Salinity modelling accuracy of a coastal lagoon: a comparative river flow analysis of basin model vs. traditional approaches

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ABSTRACT

Tomas, L.M., Rodrigues, M, Fortunato, A.B., Azevedo, A, Leitão, P.C., Oliveira, A., Rocha, A., Lopes, J.F., Dias, J.M., 2014. Salinity modelling accuracy of a coastal lagoon: a comparative river flow analysis of basin model vs. traditional approaches. *In*: Green, A.N. and Cooper, J.A.G. (eds.), *Proceedings 13th International Coastal Symposium (Durban, South Africa), Journal of Coastal Research,* Special Issue No. 70, pp. 586-591, ISSN 0749-0208..

The main purpose of this study is to investigate the uncertainties in the modelling of salinity fields in the Ria de Aveiro lagoon associated with the estimation of river flow discharges. The prediction of fresh water inputs is necessary to properly implement forcing conditions and consequently to provide accurate forecasts of baroclinic circulation in coastal lagoons. Located in the north-western Portuguese coast, the Ria de Aveiro is a shallow vertically homogeneous mesotidal coastal lagoon with a complex geometry. Although it is tidally dominated, it receives freshwater from five rivers, the Vouga, Antuã, Cáster, Boco and Ribeira dos Moínhos, whose contributions are responsible for the salinity variation within the system. This research concerns the accurate prediction of river flow to be used in the operational forecast system of the lagoon. Given the lack of observed data for river discharges, as there are only two real time measuring stations located in the Vouga and Antuã river basins, but far from the lagoon, alternative estimation approaches are needed. In order to estimate the river discharges for all five rivers, two different approaches were considered: the first estimates the Vouga river flow, the major fresh water source, based on the nearest real time measuring station and estimates the other river flows based on river basin areas proportionality; the second establishes river flows based on the precipitation/river flow relationships for the Vouga and Antuã rivers and on the areas of the other river basins using the SWAT model. The methodology comprises the exploitation of the 3D unstructured-grid hydrodynamic model SELFE, required to adequately simulate the flow and transport of salt in very complex domains such as the Ria de Aveiro. The model is forced by water elevations at the ocean boundary and river flows at the river boundaries, and atmospheric drivers at the surface (wind stress, atmospheric pressure and heat fluxes). The salinity model predictions were compared with data from seven stations, and its accuracy was assessed through Root Mean Square Error (RMSE). The river flows estimated by the first method led to the best fit between observed and predicted salinity.

ADDITIONAL INDEX WORDS: *salinity field; river flow estimation; Ria de Aveiro; SELFE 3D; circulation forecasts.*

INTRODUCTION

The successful implementation of hydrodynamical models in coastal areas depends greatly on the forcing conditions in place (Dias *et al.*, 2006a,b, Rodrigues *et al.*, 2009a). For coastal and estuarine areas, the salinity variation depends on the fresh water/salt water ratio; the fresh water from the rivers discharging and the salt water from the ocean (Vaz *et al.*, 2009). As observations for river flows are not always available for all fresh water sources, different strategies are used to estimate the river flows to be implemented in a numerical model. Correct fresh water flow estimation is necessary in order to properly simulate the salinity fields across the domain.

