Influence of morphological changes in a lagoon flooding extension: case study of Ria de Aveiro (Portugal)

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ABSTRACT

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Coastal lagoons are interface zones where land, water and atmosphere interact in a dynamic balance that is constantly being changed by natural and human influence. The hydrodynamics and morphology of these coastal systems continuously adapt to changes in the forcing agents and show a complex interconnection. Worldwide studies show that tidal propagation is strongly dependent on local morphologic features. Attending to these concerns, the present study aims to assess the changes in flooding extension at Ria de Aveiro, as well as in the tidal prism, induced by local morphological modifications. The analysis of the topo-hydrography available for the Ria de Aveiro, comprising two general surveys carried out in 1987/88 and 2011 and two updates of the inlet bathymetry performed in 2001 and 2012, shows the deepening of the lagoon main channels and of the inlet evolving region. A flooding assessment of the lagoon margins and the determination of the tidal prism were performed applying the hydrodynamic model ELCIRC considering the four morphologic configurations described and different tidal conditions. The numerical results show the importance of lagoon morphological changes, which induce an increase of about 16% between 1987/88 and 2012 in the lagoon flooded area for spring tide. The new flooded regions correspond to the margins of S.Jacinto channel head and lagoon central areas. Additionally, the tidal prism results evidence a redistribution of the water volume flowing into the lagoon among their main channels during the period under analysis.

ADDITIONAL INDEX WORDS: *tidal prism, flooded area, ELCIRC, hydrodynamic modelling.*

INTRODUCTION

Coastal lagoons are shallow water bodies that connect at least intermittently to the ocean by one or more restricted inlets (Kjerfve, 1994). Generally, its physical characteristics provide exceptional conditions to biological productivity, and therefore are ecosystems of great importance. Furthermore, the surrounding areas are usually densely populated, and consequently highly subjected to anthropogenic pressures. The flow within a coastal lagoon is determined by the exchanges between the lagoon and the ocean, by the interaction with the atmosphere and by the discharge of its tributaries. Moreover, these exchanges can be modified by geomorphological changes induced by both natural and anthropogenic factors. In fact, the effects of lagoons geomorphology on its hydrodynamics have been studied in several lagoons worldwide (Oliveira *et al.*, 2006a; Picado *et al.*, 2010; Jewell *et al.*, 2012). These studies demonstrate that tidal propagation is strongly dependent on the bathymetric and geometric configuration of the systems analysed.

Moreover, considering that several biological processes found in lagoons are strictly dependent on its physical conditions, understanding the dependence of the lagoons hydrodynamics on its geomorphology is a fundamental task in order to protect the ecosystems.

Considering these issues this study aims to assess the effects of geomorphology changes in Ria de Aveiro dynamics. The topo-hydrographic data available for this lagoon, between 1987/88 and 2012 shows that morphologic changes during this period were restricted to bathymetric modifications. Attending to this, the present study will assess the influence of bathymetric changes in Ria de Aveiro coastal lagoon flooding extension and tidal prism. To achieve this goal a detailed analysis of bathymetric changes between 1987 and 2012 was made. Furthermore, simulations with the hydrodynamic model ELCIRC were made for the available bathymetries.

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.

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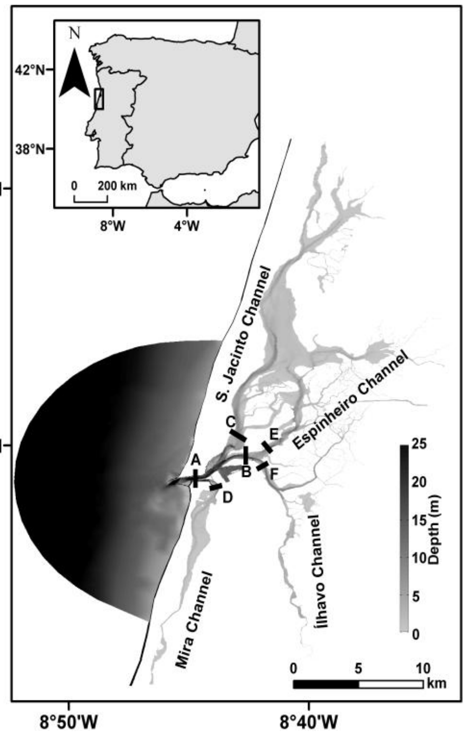

Figure 1. Location of Ria de Aveiro, indicating its main channels and numerical bathymetry of 2012. The location of cross-sections where tidal prism was evaluated is also represented.

