Sensitivity analysis of Ria de Aveiro hydro-morphodynamics to the sea level rise integration period

C.L. Lopes†, P.A. Silva†, A. Rocha and J.M. Dias†

†CESAM
Department of Physics
University of Aveiro, Aveiro
3800-193, Portugal
carinalopes@ua.pt
psilva@ua.pt
alfredo.rocha@ua.pt
joao.dias@ua.pt

ABSTRACT


Global mean sea level has been rising in the last century at a rate of 1.7±0.5 mm/year, and it is expected that during the 21st century it will rise at a greater rate, intensifying coastal hazards worldwide. The main aim of this study is to evaluate the sensitivity of the hydro and morphodynamics of the Ria de Aveiro lagoon to different local sea level rise estimates expected for the end of the 21st century. The SRES scenario A2 was considered admitting three integration periods (Period A between 2071-2080, Period B between 2071-2100, and Period C between 2091-2100), which are compared to the reference period of 1980-1999 (actual climate). The local sea level rise projections were obtained from the output of the GISS-ER model and pointed to a rise of 0.29, 0.34 and 0.42 m for the periods A, B and C respectively. The morphodynamic model MORSYS2D was applied to the Ria de Aveiro considering each forcing scenario. The residual sediment flux at the inlet region and the lagoon tidal prism were computed and analysed for the actual situation and for the three sea level rise estimates. The residual transport of sediments at the inlet region is mostly seaward both for the actual situation and for the considered scenarios. However its magnitude is very sensitive to the sea level rise: an increase of about 72%, 94% and 123% is expected for the periods A, B and C respectively. The tidal prism is also very sensitive to the mean sea level: an increase of about 19%, 22% and 28% is estimated for the periods A, B and C respectively.

ADDITIONAL INDEX WORDS: climate change, sediment transport, tidal prism

INTRODUCTION

Coastal regions are dynamic interface zones where land, water and atmosphere interact in a dynamic balance that is constantly being changed by natural and human influence. Generally, coastal areas are extremely productive and accessible to people. Therefore these areas are densely populated, intensifying the anthropogenic pressures. The natural pressures are also being intensified as a result of climate change. SLR (sea level rise) is an important consequence of climate change. Global mean sea level has been rising since the last century at a rate of 1.7±0.5 mm/year (Church and White, 2006) and it is expected to continue rising during the 21st century at a higher rate (Meehl et al., 2007a). However, both tide gauge and satellite altimetry data confirm that sea level is not rising uniformly around the world. The mean sea level is changed by long-term oscillations that can be caused by thermal expansion (response of the ocean to global atmospheric temperature rise), mass exchange (melting of mountain glaciers and ice caps and changes in Greenland and Antarctic ice sheets), dynamic changes (result of density gradients) and land subsidence (vertical movements in the solid earth related to tectonics and isostatic adjustment). Spatial sea level variability is mostly due to long-term dynamic changes and land subsidence (Meehl et al., 2007a).

Several studies based on tide gauge records showed that the sea level has risen at some places along the Portuguese coast during the 20th century. Dias and Taborda (1988) estimated a SLR at a rate of 1.5±0.2 mm/year at Lagos during 1908-1987 and 1.3±0.1 mm/year at Cascais during 1882-1987, while Araújo (2005) estimated a SLR at a rate of 1.15±0.68 mm/year at Aveiro during 1976-2003. Recently, Antunes and Taborda (2009) found an acceleration of the SLR rate during 1977-2000 at Cascais and have estimated for this period a rate of 2.1±0.1 mm/year.

In Portugal, the areas that will probably be the most affected by an accelerated SLR are the Ria de Aveiro and the Ria Formosa coastal lagoons and the Tagus and Sado estuaries (Ferreira et al., 2008 and Andrade et al., 2006). Because a large fraction of the Portuguese economy is situated near these coastal zones, coastal studies and integrated coastal management are of critical importance in Portugal (Ferreira et al., 2008 and Andrade et al., 2006). As the response of each coastal region to the SLR depends on the physical features of the coastal system and on the rate of local sea level rise, to evaluate locally the effects of SLR is a fundamental task to improve the local vulnerability assessment (Nicholls and de la Vega-Leinert, 2008).

As there are several possibilities to estimate the mean SLR, the main aim of this study is to evaluate the sensitivity of the hydro and morphodynamics of Ria de Aveiro lagoon to different local SLR estimates expected at the end of the 21st century, based on different SLR integration periods. In this study the SRES (Special
 SEA LEVEL RISE ESTIMATES

The output of GISS-ER model (Russel et al., 1995; 2000) was used to estimate the spatial distribution of SLR in the Portuguese coast. The model provides estimates that every grid point accounts for the change in sea level due to thermal expansion, dynamic change and mass exchange.

