Ria de Aveiro marginal flooding: dependence on oceanic and fluvial drivers and on morphological evolution

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ABSTRACT

The assessment of flood drivers magnitude and the flood extension mapping is essential to avoid and reduce the adverse impacts of floods in coastal regions. The main aim of this work is to determine the Ria de Aveiro flood extent area under different oceanic and fluvial drivers as well as under different morphological conditions. This study integrates statistical analysis of the lagoon flooding drivers with hydrodynamic modelling using the unstructured grid model ELCIRC. The results highlight that the lagoon flood extent is highly sensitive to changes on both driving forces and morphological behaviour. In mean tide conditions the lagoon presents an area of 73.4 km^2, which increase when sea level or fluvial discharges rise. The regions more exposed to oceanic inundation are located at the lagoon central area and at the margins of the deepest lagoon channels. Contrarily, the flat areas located at the margins of rivers channels are the regions most exposed to inundation of fluvial origin. Numerical results also highlight the high dependence of the lagoon flooded area on the morphological behaviour. Indeed, the lagoon flooded area increased 16% in spring tide conditions over 1987 and 2012 as consequence of the deepening of lagoon main channels.

Key words: inundation, storm surge, hydrodynamic modelling, ELCIRC.

1. Introduction

Coastal regions are important interface zones, involving the interaction between land, water and atmosphere processes in a dynamic balance. Their physical features provide excellent conditions for biological production, supporting consequently a high biologic diversity. At the same time, these areas are usually densely populated and strategic centres for economic development. Besides its high biological and economical value they are often highly vulnerable to both natural and anthropogenic pressures. These have been recently intensified, as result of climate change and growing of population densities, increasing its vulnerability (FitzGerald et al., 2008; Jonkman and Vrijling, 2008; Nicholls et al., 1999).

Flooding in coastal areas are one of the most widely distributed of all natural hazards across Europe, threatening millions of people, livelihoods/goods, and ecosystems. Coastal lagoons are coastal landforms particularly exposed to floods because they are typically found along low-lying coastlines (Martin and Dominguez, 1994). Usually, flooding events occur when sea levels or fluvial discharges are high or when a combination of both factors occurs. The extent of flooding depends on the magnitude of flooding drivers and on the morphological and hydrodynamic behaviour of the coastal lagoon. Therefore, considering the purpose to avoid and reduce the adverse impacts of floods it is essential to assess locally the magnitude of flooding drivers and map the flood extent.

The Ria de Aveiro is a costal lagoon located on the northwest Portuguese coast (Figure 1), which is considered a flood prone region given the low altitude and flat topography of its marginal lands. Most of the flooding events in Ria the Aveiro occur during adverse weather conditions, when high river discharges coincides with storm surges and high tides.

Attending these concerns the present study aims to quantify inundation in Ria de Aveiro lagoon under different oceanic and fluvial drivers as well as under different morphological conditions through hydrodynamic modelling. The approach followed in this study integrates an analysis of sea level and fluvial data with hydrodynamic modelling. Particularly, the flooding drivers were characterized for the present and future climates, in order to account the impacts of climate changes on the inundation patterns.

2. Study Area

The Ria de Aveiro is a shallow lagoon with a very complex geometry. It is 45 km long and 10 km wide and presents four main channels: Mira, S. Jacinto, Ílhavo and Espinheiro (Figure 1). Furthermore, it presents a large number of shallow narrow channels and is characterized by large areas of mud flats and salt marshes. The lagoon connects with the Atlantic Ocean through a single artificial inlet built in 1808, constituted by two breakwaters that protect the navigation channel from the swell. The inlet channel runs from the lagoon mouth to the Aveiro harbour. Its average depth (15 m relative to chart datum) is higher than the average depth of the remaining lagoon (1 m relative to chart datum).