The lagoon hydrodynamics is dominated by the tide, which is semidiurnal with a small diurnal pattern. The residual circulation is determined essentially by flood/ebb asymmetry. As the lower lagoon is ebb-dominant there is a trend to export sediments to the ocean (Oliveira *et al.*, 2006b). 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.*, 2000).

The inlet region provides access to the Aveiro harbour, through the navigation channel that runs from the lagoon mouth to the harbour facilities. The average depth in the navigation channel (15 m relative to chart datum) is greater than the average depth of the remaining lagoon (1 m relative to chart datum).

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 was the creation of an artificial inlet in 1808, in response to persistent accretion 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 extension grew to the last intervention in 1987.

The analysis of the bathymetric changes at the inlet after the extension of the northern breakwater (1987/88) revealed that this region is extremely dynamic, experiencing large morphologic changes in a short time period. The bathymetric changes induced by the extension of the northern breakwater together with the regular channel dredging led to a deepening of the channels in the inlet region (Plecha *et al.*, 2007).

Besides the geomorphological changes in the inlet, bathymetric changes were also found in the inner lagoon. Between 1996 and 1999 several dredging operations were made in the lagoon main channels, in order to provide conditions for navigability (Marinheiro, 2008). 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.

MODEL SETUP

The 2D horizontal hydrodynamic model ELCIRC applied in this study uses a finite-volume/finite difference Eulerian-Lagrangian algorithm to solve the shallow waters equations (Zhang *et al.*, 2004). The model was previously implemented for the lagoon channels by Picado *et al.* (2010). The present application consists in the improvement of this implementation by including the lagoon intertidal regions and adjacent margins. The model configuration applied in this study was previously calibrated for Ria de Aveiro lagoon by (Lopes *et al.*, 2013). Four numerical bathymetries are used in this study, constructed based on topo-hydrographic data from surveys of the overall channels carried out in 1987 and 2011 and of the inlet region carried out in 2001 and 2012 (Table1). The data was measured by IH-Hydrographic Institute for Portuguese Navy (1987), Sociedade Polis Litoral da Ria de Aveiro (2011) and APA-Administração do Porto de Aveiro (2001 and 2012) and its horizontal resolution ranges from 10 to 50 m. The topographic data used for the lagoon margins was the same for each case and corresponds to surveys performed in 1987 and 2011. In this way, the numerical bathymetries comprise a model grid identical for each configuration, with exactly the same geometry, and changing only the channels depth according to Table1.

Simulations with ELCIRC model were made using the four numerical bathymetries. The model was forced in each case imposing at the ocean open boundary time series of sea surface elevation determined by harmonic synthesis of the fourteen most important local constituents (M_2, S_2, N_2, MM, O_1, K_1, M_4, M_{SF}, MS_4, L_2, MU_2, Q_1, MN_4 and $2MN_6$). Three tidal conditions were analyzed, corresponding to typical mean neap tide (maximum height of 0.8 m at the inlet), mean tide (maximum height of 1.0 m at the inlet) and mean spring tide (maximum height of 1.6 m at the inlet).

The effects of wind stress and fluvial discharge were neglected in this study, considering its minor importance comparing to tidal forcing in the establishment of lagoon water levels (Dias, 2001). Furthermore, this approach is realistic to assess water levels in dry season.

