Salinity patterns adjustment of a mesotidal lagoon induced by climate change

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ABSTRACT

Climate change impacts evaluation in transitional environments is essential for the definition of effective adaptation strategies. Ria de Aveiro lagoon, a complex shallow water system located in the northern coast of Portugal, is a highly productive ecosystem susceptible to ecological stress as a consequence of salinity patterns adjustment in the scope of climate change scenarios. Ria de Aveiro is a typically estuarine environment as longitudinal salinity gradients occur during most of an average year due to the interaction between tides and river flow.
The Ria de Aveiro seasonal salinity patterns adjustment to projected changes in mean sea level and river flow regimes for the end of the XXI century according to IPCC scenarios is investigated by means of numerical modelling with MOHID 2D. The hydrodynamic and the salt transport models were calibrated so that the model is able to reproduce salt transport processes with relative accuracy. The MOHID 2D numerical model was then applied in the simulation of reference and future scenarios combining local MSL rise and projected river flow.
The results obtained, in particular: the salinity concentration increase and the salt inland intrusion; the upstream saline increase as consequence of river flow projected reduction; and the larger salinity increase in upper lagoon regions, are in accordance with the ones achieved in the majority of the studies related to SLR impact in estuaries salinity, found in literature.

KEY WORDS: *Coastal lagoon salinity, climate change, mean sea level, river flow.*

INTRODUCTION

Estuaries are highly productive ecosystems particularly vulnerable to climate change effects. An expected consequence of mean sea level (MSL) rise in these environments is the change of horizontal salinity gradients (Nicholls *et al.*, 2007). The salinity increase may cause upstream intrusion of salt water in estuaries and aquifers with consequent freshwater shortage and gradual loss of estuarine natural ecosystems (Nicholls *et al.*, 2007; FitzGerald *et al.*, 2008; Nicholls, 2010). Note that one of the requirements of the Directive on the protection of groundwater against pollution and deterioration (2006/118/EC), a sister directive of the Water Framework Directive (2000/60/EC), is to avoid saline intrusion in groundwater bodies.
The scientific community just recently has shown its interest in estuarine modelling studies focused on climate change impact in salinity. Most of the studies found in the literature project for transition environments worldwide a salt concentration increase and an upstream expansion of brackish water for a MSL rise (Grabemann *et al.*, 2001; Hilton *et al.*, 2008; Bhuiyan & Dutta, 2011; Chua *et al.*, 2011; Hong & Shen, 2012; and Rice *et al.*, 2012). According to Chua *et al.* (2011), a projected reduction in freshwater inflows in San Francisco Bay, USA, region is predicted to intensify the salinity intrusion due to MSL rise. Rice *et al.* (2012) found in a study applied to James River, a tributary of Chesapeake Bay, USA, that in climate change conditions the salinity increase is larger in the middle-to-upper zone than in its lower zone.
Ria de Aveiro salinity has been characterized by several field and numerical studies (Dias *et al.*, 1999; Vaz *et al.*, 2005; Vaz & Dias, 2008; Dias *et al.*, 2011; Vaz *et al.*, 2012). Dias *et al.* (2011) observed a notorious seasonal and spatial salinity variation and identified longitudinal saline gradients, more clear in higher river runoff. Vaz *et al.* (2005) identified saline fronts in Espinheiro channel from measurements in low river flow conditions (autumn 2003). These fronts migrated between 7 and 9 km relative to the lagoon inlet, depending on the tidal characteristics (spring or neap).
Once characterized the salinity patterns of Ria de Aveiro for the present, it matters to investigate how these patterns will adapt in the future as a consequence of climate change, so that adequate adaptation measures may be designed in advance. This study aims to explore this issue, investigating the climate change impacts in the seasonal salinity variability of the Ria de Aveiro for the end of the XXI century, as a consequence of MSL rise and projected changes in river flow.
When evaluating climate change impacts is usual to follow a methodological approach based on the Precautionary Principle (Harremoës *et al.*, 2002), enabling a more effective long-term planning in the prevention of negative consequences for these regions. Therefore, the A2 scenario defined in the Special Report on Emissions Scenarios (SRES, Nakićenović & Swart, 2000), with which are projected most significant impacts in salinity of estuarine environments, is considered in this study.

