Storm surge impact in the hydrodynamics of a tidal lagoon: the case of Ria de Aveiro

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ABSTRACT

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Storm surges are a hazardous phenomenon, since they may flood large coastal areas, causing socio-economical and habitation losses. Thus, the study of their characteristics and effects in coastal regions is crucial to prevent their negative consequences. This work aims at assessing the storm surges impact in the hydrodynamics of a tidal lagoon located in the north-western Portuguese coast (Ria de Aveiro). Storm surge amplitudes of 0.58 m, 0.84 m and 1.17 m for 2, 10 and 100 return periods, respectively, were determined adjusting the annual maximum amplitudes to a Generalized Extreme Value (GEV) distribution. To assess the hydrodynamic changes in the Ria de Aveiro under storm surge conditions, numerical modeling simulations were carried out, considering four scenarios: a single astronomical tidal forcing (reference) and astronomical tide plus 2, 10 and 100 years return period surges. Maximum levels and velocities for the entire lagoon and the tidal prism for the main cross-sections were determined and compared with the reference scenario. Generally, the model results suggest that during storm surge events the maximum levels increase in whole domain, with the largest increase found for the 100 return period storm surge scenario (1.17 m). The most significant changes occur at the main channels head for all scenarios, revealing that these regions are the most vulnerable to marginal flooding. Also, storm surges induce higher velocities and tidal prisms in the lagoon, increasing the marginal risk of erosion, as well as the salinization of the lagoon marginal lands.

ADDITIONAL INDEX WORDS: *sea levels, tidal prism, velocities, tides.*

INTRODUCTION

Most of the world coastal areas are subject to the risk from natural hazards resulting from geological or meteorological disturbances. Extreme sea levels have hazardous impacts in coastal regions, threatening infrastructures, ecosystems and even human lives. The investigation of these processes has become a major issue, in order to assess the possible consequences and contribute to coastal management and protection.

Extreme sea level events are commonly driven by the combination of tidal elevation and storm surges. Storm surges are the sea level response to wind stress and atmospheric pressure gradient and they are an important component of extreme sea levels during coastal flood events. Storm surges have been recently the subject of many studies in the European shelf seas (Marcos *et al.*, 2009; Rego and Li, 2010; Marcos *et al.*, 2011).

A storm surge usually propagates along the coast as a Kelvin wave and although affecting large areas, a single surge event will have different local impacts depending on the local topography and bathymetry (Debernard *et al.*, 2002).

In southern Europe there are two different tidal regimes, with generally small amplitudes (a few tens of cm) in the Mediterranean Sea and much larger (up to a few meters) in the Atlantic coasts (Marcos *et al.*, 2011). The tide-surge interaction is negligible in the Mediterranean Sea, but not in the Atlantic Iberian coasts, where its impact is however small (Marcos *et al.*, 2009).

There are several projections regarding the worldwide increase of storms frequency and intensity as consequence of climate change (Lambert and Fyfe, 2006). Following this trend are expected more intense storm surge events in the Atlantic Ocean and, consequently an increase of the flooding risk on their coastal areas. However, along the Portuguese coast recent studies reveal that should not be expected changes in the frequency of occurrence and intensity of storm surges in climate change scenarios (Rodrigues, 2011).

Although the expected intensification of storm surge events and respective consequences under higher amplitude tides, the probability of occurrence of a strong storm surge event under spring tide conditions is low for the Portuguese coast (Andrade *et al.*, 2006). In fact, analysis of maximum sea levels (astronomical tide plus meteorological tide) at tide gauges of Cascais, Lagos, Viana do Castelo and Leixões showed that the probability of occurrence of a high storm surge under spring tide conditions is lower than under other tidal conditions (Andrade *et al.*, 2006).

Typically, the abnormal sea level rise in the Portuguese west coast occur when low atmospheric pressure takes place in the north/northwest and high atmospheric pressure south/southwest of Portugal, associated with strong southerly winds.

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Considering the geomorphology of the Portuguese coastline, the storm surge phenomenon is mainly important in estuaries (e.g. Tagus, Sado, etc.) and coastal lagoons (e.g. Ria de Aveiro, Ria Formosa). In fact, the geometry and shallow bathymetries of these areas induce an amplification of surge level, causing often the flooding of their marginal areas, which frequently present a very low altitude and reduced topography.

