Flooding assessment under sea level rise scenarios: Ria de Aveiro case study

Carina L. Lopes†, Ana Azevedo†, João M. Dias†

†NMEC, CESAM
Physics Department,
University of Aveiro, Aveiro
3810-193 Portugal
carinalopes@ua.pt
de.azevedo@ua.pt
joao.dias@ua.pt

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ABSTRACT

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Sea level rise is an important consequence of climate change with a significant impact on society and ecosystems. The present work aims to assess the sensitivity of Ria de Aveiro marginal flooded area to the sea level rise. A previous version of the hydrodynamic model ELCIRC was improved extending its numerical grid through the inclusion of the intertidal areas and the marginal topography. The present configuration was calibrated comparing model predictions with sea surface elevation data recorded at ten stations distributed throughout the lagoon. The root mean square error and the SKILL were computed, and generally an excellent/ good agreement between predicted and observed sea surface elevation data was found. Once calibrated, the model was used to simulate the lagoon flooded area under present mean sea level and under two local sea level rise scenarios (0.42 m and 0.64 m), considering mean and spring tide conditions. In average was found an increase of 22% and 35% of the lagoon flooded area, respectively, relatively to the present. Additionally, an increase of 15% and 23% was found for the tidal prism at the inlet, for sea level rise scenarios of 0.42 m and 0.64 m, respectively. Numerical results evidenced that sea level oscillations induce important changes in the lagoon flooded area as well as on the local hydrodynamics. Consequently some activities developed in the lagoon margins may be in jeopardy, i.e. the agricultural fields located at the margins of S.Jacinto channel will be inundated by saltwater, if these sea level rise projections are confirmed.

ADDITIONAL INDEX WORDS: *ELCIRC, tidal prism, hydrodynamics, flooded area, inundation*

INTRODUCTION

Flooding in coastal areas are nowadays one of the most widely distributed of all natural hazards across Europe, threatening millions of people, livelihoods/goods, and ecosystems. Given the high ecological and economical value of coastal regions, they are generally highly populated. Furthermore, they are important interface zones, involving the interaction between the land, water and atmosphere in a dynamic balance. The natural and anthropogenic pressures are constantly changing this equilibrium and have been recently intensified over these regions, as a result of the climate change and high population densities. Sea level rise is one of the most important consequences of climate change, inducing significant impacts on society and ecosystems and other global physical effects, such as the inundation of low-lying coastal areas, landward intrusion of salt water in estuaries and aquifers, as well as coastal erosion and habitat loss highlighting (Nicholls *et al.*, 1999; FitzGerald *et al.*, 2008; Jonkman and Vrijling, 2008).

Global mean sea level has been rising during the last century worldwide, representing currently a real threat to coastal regions. Church and White (2006) referred that, since the last century, the sea level rise rate is rising 1.7±0.5 mm/year and, according to Meehl *et al.* (2007), higher rates of sea level rise are expected for the 21st century, even if not uniformly worldwide. In this way, the local study of the impacts of sea level rise on coastal systems is a fundamental task to support information essential to formulate prevention and mitigation measures regarding the protection of these systems. Concerning the Portuguese coast, several studies based on tide gauge records showed that the sea level has risen during the 20th century (Dias and Taborda, 1988; Antunes and Taborda, 2009). Lopes *et al.* (2011), based on global circulation model results for IPCC scenarios predicted that sea level will continue to rise along this coast until the end of 21st century as result of climate changes. In Portugal, the Ria de Aveiro and Ria Formosa coastal lagoons and the Tagus and Sado estuaries, are the areas that will probably be the most affected by an accelerated sea level rise (Andrade *et al.*, 2006; Ferreira *et al.*, 2008). Particularly, Ria de Aveiro is considered a flood-prone region, given that the lagoon area adjacent to the channels present low altitude and topography. However, until now, the marginal inundation in Ria de Aveiro under different sea level rise scenarios was not assessed. Concerning the physical impacts of sea level rise in Ria de Aveiro, a study carried out by Lopes *et al.* (2011) showed that the lagoon hydrodynamics and the inlet morphodynamics will be modified in the future as result of the sea level rise. Those authors

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concluded that the sea level rise will increase the lagoon tidal prism as well as the tidal asymmetry.