RESULTS AND DISCUSSION

Morphological changes

The differences between numerical bathymetries are represented in Figure 2. In general the lagoon experienced mostly a deepening of its main channels over the time, keeping its geometry unchanged. The inlet channel depth increased after the extension of northern breakwater in 1987, as depicted in the Figure 2a. Between 1987 and 2001 the deepening of the inlet channel achieved 10 meters in some areas. Figure 2b evidences a deepening of lagoon main channels and the enlargement of the

Table 1. Numerical bathymetries details.

Bathymetry	Detaills
1987	General bathymetric survey
2001	1987 + Inlet update
2011	2001 + Lagoon main channels update
2012	2011 + Inlet update

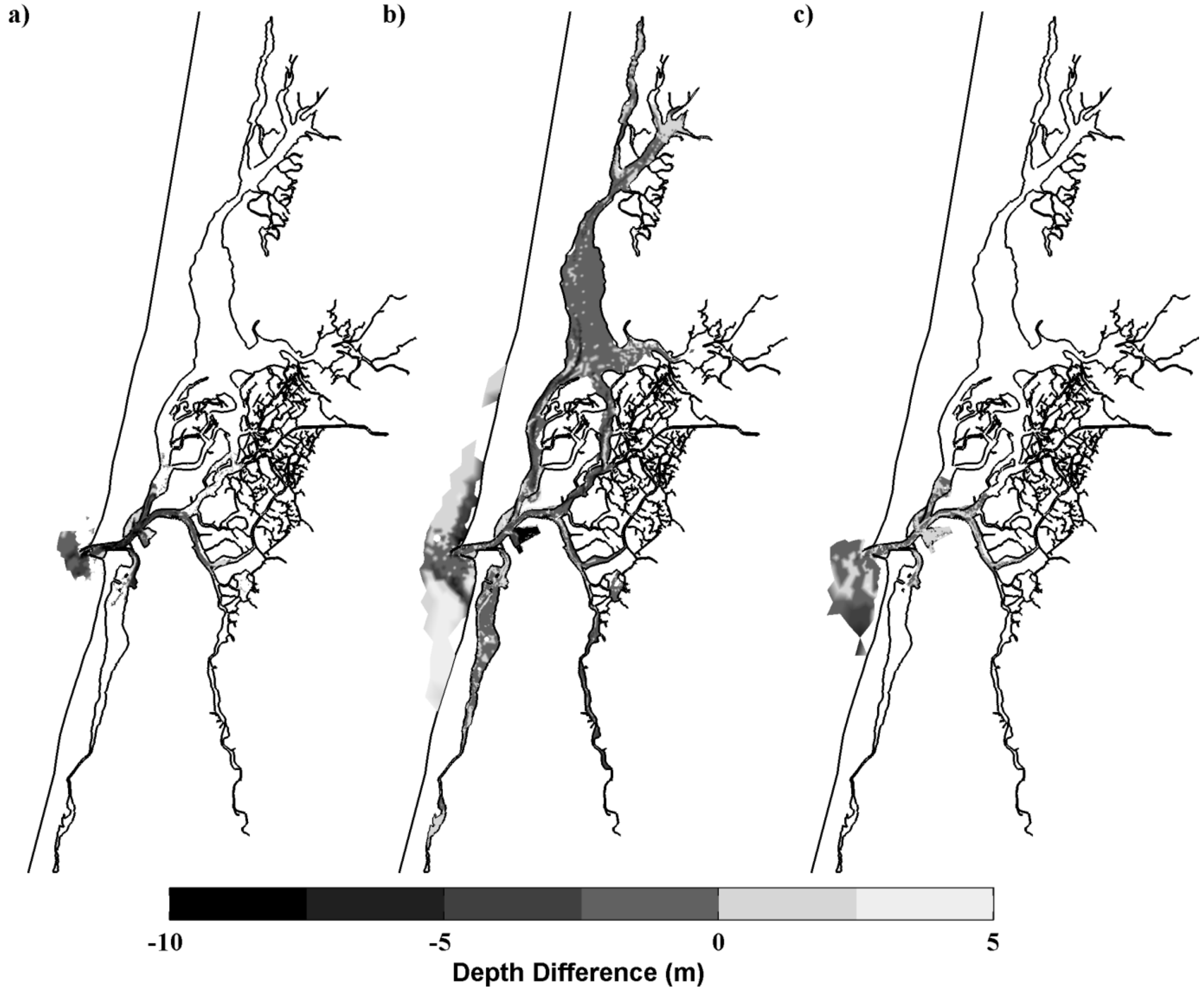

Figure 2. Depth difference (m) between: a) 1987 and 2001 bathymetries; b) 2001 and 2011 bathymetries; c) 2011 and 2012 bathymetries.

Aveiro harbour, which was the only geometric change found, but considered of minor relevance. Deepening at the Mira channel was not more than 3 meters, while at the lower reaches of S.Jacinto and Espinneiro channels can achieve 8 meters. In the upper reaches of S.Jacinto, Mira and Ílhavo channels a depth decrease is also evident. Furthermore, a mean deepening of 2 m in inlet region was found. Between 2011 and 2012 (see Figure 2c) bathymetric changes are restricted to the inlet and revealed a deepening of the inlet channel of 2 meters. Additionally, the lower reaches of Ílhavo channel had also experienced a slight deposition.

Flood extent

The hydrodynamic model ELCIRC was run for each configuration previously described, and the maximum flood extent area was determined for each case. The flood extent was determined by identifying in the model grid all the nodes that are flooded during each one of the tidal cycles under analysis.

Figure 3 represents the flood extent maps for each bathymetric configuration and for each tidal condition considered. The maps show that, for each configuration, the lagoon flood extent is extremely dependent on tidal conditions (neap, mean and spring tide) mainly in the inner part of the central lagoon, as a consequence of the small depth of the channels and of the reduced topography of the lagoon margins. The bathymetric changes influence is higher in spring tide and 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.

The total flood extension area was also computed for each configuration and tidal conditions, to globally quantify the changes induced by the bathymetric changes (Table 2). Between 1987 and 2012 the lagoon flooded area increase approximately 3%, 7% and 16% for neap, mean and spring tide conditions respectively. Moreover, the bathymetric differences that occurred in the inlet region did not influence the extension of the flooded

