Tidal dispersion and flushing times in a multiple inlet lagoon

João D. Lencart e Silva†, Carina L. Lopes†, Ana Picado†, Magda C. Sousa† and João M. Dias†

†NMEC, CESAM
Departamento de Física
Universidade de Aveiro
3810-193 Aveiro, Portugal
j.lencart@ua.pt
carinalopes@ua.pt
ana.picado@ua.pt
mcsousa@ua.pt
joao.dias@ua.pt

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ABSTRACT

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The Ria Formosa is a tidal multi-inlet shallow-water coastal lagoon located in the south of Portugal, subjected to the dry Mediterranean climate. The tide controls the Ria's exchange with the adjacent shelf for most of the hydrological year except for isolated torrential run-off events. Episodes of low hypoxia reported in the literature may be related to the lagoon's flushing time, affecting its shellfish production valued at 20 – 50 million €y^{-1}. Over the past decades several observational and modelling studies presented values for the capacity of the tide to renovate the water inside the Ria. However, these studies lack either the spatial resolution to yield results unaffected by numerical diffusion or analyze a very limited part of the lagoon's territory. In this work, we use a very-high resolution hydrodynamic model to assess the flushing time exclusively due to tidal forcing inside the Ria Formosa. A bi-dimensional implementation of the finite-volume/finite-difference Eulerian–Lagrangian hydrodynamic and transport model (ELCIRC) was used, allowing for the local refinement of the computational domain, which best suits the lagoon's complex morphology. The present model configuration was validated for tidal propagation with sea surface elevation collected in 1979/80 at 11 lagoon stations. The validation results show a good agreement between predicted and observed elevations, with root mean square errors lower than 20 cm and skill values higher than 0.98. A set of experiments were carried out by releasing a conservative tracer at different stages of the tide at discrete points of the Ria, where possible environmental hazard hot-spots are located and the flushing e-folding time calculated from the tracer's dilution. The results are discussed taking into account the propagation of the tide in this multi-inlet, meandering topography. Evidence is presented of topographic trapping due to the complex spatial distribution of the phase lags of the semi-diurnal tidal constituents. This evidence explains the significant increase of the flushing time from the inlets to the head of the channels, thus justifying the use of detailed spatial resolution when modelling such a complex system.

ADDITIONAL INDEX WORDS: *topographic trapping, Ria Formosa, contamination risk, exchange dynamics.*

INTRODUCTION

Lagoons are transitional zones between terrestrial and marine aquatic environments, usually providing shelter and nursery areas for a variety of species and often hosting anthropogenic activities which may pose a significant threat to these ecosystems. Their main characteristic of buffer zone between open ocean and land can be the source of their vulnerability to hazards related to the time the lagoon takes to exchange water through its inlets.

The Ria Formosa is a mesotidal multi-inlet shallow-water coastal lagoon located in the south of Portugal, subjected to the dry Mediterranean climate (36º06'N, 8º02'W to 37º03'N, 7º32'W, Figure 1), spanning ~55 km along the coast and ~6 km across its widest zone (Dias *et al.*, 2009). The tide controls the Ria's exchange with the adjacent shelf through 6 inlets, Ancão, Faro-Olhão, Armona, Fuseta, Tavira and Cacela on most of the hydrological year, except for isolated torrential run-off events (Newton and Mudge, 2003). The lagoon is composed of salt marshes, sand flats and a network of natural and partly dredged channels. Its complex geometry, with innumerable channels and straits and multiple inlets, makes it a considerably challenging study area. However, the study of the controls of the circulation of its water is essential to assist the management of its conflicting uses, such as tourism, fisheries, aquaculture and salt extraction industries, as well as a natural habitat for various species of birds which gives the Ria its status of Natural Reserve.