Consequently, this study aims to contribute to identify the flooded areas around Ria de Aveiro (Portugal) in response to sea level rise. To assess Ria de Aveiro flooding, a previous implementation of model ELCIRC was improved by including intertidal regions and adjacent channels areas in the prior numerical grid. The model was then calibrated comparing model predictions and observations of sea surface elevation (SSE) for several stations distributed along the main lagoon channels. Finally, the model was used to simulate lagoon flooding under present mean sea level and under sea level rise scenarios of 0.42 m and 0.64 m. The 0.42 m sea level rise scenario corresponds to Lopes *et al.* (2011) estimation, considering the SRES A2 storyline and the results from the Atmosphere Ocean General Circulation Model GISS-ER. The 0.64 m value was estimated as an upper limit for the local sea level rise, adding up the uncertainty of GISS-ER model, which was evaluated in 0.14 m, and the uncertainty of the SRES scenario adopted, which have been estimated in 0.8 m. The model and the scenarios uncertainties were estimated regarding the uncertainty on global sea level rise projections published by Meehl *et al.* (2007).

STUDY AREA

The Ria de Aveiro (Figure 1) is a shallow lagoon with a very complex geometry, located on the northwest Portuguese coast (40º38'N, 8º45'W). It is 45 km long and 10 km wide and covers an area of 83 km^2 at high water (spring tide) which is reduced to 66 km^2 at low water (Dias and Lopes, 2006). It is characterized by narrow channels and by large areas of mud flats and salt marshes. Its main channels are Mira, S. Jacinto, Ílhavo and Espinheiro. The inlet region provides access to the Aveiro harbour. The navigation channel runs from the lagoon mouth to the Aveiro harbour. The average depth in the navigation channel (15 m relative to chart datum) is higher than the average depth of the remaining lagoon (1 m relative to chart datum).

The lagoon hydrodynamics is dominated by tides, which are semidiurnal with a small diurnal pattern. The tidal range at the lagoon mouth varies from 0.6 m at neap tide to 3.2 m at spring tide (Dias *et al.*, 2000). The lagoon can generally be considered vertically homogeneous, except in rare situations of strong fresh water inflows, when the upper parts of the lagoon can present vertical stratification (Dias *et al.*, 2000; Vaz *et al.*, 2009).

Human action has been the major factor controlling the lagoon morphology (da Silva and Duck, 2001; Duck and da Silva, 2012). The most noteworthy human intervention in Ria de Aveiro was the creation of an artificial inlet in 1808, in response to persistent accretion and migration of the natural inlet. Since then, several works were performed in order to improve access to Aveiro harbour, namely the construction of two breakwaters in the first half of the 20th century, whose extensions grew until the last intervention between 1983 and 1987. After the works, a deepening of the channels in the inlet region was observed (Plecha *et al.*, 2007). Besides the inlet morphological changes, the evolution of the Ria de Aveiro during the 20th century has been characterized by erosion of mud flats, salt marsh and old salt pans, and widening of most channels, as well as by dredging operations of the main navigation channels. These changes are believed to have modified the tidal dynamics of the system, increasing the tidal amplitude along the lagoon (Araújo *et al.*, 2008) and making it more vulnerable to risks of flooding and to sea level rise (da Silva and Duck, 2001; Duck and da Silva, 2012).

The consequent lagoon flooded area grow induces important tidal modifications, namely the increase of tidal currents, tidal prism and tidal asymmetry (Picado *et al.*, 2009, 2010; Dias and Picado, 2011).