STUDY AREA

Ria de Aveiro is a shallow mesotidal lagoon located in the northern Portuguese coast (Figure 1). It is very dynamic in terms of physical and biogeochemical processes (Vaz & Dias, 2008), offering good conditions for agricultural development alongside its borders. Moreover it also plays an important ecological rule, being classified as a special area of conservation of wild birds (79/409/EEC Directive) and habitats (92/43/CEE Directive).

It has a very irregular geometry, being characterized by narrow channels and by extensive intertidal areas. Four main branches spread from the mouth (Figure 1): the Mira channel running southward, the S. Jacinto channel extending to the north and the Ílhavo and Espinheiro channels extending to inland (Dias, 2001).

This lagoon presents an average depth of 1 m relative to chart datum and in spring tide its area varies between 66 km^2 at low tide and 83 km^2 at high tide (Dias, 2001). Tidal prism in the lagoon's mouth is estimated to range between 137×10^6 m^3 (Dias, 2001) for maximum spring tide and 31×10^6 m^3 (Picado *et al.*, 2010) for minimum neap tide. Comparatively, the mean total freshwater input of about 1.8×10^6 m^3, estimated by Moreira *et al.* (1993) for a tidal cycle, is of lower significance.

Nevertheless, freshwater inflow is essential in the establishment of longitudinal salinity gradients that results from its interaction with spring/neap tidal cycle (Vaz & Dias, 2008).

METHODOLOGY

The MOHID 2D model, a baroclinic finite volume model (Santos, 1995; Leitão *et al.*, 2005), is used in this study. It was developed and has been successfully applied to shallow water environments with complex morphology like Ria de Aveiro lagoon (Vaz *et al.*, 2005, 2007).

After model calibration, reference and future scenarios were designed for present and projected wet and dry conditions. Besides the projected river flow, future scenarios result from the combination with local MSL rise.

Numerical Bathymetry

A numerical bathymetry initially developed by Vaz *el al.* (2007) was taken as starting point for the bathymetry used in this study. The structured grid has 567 by 438 cells in the *y* and *x* directions, respectively, with a spatial resolution of 40×40 m in the central area of the lagoon, with a more complex geometry, and of 40×100 in its north and south areas.

The bathymetry taken as work base already included topographic data for the adjacent low-lying areas referent to the year 2006, provided by Intermunicipality Community for Ria de Aveiro (CIRA). This bathymetry was updated with recent surveys dating from 2012 relative to the inlet and initial navigable stretches, provided by Aveiro Harbor Administration, S.A. (APA). Missing structures like dikes, roads bordering the lagoon next to main settlements and walls of active salt pans, with a rule in the protection of adjacent areas from flooding were reintroduced attributing realistic levels (5 m above the chart datum). The topographic data was limited to 10 m above the chart datum.

Model Calibration

To calibrate the hydrodynamic model the bottom friction coefficient is tuned for the entire lagoon until a good agreement between predicted and measured time series in several stations is obtained. Considering sea surface elevation (SSE) data from the most recent survey carried out between 2002 and 2003 at several stations along lagoon's main channels, the best adjustment was achieved with Manning's coefficient ranging between 0.022 and 0.045 as found by Vaz *et al.* (2007). The model's predictive ability

