Effect of morphological changes on the hydrodynamics and flushing properties of the Óbidos lagoon (Portugal)

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Abstract

This paper investigates the effect of natural and artificial morphological changes in a tidal inlet on the tidal propagation and on the water exchanges with the sea, through data analysis and numerical modeling. Bathymetric and tidal data reveal a strong seasonal signal, as a result of the changes in the relative importance of tidal and wave action: during the maritime winter the M2 tidal amplitude decreases by 50% and flood dominance increases. This trend is reverted during maritime summer, and tidal amplitudes can be further enhanced by dredging of the inlet.

Hydrodynamic and residence time (RT) simulations were set up for three different bathymetric configurations of the lower lagoon, representative of distinct situations. Hydrodynamic results confirmed that tidal propagation depends strongly on the bathymetric configuration. At the transitions between channels, tidal energy losses occur and flood dominance increases. Dredging the channels and repositioning the inlet throat improve tidal propagation and promote sediment flushing to the sea.

The spatial variability of RTs was evaluated through the integration of individual particle results in morphologically relevant units, while time variability was examined within the tidal and neap/spring cycles. Residence times depend heavily on the morphological changes associated with both dredging operations and inlet migration, and on the particle release time, both within the tidal cycle and within neap/spring cycles. The relative importance of each of these factors depends on the particle location within the lagoon. The upstream regions of the lagoon have very large RTs (years), as a result of the small tidal amplitudes and velocities. In some of these regions, RTs vary by a factor of 4 depending on the bathymetry of the inlet. In the lower lagoon, tidal amplitude also has a significant effect on RTs. Dredging the channels and repositioning the inlet throat from the southern margin to a central position improves the flushing of both southern and northern channels.

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1. Introduction

Coastal lagoons are shallow water systems connected to the sea by one or more entrances, and with little freshwater influence. The stability of their
inlets depends on an often delicate balance between tides and occasional floods, which promote the opening of the inlet, and the wave action, which feeds sediments from the coast into the lagoon. Human interventions in coastal lagoons are frequent, either to guarantee safe navigation or to avoid water quality problems resulting from insufficient water renewal. Many of these systems are maintained through regular dredging of the inlets, while many others have artificial structures, such as jetties and guiding walls, to prevent inlet migration or closure.

The Óbidos lagoon is a small and shallow coastal system located on the western Portuguese coast (Fig. 1). The lagoon is connected to the sea by a narrow inlet (on the order of 100 m), which undergoes severe migration on monthly time scales. Two main regions, with distinct morphological and sedimentary characteristics, can be identified in the lagoon: the lower lagoon, with several sand banks and channels with strong velocities, and the upper lagoon, characterized by low velocities and muddy bottom sediments (Freitas, 1989).

The upper lagoon comprises a large, shallow basin, with an average depth of 0.6 m relative to the Hydrographic vertical datum, two elongated bays (the Braço da Barrosa and the Braço do Bom Sucesso) and a small embayment on the southern margin (Poça das Ferrarias). The surface area of the upper lagoon has steadily decreased at least for the past 150 years due to land reclamation and accretion of the margins (Freitas, 1989; Henriques, 1992).

Freshwater flows enter the lagoon at both bays (Cal river at the Barrosa bay and Vala do Ameal at the Bom Sucesso bay) and in the central basin (Arnóia river). Freshwater input is generally very small. Average flows are about 3 m³/s (Vão, 1991), below 5% of the average tidal prism scaled by the M2 period (Rego, 2004). The Barrosa bay also receives wastewater discharges, which have considerably degraded the water quality of this water body. There are plans to discharge this sewage outflow to an ocean outfall in the future.

Tidal ranges vary between 2 and 4 m at the coast, and between 1 and 2 m inside the lagoon (Oliveira et al., 2005). The wave regime in front of the lagoon is very energetic, with significant wave heights exceeding 1 m during 88% of the time. Dominant wave directions are almost perpendicular to the beach, which faces 315°N, and wave periods range from 5 to 20 s (Oliveira et al., 2005).

The lagoon is characterized by large accretion rates and occasional closures of its inlet throat. This behavior is due to various factors. The length (over 2 km) and depth (about 2 m below mean sea level) of the main channel that connects the body of the lagoon to the sea damp the tidal amplitudes. The meandering and migration of the channels, as well as the ebb and flood sandbanks, further promote this damping of the tidal wave (Oliveira et al., 2005). Together with the small surface area of the lagoon (4.4 km² at mean sea level, 8.0 km² at high spring...
tide), this damping is responsible for a small tidal prism and for a limited ability of the tides to flush out the incoming sediments. In the upper lagoon, sedimentation is mainly due to inputs from the watershed (Freire et al., 2004).

Several engineering solutions have been implemented in the Óbidos lagoon over the last decade to promote tidal flushing, avoid inlet throat closure, protect the margins and stabilize the lower region channels. Dredging and repositioning of the inlet and lower channels have occurred frequently, either including the dredging of the northern channel alone (in 1999, 2001 and 2003) or dredging of both northern and southern channels (1995). Since dredging alone failed to avoid channel migration, which severely endangered the northern margin in the winter of 1993/1994, a guiding wall was built near the northern margin in 1999. Similar problems have also occurred in the southern margin in the past few years, leading to the placement of emergency sandbag walls and the development of studies for an overall solution to the system’s problems (Fortunato and Oliveira, 2004).

Several studies have been undertaken in this system over the last two decades, mostly focusing on its sedimentary properties and evolution (e.g., Freitas, 1989; Henriques, 1992) and on its biological properties (e.g., Gordo and Cabral, 2001). Given the general tendency for accretion and consequently the potential for the closure of the inlet, the search for a solution to avoid this problem motivated a former study that describes the hydrodynamics of the Óbidos lagoon (Vieira, 2001). Using an analytical and a 2D numerical model, Vieira (2001) showed that the lower lagoon controls the tidal prism, which increases with the cross-section of the channel, up to a certain limit. Most of the energy losses occur at the mouth of the inlet. The volume of maintenance dredging required to maintain the channel was estimated at 100,000 m³/year. However, perhaps for lack of bathymetric data, a detailed characterization of the hydrodynamics, accounting for the different bathymetric configurations, remained to be done.