The tide in the Ria Formosa is mainly semidiurnal with the range varying from 1.3 m in neaps tides to more than 3 m in spring tides, resulting in a submerged surface area between 14 - 43 km^2 (Instituto Hidrográfico, 1986). This results in a large tidal prism in relation to its volume, with 50% to 75% of the lagoon's volume flowing through its inlets (Salles *et al.*, 2005). Nevertheless, episodes of low hypoxia reported in the literature at the inner zones of the lagoon may be related to the lagoon's flushing efficiency there, affecting its shellfish production valued at 20 - 50 million €y^{-1} (Ferreira *et al.*, 2012).

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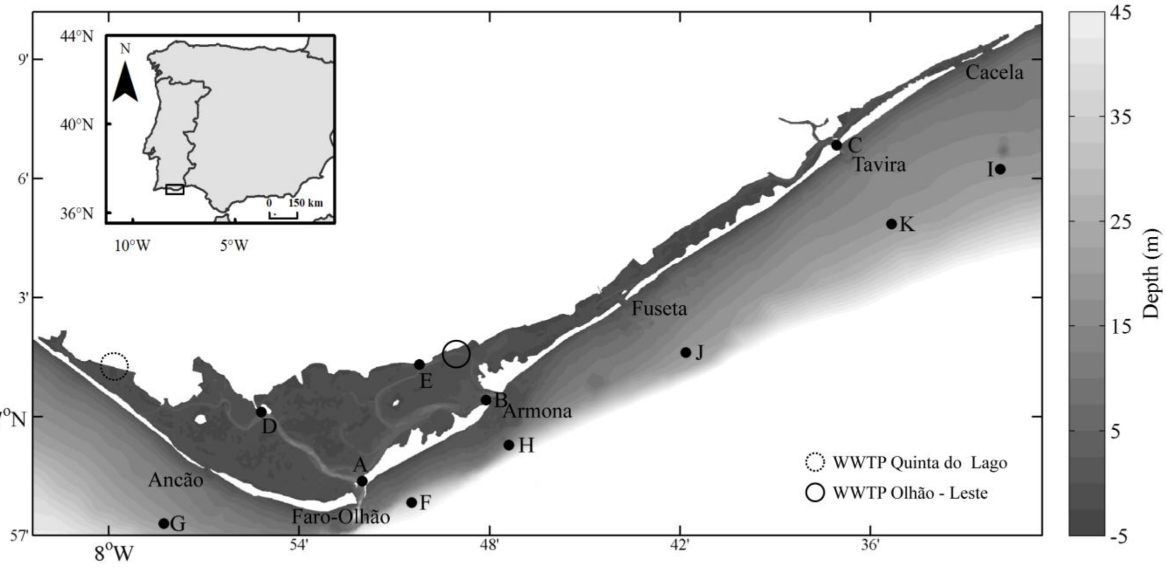

Figure 1. Location map of the Ria Formosa lagoon showing: bathymetry; location of the SSE calibration stations (A to K); names of the 6 inlets; location of the wastewater treatment plants.

The Ria can be broadly divided into 3 cells: i) the westernmost cell served by the Ancão, Faro-Olhão and Armona inlets; ii) the central cell served by the Fuseta inlet; and iii) the easternmost cell served by the Tavira and Cacela inlets (Fig. 1). Of these three cells the westernmost is the largest, most complex and subjected to more anthropogenic influence.

Over the past decades several observational and modelling studies presented values for the capacity of the tide to renew the water inside the Ria. Newton and Mudge (2003) and Mudge *et al.* (2008) used water temperature and salinity as tracers to describe the circulation around the western part of the Ria and give a measurement of the water residence time inside that area. Neves (1988) applied a numerical model to study the Ria's tidal exchange with ocean, however, the low resolution of the model used in this study was unable to resolve the more intricate morphology of the lagoon, thus giving good results for the areas near the inlets, but failing to do so in the higher reaches where higher risk to long water residence is expected. Dias *et al.* (2009) studied the Ria with a high-resolution model, but their work was mainly focused on the effects of the relocation of the Ancão inlet.