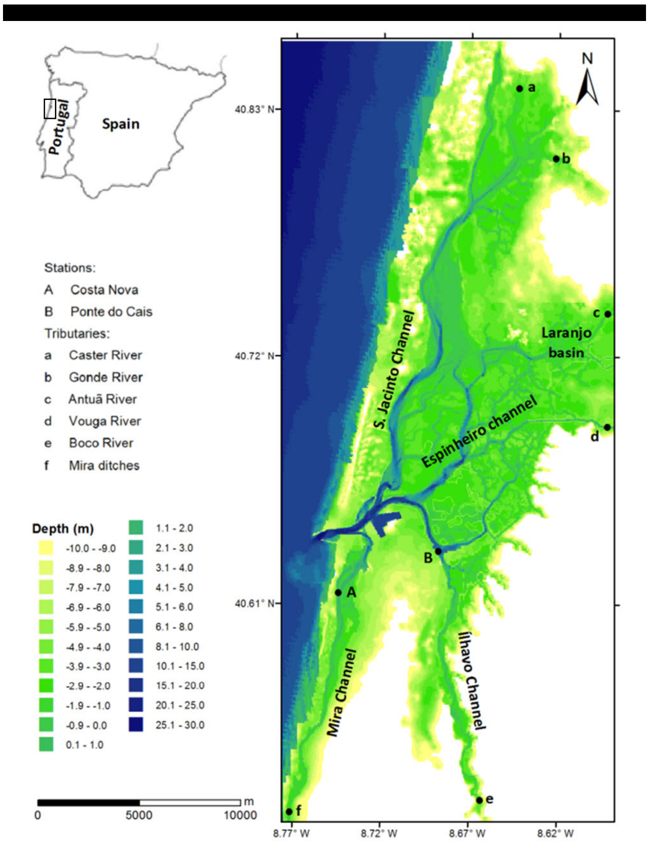

Figure 1. Location of Ria de Aveiro and numerical bathymetry.

was evaluated determining the Root Mean Square Error (RMSE) and the Skill parameter (Warner *et al.*, 2005) and comparing the amplitude and phase of the main tidal constituents obtained by harmonic analysis (Pawlowicz *et al.*, 2002) for predicted and measured SSE.

The model reveals an accurate reproduction of SSE in the central area of the Ria de Aveiro. The RMSE range from 2.5% to 10% of the local tidal amplitude for the generality of the stations located in this area, so the agreement between model predictions and measurements is in general very good to excellent. In the central area the Skill values are higher than 0.95 for most of the stations, which represents an excellent agreement. The disagreement increases with the distance from the lagoon's mouth.

For the M_2 constituent which represents 88% of the total tidal energy in the lagoon (Dias, 2001), the mean amplitude difference is about 9 cm and the mean phase difference about 12°, representing a delay of about 25 minutes in the tidal wave arrival.

The salt transport model was calibrated comparing predictions and measurements of salinity at stations along the main channels. The measurements considered were carried out in July 1996, after a long dry period. A constant salinity of 36.5 was imposed in the ocean open boundary and landward boundaries were forced with daily river flow time series concurrent with the period of interest. These daily flow series were simulated with SWAT model by IST/MARETEC team in the scope of DyEPlume Project (http://climetua.fis.ua.pt/legacy/dyeplume/index.html).

The salinity data is well reproduced in all stations, presenting RMSE values between 0.2 in station B and 1.5 in station A, corresponding to about 1% and 5% of the salinity local range.
Despite the differences found, the hydrodynamic and salt transport models can be considered calibrated.