The total or partial closure of the inlet has been a concern at least since the 15th century, when the inlet was occasionally artificially opened (Henriques, 1992). More recently, Gordo and Cabral (2001) concluded that the nursery function of the lagoon would be affected if human activities related to keeping the inlet open ceased. Closure of the lagoon would also deteriorate water quality, due to the input of sewage waters. In this context, understanding how the flushing properties of the lagoon depend on the bathymetric configuration is very important. Data from recent bathymetric surveys now allow an analysis of the retention properties of the system, focusing in particular on the impacts of the morphological changes.

This paper analyses the hydrodynamics and retention properties of the Óbidos lagoon, considering the strong bathymetric changes that occur on time scales of months to years. This study is performed through the analysis of recent bathymetric and tidal elevation data combined with hydrodynamic and particle-tracking numerical models. Field data provide a first cut at understanding the hydrodynamic properties of the system and the means to set up and validate the hydrodynamic model. Numerical models are then used to complement the hydrodynamic analysis and to quantify the spatial and temporal variability of residence times (RTs) for passive tracers.

Due to the rapid changes in bathymetry, the use of a morphodynamic model could be appealing for our objectives. However, these models are still of limited use in complex systems such as the Óbidos lagoon and prone to significant errors for medium-term simulations (Fortunato, 2006; Pinto et al., 2006). The present methodology, based on simulations for selected static bathymetric configurations, avoids these errors while providing a detailed analysis of the physical properties of the system.

This paper is divided into four sections. The methodology is presented first, including short descriptions of the data and of the numerical models and their application to the Óbidos lagoon. The analysis of the results follows. The final section summarizes the major findings.

2. Methodology

The present analysis combines recent field data with numerical models. First, bathymetric and water level data are used in a preliminary assessment of the morphological and hydrodynamic characteristics of the system. These data are then used to calibrate a hydrodynamic numerical model and to establish the bathymetry configuration scenarios which will be used in the detailed, numerically based hydrodynamic analysis. Afterwards, the hydrodynamic simulations are used to set up the conditions for the RT analysis. Finally, RTs for individual particles are integrated in space and
time to characterize the flushing properties of the lagoon.

The following sub-sections summarize the characteristics of the field data, the major properties of the selected models and the various concepts used in the Results section.

2.1. Bathymetric and water level data

Data available for this study included bathymetric surveys (Table 1), aerial photographs and water level time series (Fig. 1). Tidal data were measured at three stations inside the lagoon between December 2000 and December 2002 (IH, 2001a, b, 2002a, b). However, data are either unavailable or unreliable for extensive periods, in particular in the Barrosa bay, due to severe settling of the instrument. The vertical datum for the tidal stations was not determined.

Bathymetric data were analyzed, in combination with aerial photographs, to determine qualitative trends. In particular, the migration of the main channel was a major concern, since it was responsible for the erosion of the southern margin. Accretion rates were computed and averaged in the upper lagoon and within five zones with different behaviors in the lower lagoon (Fig. 1).

Tidal data were initially screened for errors. Errors were corrected whenever possible, and data were discarded otherwise. Correlations with meteorological time series (wind and precipitation) were performed to determine the importance of these effects on the hydrodynamics. Finally, harmonic analyses were performed with the software package of Foreman (1977). Since the goal was to determine the effect of bathymetric changes on the hydrodynamics, the harmonic analyses were performed for sequential 29-day records, using a moving window with a one-day step (McLean and Hinwood, 2000). This approach highlighted the evolution of the frequency content of the signal.

Water elevations were then used to analyze tidal asymmetry, through the difference between the ebb and flood durations. Tidal asymmetry was computed using synthesis of the harmonic analysis of monthly (29-day) records.

2.2. Hydrodynamic model

2.2.1. Model description and setup

Depth-averaged circulation was simulated with the shallow water model ELCIRC (Zhang et al., 2004). Although ELCIRC is a fully 3D baroclinic model, it was used here with a single vertical layer and neglecting density gradients. Due to the shallow depths and minor freshwater inputs to the Óbidos lagoon, its circulation can adequately be simulated with a depth-averaged model.

ELCIRC is part of a new generation of flow models which were developed for simulations within a wide range of spatial scales, ranging from the river to the deep ocean. Basic properties such as mass conservation, robustness and efficiency are sought in this model by the use of finite volumes, Eulerian–Lagrangian methods and a low-order interpolation/integration in space. Flexibility in discretizing complex bathymetries and geometries is achieved through unstructured grids in the horizontal plane. Intertidal flats are accounted for naturally in the model, given its finite volume formulation. Friction is parameterized with a Chézy formulation:

\[ \tau = c_d |u|^2 \]

where \( \tau \) is the bottom friction, \( \rho \) is the water density, \( c_d \) is the friction coefficient and \( u \) is the velocity.

Simulations were conducted for the most unfavorable conditions for water renewal, i.e., without

<table>
<thead>
<tr>
<th>Date</th>
<th>Spatial coverage</th>
<th>Scale</th>
<th>Notes</th>
<th>Tidal data available?</th>
</tr>
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<td>Whole lagoon</td>
<td>1:5000</td>
<td>Incomplete data in the inlet</td>
<td>No</td>
</tr>
<tr>
<td>November 2000</td>
<td>Lower lagoon</td>
<td>1:2000</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>July 2001</td>
<td>Lower lagoon</td>
<td>1:2000</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>November 2001</td>
<td>Lower lagoon</td>
<td>1:2000</td>
<td>Incomplete data in the inlet</td>
<td>Yes</td>
</tr>
<tr>
<td>April 2002</td>
<td>Lower lagoon</td>
<td>1:2000</td>
<td>Incomplete data in the inlet</td>
<td>No</td>
</tr>
<tr>
<td>October 2002</td>
<td>Lower lagoon</td>
<td>1:2000</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>September 2004</td>
<td>Whole lagoon</td>
<td>1:2000</td>
<td>Incomplete data in the inlet</td>
<td>No</td>
</tr>
</tbody>
</table>
freshwater inflow. Ocean boundary conditions for the main six constituents (Z0, O1, K1, S2, M2 and N2) were extracted from the regional tidal model of Fortunato et al. (2002a). The computational domain, which extends from the upstream limits of the lagoon to the continental shelf, was discretized with an unstructured grid (Fig. 2). The resolution varies from 1.3 km near the open boundary to 4 m in the narrow channels and in the inlet throat.

