Particle tracking-modeling of morphologic changes in the Ria de Aveiro

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ABSTRACT

Tidal currents in an estuary carry all types of dissolved, suspended or floating material. Particle tracking models constitute powerful tools in assessing the transport of this material, through the study of the particles trajectories and settling positions. Thus, this work aims at using a Lagrangian particle tracking model driven by hydrodynamic fields to study the impact of morphologic anthropogenic and natural changes in sediments transport at Ria de Aveiro. In fact, as many coastal systems, Ria de Aveiro is in progressive degradation associated to the lack of maintenance and to the strong currents occurring in its channels, which erode their protective walls. Hence, the model VELApart, which is driven by the hydrodynamic model ELCIRC (previously calibrated for this lagoon), was applied for two configurations of the Ria de Aveiro: one representing the present situation of the lagoon and another representing a scenario with the enlargement of its flooded area. According to model results, morphologic changes influence the sediments pathways and final position, as well as the settling time. Generally for the flooded bathymetry the sediments travel a longer distance and the preferential zones of deposition are inside the flooded area, while for the present configuration sediments settle down in the main adjacent channels. The settling times also increase with the enlargement of the flooded area.

ADDITIONAL INDEX WORDS: Flooded areas, Sediments transport, Sediments pathway, Settling time

INTRODUCTION
Particle tracking models constitute a powerful tool in assessing potential zones of sediments deposition and erosion in coastal regions and, consequently, are an important tool for the management, maintenance and conservation of these systems.

Impacts of anthropogenic activities and natural environmental changes in a coastal system will have a regional signature on the local geomorphology and on biogeochemical, ecological and social factors. A coastal lagoon is particularly vulnerable to risks of flooding that affect the dynamics of these processes. A good understanding of the transport phenomena in estuarine systems is crucial to mitigate these problems.

Particle-tracking models have been widely used to simulate the dispersion of passive tracers (Suh, 2006; Gong et al., 2008), larval dispersal (Murray and Gillibrand, 2006) and oil spills (Wang et al., 2005; Mendes et al., 2009). Dias et al. (2009), Oliveira et al. (2006a) and Fortunato et al. (2002) used the numerical model VELApart to compute residence times for passive tracers in Portuguese lagoons (Ria Formosa, Óbidos lagoon and Guadiana Estuary, respectively).

Oliveira et al. (2006b) analyzed the export/import of sediment in various channels of the Ria de Aveiro using VELApart to simulate the trajectories of particles released at several tidal stages. They concluded that the flood releases lead to sediment trapping in the upper lagoon, while ebb releases lead to an almost complete exportation of sediments.

In the present study, the quasi-3D particle-tracking model VELApart (Oliveira and Baptista, 1997, Oliveira et al., 2010) is used to investigate the effects of morphologic changes in sediment transport in a coastal lagoon system, the Ria de Aveiro. As many coastal systems, the Ria de Aveiro is in a progressive degradation process associated to the lack of maintenance and to the strong currents occurring in the channels, which erode their protective walls. The main aim of this work is to investigate the effect of morphologic changes in sediments pathways and settling time. The changes considered are associated with the collapse of the salt pans walls that increase the lagoon flooded area and may affect the bottom morphology in unknown ways. To evaluate these impacts, which may be generalized to other similar systems, the model VELApart is driven by the hydrodynamic model ELCIRC (previously calibrated for Ria de Aveiro by Picado et al. (2010)).

STUDY AREA
The Ria de Aveiro (Figure 1) is the most extensive shallow coastal lagoon in Portugal. It is located on the western Atlantic coast of Portugal and is 45 km long and 10 km wide (Dias and Lopes, 2006a, b). The average depth of the lagoon, relative to the mean sea level is approximately 3 m, although the inlet channel can exceed 28 m deep to allow the navigation of large ships to the inner commercial harbor. The tide at the mouth of the lagoon is predominantly semi-diurnal with a mean tidal range of about 2 m, decreasing for the inner channels of the lagoon (Dias et al., 2000; Araújo et al., 2008). The residual sediment fluxes are determined...
essentially by the asymmetries between the flood and ebb regimes. As the lower lagoon is ebb-dominant there is a trend to export sediments to the ocean (Oliveira et al., 2006b; Picado et al., 2010).

Although several rivers discharge into the Ria de Aveiro, the most important freshwater contribution comes from the Vouga (50 m$^3$s$^{-1}$ average flow) and Antuã (5 m$^3$s$^{-1}$ average flow) rivers (Moreira et al., 1993). Rivers influence is only noticed in the upper parts of the lagoon, where a horizontal density gradient is dynamically active (Vaz and Dias, 2008).