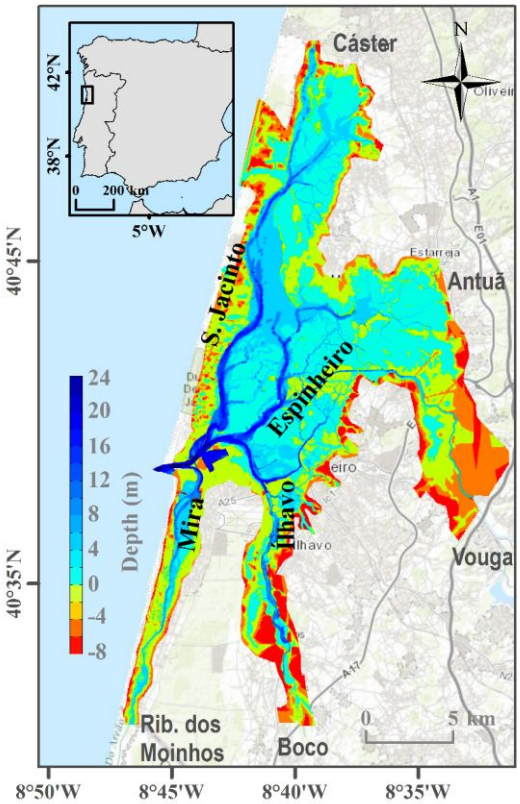

Fig. 1. Ria de Aveiro lagoon bathymetry indicating the lagoon main channels and tributaries.

The lagoon hydrodynamics is dominated by the tide, which is semidiurnal with a small diurnal pattern. As most of the lagoon channels are narrow, the wind stress and wave regime may induce only minor changes on local hydrodynamics in some restricted areas in rare situations of extreme weather conditions (Dias, 2001).

The lagoon can be considered as vertically homogeneous, except occasionally when fresh water inflows are high and the upper parts of the lagoon can present vertical stratification (Dias et al., 1999; Dias et al., 2000; Vaz et al., 2009).

The Vouga river, inflowing in Espinheiro channel, is the main source of freshwater to the lagoon (2/3 of the total fresh water) (Dias, 2001). The Boco, Mira, Cáster and Antuã rivers inflow also at the lagoon, but their discharge is significantly lower. The total mean river discharge during a tidal cycle (1.8×10^6 m^3) is considerably lower than the tidal prism at the lagoon mouth. Using the most recent bathymetry, Lopes et al. (2013a) obtained tidal prisms of 65.8×10^6 m^3 and 139.7×10^6 m^3 for neap ad spring tide, respectively.
Several lagoon morphological changes occurred recently, inducing important changes on its hydrodynamics. The extension of the northern breakwater that fix the lagoon entrance in 1987 and the generalized deepening observed at the lagoon main channels and at the inlet channel driven significant modifications on tidal propagation. Analysis of sea levels at several lagoon stations obtained in two distinct surveys performed in 1987/88 and 2002/03 revealed that the average amplitude of M_2 constituent increased approximately 24.5 cm over this period (Araújo et al., 2008). Contrarily the M_2 average phase decreased approximately 17.41º (Araújo et al., 2008). Recent results (not published) also reinforces these results, and show that the dredging of the lagoon main channels on the late nineties was the main cause of these changes. Furthermore, the deterioration of the salt pans existing in the lagoon central area has induced important tidal modifications, namely the increase of tidal currents, tidal prism and tidal asymmetry (Picado et al., 2010), which promoted the deepening of the lagoon main channels.

3. Methodology

The methodology followed in this study comprises two fundamental steps. Initially, an analysis of oceanic and fluvial flooding drivers for the present and future climates was made in order to provide the model boundary conditions. The second issue consists on the application of the 2D hydrodynamic model ELCIRC (Zhang et al., 2004) for Ria de Aveiro lagoon channels and adjacent margins in order to map inundation under different forcing conditions. This model uses a finite-volume/finite difference Eulerian-Lagrangian algorithm to solve the shallow water equations. The model configuration used in this work was previously implemented and calibrated for Ria de Aveiro. Details and results on model calibration can be found on Lopes et al. (2013a).