River Flow Regime and Local MSL

Dry and wet seasons were identified in order to estimate the average daily mean flow series to impose in reference and future scenarios. The dry and wet seasons were defined as the three consecutive months which present, respectively, the lowest and the highest values of average monthly mean flow in the Vouga River, the main lagoon's tributary. The contribution of the Vouga River represents about 76% of the total freshwater inflow to the lagoon (for an average year). Average monthly mean values were estimated from the daily flow series simulated with SWAT model for the period 1971-2000. Based on these estimates dry season corresponds to July, August and September, and the wet season to January, February and March.
Reference and future average daily mean flow time series were estimated, for wet and dry seasons, from daily mean flow values simulated with the SWAT model. The simulations from 1971 until 2000 and from 2071 until 2100 were considered to obtain, respectively, the reference and projected average daily mean flow time series.
Analyzing SWAT simulation results, the Vouga River, the main tributary of the Espinheiro channel, has the largest freshwater contribution to the lagoon, as referred above. It is followed by Antuã River (Laranjo basin tributary) and Mira ditches, contributing with 4% and 13% of total annual inflow in average. In wet conditions the total average flow more than doubles the total annual mean flow (about 143 m^3s^{-1}), while in dry conditions it has a low significance (~ 2 m^3s^{-1}).
For the future conditions, an inflow reduction during an entire average year is projected. This reduction is expected to be more significant in the dry season (83%) comparatively to the wet season (32%). The results depicted in Figure 2 confirm the decrease from reference to projected average daily mean flow time series.
Relatively to the local MSL, several studies based on tide gauge records showed that the sea level has risen along the Portuguese coast during the 20^{th} century (Dias & Taborda 1988; Antunes & Taborda, 2009). For the Aveiro tidal gauge a relative sea level rise rate of 1.15±0.68 mm/year during 1976–2003 was found by Araújo (2005). Recently, Lopes et al. (2011) investigated the trend of future mean sea level on the Portuguese Coast. For the end of 21^{st} century a rise of 0.42 m above present level was presented by those authors for the A2 SRES scenario developed by the IPCC (Intergovernmental Panel on Climate Change).

Scenarios Design

Three future scenarios for wet (A) and dry (B) conditions were defined: A1 and B1, to evaluate the isolated effect of local MSL rise projected; A2 and B2, considering the projected changes at daily average river flow of the main tributaries; and A3 and B3, combining MSL rise and river flow changes projected, therefore, the more realistic ones. Figure 3 schematizes the scenarios design.
Each scenario was simulated for a time period covering neap, spring and equinoctial tides (Figure 2). Taking in account the Precautionary Principle, analysis will be mainly focused in results obtained at equinoctial tidal conditions, when the tidal influence is felt in further upstream regions.

CLIMATE CHANGE IMPACTS ON SALINITY

Changes in maximum salinity in multiple stations disposed along the main channels of Ria de Aveiro are analysed, emphasising results in Espinheiro channel which receives from Vouga River the largest contribution of freshwater inflowing into the lagoon. The adjustment in maximum salinity patterns over the whole lagoon are also analysed at wet and dry conditions.

Along the Main Lagoon Channels

The analysis of maximum salinity projections (Figure 4) shows an upstream displacement of the saline fronts generated in wet season in all channels for all the future scenarios. This progression is more pronounced for A3 scenario, in the order of 1 to 3 km depending on the channel and tide. In the Espinheiro channel this upstream advection of the saline front is about 1.5 km at equinoctial tide (Figure 4).
In dry conditions and for any of the four channels studied, the already high salinity in reference scenario, due to the low significance of river flow, increase even more in future scenarios as a consequence of sea level rise and/or river flow reduction. This impact has higher expression in channels head.