An increasing number of accidental oil spills have been occurring in the Iberian Peninsula area, mainly due to weather events (Azevedo *et al.*, 2014). It can be expected that extreme weather events, causing most of the accidents, will increase with changing climate (Easterling *et al.*, 2000; Morss *et al.*, 2011) and causing an increase in economic losses (Barredo, 2009). Rising human and economic impacts of natural and accidental hazards have triggered the European Commission to develop legal frameworks to increase prevention, preparedness, protection and response to such events and to promote research and acceptance of risk prevention measures within society (Alfieri *et al.*, 2012). An important part of a holistic approach to risk management of hazards is the establishment of early warning systems (Alfieri *et al.*, 2012). Recent studies have illustrated that early warning systems can have significant benefits exceeding their development and maintenance cost (Rogers and Tsirkunov, 2011; Teisberg and Weiher, 2009). At the present, these systems are mainly in use for weather related events, but its implementation for other events is now being done. In this frame, oil spill accidents can be considered important hazards induced by several risk factors related to environmental conditions and associated with maritime transport and port activities, which cannot always be predicted or controlled. The number of accidental oil spills affecting the Atlantic coast of Europe in recent decades has led to a growing concern regarding oil spill preparedness and response, and has motivated the development and implementation of different tools to be used in these emergency situations. Therefore, it is essential to support the development of accurate hydrodynamic models that

DOI: 10.2112/SI70-099.1 received 1 December 2013; accepted 21 February 2014.

can be coupled to oil spill forecast models to build up operational platforms that can be used to simulate oil spill events.

Nowcast-forecast systems (NFS) are 4D (space-time) simulation environments that integrate state-of-the-art numerical models and near-real time data. In the scope of the INTERREG project SPRES, NFS applied to oil spills were developed for four coastal sites in the Atlantic Area (http://spres.ihcantabria.com/). State-of-the-art numerical hydrodynamic models driven by real-time data and meteorological, oceanographic, and/or river flow rate forecasts form the core of these end-to-end systems. The Rapid Deployment Forecasting System (RDFS-PT) is an operational system in use in the Ria de Aveiro lagoon (http://ariel.lnec.pt/ (Oliveira *et al.*, 2011)), to provide real-time data about the weather and ocean conditions and, in addition, near real-time forecast information. At the present, its application is already in use to predict hydrodynamic conditions, which are being coupled with a model to forecast oil spills drift (Azevedo *et al.*, 2014). The operational system will be used as a tool to prepare and deploy the necessary measures to minimise the effects of an oil spill within the vicinity of the lagoon.

The oil slick drift simulations rely on the outputs from the hydrodynamic model. Consequently the simulation accuracy of the different variables is very important to adequately forecast the slick drift. The oil behaviour depends on several variables such as water salinity and temperature, influencing the oil weathering (Azevedo *et al.*, 2014). Although the Ria de Aveiro is tidally dominated (Dias *et al*., 2000), its water circulation and especially its longitudinal salinity gradients are also influenced by the fresh water/sea water ratio (Dias *et al.*, 1999; Vaz and Dias, 2008; Vaz *et al.*, 2009). Despite its importance river discharges at the lagoon are not monitored permanently; there are only two real time measuring stations located in the Vouga and Antuã river basins, but far from the lagoon. Consequently, alternative estimation approaches are needed to estimate the river discharges for all five rivers, in order to give appropriate boundary conditions to the hydrodynamic model. To fulfil this gap, two different approaches were considered in this study: the first estimates the Vouga River flow based on the nearest real time measuring station and estimates the other river flows based on river basin areas proportionality; the second determines the river flows using a local application of the SWAT watershed model based on the precipitation/river flow relationships for the Vouga and Antuã rivers and on the areas of the other river basins.

STUDY AREA

The Ria de Aveiro (Figure 1) is a shallow vertically homogeneous lagoon with a very complex geometry, located on the northwest coast of Portugal (40º 38' N, 8º 45' W). It is 45 km long and 10 km wide and covers an area of 89.2 km^2 at spring tide which is reduced to 64.9 km^2 at neap tide (Lopes *et al*., 2013). The lagoon is separated from the ocean by a sand spit. An artificial inlet connects the lagoon to the open ocean. The lagoon is characterized by narrow channels and by large areas of mud flats and salt marshes (Dias *et al.*, 1999; Dias, 2001). An important national harbour, including several terminals, for commercial and fisheries activities is located within the lagoon. Due to the increase in maritime traffic, this area is more prone to accidents and possible oil spills within the vicinity. One of the terminals receives hydrocarbon products, such as unleaded gasoline, for storage and distribution for retailers. This infrastructure is quite important for the local and national economy, and justifies the actual concern with oil spill accidents.