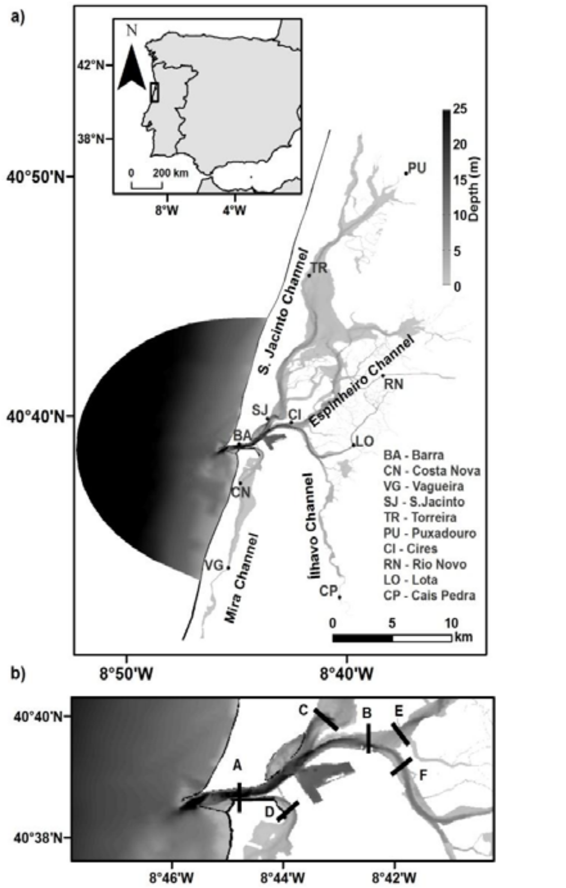

Figure 1. a) Location of Ria de Aveiro, indicating its main channels and representing the location of lagoon stations used in the model calibration; b) Location of cross-sections where tidal prism was evaluated.

HYDRODYNAMIC MODEL

The 2D hydrodynamic model ELCIRC uses a finite-volume/ finite-difference Eulerian-Lagrangian algorithm to solve the shallow waters equations, written to realistically address a wide range of physical processes (Zhang *et al.*, 2004). The equations solved in this model express the conservation of mass and momentum:

$$\frac{\partial \eta}{\partial t} + \frac{\partial [HU]}{\partial x} + \frac{\partial [HV]}{\partial y} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial V}{\partial y} = fV - g\frac{\partial \eta}{\partial x} - \frac{\tau_x}{\rho} + \varepsilon\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) \quad (2)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -fU - g\frac{\partial \eta}{\partial y} - \frac{\tau_y}{\rho} + \varepsilon\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) \quad (3)$$

Where H is the total water depth, η is the surface water elevation, U and V are the depth averaged velocity components in the x (eastward) and y (northward) directions, t is the time, f is the Coriolis parameter, g is the acceleration of gravity, ρ is the water density, ε is the horizontal eddy viscosity and τ_x and τ_y are the bottom stress in x and y directions, respectively, given by:

$$\tau_x = \rho C_D \sqrt{U^2 + V^2} U \quad (4)$$

$$\tau_y = \rho C_D \sqrt{U^2 + V^2} V \quad (5)$$

Where, C_D is the drag coefficient, which is computed by:

$$C_D = g^2 n H^{-1/3} \quad (6)$$

Where n is the Manning coefficient, which was set depth dependent for the lagoon channels (Table 1). However, for the lagoon adjacent regions it was estimated attending to CORINE Land Cover (CLC) dataset of 2006 (Table 2), which classes are represented in the Figure 2 for Ria de Aveiro.

The hydrodynamic model ELCIRC was previously implemented for the lagoon channels by Picado *et al.* (2010) and the present application consists in the improvement of this implementation by including the lagoon intertidal regions and lagoon channels adjacent margins in the former numerical grid.

The present configuration presents 219722 nodes and 437912 elements, while the mesh grid developed by Picado *et al.* (2010) presents 71996 nodes and 94352 elements. After the mesh grid construction, topo-hydrographic information was coupled to the nodes. The topo-hydrographic data used for the lagoon main channels as well as topographic data of its margins were obtained recently (2011) by Sociedade Polis Litoral da Ria de Aveiro. The remaining topo-hydrographic data were collected by the Aveiro Harbour Administration for the inlet area (2012) and by the Hydrographic Institute of Portuguese Navy (IH) for the narrowest inner channels (1987/88). The horizontal resolution of topo-hydrographic data varies from 10 m to 500 m.

The model was forced by thirteen harmonic constituents (M_{SF}, O_1, K_1, P_1, Q_1, N_2, M_2, S_2, K_2, M_4, MN_4, MS_4 and M_6) taken from the regional model developed by Fortunato *et al.* (2002) and adopts the local mean sea level determined for the Barra tide gauge for the present. The freshwater input and wind effects were neglected. The time step was set to 90 s and the calibration runs duration was 30 days.

