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Evolution of the hydrodynamics of the Tagus estuary (Portugal) in the 21st century *

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Abstract

The ongoing rise in sea level affects tidal propagation and circulation in estuaries, and these changes can have far reaching consequences on the sediment dynamics, water quality and extreme water levels. This study aims at anticipating the evolution of the tidal dynamics in the Tagus (Portugal) in the 21st century, in particular due to sea level rise (SLR). The existence of a resonance mode of about 8 hours in this estuary, that selectively amplifies both semi-diurnal and quarter-diurnal tidal constituents, makes the response of the Tagus estuary to SLR unique. The study was conducted with a shallow water model, forced by present and future conditions, namely higher mean sea levels and an extrapolated bathymetry based on present sedimentation rates. Model results showed that SLR will significantly affect tidal asymmetry, in particular because the intertidal area can decrease by up to 40% by the end of the 21st century. As a result, the strong ebb-dominance of this estuary will decrease significantly. This evolution of tidal asymmetry will be counteracted by the effect of sedimentation of the salt-marsh areas. Also, SLR will enhance the resonance in the Tagus estuary. As a consequence, extreme water levels will be higher than the sum of present levels with the SLR.

Keywords: *tidal asymmetry, resonance, climate change, SELFE, modeling.*

Resumo

Evolução da hidrodinâmica do estuário do Tejo (Portugal) no século XXI

A subida do nível médio do mar afeta a propagação da maré e a circulação em estuários, podendo estas alterações ter consequências significativas na dinâmica sedimentar, na qualidade da água e nos níveis de água extremos. O presente estudo visa antecipar a evolução da dinâmica de maré no estuário do Tejo (Portugal) no século XXI, em particular devido à subida do nível médio do mar (NMM). A existência de um modo de ressonância de cerca de 8 horas neste estuário, que amplifica seletivamente as constituintes semi-diurnas e quarto-diurnas, torna a resposta do estuário do Tejo à subida do NMM única. O estudo foi efetuado com um modelo hidrodinâmico, forçado por condições presentes e futuras, nomeadamente níveis médios do mar mais elevados e uma batimetria extrapolada com base em taxas de assoreamento atuais. Os resultados do modelo mostram que a subida do NMM irá afetar significativamente a assimetria da maré, em particular porque as áreas intertidais podem diminui até 40% até ao final do século. Em consequência, a forte dominância de vazante deste estuário irá diminuir significativamente. Esta evolução da assimetria da maré será parcialmente compensada pelo efeito da sedimentação nas áreas intertidais. A subida

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do NMM irá também amplificar o efeito de ressonância no estuário do Tejo, o que resultará em níveis extremos superiores à soma dos níveis extremos atuais com a subida do NMM.

Palavras-chave: assimetria de maré, ressonância, alterações climáticas, SELFE, modelação.

1. Introduction

Climate change is affecting the oceans. Rising temperatures are melting icecaps and glaciers and expanding the volume of the oceans. As a result, global mean sea level (MSL) is rising, affecting coastal regions in general and estuaries in particular. For example, the increase in estuarine tidal amplitudes that can result from sea level rise (SLR) can affect the water residence time and quality, promote salt-wedge intrusion (Hong & Shen, 2012) and exacerbate problems of estuarine marginal inundation (Bilskie *et al*., 2014). Simultaneously, habitats presently found along the estuarine banks may migrate landward (Pethick, 2001). The adequate management of estuaries requires therefore the anticipation of the consequences of SLR on their behavior.

The Tagus estuary in Portugal is a particularly relevant case. It is one of the largest in Europe and it is included in the territorial unit of Lisbon and Tagus Valley, involving 18 municipalities in the metropolitan area of Lisbon, with about one million inhabitants directly or indirectly exposed (INE, 2012). It harbors a major port and shipping terminal with about 3000 large vessels entering the harbor annually (Porto de Lisboa, 2013). The estuary accommodates economic activities, such as trade, maritime traffic, dredging, industry and fisheries. A substantial part of the estuarine domain is protected due to high environmental and ecological values, generating conflict with other economically-driven uses. Thus, the future rise in sea level can have severe economic and environmental implications.

In this context, this study aims at assessing how the hydrodynamics of the Tagus estuary will evolve in the 21st century. The assessment was performed using a high-resolution hydrodynamic model, which was calibrated and validated with field data. The model was then applied to study likely scenarios of future MSL and bathymetries (Table 1). SLR scenarios for the 21st century were defined from a literature review. Future bathymetries were estimated from the extrapolation of past sedimentation trends, derived from field data. Possible changes in wind patterns associated to climate change were briefly assessed and considered negligible.

This paper is organized as follows. The Tagus estuary is first presented. Then, the methods adopted in the study are described, including the model and its application, and the present and future scenarios considered. Results are then presented and discussed. The final section summarizes the major conclusions and proposes directions for further research.

2. The Tagus Estuary

The Tagus estuary is located on the Portuguese west coast (Figure 1). It covers *ca* 320 km^2, with a deep, long and narrow tidal inlet connecting the Atlantic Ocean to a shallow, tide-dominated basin, with extensive tidal flats and marshes that cover about 40% of the inner estuary. About 40 km upstream, the estuary markedly narrows at the bay head. The saline tide reaches about 50 km upstream from the mouth, near Vila Franca de Xira. The estuarine bottom is mainly composed of silt

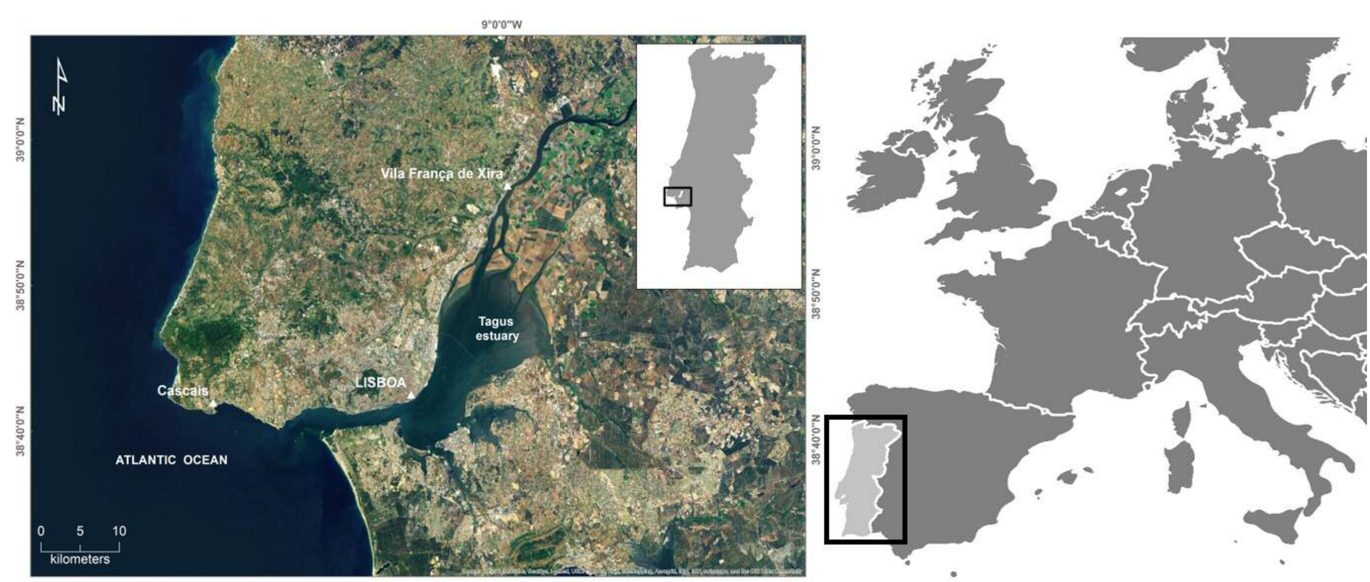

Figure 1 - Location of the Tagus estuary.

Figura 1- Localização do estuário do Tejo.

and sand, of both fluvial and local origins; marine sands are confined to the mouth and inlet channel (Freire *et al.*, 2007). Tidal ranges vary between 0.55 and 3.86 m in the open coast (Cascais data) but resonance signify-cantly amplifies the semi-diurnal tidal constituents within the estuary (Fortunato *et al.*, 1999). Simultaneously, the estuary is strongly ebb-dominated due to the large extent of the tidal flats (Fortunato *et al.*, 1999).

Table 1 - Summary of the simulations.
Tabela 1 - Sumário das simulações.

Purpose	*Bathymetry*	*Boundary conditions*
Validation	Present	Real tides
Tidal Asymmetry	Present	Real tides
	Present	Real tides + SLR
	Future	Real tides
Resonance	Present	Monochromatic tides
Extreme levels	Present	Extreme events
		Extreme events + SLR

The average river flow is 368 m^3/s (Neves, 2010), and the estuary is usually well mixed. However, stratification has been observed at high flow rates (Neves, 2010). River discharge may significantly influence water levels, but only farther than 40 km upstream of the mouth (Vargas *et al.*, 2008). Downstream, the levels are mainly controlled by tide and storm surges.