4. Results

4.1. Oceanic flooding driver analysis

Generally, the sea level at a particular location is determined by tides, storm surge and mean sea level.
Attending this, the tidal and storm surge forcing were characterised analysing the hourly sea surface elevation data recorded at the Barra tidal gauge (located at the lagoon mouth) between 1976 and 2013.
The observed annual series were decomposed in astronomic and residual series, which were analysed independently. Initially was applied harmonic analysis through the t_tide package (Pawlowicz et al., 2002) to determine the harmonic constituents. Then were determined the residual series by subtracting the astronomic series predicted through harmonic synthesis from the observed sea levels.
The tidal range of each tidal cycle was computed from astronomic series. The results highlight the fortnightly spring/neap tide cycle, generating tidal

ranges between 0.5 m at neap tide and 3.4 m at spring tide. Also, the mean tidal range is 2.1 m, while a mean spring tide has a tidal range of 2.9 m.
Concerning the residual series, the annual maximum levels were identified and fitted to a Generalized Extreme Value (GEV) distribution. Then, the storm surges height for different return periods were computed. By definition, the return period of an event is the period of time estimated for an event to be equalled or exceeded. Results show storm surges heights of 0.58 m, 0.84 m and 1.17 m for the return periods of 2, 10 and 100 years, respectively.
Statistically significant changes are not expected along the Portuguese coast in storm surge and tidal properties patterns under climate change conditions (Dias et al., 2014). Therefore changes in the oceanic drivers under future climate change conditions are only attributed to changes on the mean sea level. Indeed, an increase of mean sea level between 0.42 and 0.64 m is expected for the end of 21st century at the Portuguese coast (Lopes et al., 2011).

4.2. Fluvial flooding driver analysis

Concerning the fluvial data, daily mean discharges modelled by the watershed model SWAT for each tributary were analysed. This model, previously calibrated for each lagoon tributary, was run between 1932 and 2010 and between 2071 and 2100 in order to characterize the present and the future river discharge climates. The model was fed by observed and predicted (given by Global Circulation Model ECHAM5) precipitation data for the present and future climates, respectively.
The analysis performed to predicted discharges is almost similar to the one followed on the storm surge analysis. For each climate, the maximum annual discharges were determined and fitted to statistical distributions (GEV, Gumbel, Weibull, Log-normal, Gamma and Exponential). The best fitted distribution was determined performing t-student and Qui-square significance tests and computing the Root Mean Square Error (RMSE) between observed and fitted discharges. Once determined the best fitted distribution, fluvial discharges for 2, 10 and 100 years return periods were found for each climate (Table I). The results reflect the clear dominance of the Vouga river in freshwater inflow to the Ria de Aveiro lagoon. Also, a decrease of river discharge is expected for the future climate when comparing to the present.

	Present			**Future**		
	2	**10**	**100**	**2**	**10**	**100**
Rib. dos Moinhos	113	221	381	33	73	141
Boco	33	63	108	8	19	37
Vouga	797	1032	1943	494	955	1485
Antuã	106	173	245	39	78	145
Cáster	47	78	110	17	32	49

TABLE I. River discharges (m^3/s) of Ria de Aveiro tributaries for 2, 10 and 100 years return periods under present and future climates.

4.3. Hydrodynamic modelling

The 2D hydrodynamic model ELCIRC was used to investigate the sensitivity of the lagoon flooded area and extension to each flooding driver. A total of nine simulations were made, incorporating the flooding drivers analysis results (Table II). The lagoon flooded area was determined for each scenario (Table II). Generally, the results highlight the high sensitivity of the lagoon flooded area to changes on driving forcing and on morphology. As expected the flooded area increases when the sea level rises and when river discharges increase.
The influence of tidal forcing on the lagoon flood extent was determined comparing the model predictions for simulations S1, S2 and S3. Globally, the lagoon flooded area increases 23% and 31% in spring and equinoctial tides, respectively, when compared with mean

tidal conditions. The flood extent maps (Figure 2) show that the flood extension is not uniform along the lagoon, revealing regions more exposed to inundation than others. In this way, the more exposed regions are located at S. Jacinto channel heads and also some regions located at the lagoon central area.

	Tide	Storm Surge	Mean Sea Level	Flow	Bathymetry	Area (km^2)
S1	Mean	-	-	-	2012	73.4
S2	Spring	-	-	-	2012	90.2
S3	Equinoctial	-	-	-	2012	96.4
S4	Spring	2 years	-	-	2012	114.0
S5	Mean	-	0.42m	-	2012	90.1
S6	Mean	-	0.64m	-	2012	100.1
S7	Mean	-	-	Present 2 years	2012	89.3
S8	Mean	-	-	Future 2 years	2012	106.3
S9	Spring	-	-	-	1987	76.8

TABLE II. Summary of simulations performed with the hydrodynamic model ELCIRC and respective flooded area.