Calibration results

Although morphological changes occurred between 2002 and 2012, the calibration was performed using 2002 SSE data, given the unavailability of bathymetric data measured in 2002 for the whole region and of actual SSE data. Observed and predicted time series for 10 stations located along the lagoon (Figure 1a) where filtered in order to exclude residual signals, namely sea surface oscillations motivated by meteorological factors. The first calibration step was to change slightly the manning coefficients reported by Picado *et al.* (2010) in order to obtain better results (Table 1). The observed and predicted elevations at all lagoon stations were represented, however, in this paper are presented only the SSE comparison at Barra and Costa Nova stations, as example (see Figure 3). Observed and predicted curves evidence a good adjustment, demonstrating visually the ability of ELCIRC to simulate SSE. In order to quantify the deviation of observed and predicted data the SKILL and the root mean square errors (RMSE) were assessed at all lagoon stations.

Results are presented in Table 3 and evidence once again the good agreement between model results and observations. Considering that SKILL values higher than 0.95 are representative of an excellent agreement between model results and observations, it was concluded that this condition was not verified only for Puxadouro and Cais da Pedra. However, as the SKILL is higher than 0.90, the agreement between model and observed elevations was considered good. RMSE values should be compared with the local tidal amplitude. If they are lower than 5% of the local amplitude, the agreement between model results and observations should be considered excellent. If they range between 5% and 10% of the local amplitude the agreement should be considered very good (Dias *et al.*, 2009). This analysis was applied to these results and percentages lower than 5% were found for 6 stations (Barra, Costa Nova, S. Jacinto, Torreira, Cires and Lota), and

Table 1. Channels bottom Manning coefficients as function of depth.

Depth (m)	***Manning***
-1.0≤h<-0.5	0.028
-0.5≤h<0.0	0.026
0.0≤h<0.5	0.024
0.5≤h<1.0	0.022
1.0≤h<3.0	0.018
3.0≤h<6.0	0.016
6.0≤h<10.0	0.015
h≥10.0	0.014

Table 2. Margins Manning coefficients as function of CORINE Land Cover.

CLC	***Manning***	***CLC***	***Manning***
111	0.1205	**242**	0.0375
112	0.1200	**243**	0.0375
121	0.0850	**311**	0.1600
122	0.0850	**312**	0.1700
123	0.0850	**313**	0.1650
124	0.0850	**321**	0.0350
132	0.0400	**322**	0.0700
133	0.0900	**324**	0.0700
142	0.0600	**331**	0.0400
211	0.0375	**334**	0.0400
212	0.0375	**411**	0.0450
213	0.0350	**422**	0.0350
231	0.0400	**511**	0.0225
241	0.0375	**521**	0.0225

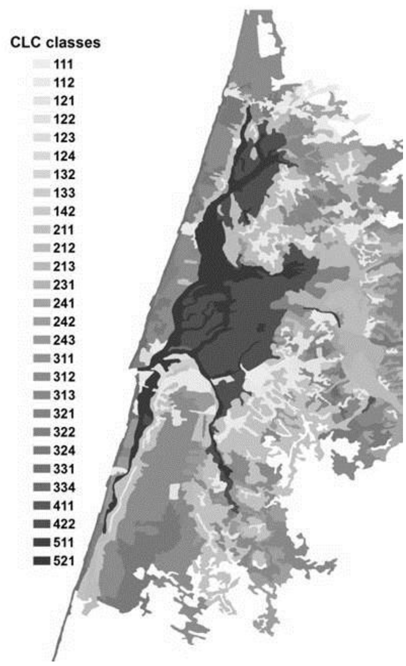

Figure 2. CORINE Land Cover classes for Ria de Aveiro lagoon adjacent area.