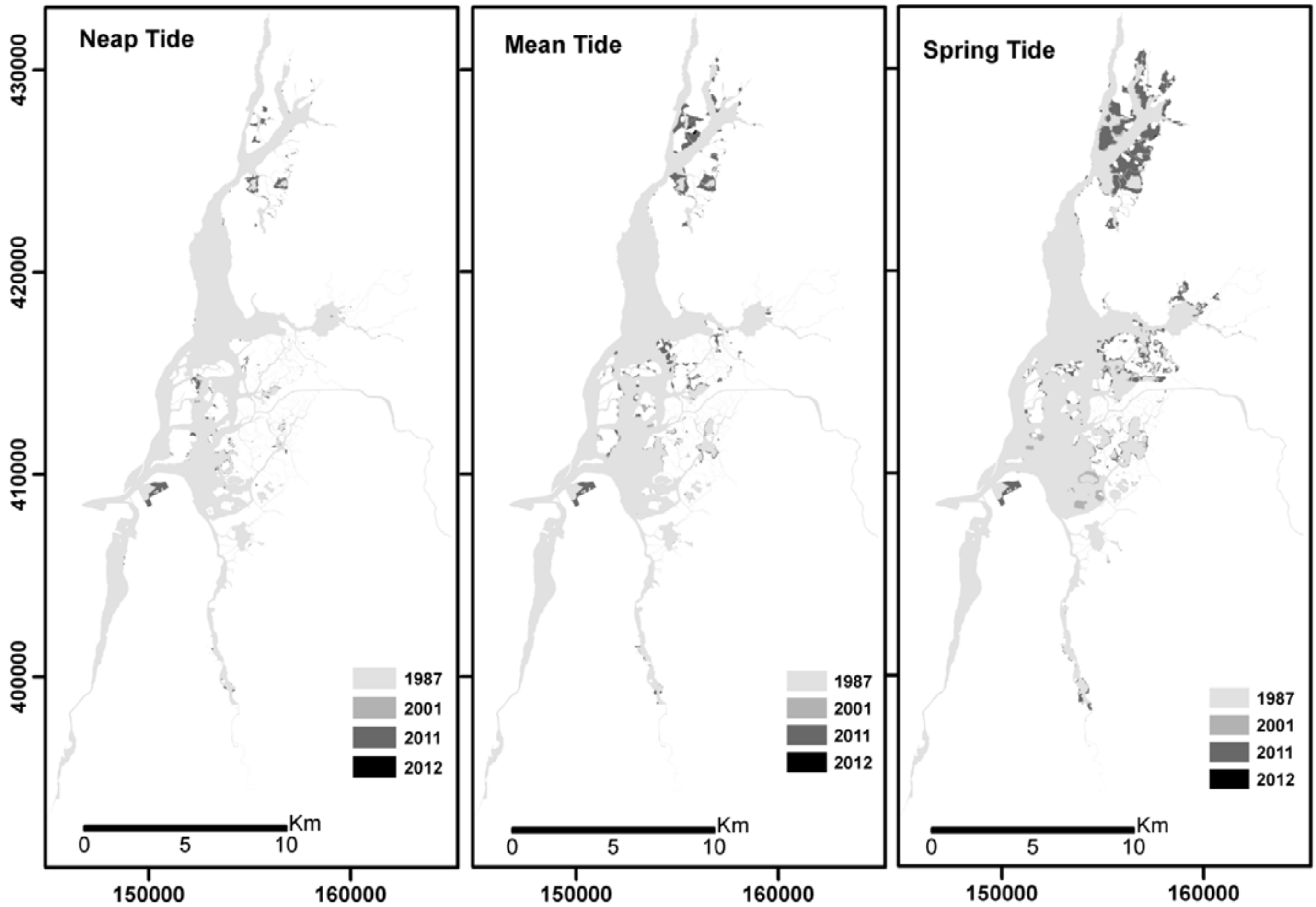

Figure 3. Lagoon flood extent maps for neap, mean and spring tide conditions, considering the bathymetries of 1987, 2001, 2011 and 2012.

area. The highest increase in the flood extension area was found between 2001 and 2011 configurations, with an increase of 3%, 6% and 12% under neap, mean and spring tide conditions respectively. These results show that the deepening of the lagoon main channels, not just the inlet, is the major factor determining the increase of the lagoon flooded area. This finding is explained by the friction effect inside the lagoon that decreases when the depth rises. Under these circumstances, the tidal wave amplitude is less attenuated, inducing higher water levels at the lagoon. As the lagoon margins have a reduced altitude the water overflows the channels, inundating some of these regions that were not flooded in the past under the same tidal conditions.

Tidal Prism

The tidal prism (*TP*) is defined as the volume of water flowing through a estuarine cross-section on each tidal cycle, excluding any contribution from freshwater inflow. Attending to this, the TP was computed at the cross-sections represented in the Figure1 for each bathymetric configuration and for each tidal condition considered. The results are presented in the Figure 4. As expected the tidal prism is strictly dependent on tidal conditions. The volume of water which crosses the inlet in neap tide conditions is approximately 45% of the volume in spring tide conditions. The total water volume crossing the inlet is distributed among the lagoon channels. In fact, for 2012 bathymetry the tidal prism for S.Jacinto (B), Mira (D), Espinheiro (E) and Ílhavo (F) channels is approximately 33%, 9%, 21% and 17% respectively, of the tidal prism value at the lagoon mouth (A).

Table 2. Lagoon flooded area (km^2).