Ria de Aveiro is a mesotidal lagoon (Dias *et al*., 2000), within which the semidiurnal tides are the main forcing mechanism of its dynamics. The lagoon has several fresh water sources composed by rivers and small streams and ponds, which contribute to the fresh water input in the lagoon (Figure 1). The main source of freshwater is the Vouga River which discharges into the Espinheiro channel, and represents approximately 2/3 of the overall lagoon fluvial input. Its mean flow is about 1.8×10^6 m^3, which is considerably lower than the tidal prism at the lagoon mouth that ranges between 65.8×10^6 m^3 and 139.7×10^6 m^3 (Lopes *et al*., 2013). In the Laranjo bay inflows the Antuã, while at the heads of S. Jacinto, Ílhavo and Mira channels inflow the Cáster, Boco and Ribeira dos Moínhos, respectively. The wind stress and waves influence are restricted to disperse areas of the lagoon in rare situations of extreme weather conditions (Dias, 2001). The lagoon can be considered vertically homogeneous, except occasionally when fresh water inflows are high and the upper parts of the lagoon can present vertical stratification (Dias *et al*., 2000; Vaz *et al*., 2009).

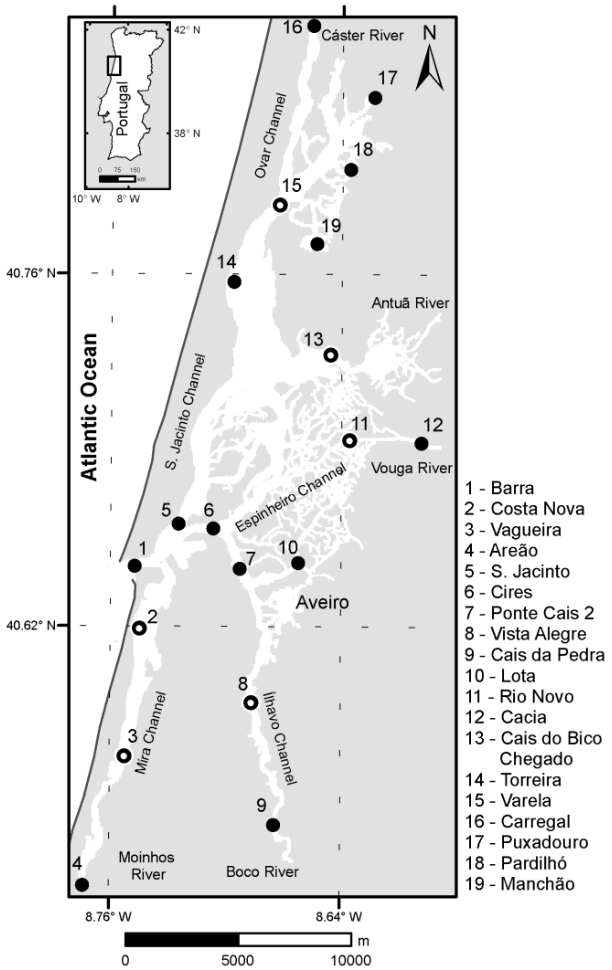

Figure 1. Map of the Ria de Aveiro with its main fresh water contributors. All stations represented by black circles, except Varela, are used for hydrodynamic calibration; for salt and heat transport, the stations used in the calibration have a white dot in its symbol.