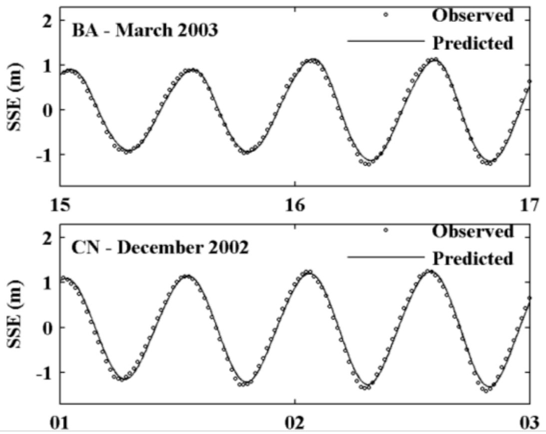

Figure 3. Observed and predicted time series of sea surface elevation at stations BA and CN.

percentages between 5% and 10% at the remaining stations (Vagueira, Puxadouro, Rio Novo and Cais da Pedra).

In summary, the calibration results showed an excellent agreement between model results and observations at the stations located at the lagoon central area, and good agreement at the remaining stations. Furthermore, these calibration results presented better results than the previous applications to this system. Particularly, the improvement of the mesh by the inclusion of intertidal areas and channels adjacent regions, as well as the update of the bathymetry of lagoon main channels proved to better represent the lagoon hydrodynamics than the application developed by Picado *et al.* (2010). In fact, the RMSE and SKILL values found in this study for the lagoon central stations are identical to those obtained by Picado *et al.* (2010). However, for the stations located at the channels heads they are more accurate than those obtained by Picado *et al.* (2010). At the channel heads stations the RMSE obtained in this study are approximately 8 cm lower than RMSE obtained by Picado *et al.* (2010). Thus, it was considered that the model was able to reproduce the tidal propagation at the Ria de Aveiro lagoon, and therefore able to simulate flooding under sea level rise scenarios.

FLOODING ASSESSMENT

After calibrated the ELCIRC model was then used to simulate Ria de Aveiro flooding under sea level rise scenarios. These scenarios were simulated imposing a sea level rise of 0.42 m and 0.64 m above present mean sea level. Flood extent was assessed for mean and spring tide conditions, with tidal ranges of 2.1 m and 2.9 m, respectively.

Table 3. Root mean square error (m) and SKILL evaluated at lagoon stations.

Station	*RMSE(m)*	*SKILL*
BA	0.0745	0.9975
CN	0.0882	0.9958
VG	0.2207	0.9559
SJ	0.0876	0.9957
TR	0.0970	0.9910
PU	0.1989	0.9269
CI	0.1260	0.9930
RN	0.1949	0.9698
LO	0.1086	0.9942
CP	0.2319	0.9176

Flood extent and lagoon flooded area

The flood extent maps where obtained identifying in the model grid the points that were flooded during the simulations along each tidal cycle considered (mean and spring tide). From the flood extent maps, represented in Figure 4, was found that the margins of the 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 sea level oscillations. Furthermore, some regions located at the lagoon central area are also flooded as result of sea level variations. As expected, the marginal flooding is higher for the largest sea level rise scenario, showing that it increases with the sea level rise extension, for both mean tide and spring tide conditions. Furthermore, the flood extent is higher for spring tide than mean tide. The behavior of lagoon flood extents evidences that lagoon inundation is highly sensitive to sea level oscillations (both short and long term oscillations).

The lagoon flooded area was also assessed for each model configuration (Table 4). The results show that the area flooded increased in average approximately 23% and 35% for 0.42 m and 0.64 m sea level rise scenarios, respectively, relatively to the reference mean sea level.

The results obtained evidence also the sensitivity of lagoon flooded area to short term sea level variations. In fact, the lagoon flooded area for spring tide increase approximately 20% relatively to that found for the mean tide.

The sensitivity of lagoon flooded area to sea level variations evidence the low altitude of the lagoon margins, indicating that some activities and infrastructures developed in the lagoon margins may be in jeopardy, i.e. the agricultural fields and residential areas are predicted to be more frequently affected by saltwater inundation, if these sea level rise scenarios predictions will be confirmed.

