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Numerical modeling estimation of the spread of maritime oil spills in Ria de Aveiro lagoon

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ABSTRACT

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In recent years, oil spill pollution resulting from maritime accidents has affected several points around the globe. After the sinking of the Prestige oil tanker off Galicia, this problem acquired high relevance in Portugal.
The portuguese coast and its EEZ are located in an area of intense maritime traffic, and therefore are under the dangerous threat of oil pollution from maritime accidents. Studies of oil-spill modeling, both offshore and in estuarine areas, have been carried out but, until present, no research on this topic has been done for the Ria de Aveiro lagoon. This is relevant because this of the largest and busiest ports in the country is located in this barrier/lagoon system, which is also an environmentally protected area that is a habitat for many species.
In this work we estimated the dispersion through Ria de Aveiro of an offshore oil-spill that reaches the Barrier/lagoon mouth. The approach used consists of the Lagrangean modeling of passive particle emissions. The Lagrangean model is coupled to a hydrodynamic model, previously calibrated and validated for this lagoon. The simulations were carried out for 3 different tide ranges (neap, spring and average) and took into account the average rivers freshwater input. In order to simulate cases of extreme drought, simulations without rivers freshwater input were also performed.
The results show that the northern area of the Ria de Aveiro lagoon would be the most affected, especially the S. Jacinto and the Espinheiro channels, and that the oil-spill only takes a few hours to spread through theses channels if it reaches the lagoon during the flooding period.

ADITIONAL INDEX WORDS: *dispersion, Lagragean model, passive particles, hydrodynamic model, estuary*

INTRODUCTION

Oil spill pollution resulting from maritime accidents largely increased during the last years, affecting several coastal areas around the globe. This problem acquired high relevance in Portugal after the sinking of the oil tanker Prestige offshore of the Iberian coast.

The maritime traffic is very intense along the Portuguese coastal zone (Portugal has one of the largest Exclusive Economic Zone (EEZ) of the European Union), and therefore there is a significant dangerous threat of oil pollution from maritime sources. Studies of oil-spill modeling both offshore and in estuarine areas have been carried out but, until present, no specific research on this topic was carried out for the Ria de Aveiro barrier/lagoon system. This is a highly relevant area, because one of the largest and busiest ports in the country is located at the mouth of this barrier/lagoon system, which is also an environmentally protected area, which serves as habitat for many species.

This work aims to provide a useful working tool for the local authorities, in case of an oil spill hazard within Ria de Aveiro lagoon confined space.

The methodology adopted in this work comprises the application of a previously developed Lagrangean particle tracking model (DIAS *et al*., 2001) coupled to a calibrated two-dimensional hydrodynamic model for the Ria de Aveiro (DIAS and LOPES, 2006a). These models were used to simulate the dispersion through Ria de Aveiro of an oil-spill that reaches the barrier/lagoon mouth, resulting from a hypothetical maritime accident offshore the Portuguese coast.

The simulations were performed with data from neap, spring and average tides retrieved from the http://neptuno.fis.ua.pt website, combined with the Vouga, Boco, Antuã, Caster, Gonde and Fontela rivers average flow values, as well as the average freshwater values discharging on the Mira Channel (Figure 1). The main purpose of these simulations is to follow the advection of the oil-spill through Ria de Aveiro main channels, in order to identify the critical areas that will be affected and to estimate the time it takes to spread along the various channels.

STUDY AREA

Located on the northern coast of Portugal (40°38’ N, 8°45’ W), the Ria de Aveiro (Figure 1) is a shallow water lagoon, separated from the Atlantic Ocean by a sand dune barrier. It has an irregular geometry, and its only connection with Atlantic Ocean is through an artificial channel (Barra de Aveiro), opened in the beginning of 19th century (DIAS, 2001). It reaches a maximum width of 8.5 km and extends for over 45 km. This lagoon presents a significant variable area due to the large tidal influence on its hydrodynamics. In spring tides it reaches a maximum area of 83 km^2 at high tide, which reduces to a minimum of 66 km^2 at low tide. The average depth of the Ria de Aveiro is 1 m (relative to the local datum), but the navigation channels close to its mouth and the areas