Over the Whole Lagoon

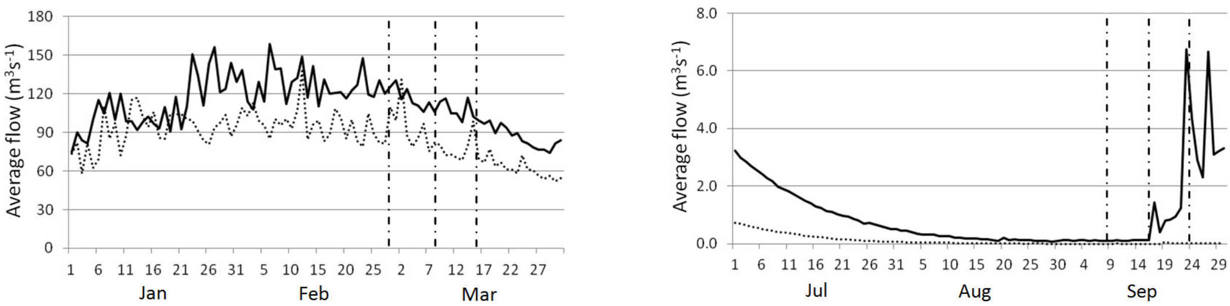

Figure 2. Estimated average daily mean flow for wet (left plot) and dry (right plot) seasons in Vouga River (solid line: flow in reference conditions; dotted line: flow in projected conditions; 1^{st} dashed-dotted vertical line: equinoctial tide; 2^{nd}: neap tide; 3^{rd}: spring tide).

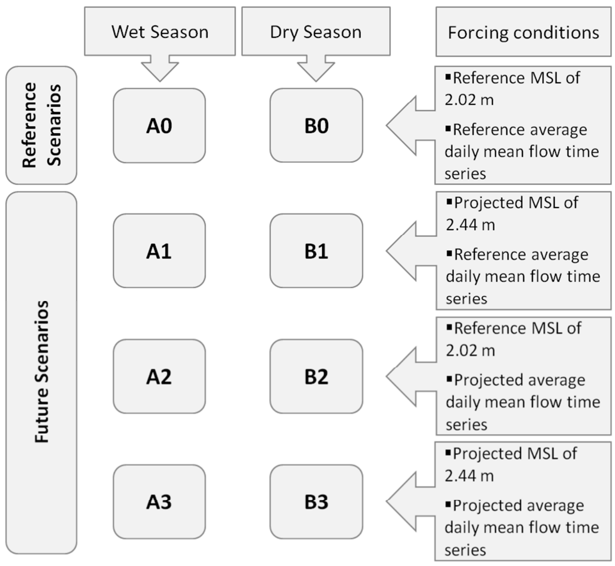

Figure 3. Schematic description of the designed scenarios.

Analyzing the projected adjustment in maximum salinity patterns for the entire lagoon, the salinity increase is generalized but more significant in the upstream regions in both wet and dry conditions. In wet conditions an increase in salinity of 5 to 7.5 is projected in the upstream areas of the lagoon considering A3 scenario at equinoctial tide (Figure 5). In dry conditions the salinity increase is not so pronounced in upstream regions, not exceeding 3.5 for B3 scenario at equinoctial tide.

The higher salinity increase in upstream regions denotes inland saline intrusion. In dry season the saline intrusion tends to go further inland due to the negligible freshwater inflow.

Results depict a tendency to an approximation between projected salt patterns in wet season (A3 scenario) to the reference salt patterns for dry season.

Most of the studies of MSL rise effect in salinity distribution at estuarine environments identified in the literature (Grabemann *et al.*, 2001; Bhuiyan and Dutta, 2011; Chua *et al.*, 2011; Rice *et al.*, 2012; Hong and Shen, 2012) lead to the same findings of this study: the salt concentration will increase in estuarine environments and the brackish water will extend landward as MSL rises. The upstream saline increase as a consequence of a river flow projected reduction, most evident at A2 scenario (Figure 3), is in accordance with Chua *et al.* (2011) conclusions. The results of this study reveals that in future scenarios the salinity increase is larger in the upper lagoon regions in accordance with Rice *et al.* (2012) finding.

CONCLUSION

It can be concluded that in wet season projected scenarios the increase in saline concentration is more significant than for the dry season ones, being more significant in the lagoon upstream regions. However, in dry season future scenarios the saline intrusion tends to go further upstream due to the projected negligible freshwater inflow.