In contrast, the flooded area at Mira and Ílhavo channels is quite similar for each case, revealing that flooded area at these channels is almost similar for maximum levels at the inlet between 2.1 m and 3.4 m (S1 and S3, respectively).

The influence of storm surge events on the lagoon extension was evaluated comparing the S2 and S4 simulations. The results evidence that the lagoon flooded area increases 26% in spring tide conditions when a storm surge of 0.58 m occurs. The spatial patterns of inundation (Figure 3) are quite similar to those obtained previously. The lagoon central area and the margins of Ílhavo and S.Jacinto channels are the regions most exposed. On contrary, the flood extent in Mira channel is again unchanged.

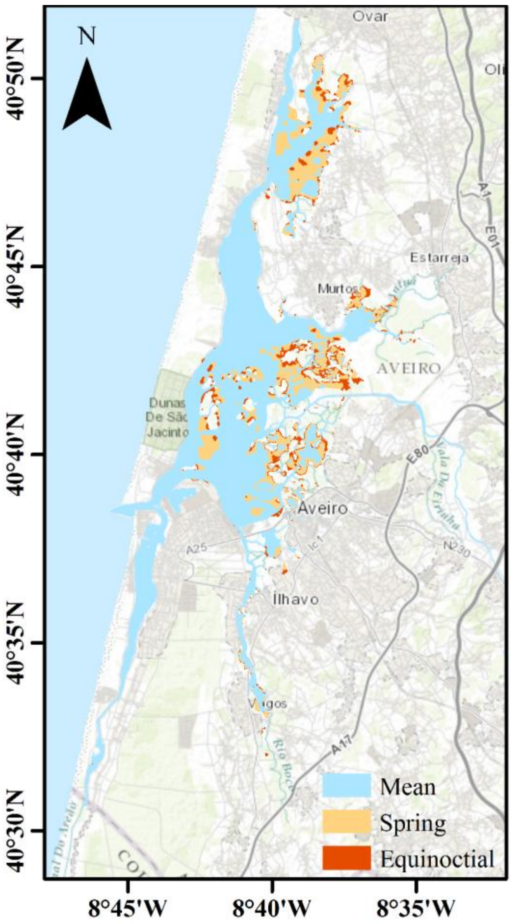

Fig. 2. Lagoon flood extent under different tidal conditions.

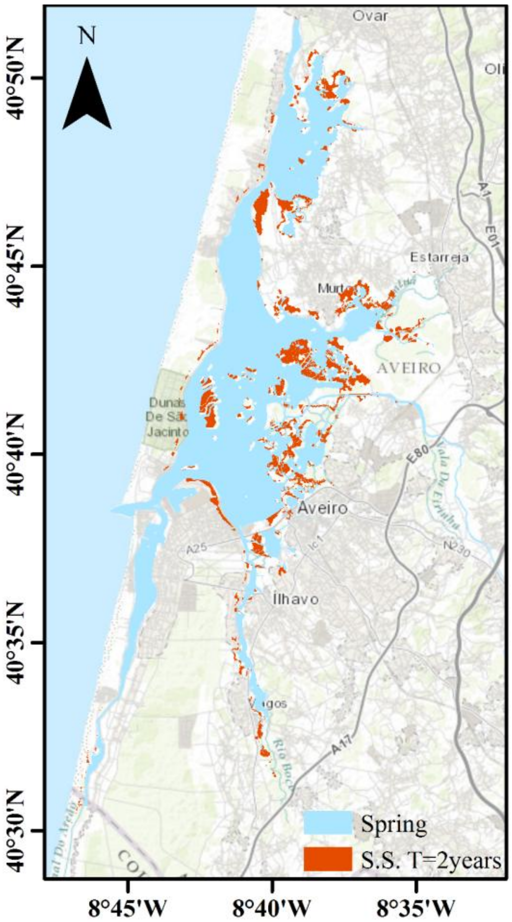

Fig. 3. Lagoon flood extent under spring tide conditions and a storm surge of 0.58 m height.