To analyze the system under different bathymetric conditions, hydrodynamic simulations were conducted for three bathymetric settings inside the lagoon (Fig. 3): November 2000, July 2001 and October 2002 in the lower lagoon and June 2000 in the upper lagoon.

2.2.2. Model calibration and validation

ELCIRC was calibrated for the bathymetric conditions of July 2001 and validated for the October 2002 bathymetry (Fig. 3), by comparison with water elevation data. Calibration and validation conditions were selected considering both the strong bathymetric changes in the lagoon and the unavailability of time series of velocity data. Although the two bathymetric settings were among the best available, the data are scarce at the inlet throat and inexistant at the ebb sandbanks, hence limiting the accuracy of the simulations.

Calibration and validation were performed using two error measures:

- the root mean square error, which is the most frequently used error measure for tidal models performance:

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\eta_m - \eta_d)^2},
\]

where \(\eta_m\) and \(\eta_d\) are the water levels computed by the model and obtained by harmonic synthesis of the data, respectively, and \(n\) is the number of time instants.

- M2 amplitude error, which evaluates the ability of the model to reproduce the tidal prism, which is vital for flushing and sediment transport calculations:

\[
E_{amp} = 100 \frac{A_{M2m} - A_{M2d}}{A_{M2d}},
\]

where \(A_{M2m}\) and \(A_{M2d}\) are the amplitudes of the main tidal constituent (M2), computed from the model results and the data, respectively.

ELCIRC was calibrated for the friction coefficient, deemed important due to the small depths of the lagoon. Calibration was performed using the range of friction factors defined in Table 2.

RMSEs are similar to those obtained for other coastal systems in Portugal, based on the use of ELCIRC and other hydrodynamic models (Fortunato et al., 1999, 2002b; Oliveira et al., 2006), but can be considered relatively large due to the small tidal amplitude in the Óbidos lagoon: the standard deviation of the synthesized observations in July 2001 are on the order of 40 cm (Table 2). These errors were expected due to the large bathymetric changes of the system, often occurring at time scales smaller than 1 month (Fig. 4), and the uncertainties
in the bathymetry at the inlet throat. The strong dependence of tides on these bathymetric changes is thus expected to be one of the major sources for these errors. This error measure is only marginally dependent on friction, but indicates that run 3 provides the best results.

M2 amplitude errors are very sensitive to the friction coefficient, also indicating that run 3 has the smallest errors (Table 2). These errors are also non-negligible as M2 data amplitudes are 0.40 and 0.38 m at Cais do Arelho and Bico dos Corvos, respectively. Run 3 also provides the smallest errors for other constituents such as the O1. The validation simulation was thus performed with a friction coefficient of 0.0064. Except for the bathymetric conditions, all other parameters are identical to those used in the calibration run. Both RMSE and amplitude errors increased (Table 2), but are still within an acceptable range. The variability of the bathymetry at small time scales is perhaps responsible for this increase, as it leads to non-synoptic measurements within each bathymetric data set.

Table 2
Error measures for the calibration runs

<table>
<thead>
<tr>
<th></th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
<td>Run 2</td>
</tr>
<tr>
<td>Friction coefficient $c_d$ (—)</td>
<td>0.0037</td>
<td>0.0055</td>
</tr>
<tr>
<td>RMSE (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cais do Arelho</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Bico dos Corvos</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>$E_{amp}$ (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cais do Arelho</td>
<td>31</td>
<td>22</td>
</tr>
<tr>
<td>Bico dos Corvos</td>
<td>28</td>
<td>16</td>
</tr>
</tbody>
</table>

Fig. 3. Bathymetry used in the simulations: (a) lower lagoon, November 2000; (b) lower lagoon, July 2001; (c) lower lagoon, October 2002; (d) upper lagoon, June 2000.
2.3. Particle-tracking model

The quasi-3D particle-tracking model VELApart (Oliveira and Baptista, 1997; Oliveira and Fortunato, 2002) is used here to compute sediment pathways (Section 3.2) and to characterize the RT of passive tracers (in depth-averaged mode), based on the release of large numbers of particles (Section 3.3). Numerical errors in particle position are avoided through the use of an adapted, embedded, fourth-order Runge–Kutta integration, with user-specified closing error. The number of particles in each simulation and the horizontal diffusion coefficient of the tracer are also chosen by the user.

Sediment pathways are computed based on sediment properties, driven by advection, horizontal and vertical diffusion and fall velocity. To adequately account for the effect of vertical diffusion (Proehl et al., 2005), a resuspension term, based on the vertical gradient of diffusion, is included. The vertical diffusion coefficient is computed following van Rijn (1984). For these simulations, the vertical distribution of velocity is assumed logarithmic:

\[
\bar{u}(\sigma) = \bar{U} \frac{\ln((H(\sigma + 1)/z_0))}{\ln([H/z_0] - 1)},
\]

where \( \bar{U} \) is the depth-averaged velocity, \( \sigma = (z - \eta)/H \) and \( z_0 \) is the roughness height (= 1 cm).

Based on particle pathways, VELApart can also be used to calculate RT for water parcels affected by both advection and diffusion (Oliveira and Baptista, 1997). This model has been successfully used for this purpose in other systems (e.g., Oliveira and Baptista, 1997; Fortunato et al., 2002b). This methodology is being used on several types of systems, ranging from coral reefs to the deep ocean (e.g., Hofmann et al., 1991; Choi and Lee, 2004) and provides the flexibility for a detailed characterization of the space and time variability of RTs. Two alternative definitions of RT can be used inside VELApart, accounting for different behaviors of the water parcels (Oliveira and Baptista, 1997).

“Once-through” RTs are defined as the time required for a particle released at a particular location in the estuary to leave the system, through a user-defined cross-section. In contrast, for the evaluation of “re-entrant” RTs, tracers are allowed to move in and out of the estuary with the tide, until they leave the system definitely. These two definitions of RTs are useful to provide the range of variability of RT with the specific environmental conditions: the re-entrant RTs quantify the flushing...
of a water parcel due to river flow and tides alone, while once-through RTs represent the opposite situation, where other mechanisms fully prevent the return of the tracer to the system. These mechanisms can either be physical (e.g., wind, littoral currents) or biochemical (e.g., the rapid decay of coliforms in high-salinity environments, coastal predators).