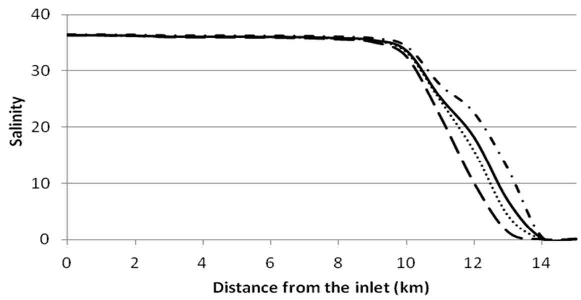

Figure 4. Maximum salinity along Espinheiro channel at equinoctial tide (black dashed line: A0 scenario; black solid line: A1 scenario; black dotted line: A2 scenario; black dashed-dotted line: A3 scenario).

The results obtained, in particular: 1) the salinity concentration increase and the salt inland intrusion; 2) the upstream saline increase as consequence of river flow projected reduction; and 3) the larger salinity increase in upper lagoon regions, are in accordance with the ones achieved in the majority of the studies related to MSL rise impact in estuaries salinity, found in literature.

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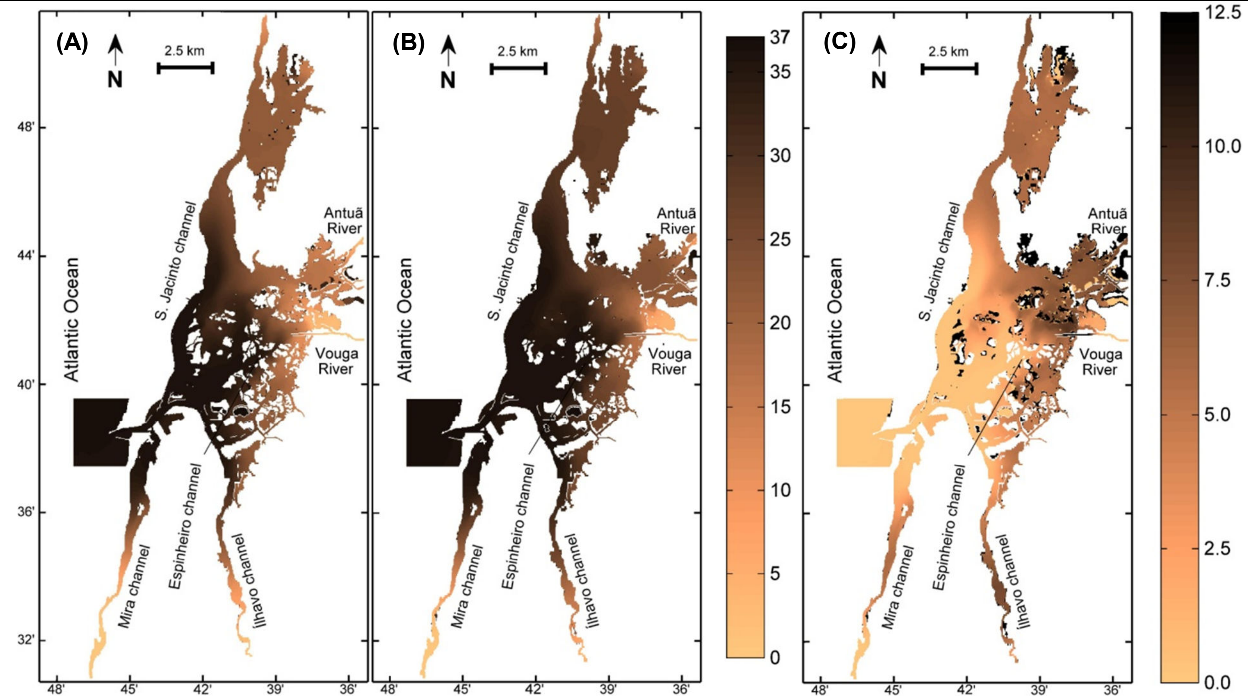

Figure 5. Salinity fields at equinoctial tide: A) A0 scenario; B) A3 scenario; and C) Difference between A3 and A0 scenarios.

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