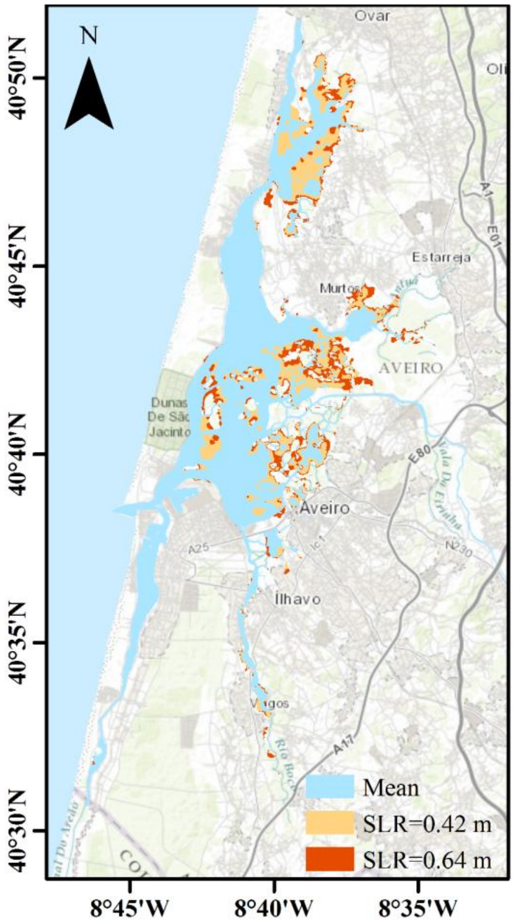

Fig. 4. Lagoon flood extent under mean tide conditions and considering 0.42 and 0.64 m mean sea level rises.

The dependence of the lagoon flooded area and extension on the mean sea level was investigated comparing the simulations S1, S5 and S6. An increase of 23% and 36% on the lagoon flooded area was found under mean sea level rise estimates of 0.42 m and 0.64 m, respectively, when compared with mean tidal conditions. The flood extent maps (Figure 4) revealed that the margins of main channels head's are the regions with a higher risk of inundation. Particularly, the regions located at the head of S. Jacinto channel are extremely vulnerable to inundation motivated by the mean sea level rise. Furthermore, some regions located at the lagoon central area are also flooded. As expected, the marginal flooding is higher for the largest mean sea level rise scenario.

Concerning the influence of the river discharges on the lagoon flood extent, the model predictions for simulations S1, S7 and S8 were compared. The results show that the lagoon flooded area increases 45% in mean tide conditions when fluvial discharges of 2 years return period are considered. For the future climate the marginal inundation tends to decrease as a consequence of the predicted fluvial discharges reduction. The flood extent maps (Figure 5) highlight that under high fluvial discharges the flood extension increases in the lowlands located close to the mouth of the lagoon tributaries. Particularly, the margins of Vouga and Antuã river channels are highly sensitive to overtopping during high discharges.

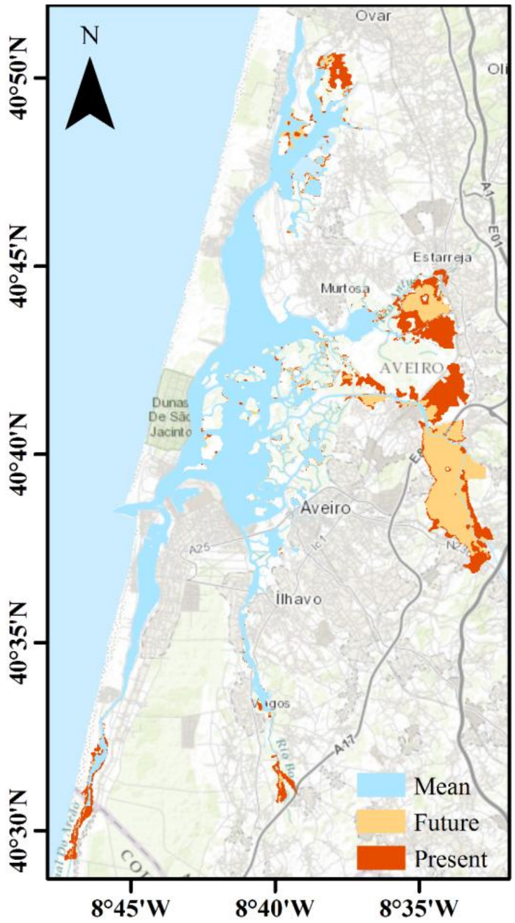

Fig. 5. Lagoon flood extent under mean tide conditions and considering fluvial discharges of 2 years return period for present and future climates.