The main aim of this work is to assess the storm surges impact in the hydrodynamics of a tidal lagoon located in the north-western Portuguese coast (Ria de Aveiro). The numerical model, Mohid (Santos, 1995; Martins *et al.*, 2001; Leitão *et al.*, 2005) will be used to study the effect of 2, 10 and 100 years return period surges in the maximum levels and velocities as well as in the tidal prism of the main cross-sections of the lagoon.

STUDY AREA

Ria de Aveiro (Figure 1) constitutes a very important coastal system in the Portuguese northwest coast, with a surrounding area of about 250 km^2. It is the most extensive Portuguese lagoon system and highly dynamic in terms of physical and biogeochemical processes. It is also considered a flood-prone region and has experienced important morphological changes, which made it more vulnerable to the effects of the external physical driving forces, namely to sea level oscillations.

The main ocean drivers affecting floods in Ria de Aveiro are the tidal wave, the mean sea level, the storm surges and the wind waves. Besides the sea level oscillations, also the freshwater flows (from rivers and precipitation) influence the floods in the lagoon.

Five sources of freshwater should be considered in Ria de Aveiro, being the Vouga and Antuã rivers the main tributaries, discharging in Espinheiro channel and Laranjo Bay, respectively. The Cáster River, that discharges in S. Jacinto channel, the Ribeira dos Moinhos in Mira channel and the Boco River in Ílhavo channel (Figure 1) present minor freshwater contributions.

Ria de Aveiro connects with the Atlantic Ocean through a single artificial inlet built in 1808 that provide access to the Aveiro harbour. The average depth of the lagoon, relative to the mean sea level is approximately 3 m, although the inlet channel can exceed 28 m deep, due to the dredging operations frequently performed to allow the local navigation as well as to the natural trend of sediments exportation of this lagoon.

The lagoon hydrodynamics is tidally dominated and the tide is predominantly 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), however, when reaching the inner parts of the lagoon tidal amplitudes decrease, while a phase delay is observed comparing to the oceanic tide (Dias *et al.*, 2000; Araujo *et al.*, 2008).

The residual circulation is determined essentially by the asymmetries between the flood and ebb regimes. The lagoon shifts from mild ebb dominance at the inlet to strong flood dominance in the upper lagoon. As the lower lagoon is ebb-dominanted there is a trend to export sediments to the ocean (Oliveira *et al.*, 2006; Picado *et al.*, 2010). Due to the low supply of sediments from the main rivers discharging in the lagoon this trend induces the inlet channel deepening along the time.

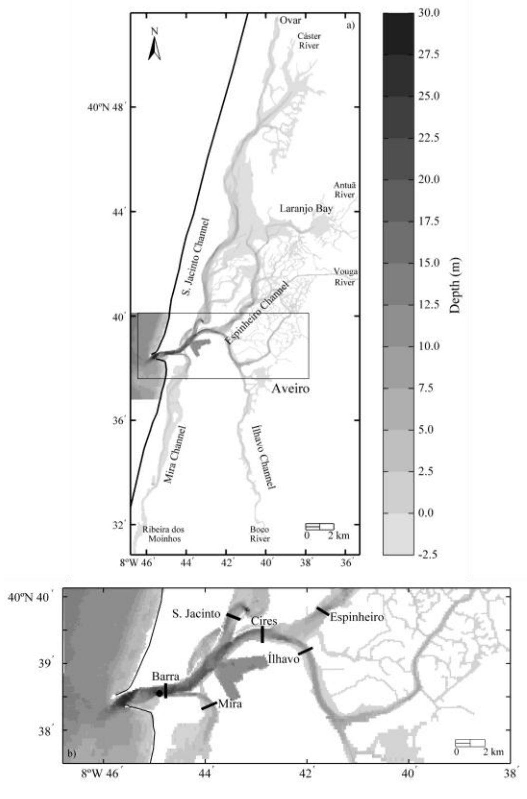

Figure 1. a) Ria de Aveiro bathymetry with depth in meters; b) cross-sections where the tidal prisms were computed; the black circle represents the tidal gauge.