METHODOLOGY

The complexity of the geometry of the Ria de Aveiro requires a multi-scale model based on unstructured grids, in order to resolve properly the narrow and meandering channels of the lagoon. The choice fell on the community model SELFE 3D (www.stccmop.org/CORIE/modeling/selfe/), from the Centre for Coastal Margin Observation and Prediction (CMOP), located in Beaverton, Oregon, USA (www.stccmop.org). This numerical model adopts a semi-implicit Eulerian-Lagrangian scheme applied to unstructured grid of finite elements (Zhang and Baptista, 2008). SELFE solves the 3D shallow-water equations, with hydrostatic and Boussinesq approximations, and transport equations for salt and heat. The primary variables that SELFE solves are the free-surface elevation and 3D velocity, 3D salinity and 3D water temperature; further details are presented in Zhang and Baptista (2008).

SELFE can be run in parallel mode, which reduces computational time significantly (Zhang and Baptista, 2008). This is a particularly relevant factor as this model is to be applied as part of an operational forecasting system, for real time forecast of hydrodynamics.

SELFE was used in previous applications to the Ria Aveiro lagoon (Rodrigues *et al.,* 2009a, b, 2012; Azevedo, 2010), proving to be an adequate tool to forecast the local dynamics. The implementation described in this study integrates the expansion of the numerical domain used in those applications, which is enlarged to the Atlantic Ocean. The domain used is based on a grid available from previous work (Oliveira *et al.,* 2007; Picado *et al.,* 2010; Rodrigues *et al.,* 2012; Lopes *et al*., 2013). The domain was extended from the shore till the edge of the continental platform, approximately 65 km from shore, to the west of the Iberian Peninsula. This extension was necessary to test the model robustness using atmospheric variables forcing.

Additionally, inside the lagoon, the resolution was increased in some areas, depending on their relevance. Changes were performed mainly in areas where the configuration and depth of the lagoon were altered due to the dredging or other interventions. The enlarged domain has an area of approximately 6400 km^2, comprising 62252 elements and 36486 nodes; the finite elements have a side length ranging from 2 to 8000 m. The domain has six open boundaries, one at the sea that covers all nodes in the ocean, and five fluvial boundaries at the main fresh water contributors.

As SELFE is a 3D model, a vertical structure has to be defined, and this vertical grid can use S coordinates or hybrid SZ coordinates, which can resolve both bottom and surface layer. For this application, the grid has a hybrid SZ coordinates system, with seven pure sigma coordinates levels, equally spaced, for the top surface layer, based on the previous work from Rodrigues *et al.* (2009a, b, 2012). Below the pure Sigma coordinates, eight layers are defined from 100 to 3000 m, as the domain extension reaches the edge of the platform. Both bottom and surface layers are resolved, thus simulating the bottom friction effect and resolving the surface horizontal velocities

The domain bathymetry was also updated with the most contemporary bathymetric data collected from recent surveys, mainly for the main channels. The data used is from 2011, for the main channels, and 2012 for the area of the commercial port, providing a good coverage and resolution for these parts of the lagoon. For the secondary channels and smaller water courses, datasets from the 1987/88 surveys were used. For the offshore part of the grid, dataset from the 2011 GEBCO surveys provided bathymetric data for the Iberian Peninsula west coast and open sea.

Sea Surface Elevation Model Calibration

The numerical model uses as open boundary conditions the input from the five fresh water contributors and tide from the Atlantic Ocean (salinity equals to 36). The model also takes into account the atmospheric forcing, such as air temperature, wind, atmospheric pressure, humidity and flux radiation. The aim is to have the best quality boundary conditions to implement in the numerical model, thus expecting better results in the simulations.

The initial salinity and water temperature fields are built based on the spatial distribution of the grid nodes in the domain. The highest salinity values, 36, are located in the open sea and in the area located right in front of the tidal inlet, station 1 (Figure 1). Then salinity gradually decreases towards the channels heads, reaching zero closer to the fresh water contributors. For the initial temperature conditions, the values vary from 14.7 to 16.5 ºC; the highest values are in the oceanic part of the grid and its variation is similar to salinity.

The hydrodynamic model was calibrated using sea surface elevation data from 18 measuring stations (Figure 1) located across the domain. The calibration used observations from several surveys performed in 2002/2003.