Given the limited capability of particles to return to the system as a result of the constricted inlet (Rego, 2004), the once-through RT definition was used herein.

The choice of the horizontal diffusion coefficient in the particle simulations should be based on the physics represented in the model and on the horizontal model resolution. In the presence of fine tidal and topographic resolution, such as the one used herein, explicit horizontal dispersion is not necessary (Proehl et al., 2005). However, wind effects are not considered in this study and may play an important role in tracer removal in the confined bays. To account for wind effects and to prevent particles from being stuck in corners and in the inner bays, a small diffusion coefficient of 0.01 m²/s was used herein.

Tracking accuracy is controlled by the pathway closing error. Sensitivity analyses performed in other systems indicate that this parameter can have a wide range of variation, depending on the system’s characteristics. The presence of strong spatial gradients of velocity, for instance, may require the use of closing errors on the order of 10⁻⁷ m (Oliveira and Baptista, 1997). In systems with smoother flow fields, a closing error on the order of 10⁻³ m is sufficient (Fortunato et al., 2002b). Given the relatively smooth flow field in the Óbidos lagoon, a closing error of 10⁻³ m was used.

Residence time calculations were performed for eight particle release times, four on neap tides and four on spring tides. On each tide, release times correspond to high and low tide and to ebb and flood slacks. Particles were released at each grid nodal location and were followed for a total simulation time of 5 years.

3. Results and discussion

3.1. Data-based morphological and hydrodynamic analysis

Aerial photographs of the last 60 years show that the lower lagoon changed significantly over the years (Climaco, 2003; Freire et al., 2004): the number and position of the channels vary, and occasional closures occur. However, the lack of data prevents a detailed analysis at decadal time scales; so we focus here on shorter scales.

The analysis of the bathymetry and aerial photographs shows that the morphological behavior varies along the lower lagoon. The downstream part of the main channel migrates very rapidly. Within a few months, a meander can form, evolve and disappear, involving migration of the channel of the order of 200 m (Fig. 4). Similarly, the flood sand banks in Zones 4 and 5 can change drastically within a month (Fig. 4b, c). In contrast, the upstream part of the channels and the main sandbank evolve at a much slower rate. The south channel (Zone 1) has been accreting a few centimeters per year (Table 3) since it was dredged in 1995. The positions of the northern channel (Zone 2) and the upstream sandbank (Zone 3) are also stable, although dredging was required to maintain adequate depths in the channel. A map of the lagoon from 1890 confirms that these two features are persistent (Girard, 1916).

In the upper lagoon, a comparison between the June 2000 and the September 2004 data sets reveals an average accretion rate of 3 cm/year. Accretion occurred mainly along the margins, indicating that the slow decline of the lagoon area identified by Freitas (1989) persists. Accretion was strongest in the two bays, where localized values close to 1 m were reached. This trend suggests that the bays can soon be separated from the main body of the lagoon in the absence of human intervention.

These strong bathymetric changes in the lagoon necessarily affect the hydrodynamics. The results of the moving window harmonic analysis at the three stations show a clear yearly cycle of the major tidal constituent, M2 (Fig. 5): the amplitude increases during the maritime summer (April–September) and decreases in the maritime winter (October–March). This behavior appears to be natural, although the dredging operations also promoted the growth of the tidal amplitude in 2001. This yearly cycle can be explained by the classical theory on the opposite roles of waves and tides on the stability of tidal inlets (e.g., Bruun, 1978): the wave-induced littoral drift tends to close the inlet, while the ebb jet flushes out the sediments that accumulate in the inlet mouth. During winter, littoral drift is stronger, and tends to close the inlet. During summer, waves abate and the tides tend to reopen the inlet. This
hypothesis is confirmed by the bathymetric comparisons (Table 3): in Zone 5, there is typically accretion in the winter and erosion in the summer. Overall, there would be a delicate balance between tides and waves that could easily be tilted to one side.

The results of the harmonic analysis are more difficult to interpret for smaller constituents due to noise (Figs. 6 and 7). Diurnal and the other semi-diurnal constituents appear to follow a similar seasonal trend (Fig. 6). However, diurnal amplitudes are less damped by the inlet than the semi-diurnal: the ratios between the amplitudes of the O1 and the M2 in the lagoon and at the coast are about 0.70 and 0.35, respectively. The inlet therefore acts as a filter, damping the higher frequencies more

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
<th>Zone 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>June</td>
<td>-6.9</td>
<td>-15.3</td>
<td>-10.6</td>
<td>-26.9</td>
<td>-49.5</td>
<td>-22.0</td>
</tr>
<tr>
<td>2000</td>
<td>November</td>
<td>-0.6</td>
<td>-13.4</td>
<td>1.6</td>
<td>13.5</td>
<td>-51.9</td>
<td>-10.2</td>
</tr>
<tr>
<td>2001</td>
<td>July</td>
<td>33.5</td>
<td>27.5</td>
<td>11.0</td>
<td>9.3</td>
<td>12.9</td>
<td>16.5</td>
</tr>
<tr>
<td>2001</td>
<td>November</td>
<td>1.4</td>
<td>-8.7</td>
<td>18.6</td>
<td>33.9</td>
<td>42.0</td>
<td>18.6</td>
</tr>
<tr>
<td>2002</td>
<td>April</td>
<td>6.3</td>
<td>10.5</td>
<td>-3.2</td>
<td>5.5</td>
<td>-37.8</td>
<td>-4.5</td>
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<tr>
<td>2002</td>
<td>October</td>
<td>0.6</td>
<td>-7.8</td>
<td>2.6</td>
<td>-0.5</td>
<td>3.3</td>
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<td>2004</td>
<td>September</td>
<td>3.0</td>
<td>-4.6</td>
<td>2.7</td>
<td>3.9</td>
<td>-10.6</td>
<td>-5.7</td>
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</table>

The main channel (Zones 2 and 5) was dredged in May–June 2001 and in March–May 2003, which explains the overall erosion. The zones are defined in Fig. 1. The bold values indicate the interval that contains the dredging operations.