METHODS

The main aim of this work is to assess the hydrodynamic changes in the Ria de Aveiro under storm surge conditions, through numerical modelling.

Despite several climate change projections foresee the increase of storm surge frequency and intensity worldwide, studies for the Portuguese coast proved inconclusive in the long-term trend identification of extreme meteorological events and resulting storm surges. Consequently, the storm surge amplitudes were predicted for return periods of 2, 10 and 100 years through a classic statistical analysis of the local tidal gauge sea surface elevation data measured from 1976 to 2005 at the lagoon inlet (Figure 1b). It is expected an underestimation of the storm surge magnitude for the 100 year return period due to the short data record available (30 years). In fact, if a longer data record was used, higher annual maximum would be found, as extreme events occur rarely, and therefore higher amplitudes would be predicted for this long return period. Despite the uncertainty, this approach has been followed under similar conditions by several authors (Andrade *et al.*, 2006; Scotto *et al.*, 2010).

Afterward, storm surges simulations were carried out for the entire lagoon and four scenarios were defined considering different ocean boundary conditions: a single astronomical tidal forcing (reference) and astronomical tide plus 2 (scenario 1), 10 (scenario 2) and 100 (scenario 3) years return period surges. In these simulations was used the numerical model Mohid, that proved to reproduce accurately the local hydrodynamics in a previous calibration (Vaz *et al.*, 2007; Vaz *et al.*, 2009).

Maximum levels and velocities for the entire lagoon as well as the tidal prism for the main cross-sections were determined and compared with the reference scenario, identifying the lagoon more vulnerable areas.

Storm surge amplitude calculation

Annual series of the residual tide were determined for each year of the period between 1976 and 2005 through the difference between the tidal gauge (see Figure 1b) sea surface elevation and the values predicted for the respective year through harmonic synthesis (H.S.) using t_tide matlab® package of Pawlowicz *et al.* (2002).

The residual series were analysed to identify the significant surge values, which are considered if greater than three times the total series standard deviation, according to the criterion proposed by Pugh (1987). Thus, 201 positive storm surges were identified with an average height of 0.43 m and a standard deviation of 0.11 m. The maximum storm surge observed has the height of 1.09 m. The annual frequency of the storm surges was also computed and 2005 was the year with more events registered, 27.

Positive storm surges were identified and the maximum annual regime was characterized (Figure 2a)) ranging between 0.4 and 0.6 m, for the most years.

A statistical analysis of the maximum annual values of the positive residual tides was performed to determine storm surges amplitude for different return periods. Thus, the annual maximums were adjusted to the Generalized Extreme Value distribution (GEV distribution) (Jenkinson, 1955).

The empirical cumulative distribution function (CDF) was computed according to Kaplan and Meier (1958), while the theoretical distributions were determined by calculating the location, scale and shape parameters of each annual maximum series. The CDF curve represents the most probable cumulative distribution function and the 5% and 95% curves represent the cumulative distribution function limit for a confidence interval of 90%. Once the empirical cumulative distribution function is between the limit curves (Figure 2b) is concluded that the storm surge annual maximums fit to GEV distribution at a confidence level of 90%. Thus, the storm surges amplitude for different return periods were computed from the most probable cumulative distribution function (CDF).

By definition, the return period of an event is the period of time estimated for an event to be equalled or exceeded. Results suggest storm surges amplitudes of 0.58 m, 0.84 m and 1.17 m for the return periods of 2, 10 and 100 years, respectively.

Model description and set up

As previous referred, the numerical model used to assess the hydrodynamic changes in Ria de Aveiro under storm surges scenarios is Mohid. It was originally developed by the MARETEC – Marine and Envirinmental Techonology Center group of the Instituto Superior Técnico (Martins *et al.*, 2001).

Mohid is a three-dimensional model that uses a finite volume approach to perform the spatial discretization, that is fully described in Martins *et al.* (2001). Mohid solves the three dimensional incompressible equations, assuming hydrostatic equilibrium, the Boussinesq and Reynolds approximations.

Since surge and tide propagate as shallow water waves, two-dimensional depth-averaged models are effective tools for storm surge prediction. Thus, the numerical model Mohid was used in 2D mode, to simulate storm surge scenarios and assess the hydrodynamic changes of Ria de Aveiro.

