Journal of Coastal Research	SI	75	123-127	Coconut Creek, Florida	2016

David and Goliath Revisited: Joint Modelling of the Tagus and Sado Estuaries

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ABSTRACT

Ribeiro, A.S.; Sousa, M. C.; Lencart e Silva, J. D., and Dias, J.M., 2016. David and Goliath Revisited: Joint Modelling of the Tagus and Sado Estuaries. *Proceedings of the 14th International Coastal Symposium* (Sydney, Australia). *Journal of Coastal Research*, Special Issue, No. 75, pp. 123-127. Coconut Creek (Florida), ISSN 0749-0208.

The Tagus and Sado estuaries discharge in the same coastal region into the Portuguese continental shelf. Several studies focus on the investigation of the complex circulation at the mouth of Tagus or Sado estuaries, however, the interaction between these two systems was never taken into account and were not performed previous studies dedicated to this topic. To study this important issue, numerical modelling is an important tool that allows researching the interaction between plumes under different conditions. Thus, it was developed an implementation of the three-dimensional model Delft3D-Flow integrating Tagus and Sado estuaries and adjacent shelf to investigate the complex interaction between flows. The numerical model was calibrated using sea surface height, salinity and water temperature data, and then applied to research the role of river discharge and wind effects on the plumes interaction. To examine the response of the estuarine plumes to different wind directions, four scenarios of moderate winds were considered blowing from each of the main four compass points. Two markedly different realistic scenarios were chosen: moderate and high Tagus and Sado River discharges. Independently of rivers discharges, the results revealed an intrusion of the Sado plume in Tagus estuary. This intrusion occurred in the bottom layers in all scenarios due to the ambient coastal current, even when the river discharges decreases. The reverse pattern was not observed, demonstrating an unexpected impact of the smaller estuary on the larger.

ADDITIONAL INDEX WORDS: *Freshwater flow, Tagus estuary, Sado estuary, Delft3D-Flow.*

INTRODUCTION

For centuries, estuaries have been regions of extremely high importance to human kind. These regions are characterized by their high productivity due to river discharges, through their role as nurseries for several animal species and by providing sheltered anchorages and easy navigational access to the Ocean. Here, small and large-scale mixing processes act to produce high mixing rates and spatially inhomogeneous concentration distributions, namely the river plumes. River plumes provide a mechanism for horizontal redistribution of nutrients and pollutants, because they spread and can advect material across long distances as coastal currents (Anderson *et al.*, 2005) and are susceptible to wind and tidal forcing (Choi and Wilkin, 2007; Otero *et al.*, 2008; Sousa *et al.*, 2014a). These conditions determine the pattern of horizontal freshwater dispersal of estuarine plumes (McCabe *et al.*, 2009; Walker, 1996).

Several rivers have their mouths in the western coast of the Iberian Peninsula, such as Tagus and Sado estuaries (Fig. 1). Given the close relationship between the Tagus and Sado estuaries, it is understandable that these two hydrodynamic distinguished systems have their discharges on the same coastal region. The Sado estuary is located south of the Tagus estuary, which is the most important freshwater source flowing into this coastal region.

In fact, the Tagus and Sado estuaries have different characteristics and dynamics, such as the topography, freshwater volume discharged and the shape of the estuary. For this reason, there are various studies using numerical models focusing on the investigation of the complex circulation of the Tagus or the Sado estuaries (Fortunato *et al.*, 1997; Martins *et al.*, 2001; Vaz *et al.*, 2009). However, the interaction between these two systems was never taken into account and there were no previous studies dedicated to this topic. The development of numerical models contemplating both Tagus and Sado estuaries as one system is a real scientific state-of-the-art challenge. This model implementation has the ability to show plume interaction patterns over shelf or even giving some insights about punctual water intrusions from the neighbor river.

Thus, the main objective of this paper is to study the propagation patterns of the Tagus and Sado estuarine plumes on the coastal region, and its interaction on the circulation and hydrography on the Tagus and Sado estuaries.