	Neap Tide	Mean Tide	Spring Tide
1987	64.7	67.9	76.9
2001	64.9	68.6	79.8
2011	66.7	72.9	89.3
2012	66.7	72.8	89.2

For 2012 bathymetry the tidal prism estimates presented here ranges between 65.8×10^6 m^3 to 139.7×10^6 m^3 at the inlet for neap and spring tide conditions, respectively. These estimations are higher than previous estimations performed by Picado *et al.* (2010) and Lopes *et al.* (2011). Using the 2001 bathymetry these authors estimated tidal prisms at the inlet ranging between 30×10^6 and 70×10^6 m^3 for neap and spring tide conditions, respectively. The differences found can be explained by morphological changes occurred since 2001, but also considering some limitations of the previous models applications, namely the exclusion of the channels margins in the numerical bathymetries used.

The results evidence also that the generalized deepening of the lagoon channels between 1987 and 2012 induced a global increase on tidal prism at the cross-sections analyzed. This outcome was expected by several reasons: the cross-sectional area increases

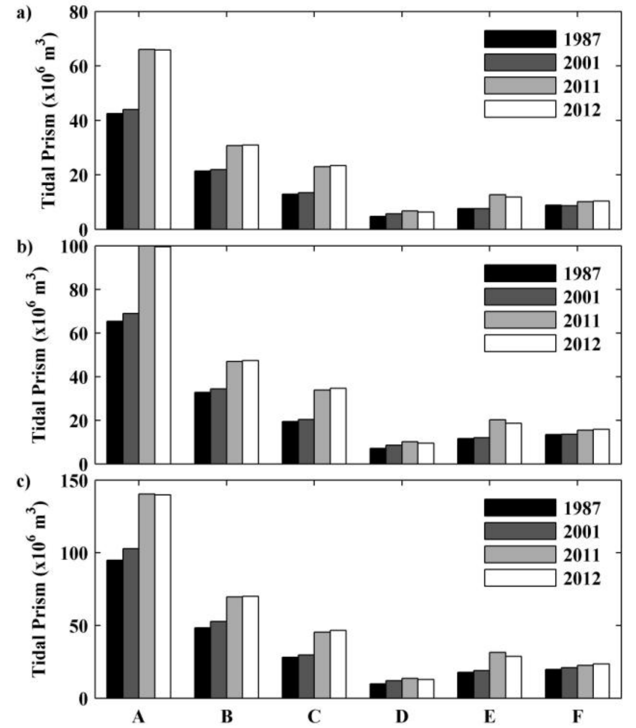

Figure 4. Tidal prism in each cross-section for: a) neap tide; b) mean tide; and c) spring tide.

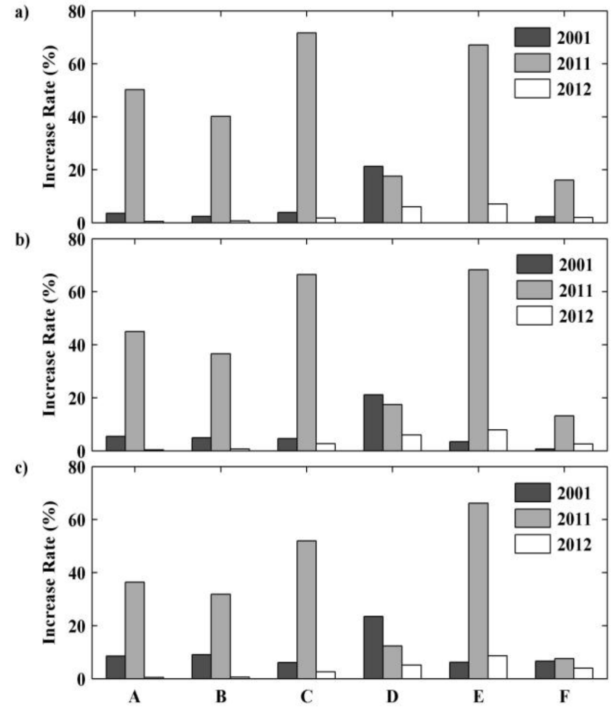

Figure 5. Tidal prism increase ratio (%) in each cross-section relative to precedent bathymetry for: a) neap tide; b) mean tide; and c) spring tide

with the channels deepening, enabling a large amount of water to cross the lagoon sections; the total water volume flowing through the inlet has to fill a higher lagoon volume resulting from the channels deepening; as friction decreases with the rising depth, the velocities inside the lagoon become higher producing higher tidal prims.