The Ria de Aveiro was discretized with a rectangular grid with a variable spatial resolution: 40×40 m in the central area and 40×100 m in the upper lagoon (Vaz et al., 2007). The initial bathymetric data set available for the present study was collected in a general survey carried out in 1987/1988 by the Hydrographic Institute of Portuguese Navy (IH), but was updated for the majority of the lagoon with recent data provided for different sources. Polis Litoral Ria de Aveiro provided bathymetric data collected during 2011 for the principal channels of the lagoon (Mira, Ílhavo, S. Jacinto and the second half of Espinheiro channel). The inlet bathymetric data was collected by the Aveiro Harbour Administration, SA during 2012. The Ria de Aveiro bathymetry used for the numerical simulations is represented in Figure 1.

At the open boundary the hydrodynamic model was forced by thirty six harmonic constituents determined from the sea surface elevations measured during 2005 at the local tidal gauge (Figure 1b). Annual mean rivers discharge from 1941 to 1991 were computed through the values presented in the catchment Vouga plane provided by the Polis Litoral Ria de Aveiro (Vouga River: 61.3 m^3s^{-1}; Antuã River: 4.5 m^3s^{-1}; Ribeira dos Moinhos: 3.0 m^3s^{-1}; Boco River: 1.0 m^3s^{-1} and Cáster River: 1.7 m^3s^{-1}).

The initial conditions were null free surface gradients and null velocity in all grid points. At the bottom boundary, a null normal velocity was imposed and a free slip condition was assumed.

Although the probability of occurrence of a strong storm surge event under spring tide condition is low for the Portuguese coast (Andrade *et al.*, 2006), simulations were carried out during a spring tide period with a tidal range of ~3.6 m at the lagoon mouth, to predict the storm surge effect in the Ria de Aveiro hydrodynamics under extreme conditions.

In Figure 3 are represented the temporal series imposed at the ocean open boundary for each scenario. These series result from the superimposition of the sea surface elevation predicted from the harmonic synthesis using the 36 harmonic constituents (reference) and the residual series for the return periods of 2, 10 and 100 years (scenario 1, 2 and 3, respectively). The harmonic synthesis was performed using t_tide matlab® package of Pawlowicz *et al.* (2002).

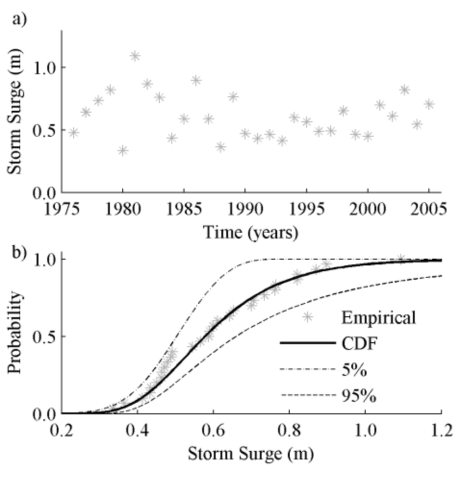

Figure 2. a) Annual maximum storm surge amplitude (m); b) Cumulative distribution functions, empirical and theoretical (CDF, 5% and 95%).

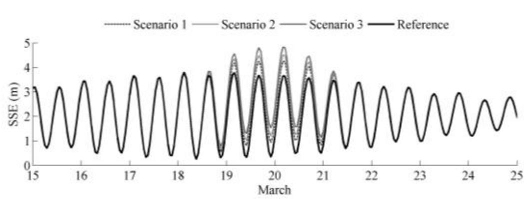

Figure 3. Sea surface elevation (m) imposed at the ocean open boundary for each storm surge scenario and reference.

NUMERICAL RESULTS

As previously referred the numerical model Mohid was used in 2D mode to study the impact of storm surges in Ria de Aveiro hydrodynamics. Maximum levels and velocities were computed for each model scenario. Once the patterns are similar for all the scenarios, only the reference results are represented, as well as the differences between each scenario and the reference results (Figures 4 and 6). To better understand the surge effects in Ria de Aveiro, the maximum levels ratio between each grid point and the average value at the inlet were also computed for all the scenarios and are presented in Figure 5.