In this article we aim to give an overall, high spatial resolution account of the flushing time in the Ria Formosa solely forced by the tide, highlighting the main features of its distribution and providing an analysis of the risk of exposure to a hypothetical release of an harmful pollutant from two risk sites reported in APA and ARH (2012).

Tidal flushing of the lagoon's water can occur by advection of the water by a coastal current away from the inlets tidal excursion, by tidal shear dispersion (Fisher, 1979), tidal rectification (Li and O'Donnell, 1997) and chaotic dispersion (Ridderinkhof and Zimmerman, 1992). On the other hand, several methods have been suggested to assess the exchange and transport processes between restricted zones and the ocean. We choose to adopt the definition of flushing time (τ) of a time varying tracer concentration $C(t)$ as proposed by Takeoka (1984), where:

$$\tau = \int_{t_0}^{\infty} C(t)\,dt \qquad (1)$$

For our case we assumed the continuously stirred tank reactor (CSTR) simplification, as in Monsen *et al*. (2002) where $C(t)$ can be found from:

$$C(t) = C_0 e^{-\frac{t}{\tau}} \qquad (2)$$

where τ can be found by linear regression, and C_0 is the initial tracer concentration:

$$\ln C(t) = -\frac{t}{\tau} + \ln(C_0) \qquad (3)$$

METHODS

Model

In order to best accommodate the complex morphology of interconnect channels and tidal flats of the Ria Formosa, we used for this study a hydrodynamic model relying on an unstructured grid. The ELCIRC (Zhang *et al*., 2004) hydrodynamic model uses a finite-volume/finite difference Eulerian-Lagrangian algorithm to solve the shallow water equations on a horizontal unstructured grid. In this application the model solves the Navier-Stokes shallow water equations for surface elevation and the bi-dimension water velocity with hydrostatic, Boussinesq and f-plane approximations. The integration in time is done with a semi-implicit scheme, where the barotropic pressure gradient in the momentum equation and the flux term in the continuity equation are treated semi-implicitly; the bottom boundary condition for the momentum equations is treated fully implicitly; and all other terms are treated explicitly.

For this study the tide was the only forcing applied, and was determined from the harmonic constituents calculated by Fortunato *et al.* (2002). A set of 11 harmonic Sea Surface

Elevation (SSE) constituents and mean sea level (Z_0, M_{sf}, O_1, K_1, N_2, M_2, S_2, MN_4, M_4, MS_4, M_6, and $2MS_6$) were prescribed at the boundary. The bed roughness was prescribed using the Manning formulation. For all of the scenarios described below, the model was started with unperturbed SSE and elevation, and a 2 day warm-up period was carried out by ramping-up the tidal forcing to production values. A 60 s time step was adopted to comply with the Courant-Friedrichs-Lewy stability parameter.

The model used in this study is based on the one used by Dias *et al.* (2009) and Dias and Sousa (2009), with further refinement in the horizontal where new bathymetric data was available. Based on the new bathymetric data, the Manning roughness coefficient was changed using the same depth-dependence strategy applied in Dias *et al.* (2009).

Given that no lagoon-wide survey of SSE or velocities were available under the most up-to-date bathymetric conditions, we chose to run the refined horizontal grid with the bathymetric data and respective bed roughness used in Dias *et al.* (2009) to check our model against the available SSE observations and the previously published model. The validation was done by comparing the measured and predicted time series of SSE for 11 stations (Fig. 1) from a 1979/1980 dataset using contemporary bathymetry. The validation results show a good agreement between predicted and observed elevations and in line with the previously published version of the model, with root mean square errors lower than 20 cm and skill values higher than 0.98.

The production scenarios were then run with an up-to-date bathymetry and inlet configuration.

Scenarios

In order to assess the flushing times in the Ria Formosa the lagoon was filled with an uniformly distributed passive tracer with a concentration of 1 kgm^{-3}. The model was then run for 75 days and the concentration outputted every hour of model calculation time.