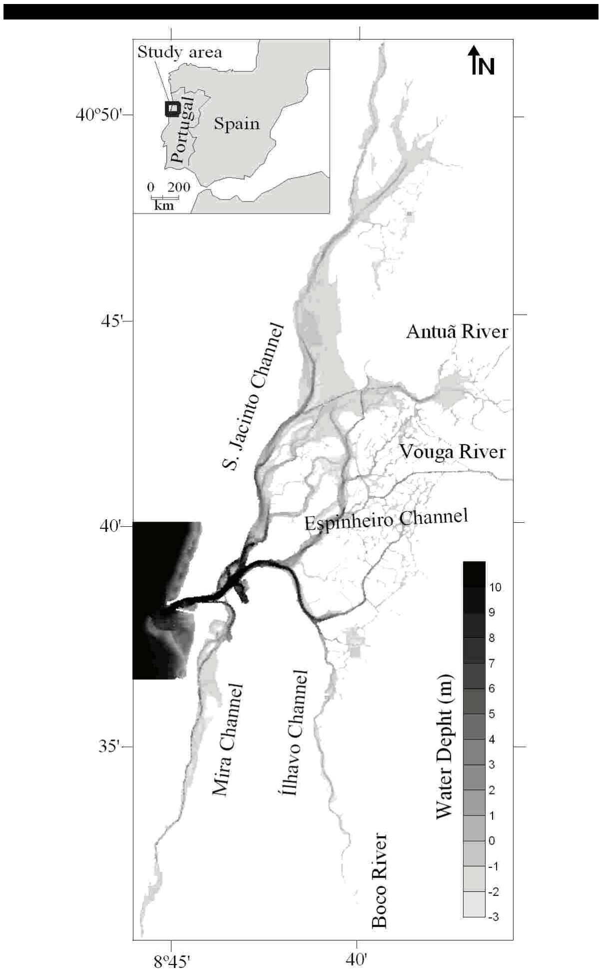

Figure 1. The Ria de Aveiro lagoon.

contiguous to the ports are deeper, because of the constant dredging operations to allow the access of large ships to the port. The lagoon is mesotidal (tidal amplitude at the inlet ranges from 0.6 m in neap tides to 3.2 m in spring tides - average 2 m) (DIAS *et al*., 2000) and the semidiurnal tides are the major factor influencing the hydrodynamics of the lagoon (DIAS *et al*., 2000).

In extreme situations of wind and freshwater forcing, these can also influence the Ria de Aveiro's hydrodynamics. There are several rivers draining along all the area surrounding Ria de Aveiro, of which the most important are the Vouga, Antuã and Boco. Besides these, there are also some other smaller rivers that drain into the northern channels (Caster, Gonde and Fontela) and to the Mira Channel. In spite of the complex interaction between its geomorphology, tidal effects and its tributary river drainage seasonal variability, the Ria de Aveiro can nevertheless be considered a vertically homogeneous estuarine environment during most of the year.

The Ria de Aveiro lagoon is very important in the local economy. Within the estuarine zone is located the port of Aveiro, which receives more than one thousand ships per year. In recent years, the tourism, mainly linked to water sports activities, largely increased. Ecology and biodiversity issues are always closely linked to estuarine areas; in the case of Ria de Aveiro this is particularly relevant due to the importance of the Reserva Natural das Dunas de São Jacinto, a well preserved dune barrier ecological system, located in the north area of the lagoon, with several ponds frequented by numerous species of local and migratory water birds. According to the available data, there have been identified 64 fish, 12 amphibian, 8 reptile, 173 bird and 21 mammal species in Ria de Aveiro waters (BORREGO, 1996)

METHODS

In this study, passive particle trajectories were used to estimate the oil paths from a potential maritime accident in Ria de Aveiro. The oil is regarded as passive particles, with their distribution mainly due to the transport induced by the currents (advective processes). Besides the oil transport through the water surface, there are several biological, chemical and physical transformations that determine the oil spread, which were not considered in this study. The oil acquires different characteristics and behavior over the time after the spill. Therefore only one flooding cycle was simulated in order to reduce the impact in the results of the changes in the oil characteristics over time.

The particle trajectories were determined from the application of a Lagrangean particle-tracking model coupled to a hydrodynamic model.

Hydrodynamic Model

The Ria de Aveiro hydrodynamics is essentially forced by the tidal propagation along its channels. Considering the system as vertically homogeneous most of the time, a two-dimensional vertically integrated model is considered the best option to simulate its hydrodynamics (DIAS and LOPES, 2006a). The hydrodynamic model SIMSYS2D (LEENDERTSE and GRITTON, 1971; LEENDERTSE, 1987), which was previously calibrated (DIAS and LOPES, 2006a,b) and applied in several studies in Ria de Aveiro (DIAS *et al*., 2000; 2001; DIAS and LOPES, 2006a,b; CEREJO and DIAS, 2007, etc.) was used in this study. This model solves the shallow waters equations, obtained by vertical integration of the continuity and Navier-Stokes equations, representing the fundamental principles of mass and momentum conservation in a fluid (assumed Newtonian) (LEENDERTSE and GRITTON , 1971; LEENDERTSE, 1987; DIAS, 2001):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = fV - g\frac{\partial \zeta}{\partial x} + \frac{\tau_x^s - \tau_x^b}{H\rho_0} + A_h \nabla^2 U \qquad (2)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -fU - g\frac{\partial \zeta}{\partial y} + \frac{\tau_y^s - \tau_y^b}{H\rho_0} + A_h \nabla^2 V \qquad (3)$$