Generally, the maximum levels in Ria de Aveiro decrease upstream from the lagoon mouth (~3.70 m). However, in the main channels head, there is a slightly increase of the maximum levels, specifically in Laranjo Bay, S. Jacinto, Mira and Ílhavo channels (Figures 4 and 5). In fact, the increase of the tidal range during the neap/spring tide cycle and the corresponding tidal excursion leads to water accumulation in these regions, causing the water level rise.

Numerical results suggest that the storm surge effect is different along the lagoon due to the tidal wave distortion as it propagates inside the lagoon. During high water the residuals at the channels head are amplified relatively to the residuals at the lagoon mouth.

Therefore, maximum surge heights are observed at the far end of the channels and could result in severe damages along the channels margins.

The maximum water levels were obtained for the scenario representative of a storm surge with 1.17 m amplitude. In fact, relatively to the reference scenario, the maximum levels increase approximately 30% (~1.12 m) at the lagoon mouth.

The most significant changes occur at the main channels head: the water level increases approximately 38% (~1.30 m) in S. Jacinto and Ílhavo channels head and 35% (~1.27 m) in Mira channel head, relatively to the reference.

Results also suggest that the maximum levels ratio in the main channels head increase with the occurrence of storm surges, reaching values greater than 1. This means that the channels head maximums are amplified comparing to the inlet levels. The lagoon area with maximum levels ratio bigger than 1 further increases with the event amplitude. In fact, for the scenario 3, whose storm amplitude is 1.17 m, these areas are found for the majority of the lagoon (Figure 5).

In summary, these results reveal that the channels head are the most vulnerable regions to marginal flood in Ria de Aveiro induced by storm surges, which threat local infrastructures and ecosystems.

A previous numerical study that evaluates the storm surge propagation in the Ria de Aveiro under different tidal conditions was performed by Dias (2001), using the 1987/88 lagoon bathymetry. The author simulated the occurrence of a specific storm surge with 0.8 m of amplitude, and concluded that the maximum water levels obtained in neap tide may be considered usual in Ria de Aveiro. Otherwise, during spring tide the water reaches unusual high levels, especially in its northern side and at the far end of Mira channel, which is agreement with the main projections of this study.

Tidal currents are strongly dependent on the lagoon bathymetry and geometry. Currents are intense in narrow channels and weaker in shallow regions due to the friction increase. In fact, maximum velocities occur in the inlet (between 1.8 and 2.0 ms^{-1}), Espinheiro and S. Jacinto channels (~1.3 ms^{-1}). Upstream are found lower velocities: in Laranjo Bay and S. Jacinto channel head the maximum velocity is 0.5 ms^{-1} and in Mira and Ílhavo channels head's is 0.3 ms^{-1}. Relatively to the inlet, these values represent a 70-80% decrease of the maximum velocity.

Storm surge events also induce higher velocities in whole domain, mainly in the inlet, S. Jacinto and Espinheiro channels, with an increase of ~16% from reference to scenario 3. It is expected that the higher velocities induced by storm surges may contribute to the erosion and deepening of the main lagoon channels. Otherwise, in the channels head's storm surge has no significant influence on the maximum velocity, being observed an increase of approximately 5%. Comparing the change between channels head's and the inlet velocities was found an increase of 5-10% from the reference case.

To further investigate the tidal changes induced by storm surge events in the Ria de Aveiro, the tidal prism was also computed for six cross-sections defining the inlet channel and the main channels of the lagoon for the reference and surge scenarios (see Figure 1b). Results are illustrated in Figure 7.