Fig. 5. Amplitudes of the tidal constituent M2 in 2001 and 2002. The gray area indicates the dredging period.
than the lower frequencies. The energy in the semi-
diurnal band is partly transferred to other frequen-
cies. The MSf, due to the interaction between the
M2 and S2, has the second largest amplitude inside
the lagoon (Fig. 7). These large amplitudes of MSf
were generally confirmed by the hydrodynamic
simulations described below. Our interpretation
for these large amplitudes is related to the higher
mean water level in the lagoon relative to the sea.
This difference in mean water levels makes it easier
for sea water to flow into the lagoon during spring
tides than during neap tides. The times of highest

Fig. 6. Amplitudes of the tidal constituent O1 in 2001 and 2002. The gray area indicates the dredging period.

Fig. 7. Amplitudes of the tidal constituent MSf in 2001 and 2002. The gray area indicates the dredging period.
MSf amplitudes in the Óbidos lagoon generally agree with this interpretation, as these amplitudes are largest when spring tides are highest (March and September). Because March coincides with the end of the maritime winter, the inlet should also have a smaller cross-section, leading to the largest difference between mean water levels in the lagoon and in the sea. According to our interpretation, this largest difference should also promote the growth of the MSf. Due to the large amplitude of the MSf, the daily mean water levels are higher during spring tides and lower during neap tides.

The extraction of high-frequency constituents with small amplitudes from noisy records is particularly difficult (Hall and Davies, 2005), and the results are difficult to interpret. Instead, we examined tidal asymmetry, which results from quarter diurnal constituents (e.g., Friedrichs and Aubrey, 1988).

Tidal asymmetry, measured by the difference between the ebb and flood durations, plays an important role in the dynamics of non-cohesive sediments (e.g., Friedrichs and Aubrey, 1988; Fortunato and Oliveira, 2005). It is therefore reasonable to expect that morphological changes also affect this asymmetry. Indeed, the data suggest that the behavior of the ebb–flood differences has a negative correlation with the amplitude of the M2 (Fig. 8): these differences decreased during the summer 2001 and increased in the following winter. The ebb–flood difference slightly decreases again in the summer 2002 and starts to increase in the beginning of the winter 2002.

Besides tides, meteorological effects also affect the water level in the lagoon. For instance, a 22% correlation was found between the daily rainfall in the region and the difference between tidal elevation and tide predictions by harmonic synthesis at the Bico dos Corvos station (Rego, 2004).

3.2. Model-based hydrodynamic analysis

Model results were compared for simulations conducted for three bathymetric settings, which represent the system under very different conditions: November 2000, July 2001 and October 2002 (Fig. 3).

In November 2000, the lagoon has a very constricted entrance, located very close to the southern margin, with severe meandering of the main channel (Fig. 3a). The impact of the 1999 dredging operations is almost unnoticeable.

Because the inlet throat and the northern channel were dredged again during May and June 2001, the
July 2001 simulations represent the system under much better flushing conditions (Fig. 3b). Without the dredging operations, one would expect the tidal amplitude inside the lagoon in July 2001 to be smaller than in October or November, which are at the end of the maritime summer.

Finally, like in November 2000, the October 2002 bathymetry represents the situation about 1.5 years...
after a dredging operation (Fig. 3c). However, the maritime winter was milder in 2001 than in 2000 (Fig. 9). As a result, the inlet throat was located in a more central position in 2002, the meandering of the channel was less pronounced and the inflow of marine sediments into the lagoon due to wave action was probably smaller during 2002 than in 2000.

Tidal propagation inside the lagoon depends strongly on the bathymetric configuration (Fig. 10). As expected, dredging the channels facilitates tidal propagation, increasing tidal amplitudes considerably in the whole system. For the November 2000 simulation, most of the tidal signal is damped at the inlet. M2 amplitudes in the northern channel for this simulation are smaller than 40 cm, while they vary from 42 to 60 cm for the July 2001 simulation. Similarly, the beneficial effects of the dredging on tidal propagation in the October 2002 run are lost in most of the lagoon, due to accretion and meandering of the channels and inlet migration. Differences in tidal amplitudes between the 2000 and 2002 simulations are significant, but confined to the area downstream of the guiding wall (Fig. 2b), where the smaller inflow of sediments in the milder winter of 2002 contributed to a less constricted entrance than in 2000.

The enhancement of tidal propagation by the dredging operations is stronger than the differences between the July 2001 and the other simulations suggest. Indeed, the seasonal cycle of the tides did not reach its peak in July 2001, as was the case in October 2000 and November 2002. Hence, the differences between the 2001 amplitudes and the others are reduced by the seasonal cycle.

In spite of the obvious benefits of the dredging operations, the July 2001 simulation exhibits some localized areas where tidal energy decreases significantly, such as the downstream end of the southern channel and the inlet. These localized energy losses suggest that the dredging plan carried out in 1999, 2001 and 2003 can be improved to further facilitate tidal propagation in the lagoon.

To further investigate the spatial distribution of tidal propagation and the relative importance of the two channels, tidal prisms were computed at several cross-sections (Fig. 11). Results show that the magnitude of the tidal prisms also depends heavily on the bathymetric configuration. The largest values were obtained for July 2001, corresponding to an increase of 68% at the inlet throat relative to the November 2000 situation (Tables 4 and 5). The impact of the seasonal cycle and the dredging operations are similar, since the tidal prisms at the inlet throat and channels for the October 2002 run are only slightly smaller than those obtained for the July 2001 simulation.

The relative reduction of tidal prisms from the inlet to the upper bays follows a similar pattern for all bathymetries: major decreases in tidal prism occur at the transitions from the channels to the large upper bay and from this bay to the upstream lateral bays (Barrosa and Bom Sucesso).

![Fig. 11. Location of transects for tidal prism calculation (dashed lines) and stations for calculation of maximum velocities (squares).](image)

Table 4
Tidal prisms ($10^6$ m$^3$)

<table>
<thead>
<tr>
<th>Bathymetry</th>
<th>Inlet throat (A–B)</th>
<th>Channels (C–D)</th>
<th>Upper bay (E–F)</th>
<th>Barrosa bay (G–H)</th>
<th>Bom Sucesso bay (I–J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2000</td>
<td>2.902</td>
<td>2.511</td>
<td>1.333</td>
<td>0.151</td>
<td>0.227</td>
</tr>
<tr>
<td>July 2001</td>
<td>4.867</td>
<td>4.232</td>
<td>2.244</td>
<td>0.225</td>
<td>0.393</td>
</tr>
<tr>
<td>October 2002</td>
<td>4.184</td>
<td>3.446</td>
<td>1.863</td>
<td>0.199</td>
<td>0.321</td>
</tr>
</tbody>
</table>
Since tidal prisms are common indicators of the water renewal capacity, results from Table 4 suggest that the upstream lateral bays have very large water RTs. In the case of the Barrosa bay, which has been receiving a considerable inflow of wastewater, these results suggest a large potential for water quality problems.