After filtering the semidiurnal tidal signal out with a pl33 low-pass filter (Flagg *et al.* 1976; Beardsley *et al.*, 1985) transient flushing times were calculated for spring and neap tide conditions using Equation 3 by least-squares fitting a 5-day window and extracting τ. These fits add r^2 in a range 0.64-0.99 and p-values < 0.001. The calculation of an aggregated fortnightly value for the flushing time was made by extending the regression window to one full neap to spring cycle with the same satisfactory fit.

To assess the risk of exposure to a hypothetically harmful pollutant concentration (LD), was emitted from the locations of 2 wastewater treatment plants (WWTP – Fig. 1) a discharge of passive tracer in spring and neap tide conditions. The discharges were carried out in separate runs for each WWTP, for each of the tidal conditions with the same flow and concentration of 1 kgm^{-3} for 2 days. Hourly in each calculation point, the exceedance of LD was counted for 7 days of the simulation run (N_{LD}). An empirical probability of exceeding LD was calculated by dividing N_{LD} by the total simulation hours. For the purpose of this study we defined LD as 10% of the concentration at the discharge outlet.

RESULTS AND DISCUSSION

Spatial distribution of flushing time

Figures 2a and 2b show the residence times calculated for 5-day window around neap and spring tides, respectively. Common to both scenarios the zones near all of the inlets, with exception to the westernmost Ancão inlet, present very low flushing times of less than 50 hours. On the opposite extreme, the westernmost region served by the Ancão inlet shows flushing times reaching about 40 days under neap tide conditions.

As expected, the neap tide snapshot shows considerably longer flushing times, with channel margins near the Armona inlet and between this inlet and the Fuseta inlet assuming a relatively longer flushing than in the spring tide.

Comparing the M_{sf} constituent in the margins and in the deeper channel shows larger amplitude (~14 cm) in the former in phase with the spring tide. During neaps the semidiurnal mean sea level is lower and quadratic friction is distributed by a smaller water column, thus reducing the efficiency of tidal dispersion.

Over the full fortnightly cycle (Figure 2c), apart from the western cell serviced by the Ancão, Faro-Olhão and Armona inlets, the lagoon is efficiently flushed by the tide.

For the lagoon's western cell the results show that the main contributor for the flushing is the Faro-Olhão inlet, with very low flushing times in its vicinity and in the channel connecting this and the Armona inlet. This is due to the combined effect of a larger tidal prism exiting through the Faro-Olhão inlet and the higher tidal velocities inducing efficient tidal dispersion. In the main channel leaving the Faro-Olhão inlet to the northwest, outside the reach of the tidal excursion of this inlet, flushing time rises considerably, reaching 15 days for the western end of the lagoon.

Remarkably confined areas in the lagoon

Hill (1994) shows that in a single inlet lagoon, the M_{sf} phase lag on the spring tide indicates the level of choking of a lagoon. In the Ria Formosa, the M_{sf} constituent is roughly in phase with the spring tide, so in this aspect the Ria can be considered a leaky lagoon according to Kjerfve (1986) terminology. However, there are significant differences in amplitude of the M_{sf}, which can be negligible near the inlets and be as high as 0.5 m near the head of the channels in the more confined areas such as the westernmost area of Ancão peninsula. This indicates that within these areas exists a fortnightly cycle of water storage, which contributes to the decrease in the lagoon's flushing.

Another aspect leading to the confinement of the water in the lagoon is its meandering morphology, which leads to topographic trapping due to the complex spatial distribution of the semidiurnal tidal phases. Figure 3 shows the phase of the M_2 tide for the Ramalhete region. Between point A and point B, the tide lags ~40º where the mean M_2 velocity is ~0.3 ms-1 for an extension of ~3000 m. By the time the water, which started the flood at point A of the channel reaches point B, the tide there is already ebbing, channeling the water to the longer channel leading to the Faro-Olhão inlet. This water will return to the A-B segment in the next tide, thus resuming the trapping mechanism. This confirms the findings of Newton and Mudge (2003) and Mudge *et al.* (2008) who observed this behaviour using salinity and water temperature as tracers. Of the four flushing mechanisms mentioned in the introduction, the water in this channel is mainly affected by tidal shear dispersion and rectification. Given that the flow is essentially confined to the channel, the water is not affected significantly by chaotic dispersion nor advection by offshore, since the reversing trapping mechanism keeps the water from reaching the inlets, with a flushing time between 5 and 7 days.