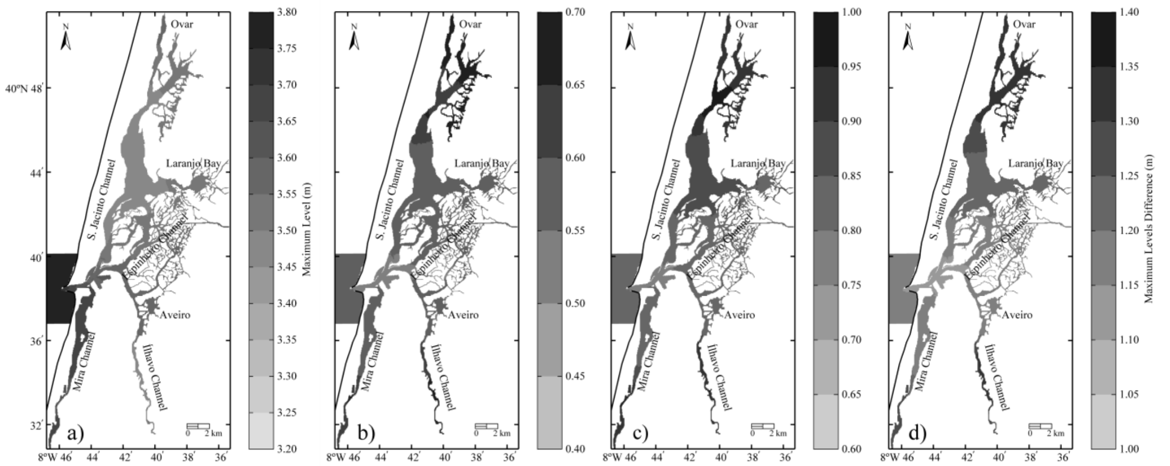

Figure 4. Maximum levels (m) a) reference scenario; b) difference between scenario 1 and reference; c) difference between scenario 2 and reference; d) difference between scenario 3 and reference.

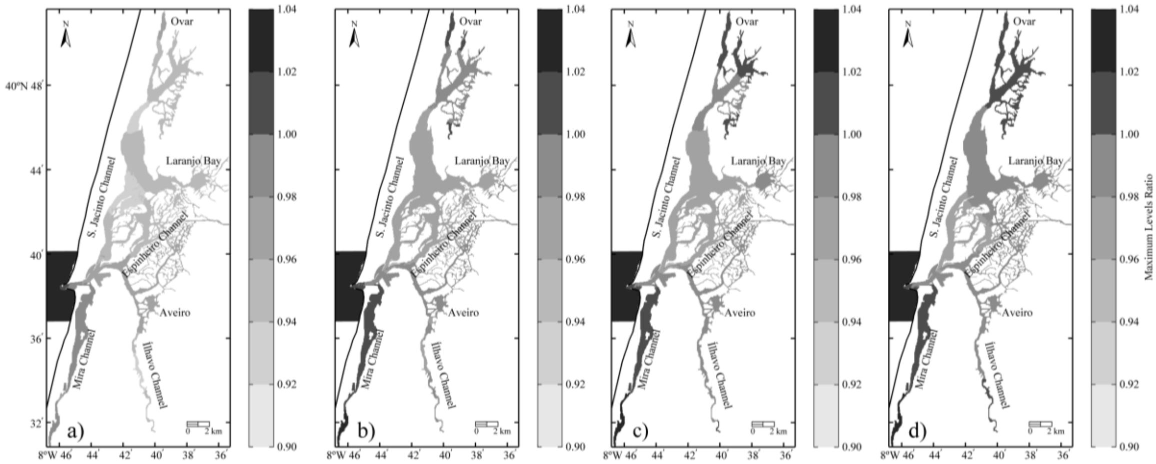

Figure 5. Maximum levels ratio between each grid point and the inlet average value: a) reference; b) scenario 1; c) scenario 2 and d) scenario 3.

The tidal prism is defined here as the volumetric flux passing through a cross-section in a flooding cycle, so it depends on the location of the cross-sections as well as on the tidal range. At the cross-section close to the lagoon mouth (Barra), the estimated tidal prism is ~135.90×10^6 m^3 for the reference case.

The tidal prism distribution through the main channels, relatively to its value at the lagoon mouth (Barra), is ~43% for S. Jacinto, ~12% for Mira, ~40% for Cires, ~14% for Ílhavo and ~27% for Espinheiro channels. These results are in accordance with those achieved by Dias (2001) and (Picado, 2008), however are slightly higher.

During a storm surge event it is expected that the water volume that penetrates in the lagoon increase significantly and, further increases with the storm amplitude increase (Figure 7). According to the model results, storm surge amplitude of 1.17 m induces an increase of ~35% at the lagoon mouth (Barra) and 38% for the other cross-sections.