Climate GISS-ER model output from simulations of the past (pre-industrial run), present (20C3M run) and future climate (different scenarios runs) have been made available to the scientific community by the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007b). The 20C3M run starts at 1880 and ends at 2003. The future climate was simulated by the model imposing different emission scenarios of greenhouse gas developed by IPCC. The scenario SRES (Special Report on Emission Scenarios) A2 was considered.

With sea surface height data given by the GISS-ER model, the change in sea level relative to the actual (reference) mean sea level was computed for the A2 scenario admitting three integration periods (A, B and C). The reference was considered to be the mean of the 1980 to 1999 period. Figure 1 shows the projected mean sea level change for the North Atlantic region, for Period B, revealing a rise in sea level for the whole region. The spatial variability near the Portuguese coast (P1-P8) was found to be very weak. To minimize sampling problems associated with uncertainty of the model at small spatial scales, the behaviour of sea level change at eight points (represented in Figure 1) surrounding the region of interest was analyzed. Figure 2 shows the evolution of simulated sea level change of a grid point, during the present climate (the 20C3M curve represents the 1970-2003 period only at P1) and for SRES scenario A2, until 2100. The figure confirms the weak spatial variability among the points considered (P1-P8).

Table 1 shows the mean (\(\eta\)) and standard deviation (\(\sigma\)) of sea level change, relative to the 1980-1999, for the 20C3M simulation, and for each future period at the points represented in the Figure 1.

Table 1: Mean (\(\eta\)) and standard deviation (\(\sigma\)) of sea level change, relative to the 1980-1999, for the 20C3M simulation, and for each future period at the points represented in the Figure 1.

Ria de Aveiro

The Ria de Aveiro (Figure 3) is a shallow vertically homogeneous 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 km² at high water (spring tide) which is reduced to 66 km² 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, Ilhavo and Espinheiro.
Table 2: SLR projections for the Portuguese coast by the end of the 21st century.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SLR ±0.02 (m)</th>
</tr>
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<tbody>
<tr>
<td>Period A</td>
<td>0.29</td>
</tr>
<tr>
<td>Period B</td>
<td>0.34</td>
</tr>
<tr>
<td>Period C</td>
<td>0.42</td>
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The inlet region (Figure 3b) 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 (5-10 m relative to chart datum) is greater than the average depth of the remaining lagoon (1 m relative to chart datum). There are two deeper areas in the inlet region (Figure 3b): at the lagoon mouth between the two breakwaters, and further upstream, in the zone of the tidal gauge and extending up to the channel bifurcation. Between these two zones, there is a wider and shallower zone, which is delimited at the south-eastern side by the Meia Laranja beach.

The lagoon hydrodynamics is dominated by tides, which are semidiurnal with a small diurnal pattern. The residual circulation is determined essentially by asymmetries between the flood and ebb regimes. As the lower lagoon is ebb-dominant there is a trend to export sediments to the ocean (Oliveira et al., 2006). 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).

Human action has been the major factor controlling the lagoon morphology (Silva and Duck, 2001). The most noteworthy human intervention was 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 extensions grew until the last intervention between 1983 and 1987.

Analysis of the bathymetric changes occurred after extension of the northern breakwater (1987/88) revealed that the inlet region is extremely dynamic, experiencing strong bathymetric changes in a short time period. The topographic changes induced by 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). Nevertheless, when dredging activities at the north of the lagoon mouth were interrupted (2001), the inlet region experienced mostly accretion of sediments. However, the deeper zone between the two breakwaters evidenced erosion (Lopes et al., 2010).

**MORSYS2D SIMULATIONS**

The 2-D modelling system MORSYS2D simulates the non-cohesive sediment dynamics and bottom changes in estuaries, tidal inlets and coastal regions, driven by tides, waves, wind and river flows. The system integrates the hydrodynamic model ELcIRC (Zhang et al., 2004), the wave model SWAN (Boij et al., 1999) and the sand transport and bottom update model SAND2D (Fortunato and Oliveira, 2004, 2007 and Bertin et al., 2009). In this application, ELcIRC was implemented for the entire lagoon and SAND2D was implemented only for the inlet evolving area (from offshore until the cross-sections 5 and 6 represented in Figure 3b). Consequently, MORSYS2D solves the hydrodynamics for the entire lagoon, but the sediment fluxes and the bathymetry updates are only evaluated in the SAND2D grid area. The applications presented in this study neglect the wave effects and therefore only the models ELcIRC and SAND2D were used. The waves have some importance in the transport of sediments in the inlet region; however, the breakwaters protect the inner lagoon from the swell and therefore the influence of waves may not be dominant in the sand transport inside the lagoon (Plecha et al., 2010).