DOI: 10.2112/SI75-025.1 received 15 October 2015; accepted in revision 15 January 2016.
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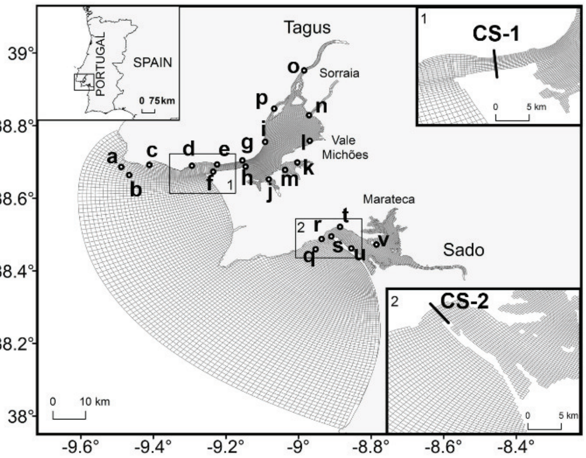

Figure 1. Location map of the study area with location of the stations used to calibrate and validate the model (white circles), Cross-sections at Tagus estuary mouth (CS-1) and Sado estuary mouth (CS-2) and freshwater inflows (black dots).

STUDY AREA

The Tagus and Sado estuaries are located on the western coast of Iberian Peninsula (38°47'N, 9°30'W to 37°58'N, 8°53'W) (Fig. 1).

The Tagus estuary has a total area of 320 km^2. A deep, narrow inlet channel and a shallow inner bay compose the estuary. The inlet channel is 15 km long (W-E), 2 km wide and reaches depths of 40 m, constituting the deepest part of the estuary. The inner bay is about 25 km long and 15 km wide, being the shallowest part of the estuary and has complex bottom topography with narrow channels, tidal flat areas and small islands on the inner most part of the estuary (Fortunato *et al.*, 1997). The tides are semidiurnal, presenting tidal ranges from 0.75 m in neap tides in the mouth to 4.3 m in spring tides in upper estuary (Fortunato *et al.*, 1997). The hydrography of the estuary is modulated by the tidal propagation and fluvial discharge from three sources of freshwater flowing into Tagus estuary: the Tagus and Sorraia Rivers and the Vale Michões tributary.

The Sado estuary is located south of Tagus estuary, with a total area of 100 km^2. It is about 20 km long and 4 km wide, with maximum depths of about 50 m and an average depth of 8 m. The tide is semidiurnal, with amplitudes varying between 1.6 m in spring tides and 0.6 in neap tides (Martins *et al.*, 2001). The estuary has intertidal sandbanks, which separate the estuary in two zones: the lower estuary behaves as a coastal lagoon with freshwater influence, and the upper estuary with a freshwater dependent behavior (Martins *et al.*, 2001). The upper estuary has two freshwater sources: the Marateca tributary and the Sado River, with 10% and 80% of the total freshwater input respectively.

METHODS

Numerical model

The hydrodynamic simulation of the study area was performed using the Delft3D-Flow modeling system. This platform was setup with a 553×174 cells curvilinear irregular grid with a mean resolution of ~100 m in the area of the interest (tidal channels) and ~1500 m at the offshore open boundary (Fig. 1). The bathymetry used results from the interpolation to the numerical grid of a set of topo-hydrographic surveys. The model uses 15 sigma layers with refined surface layers comparing to the intermediate and the bottom layers, due to most important dynamics related to the freshwater plumes occurrence in the surface layers.

Transport conditions and tidal propagation are calculated based on inputs from the Portuguese Coast Operational Modelling System (PCOMS) (http://www.maretec.org/). The propagation of the tide was modelled by prescribing a linearized Riemann invariant (Deltares, 2011) (weakly reflective boundary condition), i.e. a combination of water levels and velocities analog to the Flather (1976) and Chapman (1985) open boundary conditions. Additionally, it was prescribed the use of a per-layer specified velocity profile at ocean open boundaries.

A heat transport model was applied, taking into account air temperature, relative humidity and net solar radiation to calculate heat losses from convection, evaporation and back radiation. These data was obtained from NCEP reanalysis with a temporal resolution of 6 h. The wind intensity and direction are obtained from a local implementation of the Weather Research and Forecasting model (www.wrf-model.org), with a resolution of 4 km. A total of 5 freshwater points were defined as outflows representing the Tagus, Sorraia, Vale Michões, Sado and Marateca rivers/tributaries.

Calibration

The hydrodynamic calibration was performed comparing the measured and predicted time series of sea surface elevation (SSE) for 20 stations distributed throughout the lagoon (Fig. 1), and comparing the harmonic constants of the tides generated by the model to the respective values of the field data (Ribeiro, 2015). As an example of the model calibration results, Table 1 shows the calculated values of root mean square errors (RMSE) and Skill, for previous used Tagus and Sado stations. The best model results were obtained for the stations located near the estuary's mouth, indicated by the higher skill and lower RMSE values, and the highest disagreements were found for the most inner parts (Table 1).