Tidal prism

The tidal prism was computed at the cross-sections represented in Figure 1b, from velocities and elevations predicted by the

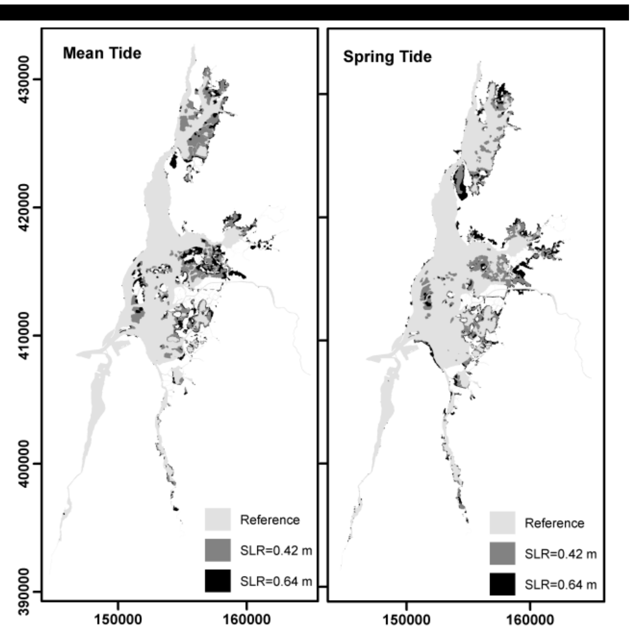

Figure 4. Flood extent maps for sea level rise under mean tide and spring tide conditions.

Table 4. Lagoon flooded area (km^2) for each model configuration.

	Reference	*SLR=0.42 m*	*SLR=0.64 m*
Mean tide	72.5	90.5	100.8
Spring tide	88.6	107.5	118.6

model. The cross-section A is intended to be representative of the Ria de Aveiro inlet and therefore of the entire lagoon, C to F cross-sections of its four main channels and a remaining one illustrating the tidal prism before Espinheiro and Ílhavo channels (denominated Cires, B). Results are presented in the Figure 5. For the reference mean sea level the tidal prism at the S.Jacinto (B), Mira (D), Espinheiro (E) and Ílhavo (F) channels is approximately 33%, 9%, 21% and 17% respectively, relatively to tidal prism value at the lagoon mouth (A).

Comparing this tidal prism distribution across lagoon channels to that given by Dias (2001), some changes can be detected. At S.Jacinto and Mira channels the percentages are quite similar, however, at Espinheiro/Ílhavo channels the percentage presented here is about 5% lower/5% higher. These changes can be related to morphologic changes occurred in the lagoon since the estimates obtained by Dias (2001), which are based on 1987/88 bathymetric data. Furthermore, the present estimates regard the Ria de Aveiro marginal channels areas, while previous estimates considered only the circulation at the lagoon channels. The results also evidence that the lagoon tidal prism is highly sensitive to sea level oscillations (both short and long term). At the lagoon mouth the tidal prism is approximately 40% higher in spring tide than in mean tide, for the present mean sea level. Furthermore, the tidal prism increases with sea level rise at all lagoon cross sections, being the increase rate higher for the 0.64 m sea level rise scenario.

The tidal prism increase rate relatively to present mean sea level was assessed for both scenarios in order to quantify the tidal prism changes induced by mean sea level rise. Results are presented in Figure 6 and show that tidal prism increases in average approximately 15% and 23% for sea level rise scenarios of 0.42 m and 0.64 m, respectively. Figure 6 evidences also that tidal prism increase rate is not similar for all cross sections. In fact, the tidal prism increase rate for cross-sections C and D is lower than for cross-section A. Otherwise, the cross-sections B, E and F present a tidal prism increase rate higher than cross-section A. This non-uniformity of the increase rate found at the cross-sections reveals that sea level rise will induce changes in the redistribution along the lagoon of the water volume flowing through the inlet. Indeed, the results show that the volume of water through Espinheiro and Ílhavo channels further increase as result of sea level rise. Contrarily, and in order to compensate this increase, the tidal

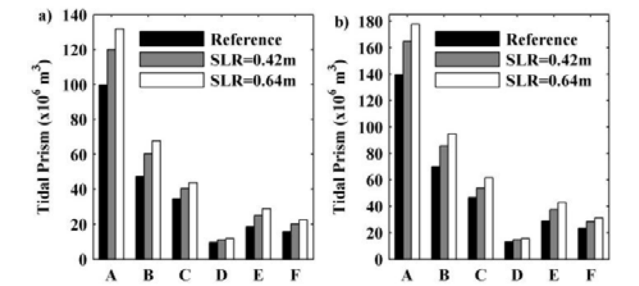

Figure 5. Tidal prism in each cross-section for: a) mean tide; and b) spring tide.