Risk analysis

Figure 4 shows that a discharge at the Quinta do Lago WWTP (QdL) has higher values of LD spread by a wider area when released at spring tide. Inversely, the discharge at the Olhão-Leste WWTP (OL) has its main effect when discharged at neap tides.

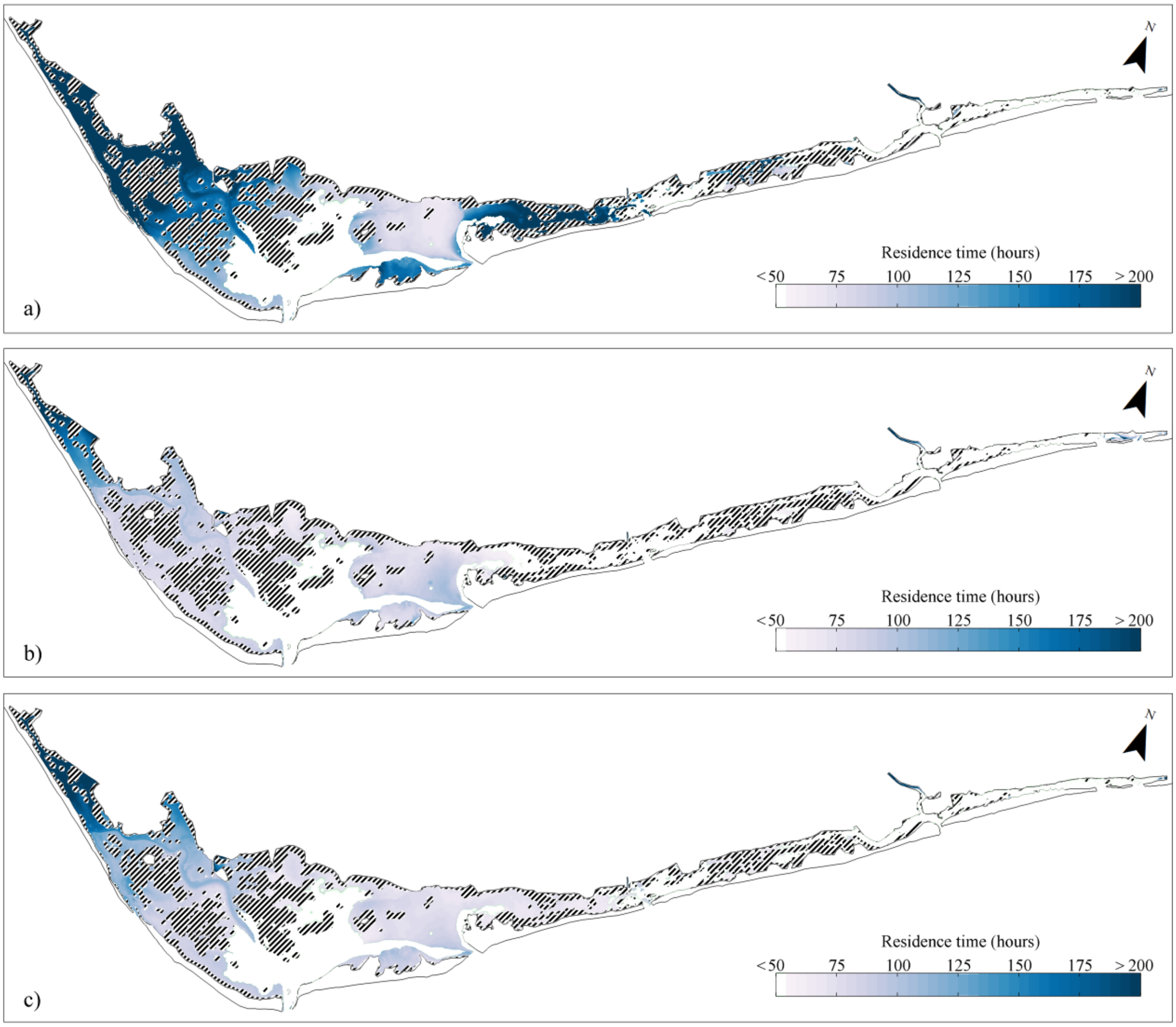

Figure 2. Flushing time in the Ria Formosa Lagoon (invalid regions in stripes): a) calculation for neap tide conditions; b) calculation spring tide conditions; c) calculation for full fortnightly cycle.

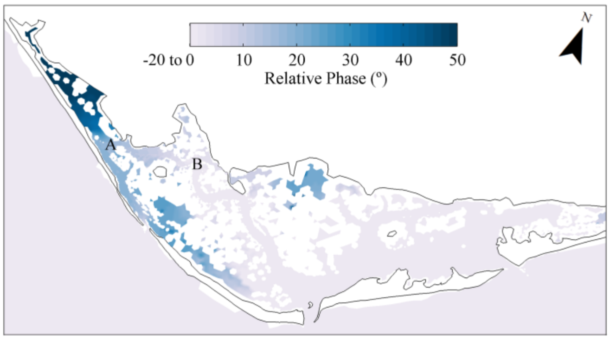

Figure 3. M_2 tidal constituent phase relative in the western cell of the lagoon relative to point. Segment AB representing the Ramalhete channel.

This contrast can be attributed to proximity of each of the discharge sites to a main inlet.

The OL site connects to the Armona inlet, which on a spring tide quickly flushes the affected area reducing the LD exceedance probability. Following the same rationale, the larger currents in neap tides in this area in comparison to the QdL site manage to spread the pollutant to a wider area before the Armona inlet is able to flush the water.

For the QdL case, low flushing in neap tides is responsible for the minute dissipation of the pollutant during the beginning of the neap to spring cycle, thus reducing the area exposed to LD. In the spring tide discharge scenario at QdL, low flushing of this western area combined with the enhanced tidal dispersion at spring tides works to spread the pollutant through a wider area before its concentration is diluted.