The salt and heat transport model was calibrated using CTD profiles obtained in two locations outside the Tagus estuary (Fig. 1). The comparison between predicted and observed water temperature values (Figs. 2a and 2c) shows that the water temperature is well represented in both stations, with differences between predictions and observations around 1.5°C. Salinity profiles (Figs. 2b and 2d) show the same pattern, with differences comprising 0.5. These values can be explained by low resolution (~6 km) of the open ocean boundary forcing. These results are similar to those found in Vaz *et al.* (2009).

According to these results is considered that the model reproduces the hydrodynamic behavior and the heat and salt transport of the study area and consequently was considered calibrated.

Table 1. *Error values for tidal water levels.*

Estuary	Station	RMSE (m)	Skill
Tagus	c	0.0874	0.9967
	g	0.1190	0.9954
	j	0.1345	0.9944
	l	0.1529	0.9938
Sado	q	0.0595	0.9984
	s	0.0801	0.9974
	v	0.1102	0.9957

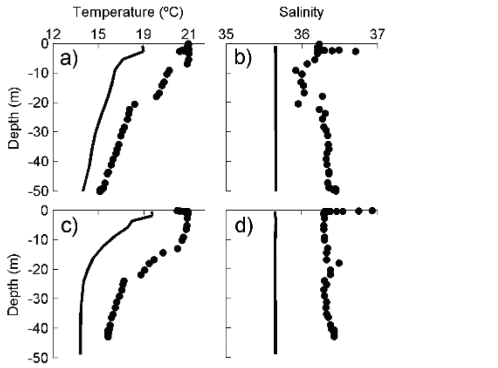

Figure 2. Observed (points) and predicted (line) water temperature and salinity vertical profiles for the sampling stations a (a, b) and b (c,d).

Model scenarios

Different scenarios were developed to investigate the necessary conditions to observe the intrusion of water from the neighboring estuary in the Tagus and Sado estuary, as well as visualize the propagation path of the estuarine water masses in the coastal region. The scenarios were run for 10 days after two weeks spin-up, under winter season of 2009-2010 conditions and produced under the conditions as the calibration run.

Following the methodology adopted by Sousa *et al.* (2014b), a statistical analysis to the river discharge was applied. Thus, two total different rivers inflow were used: high and moderate discharges (Table 2).

Taking into account these discharges, a set of ten scenarios were defined, with idealized high and moderate discharges, with different wind directions and typical moderate winds of 6 m s^{-1} blowing from each of the main four compass directions.

Two passive tracers were also introduced in all model runs, one for Tagus estuary inflows and the other for Sado estuary inflows, with a concentration of 1000 kg m^{-3} in order to investigate the estuarine plumes propagation through the domain and observe the exchanges between the estuaries.

Table 2. *River discharges estimations for January.*

	River discharges (m^3 s^{-1})				
	Tagus	**Sorraia**	**Vale Michões**	**Sado**	**Marateca**
High	11575	2771	83	1167	119
Moderate	324	45	8	35	7

RESULTS

The modelling results of the passive tracers are depicted in Fig. 3, showing the hourly cumulative advective transport determined through the cross-sections in front of both estuaries (Fig.1, sections CS-1 and CS-2) under various forcing conditions. The cumulative advective transport was also filtered with a 33 h low-pass filter in order to remove tides and high frequency fluctuations, allowing the transport analysis only due to wind and freshwater discharge.

During the high discharge event, without wind forcing and after 6 days, a small intrusion of the Sado plume is observed at the Tagus estuary (Fig. 3a). A similar pattern under the southward and westward wind scenarios is observed (Fig. 3a). Under northward winds, a maximum in cumulative advective transport (1.8×10^9 kg) of the Sado tracer across the mouth of the Tagus (CS-1) is reached on the eighth day, falling to 1.0×10^9 kg on the nine day. In the eastward scenario (Fig. 3a), a negligible influence of the Sado plume intrusion is observed, showing that for this condition, the Sado plume does not influence the Tagus dynamics.

On the other hand, Tagus plume does not propagate to the Sado estuary during the simulation (Fig. 3b). Taking into account these results, hereafter, the influence of Tagus plume in Sado plume is not considered.

Over the moderate river discharge event (Fig. 3c), Sado plume took less time (5 days) to reach Tagus estuary under westward wind scenario. For the other wind conditions, the pattern is very similar to the high river discharge event.