The northern channel conveys most of the tidal volume, its tidal prism increasing considerably with the dredging operations and mild winters (Table 5). In contrast, the tidal prism through the southern channel has declined over time. These results are consistent with the continuous accretion of this channel revealed by the data (Table 3). The southern channel also has a potential for larger RTs than the northern channel, which may be responsible for the existence of spawning areas in the former but not in the latter (Freire et al., 2004).

Maximum ebb and flood velocities in the channels depend strongly on the bathymetry, in particular at the inlet and in the northern channel (illustrated in Fig. 12 along the pathway defined in Fig. 11, points 2–6). Before the maintenance dredging, velocities are always stronger on flood than on ebb inside the lagoon. Close to the mouth, the effect of the maintenance dredging (July 2001) leads to ebb-dominant velocities, which are further amplified at the end of the maritime summer, for a mild winter year (October 2002). However, velocities are always considerably larger on flood than on ebb upstream of the guiding wall (Table 6).

The differences between ebb and flood velocities arise from the asymmetric nature of tides in this system. As showed in the data analysis, ebbps are longer than floods, leading to larger flood velocities. This flood dominance has an important impact on the sediment dynamics, promoting the inflow of sediments into the lagoon. To evaluate the critical areas that promote sediment accretion, differences between ebb and flood durations were computed for the three hydrodynamic simulations.

The July 2001 run presents the weakest flood-dominance in the lower lagoon (Fig. 13), stressing the importance of the dredging operations to counteract the tendency for closure of the inlet. The largest increases in ebb duration occur in the locations where most of the tidal energy is dissipated (transitions from the sea to the lagoon, from the main to the south channel and from the northern channel to the upper bay). However, even after maintenance dredging, the system is still mostly flood-dominated. The impact of dredging on flood dominance is reduced over the channels and upstream of the inlet throat after 1.5 years, even after a mild winter (October 2002). Ebb–flood differences over the sand banks and in the area near the southern margin opposite to the guiding wall remain similar in October 2002.

The impact of tidal asymmetry on sediment dynamics was assessed through sediment pathways computed with the particle model VELAApart, forced by the hydrodynamic model results. A patch

Table 5
Relative tidal prisms (%), scaled by the value for the July 2001 inlet section

<table>
<thead>
<tr>
<th>Bathymetry</th>
<th>Northern channel</th>
<th>Southern channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2000</td>
<td>36</td>
<td>23</td>
</tr>
<tr>
<td>July 2001</td>
<td>67</td>
<td>18</td>
</tr>
<tr>
<td>October 2002</td>
<td>56</td>
<td>17</td>
</tr>
</tbody>
</table>

Fig. 12. Maximum velocity on (a) ebb and (b) flood (m/s).
of 3024 sediment particles, with diameters of 0.5 mm, was released at the inlet throat for 11 different instants in the tidal cycle and followed for 15 days to evaluate the deposition locations (Fig. 14a–c). The distributions of the particle's final positions were integrated in four areas (Fig. 14d), and are presented in Table 7.

The dredging operations considerably increase the sediment export capacity of the lagoon, raising from 42% to 65% the total number of particles that settle outside the lagoon (region S1). This export capacity remains similar after 1.5 years, with approximately the same number of particles deposited outside the lagoon in October 2002. These

### Table 6

<table>
<thead>
<tr>
<th>Region</th>
<th>Location</th>
<th>November 2000</th>
<th>July 2001</th>
<th>October 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside the lagoon</td>
<td>1</td>
<td>0.51</td>
<td>0.40</td>
<td>0.68</td>
</tr>
<tr>
<td>Inlet</td>
<td>2</td>
<td>1.26</td>
<td>0.91</td>
<td>0.68</td>
</tr>
<tr>
<td>Wall area</td>
<td>3</td>
<td>2.08</td>
<td>1.09</td>
<td>1.04</td>
</tr>
<tr>
<td>North channel</td>
<td>4</td>
<td>2.12</td>
<td>1.13</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.94</td>
<td>1.38</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.22</td>
<td>1.60</td>
<td>1.86</td>
</tr>
<tr>
<td>South channel</td>
<td>7</td>
<td>1.91</td>
<td>1.64</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.27</td>
<td>2.17</td>
<td>2.16</td>
</tr>
<tr>
<td>Upper large bay</td>
<td>9</td>
<td>1.89</td>
<td>1.78</td>
<td>2.03</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.99</td>
<td>1.74</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Fig. 13. Ebb–flood durations (minutes): (a) November 2000; (b) July 2001; (c) October 2002.
results stem directly from the ebb-dominant velocities in the inlet throat in July 2001 and October 2002.

The large deposition in the lower lagoon (region S2) in November 2000 illustrates the poor tidal propagation under these conditions and the high potential for inlet closure if flood-dominated flows are not controlled by interventions such as channel dredging. Results indicate that these sediment particles are mostly exported for the other bathymetries. Immediately after the dredging operations, some deposition still occurs downstream of the large sank bank and close to the southern margin, near the inlet throat (about 7%). This sediment deposition almost disappears for the more stable bathymetry of October 2002 (Fig. 14b, c).

Deposition in the main upper bay, due to sediments transported along the northern channel, is similar for all bathymetries. These results show that the import of marine sediments to the upper bay are roughly on the order of 30–40% of the total sediment patch. The sediment particles’

Fig. 14. Final location of sediment particles: (a) November 2000; (b) July 2001; (c) October 2002. (d) Areas of integration of sediment deposition. The initial location of the particle’s patch is indicated by the black square (a–c). Isobaths of each model grid, in 1 m intervals.
distributions upstream of the northern channel are supported by the distribution of surface sediments median diameters presented in Rodrigues and Quintino (1985): although the upper main lagoon has a dominant percentage of mud, a patch of sediments with d50 in the interval 0.25–0.5 mm (sands) can be found upstream of the northern channel.