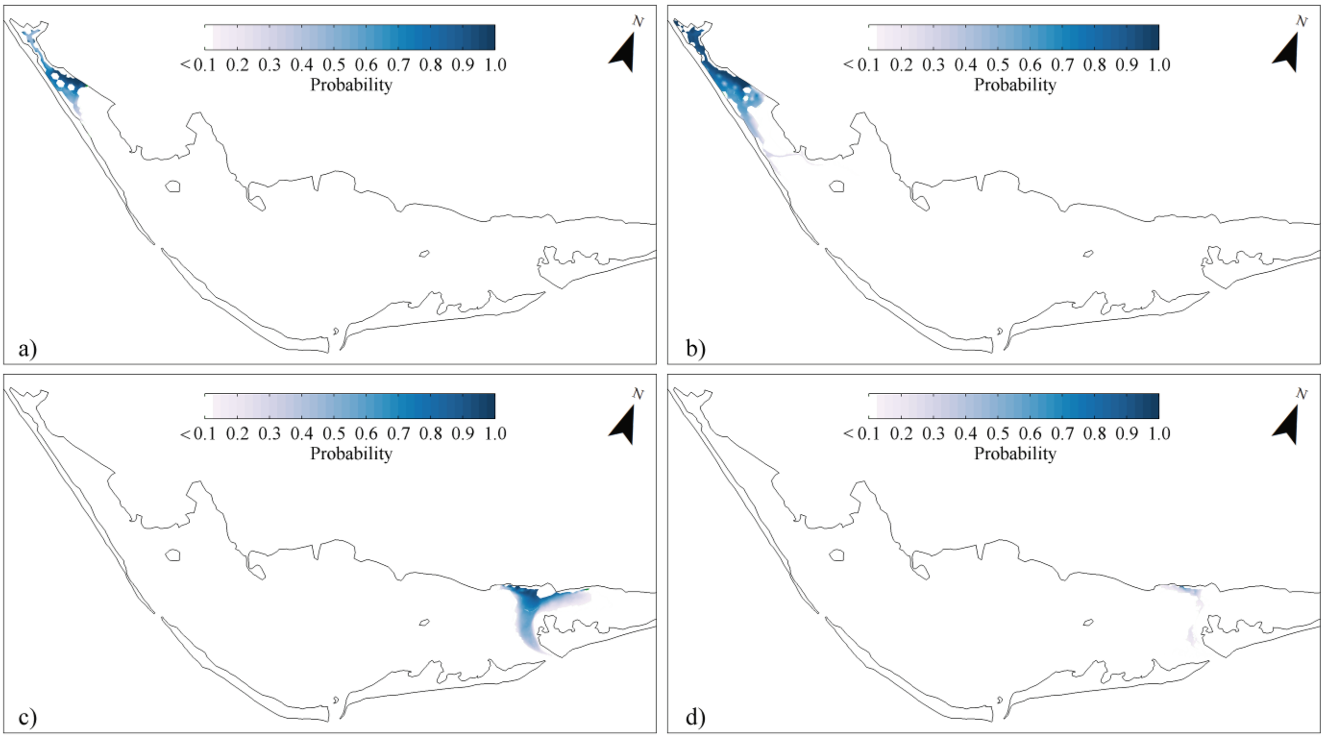

Figure 4. Probability of exceedance of LD: a) discharge in neap tide conditions at Quinta do Lago WWTP (QdL); b) discharge in spring tide conditions at QdL; c) discharge in neap tide conditions at Olhão-Leste WWTP (OL); d) discharge in spring tide conditions at OL.

CONCLUSIONS

A high resolution unstructured grid hydrodynamic model was used to assess the spatial distribution of the flushing time in the Ria Formosa lagoon solely due to tidal forcing.

It was found that although near the inlets the lagoon has very low flushing of less than 50 hours, further away from the inlets the residence time rises considerably, reaching about 15 days in problematic areas such as Ancão peninsula.

The main tidal controls found to these remarkably confined zones are the M_{sf} amplitudes there, reaching as high as 0.5 m in areas where depths are under 2 m, and topographic trapping due to the complex spatial distribution of the phase of semidiurnal tidal constituents.

Furthermore, a marked neap to spring cycle of flushing was found where the tide can efficiently flush the lagoon at springs but is unable to do so at neaps.

The release of a hypothetically harmful pollutant concentration (LD) in two locations of the bay showed tidal dispersion and the distance from an efficient exchange inlet combine to disperse LD for a wider area of increased exposure.

This work only takes into account the role of the tide in the control of the exchange between the Ria Formosa and the Atlantic Ocean. Although the tide is the main driver inside the Ria, due to the absence of significant density driven flow or relevant wind fetch, the shelf outside of the Ria is controlled by nearshore wind, remote wind, thermohaline circulation and mesoscale features of the Gulf of Cadiz. The circulation at the shelf may contribute to the lagoon's flushing through enhanced mixing with the ocean waters or by advecting the lagoon water away from the tidal excursion of its inlets. Conversely, trapping mechanisms such as downwelling and the formation of an inner shelf (Lenz, 1995) may lead to the permanence of the lagoon water within reach of its inlets and promote offshore connectivity between its 3 cells. Future modelling studies of the Ria's flushing time and the connectivity between its 3 cells should take into account the currents and mixing conditions at the Ria's neighbouring shelf.

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