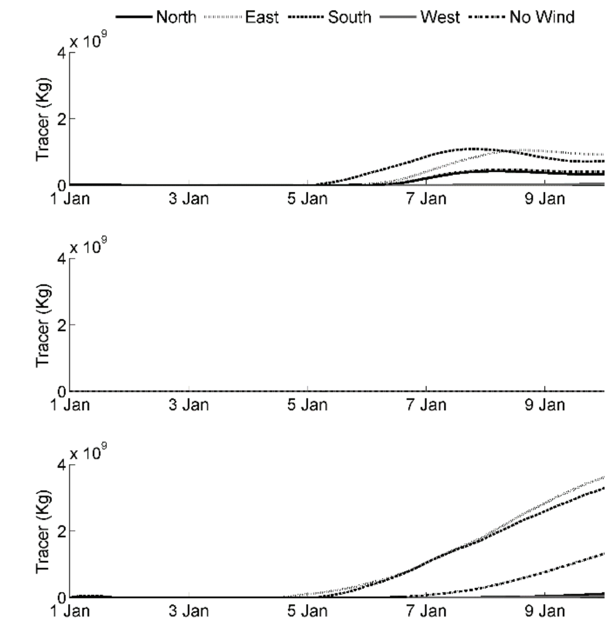

Figure 3. Cumulative advective transport of Sado tracer in CS-1 section (a, c) and Tagus tracer in CS-2 (b), under high river discharges (a, b) and moderate (c) river discharges, for the different wind conditions.

Considering the previous results, events of moderate-to-high Sado River discharge result in plume intrusion into Tagus estuary. Thus, the distribution of the tracers at the deepest region of the Tagus inlet channel (CS-1) was investigated in order to evaluate the effect of Sado plume on the hydrodynamic features of the Tagus.

Under high river discharges and for all wind conditions, the concentration of Tagus tracer is higher on the surface layers than at the bottom ones, which indicates that a more buoyant Tagus plume flows out of the estuary (Fig. 4a), whilst the denser water containing the Sado tracer flows upstream the Tagus estuary at the bottom layers (Fig. 4b). These results are corroborated by the zonal velocity and density profiles (Figs. 4c and 4d). The positive velocities are observed at bottom layers (Fig. 4c), indicating that the Sado plume propagation flows in these layers.

When the river discharges decreases (Figs. 4e, 4f, 4g and 4h), the pattern remains the same found for high river discharges. However, in these conditions, the zonal velocities are positive in all water column, indicating that a higher volume of denser sea water (Fig. 4h), along with Sado plume, flows towards Tagus estuary (Fig. 4f). This result is more evident in the presence of westward and northward wind conditions. The result for eastward wind conditions corroborate Figs. 3a and 3c outcomes, where low concentrations of Sado tracer are recorded in the CS-1.

DISCUSSION

The analysis of Figs. 3 and 4 reveal that the Sado plume intrudes into Tagus estuary, however, the contrary pattern does not occurs. This intrusion is more evident during northward winds. The northward winds confine the plume close to the coast, which enhance the mixing process within the plume, forming vertically well-mixed and narrow plumes (Soares *et al.*, 2007). This result is consistent with the findings obtained in the Wallapa Bay (Columbia) plume study (Banas *et al.*, 2004).

The Sado tracer is shown to intrude into the Tejo estuary in the absence of wind forcing, reproducing the classic ROFI dynamics (Simpson, 1997). When wind forcing is applied, westward and northward winds transport more Sado water into the Tagus than when the wind is blowing to south or east. This shows again the expected behavior of a density gradient under a rotational reference system. The results show this behavior at the start of sixth day, in southward and in the absence of wind scenarios, when the Sado plume if found to intrude in Tagus estuary. For eastward wind, the Sado plume took longer to reach the Tagus estuary than in the other scenarios, with the presence of residual cumulative concentrations, indicating that eastward winds are not favorable for the Sado plume propagation to Tagus estuary.

According to the results obtained in velocity and density profiles (Figs. 4c, 4d, 4g and 4h), the river discharge plays an important role in plume spreading compared to wind. Using a numerical model, Mao *et al.* (2008) also show that the variations in Yellow River runoff are important to the salinity not only in the area around the river mouth but also in entire Bohai Sea.

The currents at the Tagus inlet channel in neap tide (the velocities are lower comparing to spring tide (Fortunato *et al.*, 1997) are favorable to form a downstream flow towards the ocean. This structure is enhanced by the increase of the river discharges, leading to a higher density gradient in the water column (Figs. 4d and 4h).

Although the ambient current can restrain the Sado plume intrusion by advecting the Tagus freshwater outflow outside the estuary, it cannot eliminate the drive of the Sado plume. This is due to the apparently negligible effect that the ambient coastal current has on the current structure at the Tagus inlet channel. Similar results were obtained by Guo and Valle-Levinson (2007) in Chesapeake Bay.