Ocean waves do not penetrate significantly in the estuary. However, the large extent (fetch) of the estuary allows locally-generated waves to develop and rework the southern embankment (Freire & Andrade, 1999).

The population growth and development of port activity has affected both margins, which are extensively intervened by construction to support nautical activities, industrial facilities, farming plots, and urban areas. These factors increased the pressure on the estuarine waterfront and prevented the natural evolution of the majority of the margins. The Tagus estuary harbors the main Portuguese shipping terminal and the nautical activity requires frequent maintenance dredging along the estuary.

3. Methods

3.1. Model description

This study was conducted with the community model SELFE – Semi-implicit Eulerian-Lagrangian Finite-Element (Zhang & Baptista, 2008). SELFE is a 3D baroclinic shallow-water model, although the 2D barotropic version (Zhang *et al.*, 2011) is used herein. SELFE uses unstructured triangular meshes, which makes it particularly suited to problems with different spatial scales and complex geometries. The Eulerian-Lagrangian semi-implicit algorithm provides stability at high Courant numbers, and parallelization of the code offers computational efficiency. SELFE is the core of a suite of community models, which include modules for ecosystem dynamics (Rodrigues *et al.*, 2009, 2012), fecal contamination dispersion (Rodrigues *et al.*, 2011), oil spill dynamics (Azevedo *et al.*, 2014), sediment transport and morphodynamics (Pinto *et al.*, 2012; Dodet *et al.*, 2013) and wave-current interaction (Bruneau *et al.*, 2011, Roland *et al.*, 2012).

3.2. Application, calibration and validation

Since the late 1980's many hydrodynamic models of the Tagus estuary have been implemented (*e.g.*, ADCIRC – Fortunato *et al.*, 1997, 1999; MOHID – Portela & Neves, 1994; ELCIRC – Vargas *et al.*, 2008; SIMSYS – Dias & Valentim, 2011). In general, barotropic models have been used, since the estuary is well mixed or partially mixed, except in peak discharge situations (Neves, 2010). One main limitation of these models is their poor horizontal resolution, unable to properly resolve all channels (Fortunato & Oliveira, 2000). Hence, a barotropic model was run using a computa-tional grid with significantly higher resolution than used in previous studies. The fine resolution is also necessary to properly represent the marginal inundation (e.g., Martyr *et al*., 2013, Bertin *et al*., 2014).

The horizontal domain was represented by an unstructured mesh with 77,300 nodes that extends from the river (100 km upstream from the mouth) to the open ocean (Figure 2). The horizontal limits of the grid were defined based on the limits of the water line at maximum high spring tide, defined for the Tagus estuary by Rilo *et al.* (2014), which was further extended inland by 50 m in the southern margin of the estuary. This extension aimed at accommodating a possible extension of the estuary in the SLR scenarios. The grid was not extended in the northern margin of the estuary because most of this margin is highly urbanized and protected. Hence, it was assumed that retreat will not be socially acceptable in this area.

The grid resolution is about 25 m in the upper estuary and 2000 m in the ocean. The bathymetry combines the latest available data, surveyed between 1964 and 2011. Simulations were made for 30 days, with a time step of 30 s. The ocean tidal boundary conditions were taken from the Cascais tidal gauge, located close to the outer estuary, through harmonic analysis and synthesis.

The Manning friction coefficient varies between 0.015 and 0.023 $m^{1/3}/s$ (Figure 3) and was used as a calibration parameter, but its spatial variability was determined based on the distribution of the bottom sediments (Freire, 2003). The model was calibrated using the elevation data collected in 1972 at 13 stations along the estuary (Figure 4). The root mean square errors obtained (Figure 4) are smaller than those obtained in previous studies of this estuary.

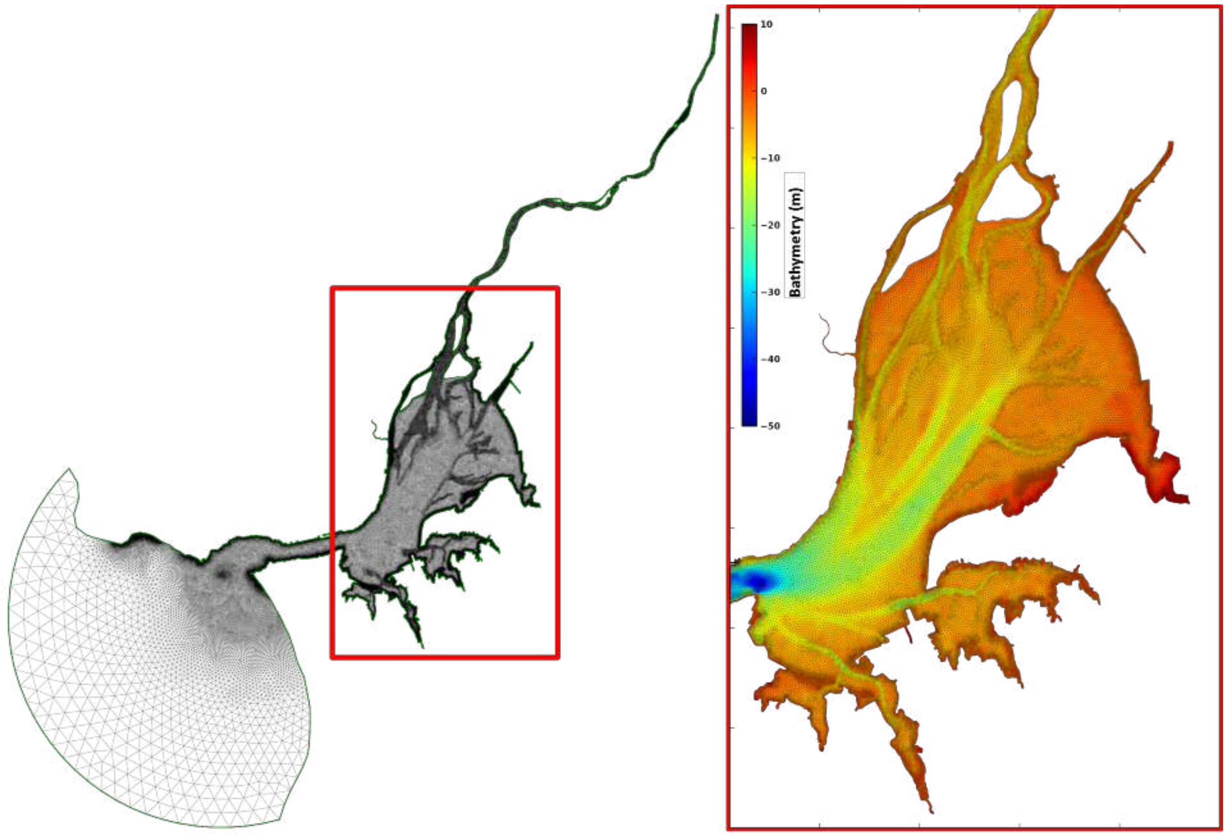

Figure 2 - Finite element grid and bathymetry of the upper estuary. The bathymetry is relative to Chart Datum, 2.21 m below present MSL.

Figura 2 - Malha de elementos finitos do modelo hidrodinâmico do Tejo e batimetria da área montante do estuário. A batimetria está referida ao Zero Hidrográfico, 2.21 m abaixo do nível médio do mar atual.