In contrast, sediment transport along the southern channel is significantly reduced by the progressive siltation of this channel (Table 3), and the consequent reduction in tidal prism (Table 5).

Table 7
Distribution of sediment particles (% of the total number of particles for all time releases)

<table>
<thead>
<tr>
<th>Region</th>
<th>November 2000</th>
<th>July 2001</th>
<th>October 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside the lagoon (S1)</td>
<td>42</td>
<td>65</td>
<td>66</td>
</tr>
<tr>
<td>Lower lagoon (S2)</td>
<td>21</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Upstream end of northern channel (S3)</td>
<td>28</td>
<td>21</td>
<td>29</td>
</tr>
<tr>
<td>Upstream end of southern channel (S4)</td>
<td>9</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

Regions defined in Fig. 14d.

Fig. 15. Maps of time-averaged residence times of the lower lagoon (days): (a) November 2000; (b) July 2001; (c) October 2002. The mean water level isoline is represented by the black, dashed line.
3.3. Residence time analysis

Residence time variability in space and time is significant in the Obidos lagoon, as expected for a system with such a complex and evolving bathymetry and geometry. To analyze in detail both the space and time scales, as well as the dependency on the magnitude of the tides and on the bathymetric configuration of the lagoon, two distinct analyses were performed.

3.3.1. Maps of residence times

In this analysis, time variability was eliminated by averaging the RT results for all release times at each release location. Results were used to produce the maps of RTs presented in Fig. 15. Some patterns of RTs are common to all bathymetries. For instance, RTs are always larger in the southern channel than in the northern channel, as a result of shallower depth of the former. Residence times are always small over the sand banks (mostly under 15 days), because they dry out at low tide. Differences of RTs in the sand banks between bathymetries are thus related to the differences between the flushing ability in the channels for each bathymetric configuration.

Dredging and repositioning of the inlet throat promotes flushing of the lower lagoon, in particular for water parcels released in the channels and over the sand banks. The southern margin upstream of the inlet throat also has smaller RTs in July 2001 than on the other two occasions, but differences are less significant. RTs in these areas are still on the order of 5–30 days (Fig. 15).

The dredging operations have a very small impact on the flushing of the narrow strip along the northern margin, which presents large RTs (over 1 year). The meandering of the channel appears to have a larger impact, as suggested by the comparison of the RTs for November 2000 (order of 1–2 years) and October 2002 (order of 6 months). The impact of the maritime winter is also noticeable in the flushing of the southern margin, along the southern channel and at the inlet throat. Although RT patterns are similar for November 2000 and October 2002, RTs are considerably smaller for the latter in each of these regions (Fig. 15).

The limited flushing ability of the November 2000 bathymetry relative to July 2001 is explained by the residual velocity fields (Fig. 16). Residual velocities in July 2001 are about twice as large as in November 2000 and mostly directed downstream. Additionally, a large circulation cell located upstream of the inlet throat in the November 2000 run limits the flushing of the particles. This effect is further supported by many other eddies located along the northern and southern channels. Some eddies are still visible in July 2001, but they are smaller and located outside the main channels and away from the inlet throat.

In the upper lagoon, differences between RTs for the three bathymetries are generally minor (Fig. 17). RTs present similar patterns, with large values in the lateral bays and along the margins, and smaller values in the central bay, in particular in the region immediately upstream of the large sand bank (with RTs smaller than 15 days). This last feature results from the eddy that develops for all bathymetries (Fig. 18), which promotes the mixing of the water parcels in the central bay, mobilizing them towards the northern or the southern channels.
The comparison between the maps of RTs for July 2001 and for the other bathymetries suggests that the effect of the maritime winter is dominant over the dredging impact. Differences between July 2001 and November 2000 RTs are smaller than those from November 2000 and October 2002 RTs. In some areas, such as in the Bom Sucesso embayment, the RTs are actually larger for July 2001 than for October 2002.

Overall, RTs in the upper lagoon are very large, exceeding 5 years in some areas and for some bathymetric configurations. From a hydrodynamics viewpoint, some carefully planned intervention, such as the dredging of a web of narrow channels connecting the lateral embayments to the lower lagoon, appears adequate (Portela, 2004). This intervention could, for instance, improve the water quality of the Barrosa
embayment, which currently receives wastewater discharges.

3.3.2. Spatial integration of residence times

Nine key regions, with distinct hydrodynamic and morphodynamic characteristics, are identified in Fig. 19. In the lower lagoon, these regions were based on the morphological analysis (1–5), being identical to those presented in Section 2, except for the northern tip in region 5. The two lateral bays were isolated in the upper lagoon (regions 7–8), as well as the deepest area in the main bay (6) and the region in front of the Arnóia delta (9). This division is also based on the maps of RTs from the previous section. Average RTs were computed in each of these regions, for each release time. Time variability within the tidal and neap/spring cycles was then examined by averaging the RTs in each region for the neap tide and spring tides releases.

Accumulated histograms show that RTs vary significantly within each region, in particular in the upper lagoon, and from region to region (Figs. 20–22). The lagoon can be coarsely divided into two large areas of different magnitudes of RTs, which do not fully coincide with the traditional separation of lower and upper lagoon, based on the characteristics of the bottom sediments. The first area includes regions 1–6, where at least 80% of the particles leave the system in less than 15 days. The second area includes the remaining upper lagoon (regions 7–9), where removal of 50% of the particles can take over 3.5 years. Within each of these large areas, different patterns and characteristics of RTs can be found.
Fig. 19. Location of integration regions in the (a) lower lagoon (1–5) and (b) upper lagoon (6–9). Isolines of the July 2001 grid, in 0.5 m intervals.

Fig. 20. Cumulative histograms of residence times for the November 2000 bathymetry: (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4; (e) Region 5; (f) Region 6; (g) Region 7; (h) Region 8; (i) Region 9.
In some regions, flushing is also affected by the amplitude of the tide. This dependence is, in general, lost as particles take longer to be flushed and thus lose memory of their starting hydrodynamic conditions. This pattern occurs for November 2000 in regions 1, 3, 4 and 5, where the dependence on tidal magnitude is important for RTs under 5 days, and for October 2002 in the same regions, where neap/spring releases lead to distinct RTs in the range below 10 days.