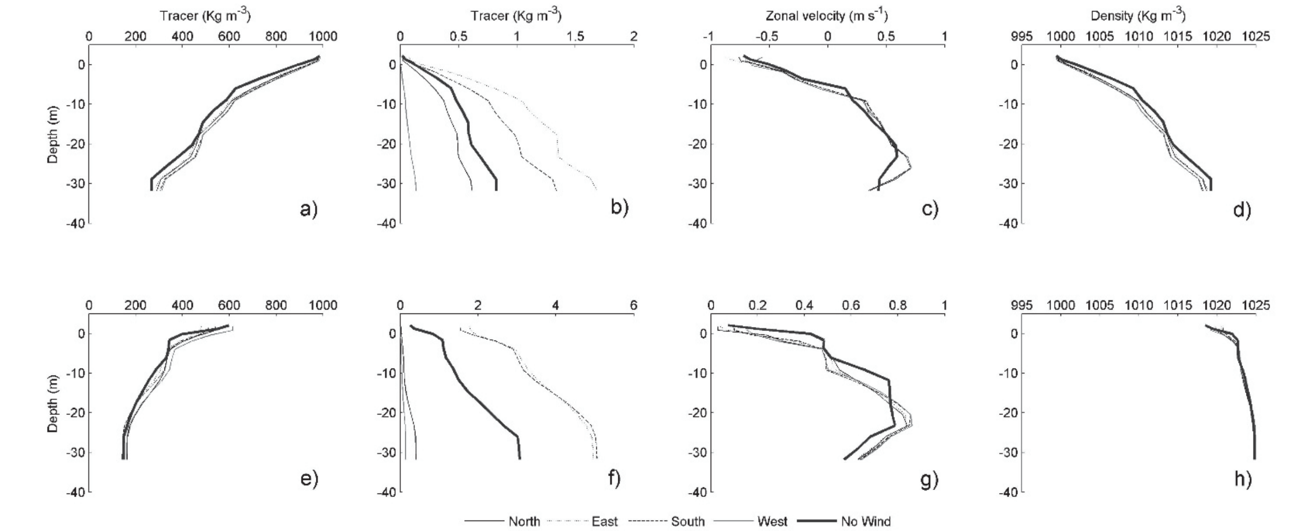

Figure 4. Vertical profiles of Tagus tracer (a, e), Sado tracer (b, f), zonal velocity (c, g) and density (d, h) registered at a location in the center of CS-1 under high (a, b, c, d) and moderate river discharges (e, f, g, h), for the different wind conditions for 10 days after the simulation start, during neap tide.

The density pattern can be partly explained by the research of Fujiwara *et al.*(1997), which observed that in large estuaries and Regions of Freshwater Influence (ROFIs) (Simpson, 1997) the fate of the density field is controlled not only by buoyancy and tidal forcing but also by the Tagus inlet channel morphology under the influence of Earth's rotation.

Garvine (1999) examined the tidal effects on the downstream intrusion of buoyant water and concluded that shelf tides have a detectable but moderate influence on plume downstream intrusion. In this study, this pattern was observed for high river discharges. When the river discharges decreases, despite Sado small outflow compared to the Tagus, the Sado outflow was the only one to propagate a significant distance to affect the neighbor estuary.

CONCLUSIONS

The three-dimensional hydrodynamic model Delft3D was applied to Tagus and Sado estuaries in order to investigate their interaction. Numerical experiments were conducted testing several scenarios with different wind directions and river discharges.

The results for a high discharge suggest an intrusion of the Sado estuarine water in Tagus estuary after a 10-day simulation for all scenarios, except for eastward wind scenario. Otherwise, the Tagus plume does not reach the Sado estuary. When the river discharges decreases, the results showed that during northward and westward winds, the Sado plume influences with more intensity the Tagus estuary. However, Tagus plume does not propagate to the Sado estuary. During these conditions, the Sado plume is advected to north, and flows on the bottom layers towards Tagus estuary, whereas Tagus estuarine water flows on top layers.

In summary, despite the difference in magnitude of these estuaries, the small Sado plume influences the large Tagus estuarine water, even with lower river discharges.

ACKNOWLEDGMENTS

The second author of this work has been supported by the Portuguese Science Foundation (FCT) through a postdoctoral grant (SFRH/BPD/99707/2014). This study was partially supported by the National Foundation for Science and Technology – FCT, through CESAM (UID/AMB/50017/2013).

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