CONCLUSIONS

This work reports the potential effect of storm surge events in Ria de Aveiro hydrodynamics, regarding the water levels, velocities and tidal prism. With this purpose a statistical analysis of the local tidal gauge data was performed, and storm surges amplitude of 0.58 m, 0.84 m and 1.17 m were determined for 2, 10 and 100 years return periods respectively. Thus, simulations were carried out regarding these results and four scenarios were defined: a single astronomical tidal forcing (reference) and astronomical tide plus 0.58 m, 0.84 m and 1.17 m surge amplitudes.

According to model results, the occurrence of storm surge events during spring tide conditions could increase the maximum levels, velocities and tidal prisms in Ria de Aveiro. These changes are more significant as the storm surge amplitude increase.

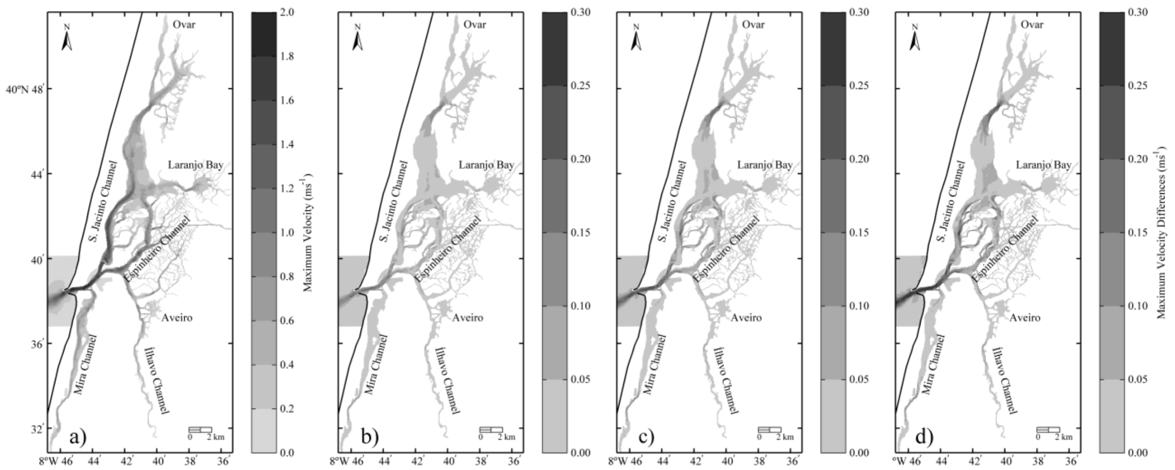

Figure 6. Maximum velocities (ms^{-1}) a) reference scenario; b) difference between scenario 1 and reference; c) difference between scenario 2 and reference; d) difference between scenario 3 and reference.

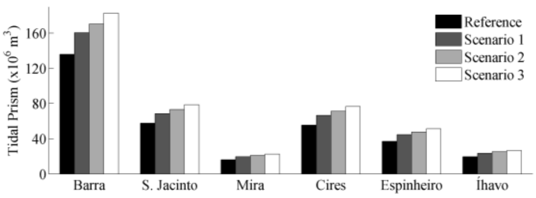

Figure 7. Tidal prism for the reference and storm surges scenarios.

Maximum levels ratio between each grid point and the inlet average value increase with storm surges occurrence. This increase is more significant in the main channels head, where maximum levels may become higher than inlet levels.

The most vulnerable regions to marginal flood due to the sea level rise caused by storm surge events are identified. At the main channels head, mainly S. Jacinto, Laranjo Bay, Ílhavo and Mira, maximum levels increase significantly induced by storm surges propagation.

Maximum velocities also increase in whole domain, with the largest increase in the inlet, S. Jacinto and Espinheiro channels (~16%). In the main channels head's no significant changes occur. In fact, the maximum velocity increases only 5% relatively to reference case.

Storm surge events also induce changes in the lagoon's tidal prism, which are further significant for the surges of higher amplitude. Therefore, the maximum increase of more than 35% was observed in all cross-sections defined from reference case to scenario 3.

In summary, model results suggest that storm surges induce changes in the lagoon hydrodynamics, flooding its marginal areas and increasing the marginal risk of erosion, as well as the salinization of the lagoon marginal lands.

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