Simulations were made by imposing a dynamic water elevation at the ocean open boundary, using ten tidal constituents (MS, O1, K1, N2, M2, S2, MN2, M4, MS4 and M6) and the mean sea level (Z0) taken from the regional tidal model of Fortunato et al. (2002). The effects of wind and fluvial inflow were neglected because they have minor importance compared with tidal forcing in determining the lagoon dynamics and morphodynamics. The median sediment grain size (d50) used is variable in space (Plecha et al., 2007). Nevertheless, when dredging activities at the north of the lagoon mouth were interrupted (2001), the inlet region experienced mostly accretion of sediments. However, the deeper zone between the two breakwaters evidenced erosion (Lopes et al., 2010).

Residual fluxes

Residual sediment fluxes were computed in the study area by averaging the sand fluxes during one lunar month (two MS4 constituent periods), for the present mean sea level and for the SLR estimates (Figure 4). Similar patterns of the residual fluxes are found for each sea level forcing. The residual flux is generally seaward; the exceptions are at the head of the south jetty
(northward flux) and in the upper part of the navigation channel close to the north jetty (landward flux). The patterns suggest that there is a tendency for accretion close to the bifurcation and to the south jetty. On the other hand, downstream, the cross-section 1 pattern suggests erosion. Although the direction of the residual fluxes is similar for each sea level forcing, its magnitude is very sensitive to SLR estimates: a mean increase of about 72%, 94% and 123% for the periods A, B and C respectively, was found at the inlet region.

Figure 5 presents the net residual sediment transport through the cross-sections represented in the Figure 3b), for the reference period and for the future SLR estimates. The net residual sediment transport is seaward (negative values), except at cross-section 2. The net transport direction at each cross-section does not change with the SLR; however, an intensification of the net residual transport with the SLR is found.

There is sand accretion into the inlet region, given that the net volume of sediments exported to the ocean at cross-section 1 is smaller than the net volume of sediments through cross-sections 5 and 6. The residual volume of sand deposited between section 1 and sections 5 and 6 is 41.8 m$^3$/day for the present, 74.3 m$^3$/day, 80.4 m$^3$/day and 89.0 m$^3$/day for the Periods A, B and C, respectively. Hence, an increase of 78%, 92% and 113% relative to the present was found for the periods A, B and C, respectively.

**Tidal Prism**

The tidal prism was computed at the cross-sections represented in Figure 3a, for the present mean sea level and for the SLR estimates, under spring tide conditions (Figure 6). The cross-section A is representative of the inlet, and the cross-sections B, C, D and E represent the mouth of the four main channels of the Ria de Aveiro. The results obtained for the present mean sea level shows that the tidal prism for each of the main channels relative to its value at the inlet is about 13% for the Mira channel, 45% for the V. Mira channel, 0.08 m.

Figure 5. Net residual sediment transport (m$^3$/day) through the cross-sections represented in the Figure 3b) for the present mean sea level and for each SLR projection.

Table 1 shows that the tidal prism for each of the main channels relative to its value at the inlet is about 13% for the Mira channel, 45% for the V. Mira channel, 0.08 m. The sensitivity of Ria de Aveiro hydro-morphodynamics to different SLR estimates expected for the end of the 21st century, based on different SLR integration periods. The SLR analysis for the Portuguese coast evidenced an acceleration of the SLR, given that the difference between the Period B and A is 0.05 m, while the difference between the Period B and A is 0.08 m.

Figure 6. Tidal prism at spring tide for the present and for the SLR estimates (left panel) and respective increase rate relative to the present (right panel).

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The sensitivity of Ria de Aveiro hydro-morphodynamics to different local sea level rise estimates expected for the end of the 21st century was studied through simulations with MORSYS2D model. The model predictions showed that sediment dynamics at the inlet region is strictly dependent on the mean sea level forcing. Although the fluxes direction remains unchangeable, its intensity increases when the estimates for the sea level rise are higher.

This study also demonstrated that smaller variations in the SLR induce an increase on sediment fluxes intensity and on tidal prism. Thus, define adequately the sea level rise integration period is a fundamental task in order to obtain reliable predictions of hydro-morphodynamic changes of coastal systems induced by the local SLR.

**CONCLUSIONS**

This study reports the sensitivity of Ria de Aveiro hydro-morphodynamics to different SLR estimates expected for the end of the 21st century, based on different SLR integration periods. The SLR analysis for the Portuguese coast evidenced an acceleration of the SLR, given that the difference between the Period B and A is 0.05 m, while the difference between the Period C and B is 0.08 m.

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**LITERATURE CITED**