Regions 2 and 6 present a different behavior, with a strong dependence on the neap/spring cycle, which is justified by the large dependence of the velocity in the northern channel on tidal amplitude. This velocity variability affects both particles released in the northern channel (region 2) and part of those released in region 6, which are transported to this channel due to the large circulation cell shown in Fig. 18.

The flushing of regions 1, 3 and 4 for the July 2001 bathymetry is less dependent on tidal amplitude than for the other bathymetries, being only relevant in the first 4–5 days. Regions 2 and 5 do not depend on tidal amplitude. RTs for these regions are very small, as a result of the repositioning of the inlet throat and dredging of the northern channel, which creates very large velocities towards the sea.

Removal rates in regions 7–9 are much smaller than in the other regions, for all bathymetries. Over 50% of the particles released in these areas take over 1 year to leave the system, due to the very small velocities in these regions, even for spring tides. As such, tidal magnitude plays a minor role in their flushing. For the region in front of the Arnóia delta (9), dependence of tidal magnitude is stronger as a result of the proximity with region 6 and the lower lagoon. Still, RTs here are very high: over 3 years for a 90% removal.
To further compare the RTs for each region, results were averaged over all release times (Fig. 23). Results suggest that the dredging operations have a much larger impact than differences in the seasonal morphodynamic cycle on the flushing of regions 1, 3 and 4. This behavior may be due to the reduced ratio between flood and ebb velocities in July 2001 (Table 6), which promotes the export of the particles towards areas of greater flushing such as inlet throat (region 5).

For regions of rapid flushing (2 and 5), flushing differences are small for all bathymetries. November 2000 has slightly larger RTs, but with differences on the order of only a few days. For the lateral upstream bays, removal for the November 2000 bathymetry is much slower than for the other bathymetries. Differences in the seasonal morphodynamic cycle (October 2002 versus November 2000) can lead, for instance, to differences from 250 days to 1000 days to remove 50% of the Bom Sucesso bay particles from the system.

Although the bathymetry in the upper lagoon is the same for all simulations (from June 2000), differences in the bathymetry of the lower lagoon can have a very significant impact in the upstream bays. This analysis strengthens the need for a detailed analysis of the hydrodynamic and flushing of the whole lagoon if any interventions are being planned for the lower system.

Residence times in the Óbidos lagoon depend on the location of the water parcels, tidal amplitude and bathymetric changes in the lower lagoon due to either dredging operations or natural inlet migration. However, the relative importance of these factors on RTs depends on the release region for the water parcels. Differences in RTs for each of these factors are minor in areas of rapid flushing, such as the inlet throat or the deeper areas in the northern

Fig. 22. Cumulative histograms of residence times for the October 2002 bathymetry: (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4; (e) Region 5; (f) Region 6; (g) Region 7; (h) Region 8; (i) Region 9.
channel, but are very important in regions such as the lateral bays or the southern channel. Dredging operations seem to have a larger impact than the effect of the maritime winter in the regions of slow renewal in the lower lagoon, such as the southern channel and region 4. An opposite dependence is observed in the upper lagoon lateral bays, where the inlet displacements associated with the maritime winter effects plays the major role.

4. Conclusions

Traditional analyses of estuarine flow and transport are based on static bathymetries, taking advantage of large differences between the time scales of hydrodynamics and morphodynamics. However, in small coastal lagoons, bathymetries can vary significantly on monthly time scales. For these systems, analyses based on a single, static, bathmetry can be misleading. Hence, the analysis of the Óbidos lagoon presented herein considered the effect of morphological changes on the hydrodynamics. Based on three bathymetric data sets for very different conditions, we have characterized the hydrodynamics and flushing properties of the Óbidos lagoon.

The inlet follows a seasonal cycle, attributed to the relative importance of tides and waves during the year. During the maritime winter, waves promote the inflow of sediments into the lagoon and the inlet undergoes accretion. As a result, tidal amplitudes in the lagoon can decline by about 50%, in particular during harsh winters. Channel meandering, which occurs on time scales of a few months, is expected to further damp tidal amplitudes, although the extent to which this occurs could not be determined. This trend is reverted during the maritime summer, when waves abate and tides can flush out incoming sediments.

Fig. 23. Cumulative histograms of residence times for all bathymetries: (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4; (e) Region 5; (f) Region 6; (g) Region 7; (h) Region 8; (i) Region 9.
Dredging operations can have a significant effect on the inlet dynamics. These operations, which have consisted in deepening and repositioning the main channel, increase tidal prisms and reduce flood dominance, hence improving inlet stability. In addition, they reduce the tendency for sediments to settle close to the inlet throat, where accretion is the most damaging to channel meandering and tidal damping. However, the effect of the dredging operations is only temporary, as little evidence remained of these operations after 1.5 years. Model results suggested that the dredging plan could be improved, since some areas of localized energy losses remained after dredging. Strong local gradients in both the amplitude of M2 (Fig. 10b) and the differences in ebb–flood durations (Fig. 13b, c) indicate that the transition between the two channels was responsible for a significant part of the tidal damping and the generation of tidal asymmetry. This behavior suggests that dredging the connection between the two channels could increase the tidal prism and reduce flood dominance, hence contributing to improve the stability of the tidal inlet.

Residence times are shown to vary considerably due to morphological changes associated to dredging operations and inlet displacements due to the characteristics of the wave action during the maritime winter. Water flushing also depends on the spring–neap cycle. However, the relative importance of each of these factors varies in different areas of the lagoon. For instance, the water flushing in the southern channel depends more on the dredging operations on the inlet throat and northern channel than on the characteristics of the wave action, while the flushing of the Bom Sucesso and Barrosa bays is improved after a mild winter.

The dependence of RTs on the morphological characteristics of the lagoon prevents the traditional monitoring of the water quality of the system based on stations with fixed locations, as changes in pollutant concentrations may not be due to an increase of pollutant input into the system but to reduced rates of dilution related to smaller water flushing. Analyses based on hydrodynamic and flushing model simulations for characteristic bathymetric settings, such as the ones presented here, as well as updates based on simulations for new bathymetric settings, can help to establish an efficient monitoring program that accounts for the evolution of this coastal system.

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References