where U is the depth integrated velocity component in the x direction (eastward); V is the depth integrated velocity component in the y direction (northward); ζ is the surface water elevation; H is the water height (H=h+ζ; h=water depth); t is the time; f is the Coriolis parameter; g is the acceleration of gravity; ρ_0 is the water density; A_h is the turbulent horizontal viscosity kinematic constant; τ^b is the magnitude of the shear stress on the bottom caused by the flow of water over the bed; and τ^s is the magnitude of the shear stress on the surface.

The equations (1) to (3) were discretized using a finite differences method, and the resulting difference equations solved through the ADI (Alternating Direction Implicit) method, using a space-staggered grid (LEENDERTSE and GRITTON, 1971; DIAS and LOPES, 2006a). The velocities, the depths and the water levels were described for different points of the grid (DIAS, 1993).

The numerical bathymetry developed for the Ria de Aveiro has dimensions $\Delta x = \Delta y = 100$ m, resulting in 160 cells in the *x* direction and 393 cells in the *y* direction. The values adopted for the computational time step and A_h were 40 s and $20 m^2 s^{-1}$, respectively (DIAS *et al*., 2006a). At the ocean open boundary water level data over time was specified. At the river open boundaries averaged freshwater inputs, or null inputs corresponding to cases of extreme drought, were imposed.

The initial conditions were horizontal level and null velocity in all the grid points. Along the solid boundaries a null normal velocity was imposed and a free slip condition was assumed.

Particle-tracking Model

A Lagrangean particle-tracking model is used in this study, to follow the paths of passive particles emitted at the lagoon mouth. This model is coupled to a two-dimensional hydrodynamic model, which provides the initial conditions that consist on the current velocity values for each grid cell. This approach considers the continuous emissions of the passive particles in pre-determined locations and time, which paths are induced by the advective processes. The advection is the only component of the dispersive system that is simulated by the model, not being considered any other features characteristic of the pollutant.

The Lagrangean model computes the position of the particles at each time step, with $\Delta t_{lag} = \Delta t_{hid}$, through the resolution of the following equation (DIAS *et al*., 2001):

$$X_i\left(x_0, y_0\right)^{n+1} = X_i\left(x_0, y_0\right)^n + \int_{t_0+n\Delta t}^{t_0+(n+1)\Delta t} u_i\left(x, y, t\right) dt \quad (4)$$

$X_i(x_0,y_0)^{n+1}$ is the position at the time *n*+1 of the particle emitted at the point $X_i(x_0,y_0)^n$. Based on a 4th order Runge-Kutta integration method , the time integral is determined solving the following equations (HOFMANN *et al*., 1991; DIAS *et al*., 2003):

$$K_{1i} = \Delta t \times u_i \left[t.X_1(x_0, y_0)^n \right] \quad (5)$$

$$K_{2i} = \Delta t \times u_i \left[t + \frac{\Delta t}{2} \cdot X_1\left(x_0, y_0\right)^n + \frac{K_{1i}}{2} \right] \quad (6)$$

$$K_{3i} = \Delta t \times u_i \left[t + \frac{\Delta t}{2} \cdot X_1\left(x_0, y_0\right)^n + \frac{K_{2i}}{2} \right] \quad (7)$$

$$K_{4i} = \Delta t \times u_i \left[t + \Delta t \cdot X_1\left(x_0, y_0\right)^n + K_{3i} \right] \quad (8)$$

$$X_i\left(x_0, y_0\right)^{n+1} = X_i\left(x_0, y_0\right)^n + \frac{K_{1i}}{6} + \frac{K_{2i}}{3} + \frac{K_{3i}}{3} + \frac{K_{4i}}{6} \quad (9)$$

$X_i(x_0,y_0)^n$ represents the starting position of the particle. $X_i(x_0,y_0)^{n+1}$ is the new position of the particle after being advected with a velocity $u_i=(u_i,v_i)$ during a period of time Δt ; K_{ji} represent the Runge-Kutta coefficients. This model has been tested and validated by advecting a particle in a well-know velocity field and with similar conditions to those of Ria de Aveiro (DIAS *et al*., 2001).