The system has four main channels as represented in Figure 1: Mira and îlhavo channels in its southern region, S. Jacinto and Espinhoere channels in the central area of the lagoon. It is connected to the sea by a 350 m wide inlet, fixed by two jetties. Despite these maritime structures, important morphological changes have occurred at the inlet. Until recently, the Aveiro Harbour Administration has regularly dredged the sand that accumulates in the inlet driven from the southward littoral drift along the West Portuguese coast. Recent bathymetric surveys reveal erosion at the entrance channel close to the north jetty, and accretion close to the south jetty (Plecha et al., 2007; 2010).

Due to the small lagoon depth and to the significant tidal wave amplitude there are zones, especially along the borders of the lagoon and its central area, which are alternately wet and dry during a tidal cycle. Therefore Ria de Aveiro is characterized by a large number of channels, between which lie significant intertidal areas, essentially mudflats, salt marsh and old salt pans. The salt pans of Aveiro occupy about 15 km$^2$, but many of them are now abandoned or replaced by aquaculture tanks and their walls exhibit a growing degradation associated to the lack of maintenance. While the causes for this degradation are not fully understood, potential explanations include the strong flood currents inside the lagoon and the erosion in surrounding channels, which might threaten the stability of the walls.

**METHODOLOGY**

In this study, a particle-tracking model, VELApart (Oliveira and Baptista, 1997, Oliveira et al., 2010) was used to investigate the influence of morphologic changes in sediments (considered as particles) pathways and settling time in the Ria de Aveiro.

The study was performed for two configurations of the Ria de Aveiro: one representing the present situation of the lagoon and the other representing a future flooded scenario. In fact, as previously referred, the Ria the Aveiro is in progressive degradation. The enlargement of the flooded area (future scenario) was performed in the central area of the lagoon, where a high degradation of the walls that involves the existing salt pans is observed (Box A in Figure 1 and Figure 2).

Thus, the particle-tracking model driven by hydrodynamic fields was used to compute the settling time and final position of over 4000 particles released in pre-selected emission points located in the degraded area for both configurations of the Ria de Aveiro. Thousands of particles were also released in the Espinhoere and îlhavo channels for several tidal conditions.

**PARTICLE-TRACKING MODEL**

The model VELApart is used here to compute the sediment pathways, based on the release of large numbers of particles in pre-selected locations.

VELApart is a two-dimensional or quasi-three-dimensional model that simulates the pathways of particles in surface waters. Sediment pathways are computed based on sediment properties, driven by advection, horizontal and vertical diffusion and settling velocity. 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 system characteristics. The presence of strong spatial gradients of velocity, for instance, requires 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., 2002).

In this work, VELApart is used in quasi-three-dimensional mode. The quasi-three-dimensional mode tracks the particles...
using a depth-dependent horizontal velocity following a logarithmic profile, and solves the advection-diffusion equation in the vertical, thus allowing for settling and vertical diffusion of the particles. Particles are subjected to a settling velocity defined according to the type of sediments under study and using the expression proposed by van Rijn (1984).

The horizontal displacement of a particle $\Delta x_i$ due to diffusion is given by:

$$\Delta x_i = z_n \sqrt{2D\Delta t}$$

where $z_n$ is a random variable with zero mean and a standard deviation of 1, $D$ is the horizontal diffusion coefficient and $\Delta t$ the time step.

The particle-tracking model was forced by results from the hydrodynamic model ELCIRC, previously calibrated and assed for skill for Ria de Aveiro by Picado et al. (2010), provided in the frequency domain.

The sediments size used in this study is 0.02 mm with a settling velocity of $3.45 \times 10^{-4}$ ms$^{-1}$. Particles were released at 0.5 m from the bottom, and followed until they settled for the first time. A sensitivity analysis to the horizontal diffusion coefficient was performed, but significant changes in the results weren’t observed. The absence of changes may be explained by the fine hydrodynamic resolution used herein.

**RESULTS**

To illustrate the impact of the bathymetric changes on the sediments movement, the pathways of a large number of particles were simulated for the two bathymetries represented in Figure 2. 4700 particles were released in a tidal channel located in the central area of the lagoon. To account for the variability of the particles trajectory with tidal amplitude and phase, different initial tidal stages were considered for particles released: ebb and flood and neap and spring tides.

Figure 3 represents the particles trajectory as well as their initial and final positions for ebb releases on neap and spring tides and for both configurations (present and flooded) considered.