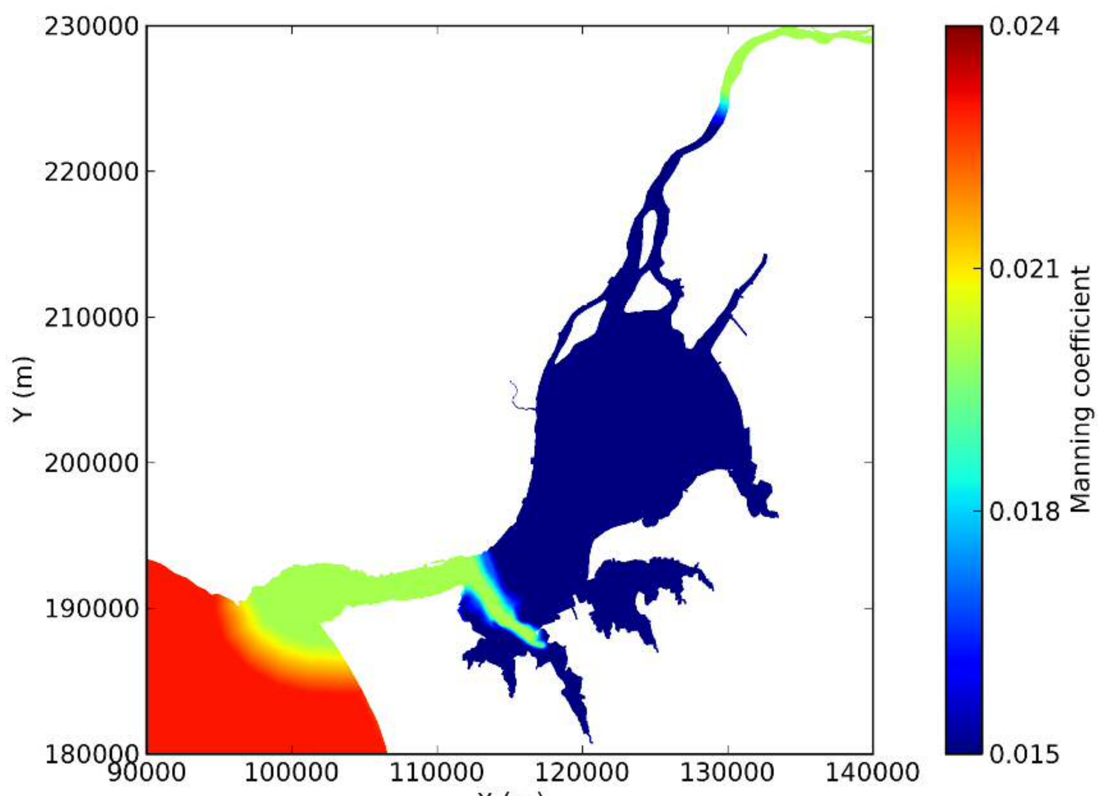

Figure 3 - Distribution of the Manning coefficient ($m^{1/3}/s$).

Figura 3 - Distribuição do coeficiente de Manning ($m^{1/3}/s$).

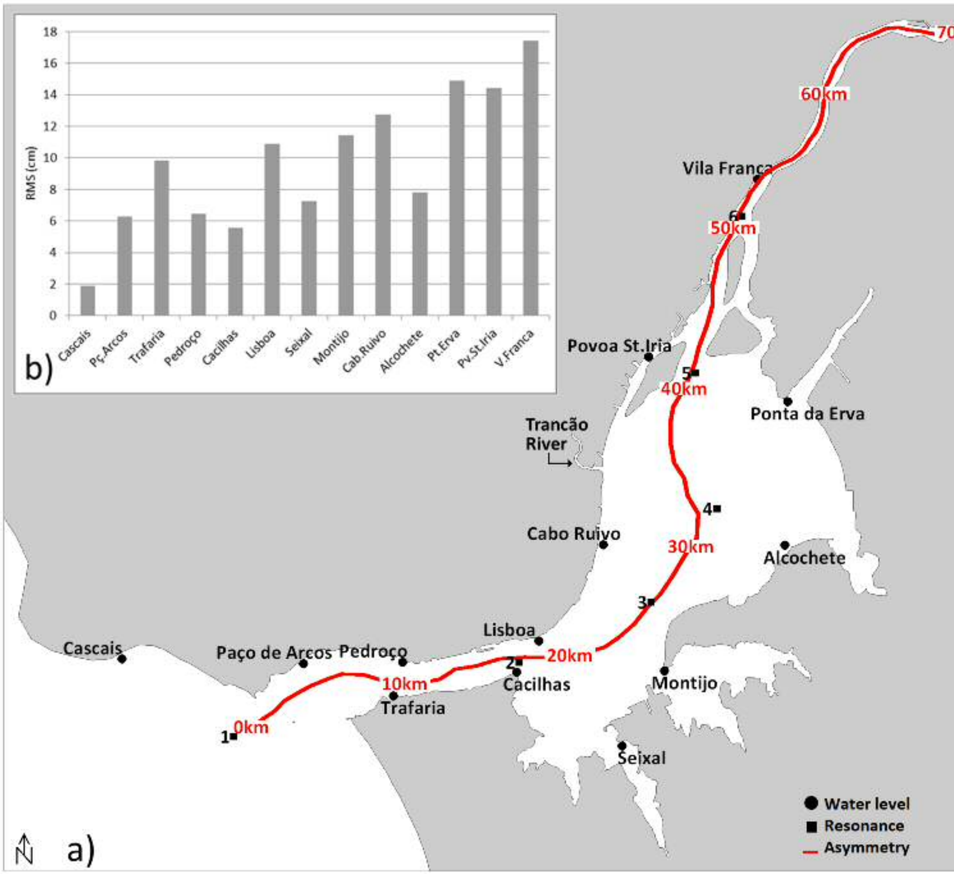

Figure 4 - a) Tidal gauges and points used in the analysis; b) root mean square errors at the tidal gauges.

Figura 4 - a) Marégrafos e pontos usados na análise; b) erros quadráticos médios nas estações maregráficas.

3.3. Scenarios

3.3.1. Sea Level Rise

During the 20th century, MSL along the Portuguese coast rose by about 0.15 m (Antunes & Taborda, 2009), a value consistent with the global estimates for mean SLR (*e.g.,* Church and White, 2006; Hagedoorn *et al.*, 2007). This agreement stems from negligible glacial-isostatic adjustment and vertical movements in the region (Antunes & Taborda, 2009). Hence, future local sea level scenarios for the region can be based on global estimates. GPS-based methods indicate that this area has an upward vertical movement which is an order of magnitude smaller than SLR (http://www.sonel.org/spip.php?page=gps&idStation=648.php)

The magnitude of future SLR remains controversial among the scientific community and projections still present a large uncertainty. Most estimates for SLR at the end of the 21st century published after the 2007 report of the Intergovernmental Panel on Climate Change (IPCC, 2007) vary between 0.2 and 2 m (Rahmstorf, 2010). The discrepancies are related not only with uncertainties in assessing future global temperatures, but also with difficulties in evaluating the contribution of melting of both glaciers and ice caps and uncertainty concerning the dynamics of Antarctic and Greenland ice sheets. In this context, two mean SLR scenarios were defined: the "best estimate" (0.5 m), which corresponds to the central value of the various estimates published after 2007, and a "high-end value" (1.5 m), accepted as suitable for use in coastal zone management, since it satisfies the precautionary principle. It must be noted that the last IPCC assess-ment report, published after this work was concluded, suggests global mean SLR by the year 2100 that vary between 0.26 and 0.98 m (IPCC, 2013). The present sea level was estimated as 2.21 m above Chart Datum.

3.3.2. Wind

Results of the global climate model ECHAM5 in front of the Tagus estuary, for IPCC (2007) scenario A2, reveal modest differences between the statistics of wind at the end of 20th (1970-2000) and 21st (2070-2100) centuries (Figure 5). Also, global climate models cannot yet reproduce adequately the historical trends, and attempts at downscaling present a variability between models higher than the signal associated with climate change (Pyor & Barthelmie, 2010). The same authors consider unlikely that, during the 21st century in Europe, wind speed and energy density will change more than the present inter-annual variability (*i.e.*, ± 15%). Thus, the wind regime was considered invariant.