To assess the tidal prism modifications between 1987 and 2012, the tidal prism increase ratio (*IR*) was computed according to:

$$IR_{i+1} = \frac{(TP_{i+1} - TP_i)}{TP_i} \times 100 \quad (1)$$

Where i is the index defining the year of a numerical bathymetry and $i+1$ represents the year of the following numerical bathymetry. Figure 5 presents the results for neap, mean and spring tide conditions. Its analysis show that the tidal prism is increasing along the time in all the cross-sections analyzed and independently of the tidal conditions.

The highest tidal prism amplification was found between 2001 and 2011. The enlargement is not uniform for all the cross-sections: at the inlet (cross-section A) the tidal prism increased on average approximately 43%, while at the cross-sections B, C, D, E and F the enlargement was on average 36%, 63%, 16%, 67% and 12%, respectively. Furthermore, between 1987 and 2001 the increase rate at the inlet is approximately 9%, while at the cross-sections B, C, D, E and F the tidal prism increase rate was on average 9%, 6%, 23%, 6% and 7%, respectively. Otherwise, between 2011 and 2012 the changes in the tidal prism are negligible.

In summary, the tidal prism increase is emphasized in the cross-sections A, B, C and E, presenting the highest values at cross-sections C and E. This non-uniformity of tidal prism enlargement at the cross-sections evidences that the bathymetric changes modify the water flow within the lagoon. Particularly, the deepening of inlet region observed between 1987 and 2001 induced a higher increase in the tidal prism at the Mira channel than in the other channels. Otherwise, the deepening of the lagoon main channels found between 2001 and 2011 leaded to a higher increase of tidal prism at S.Jacinto and Espinheiro channels than in the other channels.

The flood extent results may be discussed now considering the modifications found for the tidal prism in each cross-section. This analysis evidenced that the highest changes in the flooded extension occurred for the regions with the highest increases in the tidal prism. Therefore the tidal prism modifications found at the S.Jacinto channel between 2001 and 2011 are related with the important modifications in S.Jacinto channel flooding extension. Conversely, the increase of tidal prism of approximately 23% at Mira channel between 1987 and 2001 didn't induce significant changes in the Mira channel flooding extension.

CONCLUSIONS

This work reports the response of Ria de Aveiro flooding extension to the morphological changes occurred between 1987 and 2012 in the lagoon. The main outcome of this work is that a general deepening of the lagoon main channels induces an increase in the lagoon flood extent area and tidal prism.

In fact, the analysis of bathymetric changes between 1987 and 2012 showed that the lagoon depth has increased. A deepening of 10 meters was found at the inlet region between 1987 and 2001. Additionally, a deepening of the lagoon main channels was found, being the S.Jacinto and Espinheiro channels the most affected, with changes of approximately 8 meters in some areas.

The results of the hydrodynamics simulations show that Ria de Aveiro marginal flooding extension is highly sensitive to the bathymetric changes occurred. In fact, the deepening of the inlet region and lagoon main channels that occurred between 1987 and 2012 induced an increase of the lagoon flooded area of 3%, 7% and 16% for neap, mean and spring tide conditions, respectively. Analysis of flood extent maps showed that S.Jacinto channel head and lagoon central area are the regions most affected.

Furthermore, the results of tidal prism at the lagoon main channels revealed important modifications between 1987 and 2012, namely changes in the redistribution of the water volume flowing into the lagoon among the main channels. Between 1987 and 2012 a generalized increase of lagoon tidal prism was found, however the highest increases were found at S.Jacinto and Espinheiro channels.

In summary, the generalized lagoon deepening observed leaded to a generalized increase in the extension of lagoon flooded area as well as of the tidal prism, making the lagoon more vulnerable to sea level oscillations today than in 1987.

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