The direct comparison between observations and simulations led to the calculation of the Root Mean Square Error (RMSE) (eq. 1), Skill (eq. 2) and the relative error (Δ) (eq. 3). The equations used to obtain these values were the following (Dias, 2001; Dias and Lopes, 2006a,b):

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left[\zeta_0(t_i) - \zeta_m(t_i)\right]^2\right]^{1/2} \tag{1}$$

$$Skill = 1 - \frac{\sum_{i=1}^{N}\left|\zeta_m(t_i) - \zeta_0(t_i)\right|^2}{\sum_{i=1}^{N}\left(\left|\zeta_m(t_i) - \bar{\zeta}_0\right| + \left|\zeta_0(t_i) - \bar{\zeta}_0\right|\right)^2} \tag{2}$$

$$\Delta(\%) = \frac{RMSE}{Tidal\ Range} \times 100 \tag{3}$$

where ζ_o and ζ_m are observed and predicted sea surface elevation, respectively, $\bar{\zeta}_0$ is the average observed elevation and N is the number of measurements in the time series.

River flow estimation

The Ria de Aveiro simulation comprises the contribution of five fresh water sources namely, the Vouga, Boco, Cáster, Antuã and Ribeira dos Moínhos. The main contributor is the Vouga river, followed by the Cáster and the Antuã. The Boco is a small contributor and Ribeira dos Moínhos is composed by a network of pounds and underwater sources, which are not entirely known (Figure 1). There are only two real-time fresh water stations from Sistema Nacional de Informação de Recursos Hídricos (SNIRH) located in Vouga and Antuã basins, recording periodically river flow data (Figure 2). The data available is measured far from the lagoon, and is scarce and incomplete; thus fresh water inputs to the lagoon have to be estimated from climatological analysis supported with previous *in-situ* observations.

In order to include the fresh water flows into the hydrodynamic model, two different strategies for river flow estimation were used: the first adopts, as a reference, data from a measuring station in the river Vouga (Ponte Redonda), this will be designated as method A; the second uses the SWAT watershed model (Neitsch *et al*., 2011) to estimate the flow, this will be designated as method B.

Method A uses observations from an *in-situ* flow measuring station located at the Ponte Redonda, Vouga river, located a few kilometres upstream from the lagoon.

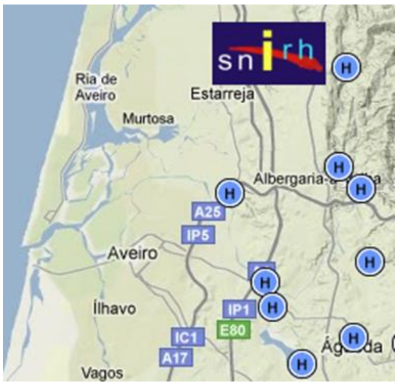

Figure 2. Location of fresh water measuring stations for the Vouga and Antuã river basins (http://snirh.pt).

The flow for the Vouga at the lagoon entrance is estimated with the following equation, which takes into account the Vouga basin area:

$$flow\ Vouga = flow\ Ponte\ Redonda\ \ 0.35$$

The estimated flows for the other fresh water contributors are based in river basin areas proportionality.

Method B applies the SWAT watershed numerical model to estimate the flow according to the terrain conditions, such as basin area, basin run-off, precipitation, soil infiltration (Arnold *et al.*, 1998; Neitsch *et al.*, 2011).

The hydrologic cycle is simulated based on the water balance (Setegn *et al.*, 2008, Akiner *et al.*, 2012):

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$$

where SW_t (mm) is the final soil water content; SW_0 (mm) is the initial soil water content on day i, t (days) is the time; R_{day} (mm) is the amount of precipitation on day i, Q_{surf} (mm) is the amount of surface runoff on day i, Q_{gw} (mm) is the amount of return flow on day i, E_a (mm) is the amount of evapotranspiration on day i, and W_{seep} (mm) is the amount of water entering the unsaturated zone from the soil profile on day i.