The sensitivity of the lagoon flooded area to bathymetric changes was investigated comparing the model predictions for simulations S2 and S9.
The only difference between S2 and S9 simulations is the bathymetric configurations that are used for model predictions, which are representative of 1987 and 2012 morphological conditions. Over this period the lagoon experienced mostly a deepening of its main channels, keeping its geometry unchanged. The inlet channel depth increased 12 m in some areas. Furthermore, the deepening at the Mira channel was not more than 3 m, while at the lower reaches of S.Jacinto and Espinneiro channels can achieve 8 m (Lopes et al. 2013b). The bathymetric changes occurred influenced the lagoon hydrodynamics and consequently the flood extent (Figure 6). Globally, between 1987 and 2012 the lagoon flooded area increase approximately 16% in spring tide conditions.

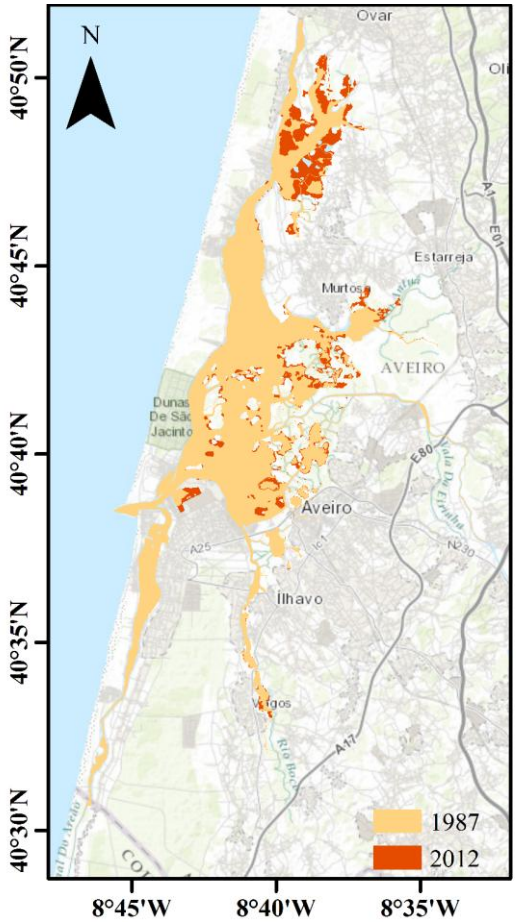

Fig. 6. Lagoon flood extent under spring tide conditions considering the bathymetries of 1987 and 2012.

The flood extent maps show that the bathymetric changes influence is higher at the upper reaches of S. Jacinto channel, which show the highest increase in flood extension. Although with a minor significance, some central lagoon regions were also flooded in response to depth variations. The flood extent in Mira and Ílhavo channels is similar for each model configuration, demonstrating that bathymetric changes did not influence significantly the hydrodynamics of these channels.

5. Conclusions

This study reports the sensitivity of Ria de Aveiro flood extent to changes on both driving forces and morphological conditions. The results of the hydrodynamic simulations show that the Ria de Aveiro marginal flooding extension is highly sensitive to changes on both driving forces and bathymetry. Generally, oceanic forcing changes affect the lagoon central area regions and the margins of S. Jacinto and Ílhavo channels. On contrary, fluvial driver changes impact the surroundings of the river channels. Regarding the main channels deepening, an increase of the lagoon flooded extension was found motivated by the rising influence of the oceanic forcing.

Under climate change conditions an increase of the mean sea level and a reduction of fluvial discharges are expected. As consequence, an increase of the lagoon flood extent at the central area regions and margins of S.Jacinto and Ílhavo channels is expected. Also, a reduction of the flood extent in the river channels marginal areas is predicted.

This study evidenced also the great potential of hydrodynamic modelling on flood assessment. Moreover, the understanding of the lagoon flooding mechanisms can be useful on the definition of structural measures to protect the more exposed regions.

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