Simulations

As the hydrodynamics of the Ria de Aveiro lagoon are mainly determined by tidal forcing (DIAS, 2001), the simulations carried out were focused on this forcing. Three different tides were used: the extreme neap tide, the spring tide and an average tide. The ocean boundary conditions were obtained from the site http://neptuno.fis.ua.pt (Ocean Modeling Group, Aveiro University). The oil emissions (Lagrangean model) were simulated for the following periods: 19th of May 2008 (average tide: 3.23 m of tidal range), 31st of August 2008 (spring tide: 3.76 m of tidal range) and the 8th of September 2008 (neap tide: 2.23 m of tidal range). The hydrodynamic model started running 3 days before, for each case, in order to provide reliable velocities.

The simulations were conducted imposing average river flow data for the Vouga, Boco, Antuã, Caster, Gonde, Fontela and Mira Channels (DIAS, 2001). A second set of simulations was performed eliminating the influence of the freshwater input (assuming null values for the rivers flow), in order to reproduce cases of extreme drought.

For the particles emission, locations were chosen at seven grid cells that define the entrance of the Ria de Aveiro. With this methodology two hypotheses are assumed: (1) the maritime accident occurred in this local; (2) the maritime accident occurred offshore of the Aveiro coast, but due to the wind, waves and currents conditions the oil dispersed into the lagoon mouth. The particles emission started 2 hours after of the low tide, to prevent ebb residual movements, and to guarantee that the oil spill spreads into the lagoon. The simulations continue during the flood period (6-7 hours after starting emitting the particles), and the results were sequentially analyzed for this period.

RESULTS

The analysis of the oil spill dispersion along the Ria de Aveiro show that it attains its maximum distance from the inlet 6 hours after the beginning of the simulations, corresponding to the end of the flooding period. When the ebb develops, the oil spot inverts its path, starting to come back outward of the lagoon. Figure 2 shows the area of Ria de Aveiro affected by the oil spill dispersion after six hours of simulation, for neap, average and spring tide conditions, and corresponding to null freshwater inputs and to average freshwater inputs. It is clear that in a tidally dominated environment such as Ria de Aveiro, the oil spill only requires a few hours to spread along a large area, if it reaches the mouth of the lagoon during a flood period.

Neap Tide

The analysis of Figures 2a) and d) reveals that after 6 hours of dispersion along Ria de Aveiro, the pollutant only spreads into the beginning of São Jacinto channel, although approaching the area of the São Jacinto village, where is located the Reserva Natural das Dunas de São Jacinto, an environmentally sensible and protected area. It also affects the upstream area of Aveiro port, along the Espinheiro channel. Therefore, in neap tide conditions the oil spot does not cover a large area, which makes possible a well succeed cleaning mission.

Comparing Figures 2a) and d), it is verified that the areas of the lagoon affected by the oil spill are very similar. As the flood currents in neap tide are relatively weak, the particles do not reach the upstream areas of the channels, where the freshwater flow exerts its influence. Therefore, in case of occurrence of an oil spill event in the entrance of the lagoon during a neap tide, its dispersion should be essentially controlled by the tidal currents, and therefore considered independent of the freshwater inflow.

Average Tide

During the average tide, the particles progress further through the S. Jacinto and the Espinheiro channels (Figures 2b) and e)). Six (6) hours after the beginning of the simulation, all the area of the lagoon mouth and around half of the São Jacinto and the Espinheiro channels are affected by the oil spill dispersion, as well the initial area of the Ílhavo channel (Figures 1 and 2).

In the simulation without rivers inflow, the oil dispersion goes further away, reaching the downstream area of the Torreira.