According to the model results, the particles travel a longer distance for the flooded configuration. According to Table 1, the average settling time for the ebb releases increases approximately 1.5 times from the present bathymetry to the flooded one, for both neap and spring tides. This result suggests that velocities are higher for the flooded configuration, once the particles remain in suspension longer. This conclusion can be corroborated from the velocity field for this area (Figure 4). In fact, when the particles are released, a significant increase of the velocity is observed for the flooded configuration near the releasing position. As the particles are carried out by the flow, it is expected that their initial velocity is significant higher for the flooded configuration.

At spring tides (Figure 3b) the particles settle down into the flooded area, while for the present configuration the particles deposit in the south margin of the adjacent main channel.

The particles released on flood (not shown) follow different trajectories for each configuration. While for the present configuration particles tend to move upstream, for the flooded configuration they tend to move and deposit into the flooded area. The velocity fields corroborate these results. In fact, flood velocities increase with the enlargement of the flooded area.

The settling time of the particles released on flood, for both neap and spring tides, increases by about 70% from the present bathymetry to the flooded one (Table 1).

The settling times are higher for the particles released on ebb than on flood, which traveled a longer distance. This pattern is explained by the higher ebb velocities, revealing ebb-dominance of the central area of the lagoon. This result is enhanced with the enlargement of the lagoon flooded area, revealing that ebb currents further increase, promoting the turbulence and resuspension.

Similar simulations considering other initial positions for the particles release were also performed, for both configurations. Thousands of particles were released in the Espinheiro and Ilhavo channels for both ebb and flood instants at neap and spring tides (Figure 5).

The pathways and final position of the particles released in Espinheiro channel (Figures 5c and d), do not change significantly with the enlargement of the flooded area. For these situations, particles tend to be exported outside the lagoon, for ebb

<table>
<thead>
<tr>
<th>Neap Tide</th>
<th>Ebb</th>
<th>Flood</th>
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<tbody>
<tr>
<td>Present</td>
<td>4.9</td>
<td>2.1</td>
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<tr>
<td>Flooded</td>
<td>6.1</td>
<td>3.8</td>
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<tr>
<th>Spring Tide</th>
<th>Ebb</th>
<th>Flood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>5.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Flooded</td>
<td>8.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>
channels. Present configuration they settle down in the adjacent main
flooded area for flood configuration, while for flood releases particles settle
into the flooded area for flood configuration, while for ebb releases particles
settle down. Also the results show an increase of the ebb currents,
enhancing the ebb dominance of the central area of the lagoon and
therefore changing the preferential zones of sediment settling. The
sediments tend to deposit into the flooded area, while for the
present bathymetry they settle down in the main adjacent
channels. This means that large areas of flooding tend to be
accrated.

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wave action on transport and sediment dynamics in a coastal
configuration than for the present situation, and take longer to
settle down. Also the results show an increase of the ebb currents,
enhancing the ebb dominance of the central area of the lagoon and
therefore changing the preferential zones of sediment settleing. The
sediments tend to deposit into the flooded area, while for the
present bathymetry they settle down in the main adjacent
channels. This means that large areas of flooding tend to be
accrated.

**CONCLUSIONS**

The present work established the preferential depositional
places for fine particles (0.02 mm), considered as sediments,
released within the Ria de Aveiro: at a low depth small channel
located in the central part of the lagoon and at two main channels
(Espinheiro e Ílhavo).

The results show that sediments tend to be exported to the ocean
for ebb releases and for the locations close to the inlet (e.g.,
Espinheiro channel). The releases of the sediments at the main
channels, where larger velocities occur, revealed larger areas for
their settling.

The simulations performed with the enlargement of the flooded
area, due to the salt pans walls collapse, suggest that the
morphologic changes in this system will induce changes of the
preferential zones of sediments deposition and settling time.
Generally they travel a longer distance for the flooded

Figure 4. Velocity fields for both present a) and flooded b)
configurations, on ebb at spring tide (A in Figure 1).

releases and trapped in the upper channel of the lagoon for flood
releases. These results are in accordance with Oliveira et al.
(2006b), which concluded that the lagoon shifts from mild ebb-
dominance at the inlet to strong flood-dominance in the upper
lagoon. Particles position follows the same pattern for neap tide,
however, for ebb releases particles are trapped in Mira channel.

Particles spread in the lagoon central area for both
configurations and sinks in shallow water at the upper lagoon for
the present configuration, for ebb releases in Ílhavo channel. Once
current velocities are smaller for the present configuration
particles spread in a larger area. For flood releases particles settle
down into the flooded area for flood configuration, while for
present configuration they settle down in the adjacent main
channels.


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