The SWAT model was implemented to the Vouga basin using, as a base, the topography obtained from SRTM (http://srtm.usgs.gov/). The soil usage, which is also important in terms of terrain run-off, was built based on a map from 2006, whilst the soil physical properties were gathered from a 1:1000000 map; both maps were supplied by the European Environment Agency. In order to complete the initial conditions, meteorological data, such as monthly air temperature, relative humidity, wind velocity and direction and solar radiation was gathered for the area concerned; these datasets were for a 30 years period, for 8 stations from the Portuguese Institute for the Sea and Atmosphere (IPMA). Precipitation gauges were chosen according to data availability, thus 6 stations were selected because they had over 30 years of daily precipitation values available (SNIRH). Flow data was collected for several stations along the Vouga basin to be used for model calibration and validation. Based on the model calibration and validation, the flow, for the lagoon fresh water contributors, was estimated for the period necessary for this study.

Salt and heat transport simulations

To compare both methods for flow estimation, the period from December 1st, 2012 till January 18th, 2013 was simulated; this period was chosen because adequate quality data, for several stations, was available for the whole period. For this particular exercise, seven stations were used for water free surface elevation and six stations for salinity and water temperature (Figure 1). The 7th station is located at the entrance of the inlet, which is important in assessing the quality of the tidal signal arriving from the ocean. The data was obtained from a tide gauge in use since the 1970s.

The boundary conditions implemented for the simulations were water elevation, water temperature and salinity for the ocean open boundary (data obtained from reanalysis available from http://www.myocean.eu/). Atmospheric conditions obtained from the WRF model from the University of Aveiro (http://climetua.fis.ua.pt/weather) for the whole grid. These boundary conditions were implemented in both sets of simulations, the first with flows estimated from method A and the second with the flows obtained from method B.

RESULTS AND DISCUSSION

SSE Model Calibration

According to Dias *et al.* (2009), the RMSE values should be compared with the local tidal amplitude. Typically, if the error is lower than 5%, the agreement between observed and simulated data is considered excellent; if the error is between 5 to 10%, the agreement is considered good.

An excellent fit is found at the measuring stations located nearest the lagoon inlet (Table 1), where the tidal signal is strongest and less energy is dissipated. As the morphology of the channel increases in complexity, the model has more difficulties to replicate the hydrodynamic conditions. At the lagoon central area the fit is still good, while for the stations located the furthest away from the inlet the model encountered some difficulties in replicating the hydrodynamics, mainly when the model simulates the flow in the narrow channels. As the most relevant area for the oil spill forecast is concentrated in the Port jurisdiction area, close to the tidal inlet, considering it is more prone to an accident due to maritime traffic from the Aveiro harbour, the lower values that were found in this area reveal that the quality of the simulation is considered good for these purposes. Consequently, the calibration and validation was successful, considering the RMSE, Skill values and also by direct comparison between observations and simulations.

Table 1. Values for RMSE, Skill and relative error (Δ) error obtained for the hydrodynamic model calibration for the whole 18 measuring stations.

Station	***RMSE***	***Skill***	***Tidal range* (m)**	**Δ (%)**
Barra	0.0867	0.9967	3.39	2.56
Costa Nova	0.0982	0.9954	3.01	3.27
Vagueira	0.2407	0.9590	2.79	8.62
Areão	0.4163	0.7627	1.59	26.10
Cais de Pedra	0.3460	0.8844	1.81	19.14
Vista Alegre	0.2759	0.9322	1.97	13.97
Ponte Cais 2	0.1088	0.9945	2.92	3.76
Lota	0.1807	0.9843	3.19	5.67
Cires	0.1599	0.9888	3.06	5.22
São Jacinto	0.1712	0.9839	2.82	6.06
Rio Novo	0.9432	0.4203	2.58	36.61
Cacia	0.2844	0.9432	2.26	12.57
Laranjo	0.3587	0.8984	2.54	14.12
Torreira	0.3335	0.9014	1.97	16.96
Manchão	0.5255	0.6667	1.92	27.42
Pardilhó	0.5180	0.6063	1.76	29.37
Puxadouro	0.5200	0.5943	1.44	36.23
Carregal	0.3640	0.8261	1.78	20.43