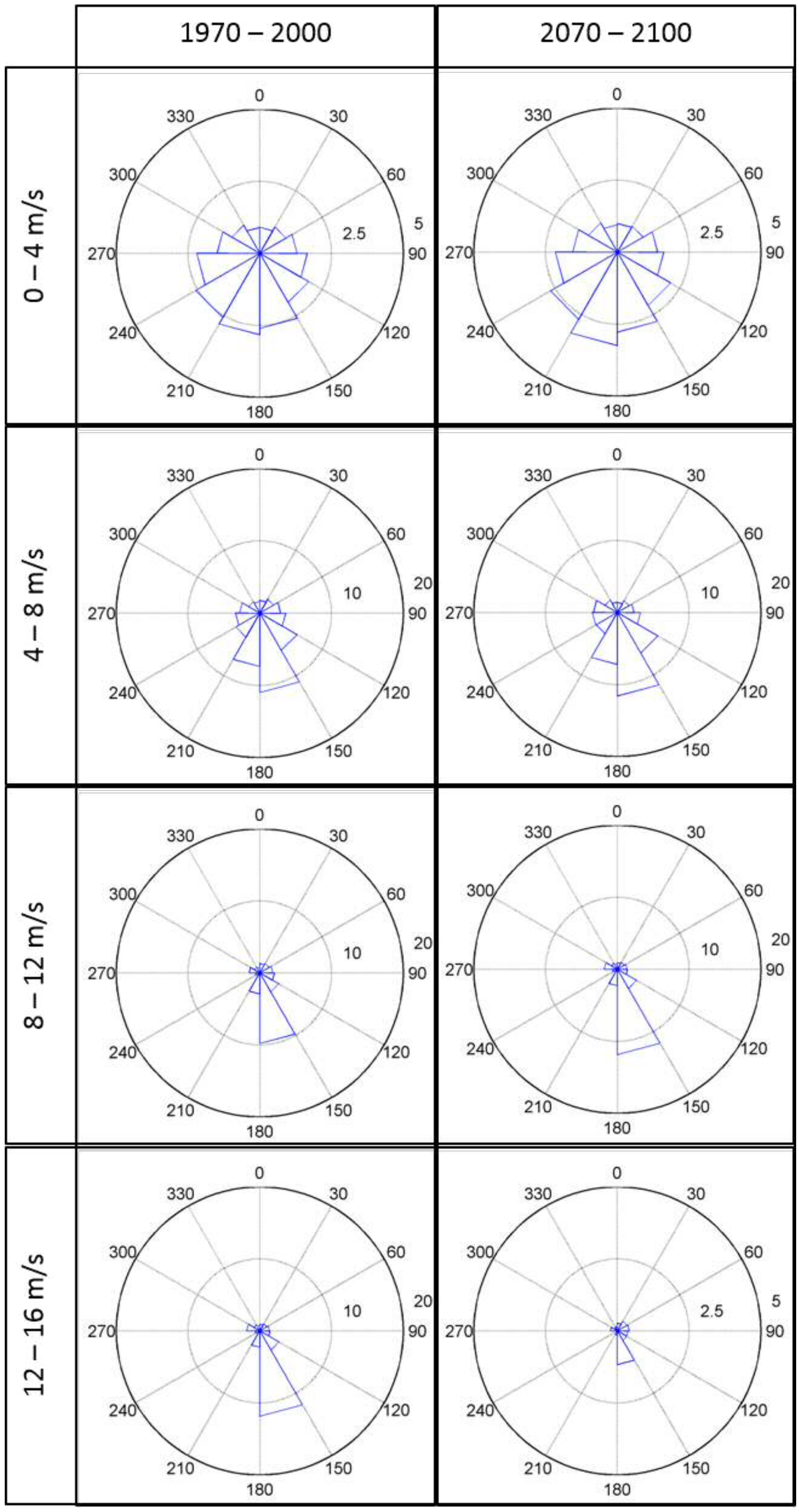

Figure 5 - Evolution of the wind regime near the Tagus estuary between the end of the 20th (1970-2000) and 21st centuries (2070-2100), from the results of the model ECHAM5, for the scenario A2 of the IPCC (2007).

Figura 5 - Evolução do regime de vento nas imediações do estuário do Tejo entre final do século XX (1970-2000) e século XXI (2070-2100), dos resultados do modelo ECHAM5 para o cenário A2 do IPPC (2007).

3.3.3. Sedimentation rates

The bathymetric charts available for different areas of the estuary, dated from 1928/32, 1964, 1981, 2009 and 2011, were analyzed and used to build digital terrain models, which were further compared to determine and map sedimentation rates. The intertidal areas show an average infilling trend *ca*. 0.3 cm/year. The main channels show a slight erosional trend (mean value *ca*. -0.1 cm/year), which partly reflects continuous dredging of navigation channels.

Sedimentation rates were also inferred for marginal marsh expansions at several locations, by extrapolation of the isotopic (^{210}Pb, ^{137}Cs) vertical profiles in sediment cores. Results indicate that sedimentation rates in these areas vary between 0.7 and 2.2 cm/year with the higher values occurring in the upper estuary (Silva *et al*., 2013). A map of sedimentation rates was built by integrating all these data, and used to project future bathymetries (Guerreiro *et al*., 2013). This projection was based on an extrapolation of the present bathymetry, assuming sedimentation rates that are constant in time, but variable in space. Since the accretion rates are modest (i.e., below 0.3 cm/year in most of the domain), the predicted variations in bottom elevations do not exceed a few tens of cm.

3.3.4. Extreme water levels

Flooding of the estuarine margins, of both marine and fluvial origin, is an increasing concern. Presently, the European Floods Directive requires all member states to develop inundation maps for areas at risk. In estuarine areas, these floods are often due to the combined effect of tides and storm surges. SLR will thus aggravate inundation hazards and in the case of the Tagus, tidal amplification by resonance can exacerbate this problem.

To determine extreme forcing conditions, we followed the approach developed by Fortunato *et al*. (2013). This approach analyses data from tide gauges to determine both the extreme levels corresponding to various return periods and the time series that include these extremes. These series are then used to force a hydrodynamic model of the estuary and construct inundation maps.

The determination of the time series associated to various return periods starts from a dataset of elevation measurements. In this case, we used a 24 year-long data series of hourly water elevation measured at the Cascais tide gauge, extracted from the 1961 – 2005 series, after discarding years with significant information gaps. Gaps were considered significant when they included periods with high waves. Waves were determined from the hindcast simulations of Dodet *et al.* (2010). The measured signal was split through harmonic analysis in the following components: the yearly MSL, the astronomical tidal level and the residual, which corresponds to the signal of meteorological origin. From these three components, synthetic annual series were generated by combining:

1. The average level determined for a particular year (present or projected, according to a sea level scenario).
2. The astronomical tide for a set of 19 consecutive years, which allows the consideration of the lunar cycle (*ca*. 18.6 years).
3. Residuals, with a variable phase lag with the tidal signal. These phase lags vary with one hour intervals between plus and minus 15 days, thereby ensuring that a given storm surge can occur at any moment in the neap-spring tidal cycle.

Like most other approaches to determine extreme sea levels (e.g., Pugh & Vassie, 1980; Tawn, 1992), this procedure implicitly neglects tide-surge interactions. These interactions, which are still poorly understood, are believed to be associated to different phenomena. First, tidal propagation can be accelerated (decelerated) by a positive (negative) surge (Horsburgh & Wilson, 2007). This acceleration leads to a phase shift between the measured and predicted tide, which translates into positive (negative) residuals during the rising (falling) tide. Secondly, the wind contribution (*i.e*., the wind stress divided by depth in the shallow water equations) is inversely proportional to the water depth. The storm surge will thus tend to be higher at low tide, in particular in shallow areas with a large tidal range.

Other mechanisms may be present, such as the increase in bottom friction at low tide (Rego & Li, 2010) and advection (Idier *et al*., 2013). Hence, the relation between the tide and the residual is complex and strongly space-dependent. Yet, it is clear that all these mechanisms are related to the non-linear terms in the shallow water equations. Since the continental shelf in front of the Tagus estuary is very narrow (20-30 km), it is unlikely that tide-surge interactions are significant outside of this estuary.

This procedure provides a very large number of hypothetical annual series for each MSL scenario: in the present case, 328,320 (*i.e*., 24x19x30x24) series. The set of all maxima in all series makes it possible to determine the probability of occurrence (P) of a certain extreme level (z).

Traditional analyses of extreme water levels work with limited numbers of extreme observations (typically a few tens of years). Statistical distribution functions must therefore be fit to the data to extrapolate the maximum levels for high return periods. In contrast, the approach used herein leads to a number of annual maxima large enough to avoid the use of analytic functions. Finally, the return period associated with a certain level is given by $T(z) = 1/(1-P(z))$ (Figure 6a).

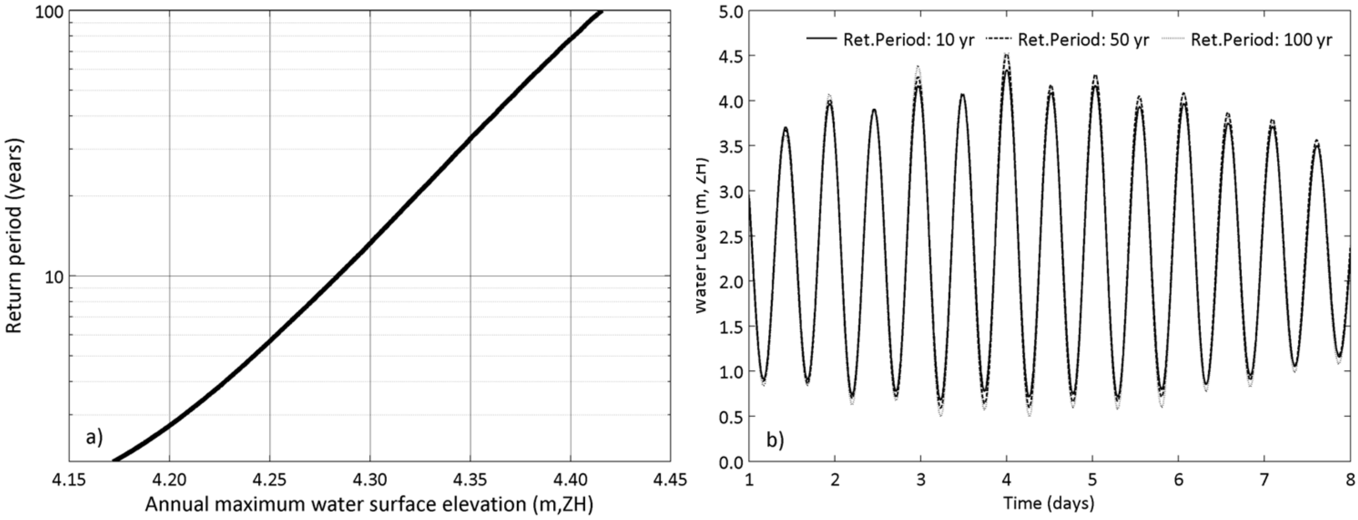

Figure 6 - Boundary conditions for the inundation simulations: maximum elevations at Cascais for different return periods (a) and time series to force the model (b). ZH stands for Hydrographic Zero, the Portuguese Chart Datum (close to lower low tide). Presently, ZH is about 2.21 m below MSL.