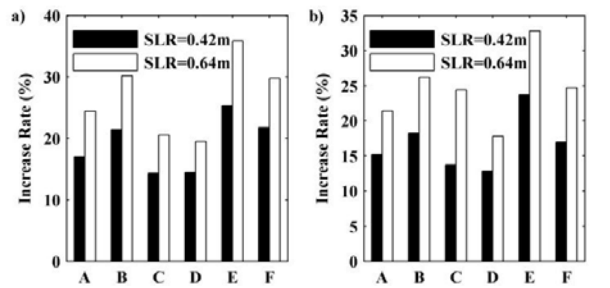

Figure 6. Tidal prism increase rate (%) relative to reference mean sea level for: a) mean tide; and b) spring tide.

prism increase rate is lower at S.Jacinto and Mira channels.

The sensitivity of lagoon tidal prism to sea level rise was evaluated in a previous study carried out by Lopes *et al.* (2011). Those authors estimated an increase of tidal prism by approximately 28% in spring tide. The differences between present results and those given by Lopes *et al.* (2011) can be partially explained by the differences between numerical domains. Effectively, the present model configuration represents an improvement relatively to the earlier study, including the marginal lagoon areas, while in the previous implementation the circulation was restricted to the lagoon channels.

Relating the tidal prism results to flood extent maps obtained for each model scenario, some conclusions can be found. Namely, the tidal prism increase detected at Mira channel does not influence the flood extent at this channel, once flood extent is similar for each model configuration. Otherwise, the S.Jacinto channel flood extent is extremely sensitive to tidal prism increase motivated by sea level rise. These results evidence that S.Jacinto channel adjacent regions present low altitude and topography, and are therefore extremely sensitive to sea level oscillations.

CONCLUSIONS

The sensitivity of Ria de Aveiro marginal flooding under scenarios of sea level rise was explored in this paper. First, a previous implementation of ELCIRC model was improved incorporating the intertidal regions and channels adjacent areas in a prior numerical grid. The calibration results showed that the agreement between predicted and observed data is excellent at the stations located at the lagoon central area. Moreover, the agreement between predicted and observed data at the stations located at the lagoon channels head is considered good. Nevertheless, the present configuration presents for these stations RMSE errors 8 cm lower than those found for the previous model configuration, revealing that the grid enhancement and the main channels bathymetry update resulted in an improvement of the predictions accuracy.

The flood extent maps obtained from model simulations evidence that the risk of flooding was not uniform along the lagoon. In fact, the marginal areas of S.Jacinto channel evidence higher risk of inundation comparing with other channels. Otherwise, in the Mira channel the flooding patterns are similar for all mean sea levels considered. It is noteworthy that some regions located at the lagoon central area will be also further inundated as result of the sea level rise.

The quantification of the flood extension evidenced that lagoon flooding area is extremely sensitive to sea level oscillations (both short and long term). In fact, the lagoon flooded area is approximately 40% higher for spring tide (tidal range of 2.9 m) than for mean tide (tidal range of 2.1 m). Also, the lagoon flooded area is extremely sensitive to mean sea level changes. In average, the flooded area increases 23% and 35% for 0.42 m and 0.64 m sea level rise scenarios, respectively, comparing to the reference mean sea level.

The tidal prism results evidence that the volume of salt water flowing through the lagoon mouth during the tidal flood will increase in average 15% and 23% for sea level rise scenarios of 0.42 m and 0.64 m, respectively, comparing to the present. Generally, tidal prism also increase at the mouth of lagoon main channels, however the increase rate is not uniform, evidencing a redistribution of the water volume which cross the inlet. At Espinheiro and Ílhavo channels the increase rate is higher than at the inlet, while at Mira and S.Jacinto channels the increase rate is lower comparing to that found for the inlet.

As final conclusion, it should be addressed that the resulting changes identified for the flood extension and location may have potentially effects on the productivity and socio/economy of this coastal ecosystem affecting therefore the local populations.

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