Salt and heat transport simulations

The two methods for estimating river flows were evaluated against salinity and water temperature (not show in this study) data at the six stations (Figure 1). Figure 3 shows the comparison between salinity observations and model predictions using both flow estimation methods. This variable was selected considering variable it is particularly sensible to freshwater flows. To quantify the accuracy of the model predictions, the RMSE and Skill between observed and predicted salinity were determined (Table 2). The results show that the simulation with method A provides a better fit between observations and predictions for all stations, although the predicted salinity values are most of the times lower than the observations, especially at low tide (Figure 3). Both methods overestimate the freshwater flows being imposed at the model open boundaries. The only exception is for Chegado (Figure 3), where the best fit was obtained with method B, and method A underestimates the fresh water from Cáster River.

When analysing the RMSE for both strategies, method A provides the best results; the same occurs for the Skill. The RMSE present major differences mainly for the stations located in the main channels (Costa Nova, Vagueira and Varela); when the stations are located further away from the tidal entrance and therefore closer to the river's mouth, in the narrowest parts of the lagoon, the difference in RMSE values decreases significantly. For the Rio Novo station, located in the Vouga River, similar RMSE values are found for both methods. Method B was primarily implemented to replicate the Vouga River, as this area has the best coverage in terms of hydrological and meteorological stations; thus both methods have similar estimations for the Vouga.

Table 2. RMSE and Skill values obtained for both flow estimation methods, for the 6 measuring stations.

Station	***RMSE A***	***Skill A***	***RMSE B***	***Skill B***
Costa Nova	3.9425	0.8674	16.0973	0.4346
Varela	5.7349	0.7111	11.7804	0.4162
Rio Novo	9.4886	0.4620	10.1195	0.3672
Vagueira	5.7479	0.8871	13.4164	0.4526
Chegado	8.4000	0.7191	10.1021	0.5308
Vista Alegre	7.7904	0.6613	17.8931	0.3971

When analysing the Skill, significant differences are observed between simulations, with the best fit found again for method A, except for Rio Novo station where the values do not differ significantly. For this station the agreement between predictions and observations is poor, revealing that the Vouga River flow is probably overestimated. The best fit is found for the Costa Nova and Vagueira stations, which are located in the same channel; this may be due to a good estimation of the freshwater discharge in this channel and to the high resolution of the numerical grid in this area of the domain.

CONCLUSIONS

The SELFE implementation developed for Ria de Aveiro reproduces accurately the tidal propagation and salinity patterns in the central area of the lagoon. This is the most relevant area for