Figura 6 - Condições de fronteira para as simulações de inundação: elevações máximas em Cascais para diferentes períodos de retorno (a) e séries temporais (b) para forçar o modelo. ZH corresponde ao Zero Hidrográfico, atualmente cerca de 2.21 m abaixo do NMM.

The values obtained in this study are slightly higher than those reported by Andrade *et al.* (2006) (Table 2). Fortunato *et al.* (2013) observed similar differences between the extreme values obtained by the method presented here and traditional methods, and showed that the former yields more accurate results.

Table 2 - Comparison between the maximum water levels (m above Chart Datum) obtained in this study and with traditional methods (source: Andrade *et al*., 2006).

Tabela 2 - Comparação entre os níveis extremos (m, acima do ZH) obtidos neste estudo com métodos tradicionais (fonte: Andrade *et al*, 2006)

Method	Return period (years)				
	5	10	25	50	100
This study	4.24	4.28	4.33	4.37	4.42
Traditional	4.1	4.2	4.3	4.3	4.4

To determine the series used to force the model, the synthetic annual time series (from the set of 328,320 series) containing a maximum level corresponding to the selected return period are retained. The initial time for each of these series is adjusted, so that the time of maximum elevation coincides, and then the series are averaged to provide the final forcing (Figure 6b) This approach only provides the maximum levels associated with events of marine origin. Vargas *et al.* (2008) showed that the Tagus flow has a negligible influence on the maximum water levels observed in the lower 40 km of the estuary, thus neglecting the effects of this variable does not significantly influence the results.

The European Floods Directive recommends that three cases are studied: a high, a medium and a low probability scenario. In Portugal, these scenarios were taken as those corresponding to return periods of 20, 100 and 1000 years. For consistency with future studies, these return periods were considered herein, even though the uncertainty on the water levels associated to the 1000-year return period is clearly very high.

4. Results and discussion

4.1. Tidal asymmetry

Ocean tides are usually symmetrical, i.e. floods and ebbs have similar durations. Non-linear processes, important in shallow areas, generate high-frequency harmonic constituents that may distort the tide (*e.g.*, Aubrey & Speer, 1985; Speer & Aubrey, 1985). Typically, floods are shorter than ebbs when the ratio between the tidal amplitude and depth is low. In contrast, extensive intertidal flats favor shorter ebbs (Friedrichs & Aubrey, 1988, Fortunato & Oliveira, 2005), as is the case in the Tagus estuary (Fortunato *et al.*, 1999).

Tidal asymmetry is an important characteristic of each estuary, and there is a large body of literature on the subject (e.g., Brown & Davies, 2010, Jewell *et al.*, 2012). Tidal asymmetry is particularly relevant to sediment dynamics (Aldridge, 1997). Shorter ebbs promote higher average flow velocities on ebb than on flood because the same volume of water flows in a shorter period of time. Under those circumstances, the estuary is said to be ebb-dominant. Since the sediment fluxes depend non-linearly on the velocity, an ebb-dominated estuary will tend to export sediments. In contrast, a flood-dominant estuary will tend to silt-up more rapidly (Lanzoni & Seminara, 2002).

Since SLR will affect the generation of tidal harmonics by nonlinear processes, it is likely to affect the pattern of tidal asymmetry. The effects of SLR on tidal asymmetry were assessed by evaluating the difference between ebb and flood durations along the estuary (Figure 7).

Results confirm that the estuary is ebb-dominated in the 40 km reach upstream from the mouth (Fortunato *et al.*, 1999) and shows that it switches to flood-dominated further upstream. The reduction of the ebb-dominance from km 40 upstream is likely associated to the change in morphology, from a wide bay with extensive tidal flats to deep and narrow channels (Figure 2).

SLR will shift tidal asymmetry towards flood dominance. For the 1.5 m SLR scenario, tidal asymmetry becomes negligible in most of the estuary. This result is consistent with the known processes that control tidal asymmetry (Aubrey & Speer, 1985). Flood dominance is fostered by small tidal amplitude to depth ratios, while ebb dominance is promoted by extensive tidal flats. SLR will increase the depth of the estuary, hence reducing the tidal amplitude to depth ratio. As a consequence, flood dominance should increase. Perhaps more importantly, the extent of the tidal flats will decrease, further reducing ebb dominance: the intertidal area in the Tagus estuary decreases by 40% for a SLR of 1.5 m (Figure 8). Note that the reduction of intertidal flats obtained herein implicitly assumes that the existing margins would be protected and prevented from flooding. This choice was dictated by the extensive urbanization of the margins, and by the dykes that protect the agricultural lands (*e.g.,* in the islands in the upper estuary).

The results obtained in the Tagus cannot necessarily be extended to other estuaries, since the consequences of SLR will depend on the particular hypsometry of each estuary. Also, the consequences of SLR on the hypsometry, hence on tidal asymmetry, will depend on whether or not the margins are protected or allowed to flood. In general, allowing the margins to flood will mitigate the reduction of the intertidal areas, thereby avoiding the sharp decrease in ebb-dominance.

In contrast to the effect of SLR, morphological changes in the Tagus estuary induced by the inferred rates of sedimentation will increase ebb dominance. This increase is of the same order of magnitude as the reduction associated to a SLR of 50 cm (Figure 7). The com

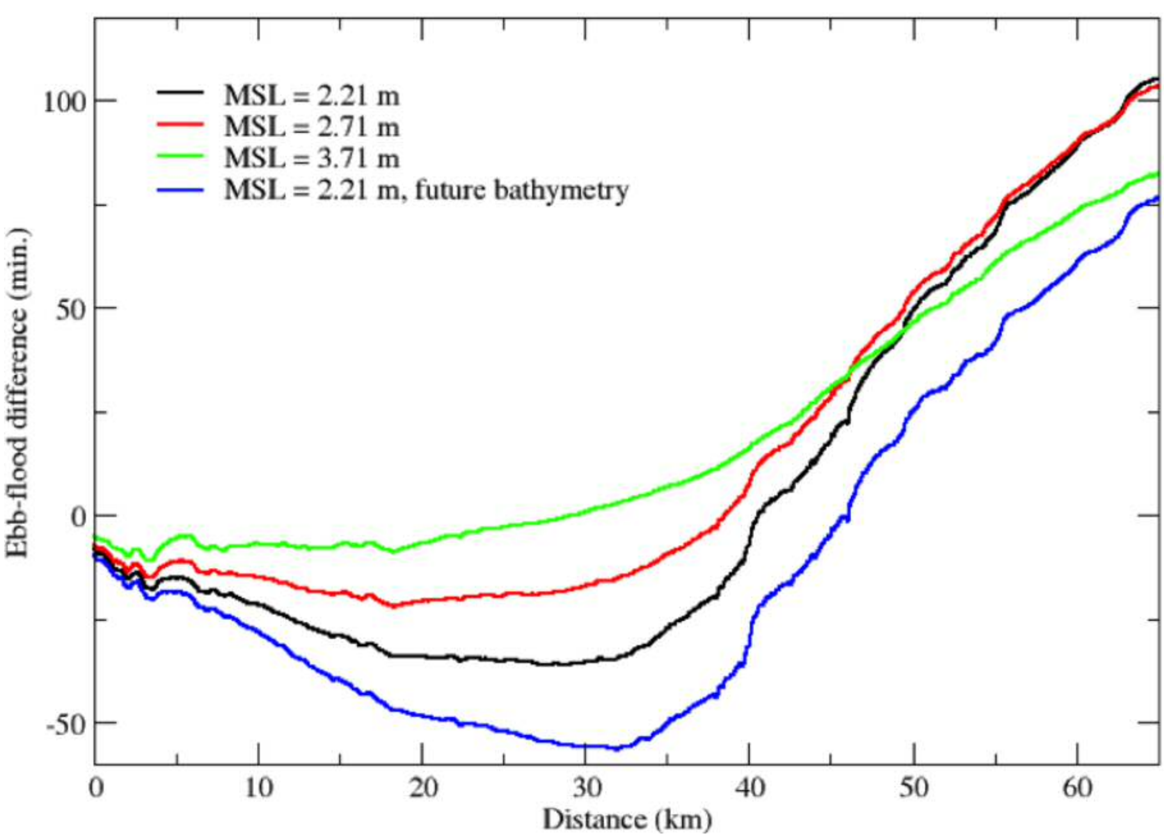

Figure 7 - Difference between of the ebb and flood durations along the estuary for different MSL scenarios and the reference bathymetry, and for a future bathymetry calculated using the estimated sedimentation rates.

