources and different dates; lack of high resolution topographic data on all estuarine fringe; uncertainties associated with the model approach; model resolution.
Digital Elevation Model	Lack of high resolution topographic data on all estuarine margin fringe; different sources of topographic data with different spatial resolutions; interpolation techniques to process DEM; spatial resolution of the DEM.
Land use and future occupation scenarios	Uncertainties associated with vectorization work over orthophotos and adopted work scale; georeferencing; inadequate temporal frames between territorial development instruments and sea level rise temporal estimates and uncertainty regarding the implementation of these plans in future.

Figure 3. a) View of the beach at northern side of Alfeite sand spit; b) Salt marshes in Seixal bay.

acquiring and developing long-term monitoring programs.

The presented results and the above mentioned synthesis also show that this type of approach is desirable since it integrates various types of knowledge that can raise awareness of local authorities to future challenges on how to adapt and cope to SLR.

CONCLUDING REMARKS

This paper highlights Tagus estuarine vulnerability to SLR through a study at a local level in the above mentioned estuary. Results suggests that industrial and urban areas will be the most affected occupation types in both scenarios, with 4.6% and 4.0% of flooded area for 2050 and 7.8% and 6.0% of flooded area for 2100.

Future development scenarios for the study area point to a reconversion of the present industrial facilities into future urban areas. This prospective intention will increase vulnerability and raises new challenges on how to cope and adapt to SLR at a municipal scale. Therefore, the approach followed in this study is desirable since only the effort to integrate knowledge can improve and enable vulnerability studies.

The presented results also point to the importance of communicating and understanding uncertainties since they may affect conclusions and therefore management decisions. Simultaneously, we highlighted the need to improve methodologies to perform studies at a local scale, as well as the quality of data acquisition, through further research.

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