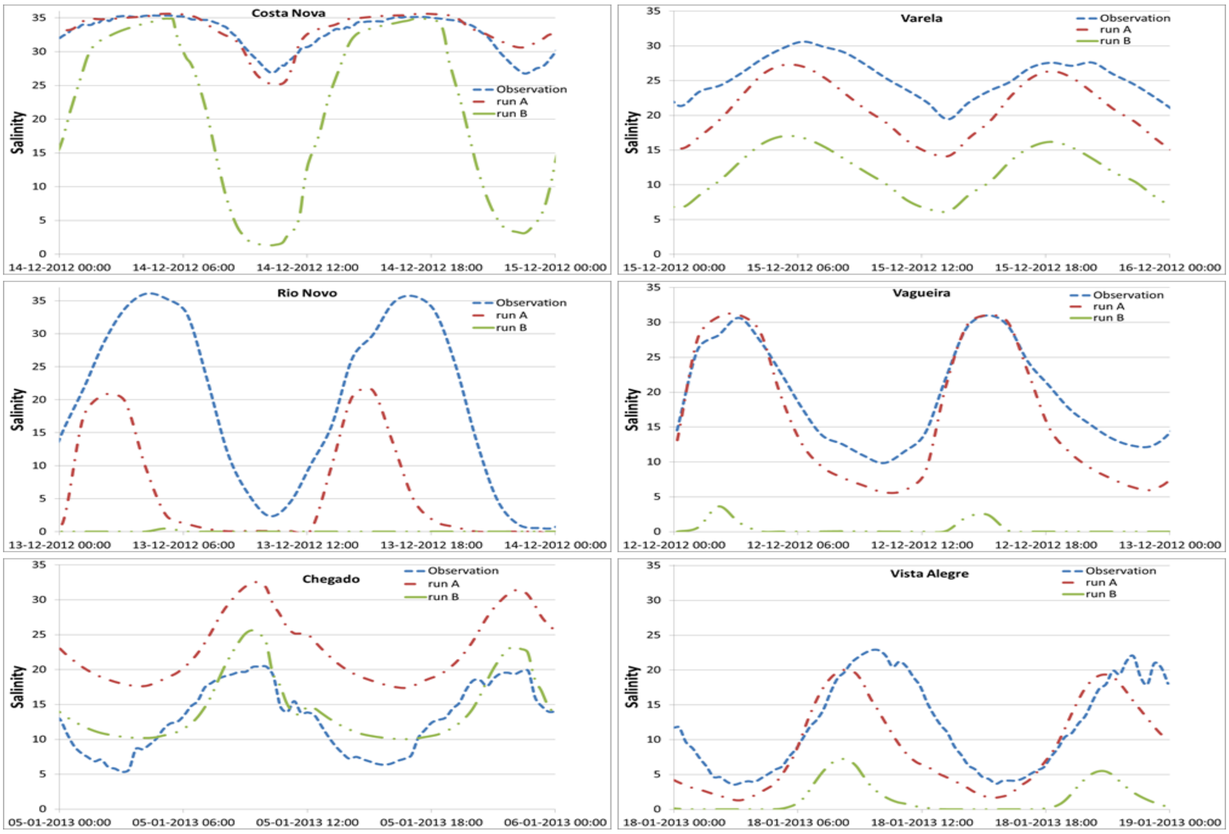

Figure 3. Salinity variation during a full tidal cycle, for the 6 measuring stations. ••••: Observed data; □ • □ •: runs with flow estimation using method A; □ □ ••: runs with flow estimation using method B

this study, considering it is more prone to accident due to maritime traffic from the Aveiro harbour. The best results for salinity simulations are found when the fresh water flows are estimated using the method A, based on the use of freshwater flows measured at Ponte Redonda, which is the nearest real time measuring hydrologic station, rather than the use of the SWAT basin model. This application is therefore ready to use to predict hydrodynamic conditions in the frame of the operational system developed for the Ria de Aveiro.

ACKNOWLEDGEMENTS

The European Union, under the European Regional Development Fund and INTERREG IV B: Atlantic Area Transnational Programme, supported this study through the research project SPRES-2011-1/168. The Portuguese Foundation for Science and Technology FCT also supported this study in the frame of the research project PTDC/AAC-AMB/113469/2009 - PAC:MAN, co-funded by COMPETE, QREN, FEDER. The second and fourth authors are co-funded by the Portuguese Foundation for Science and Technology FCT grants SFRH /BPD/87512/2012 and SFRH/BPD/73089/2010, respectively. The authors thank António Baptista, from CMOP, and Joseph Zhang, from VIMS, for the model SELFE. The team also thanks the Port of Aveiro authority for all the data and support provided in the development of this study and Polis Ria de Aveiro for the data provided.

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