Figura 7 - Diferenças entre a duração de vazante e de enchente ao longo do estuário para diferentes cenários de subida do nível médio do mar e batimetria de referência, e para uma batimetria futura calculada usando as taxas de sedimentação estimadas.

parison between the hypsometries of the estuary for the present and future bathymetries does not show a significant change in the intertidal area (Figure 8), consistent with the mostly low sedimentation rates used in the extrapolation of the bathymetry (0.3 cm/year in the tidal flats). For instance, the area that is permanently dry (roughly 2 m above MSL) only increases by about 2.5 km^2. However, there is a larger increase of the area of the estuary just above MSL (about 8 km^2). The strengthening of ebb dominance is thus consistent with the findings of Fortunato & Oliveira (2005), which showed that intertidal areas slightly above MSL maximized ebb dominance.

In summary, while SLR will significantly reduce ebb-dominance in the Tagus estuary, sedimentation in the tidal flats will tend to enhance it. The balance may tend either way, depending on the rate of SLR, the changing sedimentation rates, and how the marginal areas are allowed to flood.

4.2. Resonance

Tides can be strongly amplified as they propagate along an estuary when the characteristic period of the tide is similar to the resonance period of the basin. Denoted resonance, this phenomenon results from the overlapping of two or more waves with the same frequency, creating a partially stationary wave. Tidal resonance tends to occur in estuaries of large dimensions, since the resonance period increases with the length of the estuary. Tidal amplification increases the tidal prism and the water renewal rate in the estuary (*i.e.*, it reduces the residence times).

Due to its physical characteristics, the Tagus estuary presents significant resonance. Fortunato *et al.* (1999) showed that the resonant period is about 8 hours, and that the semi-diurnal constituents are significantly amplified in the upper estuary.

The effect of SLR on tidal resonance was studied by simulating the propagation of sinusoidal waves with amplitudes of 1 m at the ocean boundary and periods between 3 and 19 hours, for all defined scenarios. The wave amplitudes predicted at several points along the estuary (Figure 9) confirm that the resonant period is of about 8 hours, and that the waves with periods between 5 and 19 hours are significantly amplified between Cacilhas and Vila Franca (Figure 9a). Results show that SLR will enhance the tidal amplification in the Tagus estuary for all frequencies considered (Figure 9a).

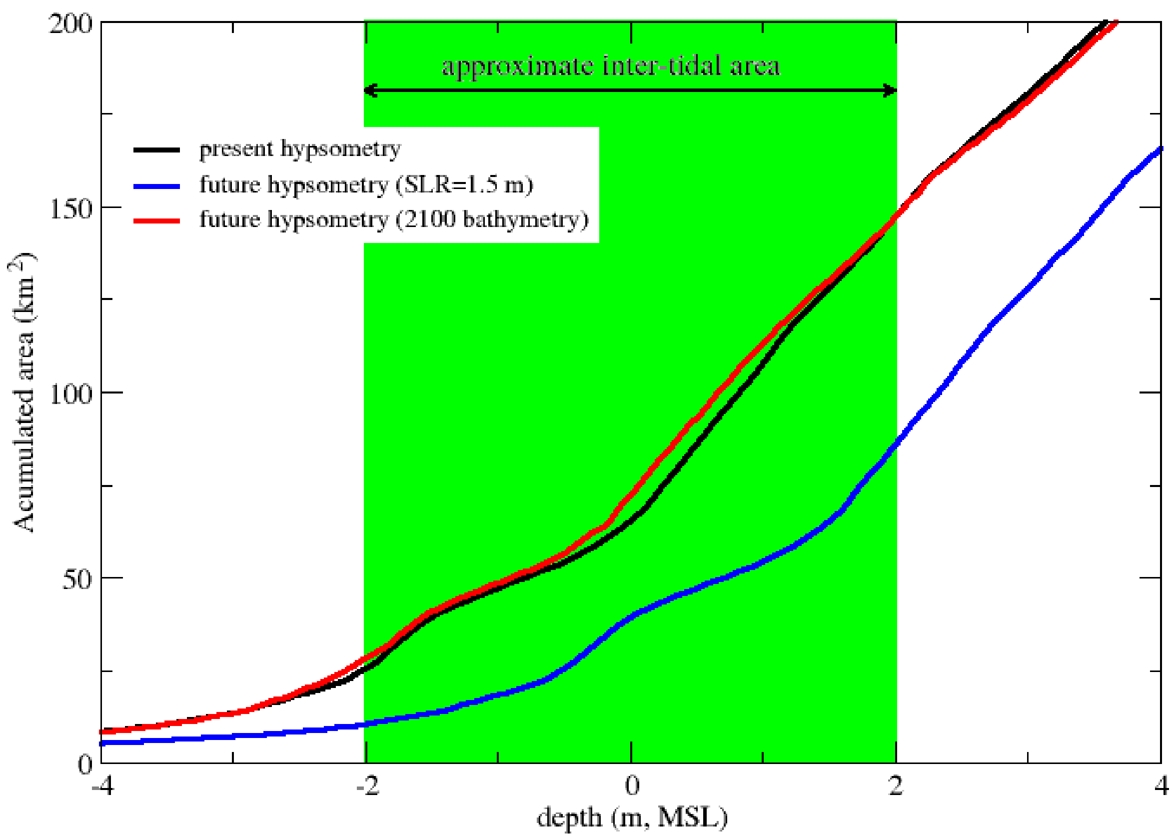

Figure 8 - Effect of future changes on the hypsometry of the Tagus estuary. The present hypsometric curve (black line) shifts downward due to SLR (blue curve) and upward due to accretion (red curve). The future bathymetry was obtained by extrapolating the present bathymetry using estimated accretion rates.

Figura 8 - Efeito de mudanças futuras na hipsometria do estuário. A hipsometria atual (linha a preto) desloca-se para baixo devido à subida do NMM (linha azul) e para cima devido à acreção (linha vermelha). A batimetria futura foi obtida extrapolando a batimetria atual usando taxas de sedimentação estimadas.

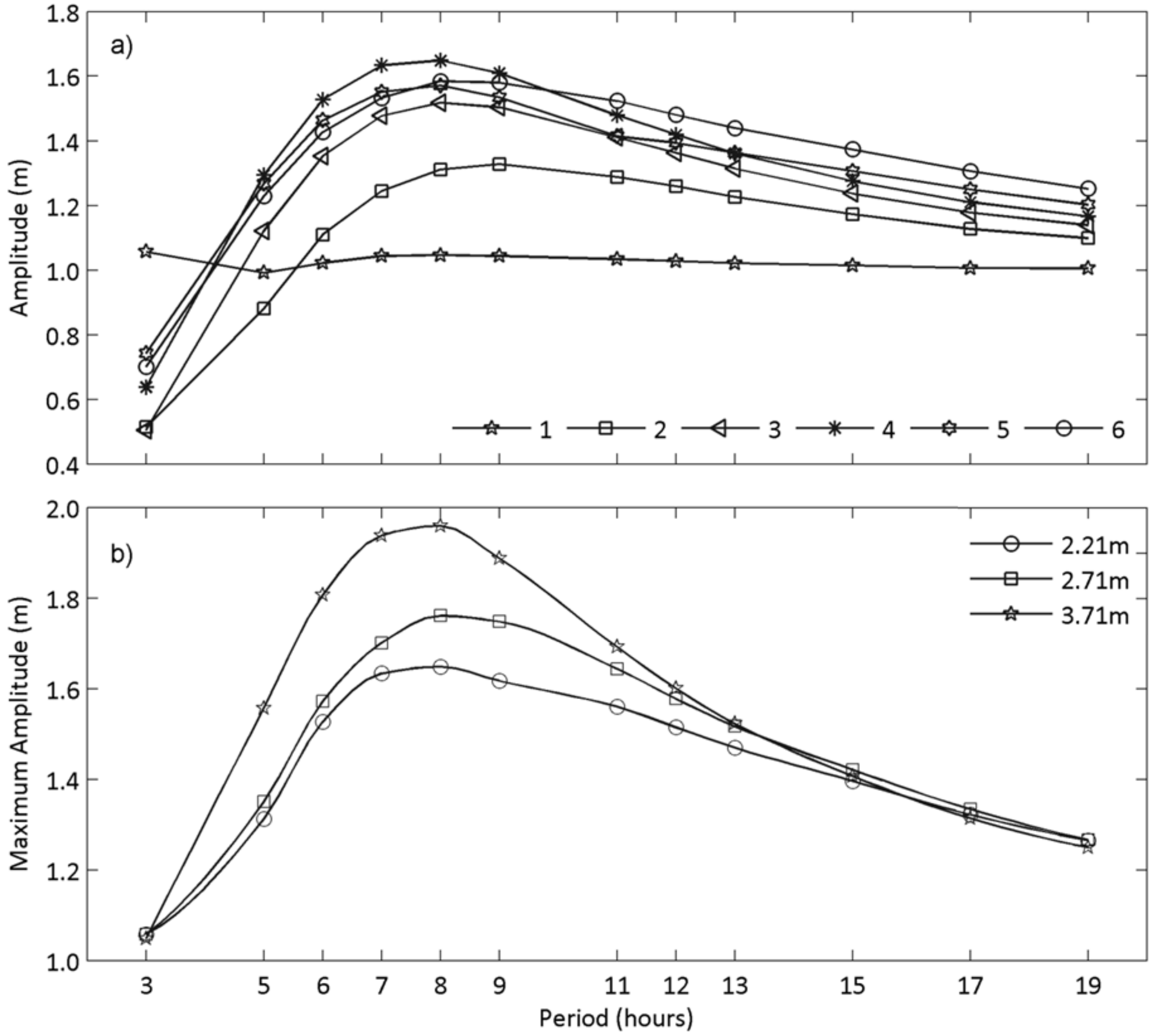

Figure 9 - Effect of the resonance: a) along the estuary for the present MSL (2.21 m); b) maximum amplitude for the different SLR scenarios and the different frequencies of the tidal wave.

Figura 9 - Efeito da ressonância no estuário: a) ao longo do estuário para o NMM atual (2.21m); b) máxima amplitude para os diferentes cenários de subida do NMM e diferentes frequências de onda de maré.

For the present-day situation, the maximum amplification obtained is 65%. For the highest MSL considered, *i.e.*, 3.71 m above Chart Datum, the predicted amplifycation increases up to 95%, with the amplification varying non-linearly with different frequencies. In particular, for the semi-diurnal constituents the amplification grows asymptotically. For a SLR of 1 m, the maximum amplification will approximately be reached (Figure 9b).

Results indicate that the resonance period of the Tagus estuary does not change significantly with SLR (Figure 9b). Hence, the amplification of the resonance effect may be due to smaller frictional losses associated with the higher mean depth.

The effects of resonance depend on the period of each constituent. Results indicate that quarter-diurnal constituents will be more amplified than semi-diurnal constituents by the 1.5 m SLR ((Figure 9b). Since tidal asymmetry is mostly due to the interaction between semi-diurnal and quarter-diurnal constituents, this result is apparently contradictory with the reduction of tidal asymmetry shown above. These results thus suggest that the reduction in tidal asymmetry will occur due to a shift in the relative phase lag between the major semi-diurnal and quarter-diurnal constituents.

4.3. Extreme water levels

Marginal flooding in the Tagus estuary can have adverse effects. Some urbanized marginal areas, such as Seixal, are low-lying, so that the potential human and material costs of a flood are high. One of the most severe historic episodes described was originated by the combination of extreme storm surge levels and locally-generated waves during the February 15, 1941, windstorm, causing high human casualties and property damages along the estuarine margins (Muir-Wood, 2011). Recently, the effects of the Xynthia windstorm, that reached the Portuguese coast on February 27, 2010, were also observed along the estuary margins, where

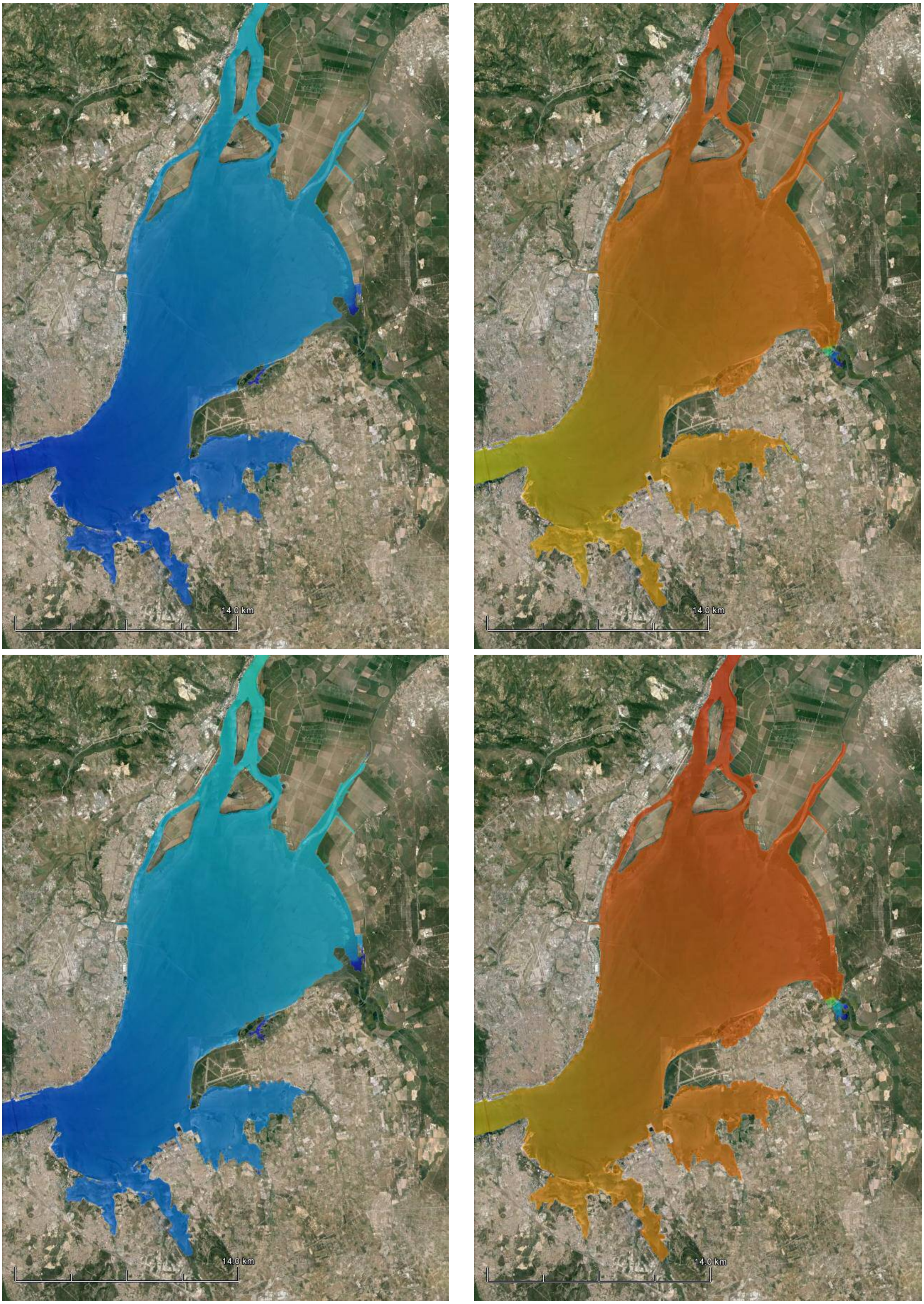

Figure 10 – [caption in the next page].

Figura 10 – [legenda na página seguinte]

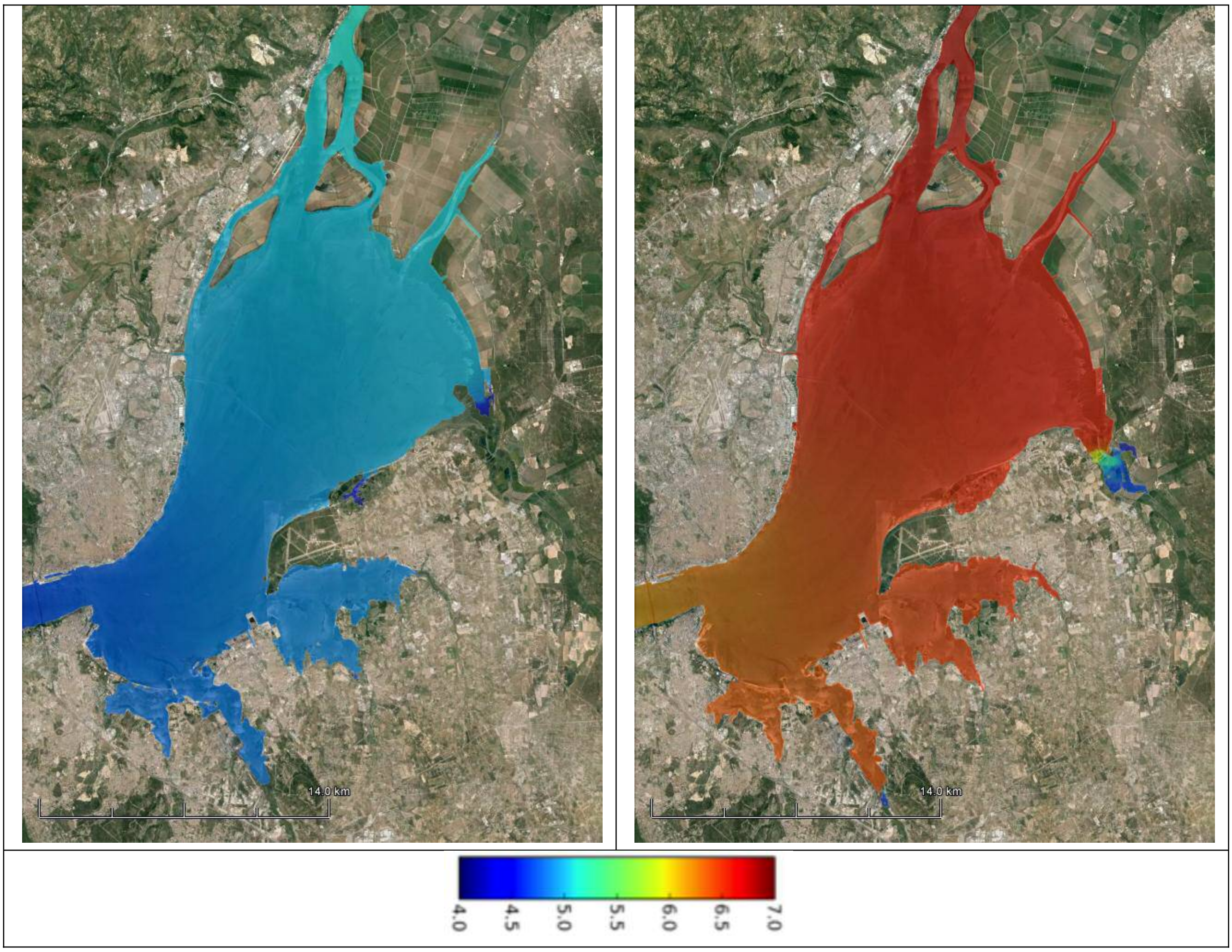

Figure 10 - Maps of extreme water levels for the present MSL (left panels) and considering a 1.5 m SLR (right panels). From top to bottom: high, medium and low probability scenarios, corresponding to return periods of 20, 100 and 1000 years. Levels are in meters, relative to Chart Datum.

Figura 10 - Mapas de níveis extremos para o atual NMM (figuras da esquerda) e considerando uma subida do NMM de 1,5m (figuras da direita). De cima para baixo: cenário de probabilidade alta, média e baixa, correspondendo a períodos de retorno de 20, 100 e 1000 anos. Níveis em metros, relativos ao ZH.

significant damages in infrastructures occurred. In the upper area of the estuary, with extensive agricultural areas, floods may induce salinization and loss of fertile land. Raising the MSL implies more frequent floods of marine origin. In the particular case of the Tagus estuary, this problem will be exacerbated by the increased tidal amplification due to resonance.

The simulations confirm the importance of SLR on extreme water levels (Figure 10). Due to resonance, the maximum levels grow strongly between Cacilhas and the section of the Trancão River and increase faster than the MSL rise rate. This behavior is illustrated in Figure 11, which shows, for different return periods and values of the MSL, the difference between the maximum water level and the MSL. Due to increased resonance, the maximum water levels at this point grow by 4 to 7 cm more for the higher MSL case than for the present MSL. However, in spite of this non-linear growth of the maximum water levels with the SLR, due to the resonant effects, these non-linear effects are small relative to the uncertainty in SLR. Simply adding the expected SLR to the maximum water levels in the estuary appears therefore as an acceptable simplification.

5. Conclusions

The impacts of climate change on estuaries should be anticipated in order to allow for the implementation of adaptation measures, and to inform decision-makers about interventions in the estuary (*e.g.*, construction of infrastructures). This paper contributes to this anticipatory procedure in the case of the Tagus estuary.

The simulations undertaken in this study show that SLR will have significant effects on estuarine hydrodynamics. In the case of the Tagus they will be particularly significant due to the occurrence of resonance, which amplifies the semi-diurnal constituents of the tide. SLR will trigger two major direct effects:

1. Tidal asymmetry will decrease significantly. The present ebb-dominance will be reduced, and the estuary may even become flood-dominant. This be

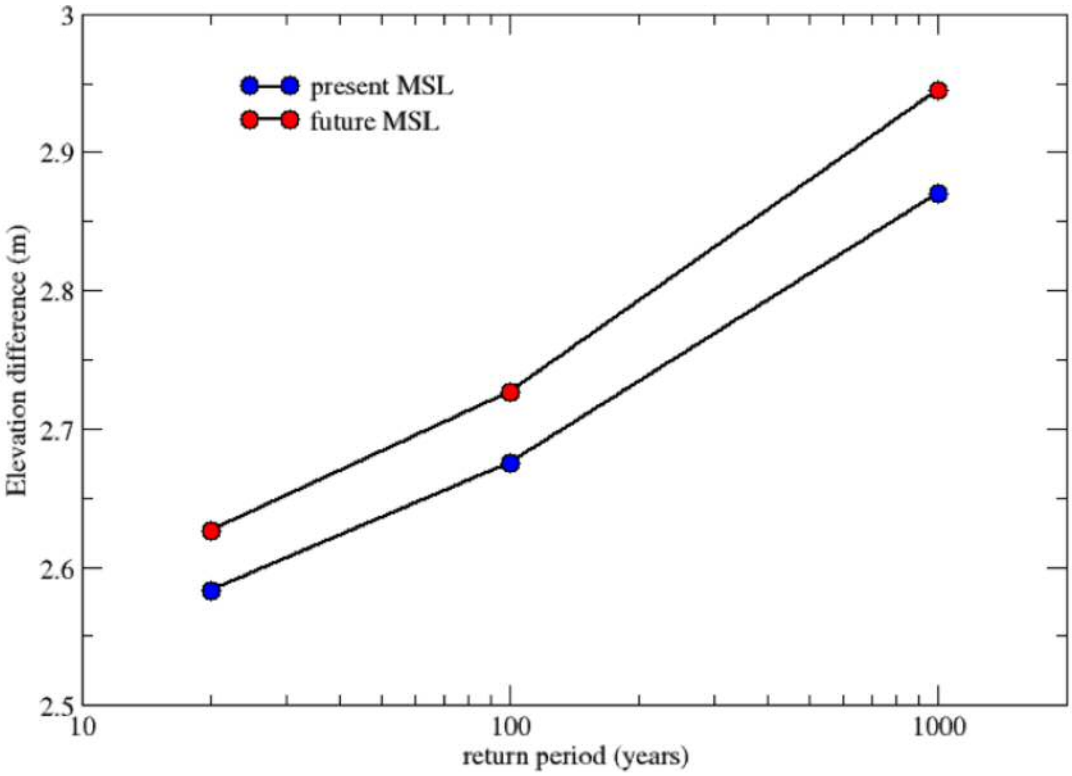

Figure 11 - Effect of SLR on extreme water levels at point 4 from Figure 3a.

Figura 11 - Efeito da subida do NMM nos níveis extremos no ponto 4 da Figura 3a.

havior appears to be mostly due to a significant reduction of the intertidal areas (roughly 40% for a 1.5 SLR) and will be partly compensated by sedimentation in the tidal flats.

2. The resonance within the estuary will be strengthened, increasing the tidal amplification. As a result, the maximum levels in the estuary will increase slightly faster than the SLR.

The contrasting effects of SLR and sedimentation on tidal asymmetry suggest a morphodynamic feedback that prevents major changes in the estuary. As SLR pushes the estuary towards flood dominance, sedimentation increases and promotes ebb dominance.

The approach followed herein to assess the interplay between SLR, sedimentation and hydrodynamics is simplified. First, the future bathymetries are based on simple extrapolation of estimated trends. Ideally, a full morphodynamic model, calibrated and validated with field data, should be applied to better quantify these interactions. Secondly, the evolution of the temperature and precipitation associated with climate change is also likely to affect the sediment input into the estuary, thus changing the sedimentation rates. Thirdly, tidal asymmetry was characterized based on tidal elevations alone. While this approach is common, a more detailed analysis should focus on velocities or even sediment fluxes. Indeed, in very shallow areas, the asymmetry in sediment transport can be the opposite as the one indicated by the asymmetry in tidal elevations (e.g., Bertin *et al.*, 2009).

Using more sophisticated and accurate approaches is desirable, but entails significant difficulties. First, the predictability of century-scale estuarine evolutions by process-based morphodynamic models remains sketchy, in particular when mixed sediments are involved (e.g., Dastgheib, 20112). In the case of the Tagus estuary, the lack of extensive bathymetric data also prevents a detailed calibration and validation of such a model, just as it provided only coarse estimates of sedimentation rates. Also, existing estimates of sediment input into the estuary are coarse (Vale and Sundby, 1987), and there seems to be a long way before the effect of climate change on those inputs can be determined. While the approach followed herein is a compromise between the need to assess different processes and the limited accuracy of the most sophisticated existing methods, it highlights the complex interactions between processes and their contrasting effects. However, further studies using more sophisticated models, supported by more data, are required to verify the conclusions and quantify how the estuary will evolve under a changing climate.

Further consequences of SLR, both positive and negative, are yet to be investigated in detail. The increase in tidal amplitude will result in larger tidal prisms. This consequence will reduce the saline stratification (observed in high flow conditions), and decrease the residence times, thereby improving the overall water quality. Salt-wedge intrusion will increase with potentially negative consequences on water used for irrigation and industrial purposes (*e.g.*, cooling of thermal power plants). Higher tidal prisms can also reduce the dredging efforts at the inlet channel.

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