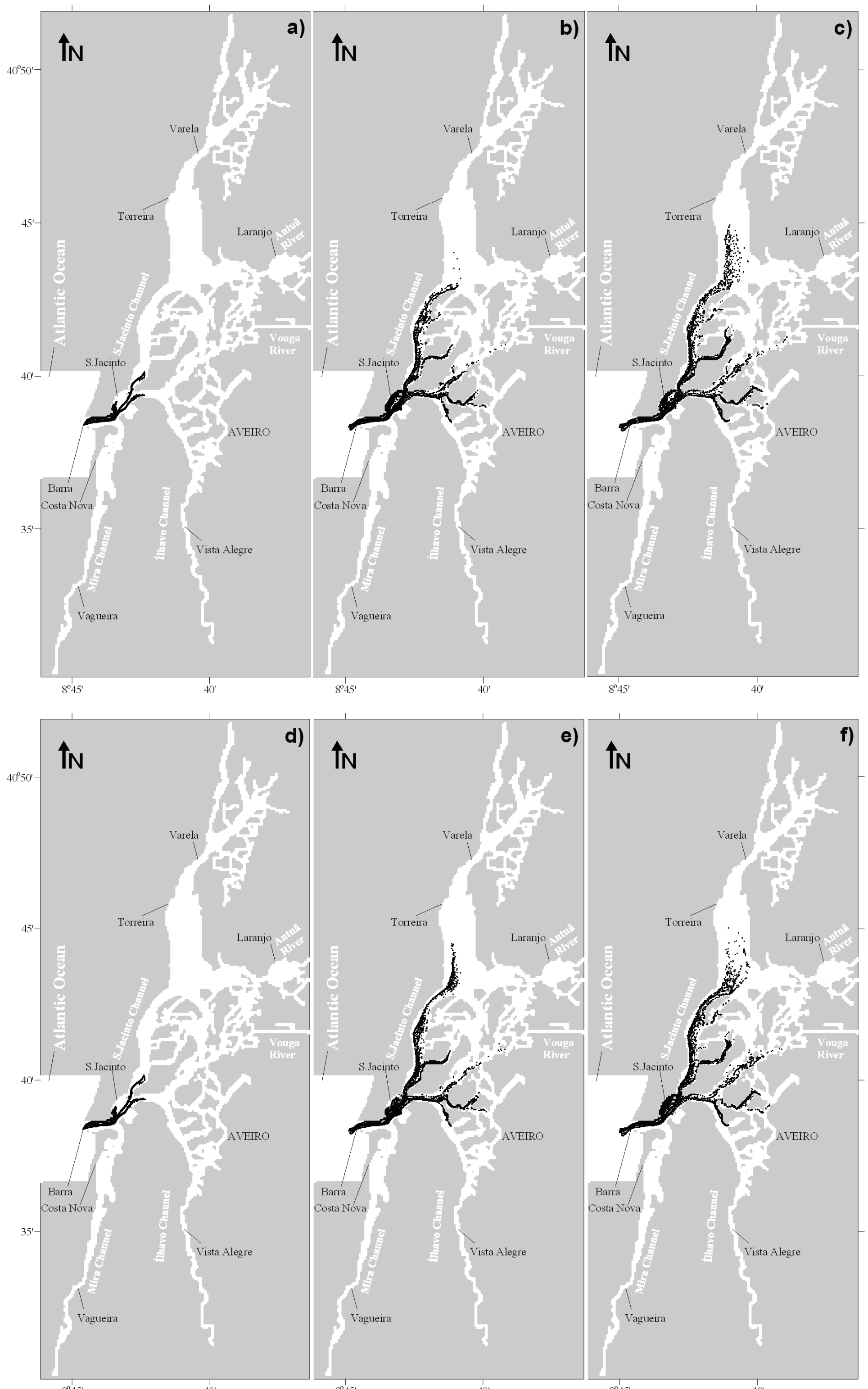

Figure 2. Area of Ria de Aveiro affected by the oil spill dispersion after six hours of simulation. a), b), c) represents the neap, average and spring tide conditions, respectively, with null freshwater inputs. d), e), f) represent the neap, average and spring tide conditions, respectively, with average freshwater inputs.

Spring Tide

From Figures 2c) and f) it is noticeable that the area affected by the oil spill dispersion during spring tides is the largest. The oil spill reaches more areas upstream than in the previous cases. After 6 hours of dispersion all the central area of Ria de Aveiro is affected by the spread of the oil spot, with a dimension that would probably make difficult an eventual cleaning mission.

The differences between the simulations with and without rivers inflow are more obvious than in other tides, with a larger area at the middle of S.Jacinto channel affected when the rivers inflow is considered.

DISCUSSION

The results obtained revealed that in case of an oil dispersion from the lagoon mouth the Mira channel would not be affected, and only the beginning of the Ílhavo Channel would be affected. The central area of the lagoon would be drastically affected, with the worse results having been found for the spring tide case. The observed patterns are closely linked to the tidal prism characteristics of the Ria de Aveiro. For the spring tide, the tidal prism is 136.7 Mm^3 and for the neap tide it only reaches 34.9 Mm^3 (DIAS, 2001). Therefore, the water volume flowing into Ria de Aveiro during spring tide is much higher than during neap tide, justifying the higher inland progression of the oil spot for that case.

The lagoon tidal prism is divided for the main channels as follows: 10% for the Mira channel, 13.5% for Ílhavo channel, 35.4% for S.Jacinto channel and 25.6% for Espinheiro channel (DIAS, 2001). This water inflow distribution clearly makes the S.Jacinto and the Espinheiro the most dynamic channels, and the Mira channel the less dynamic. Therefore, the oil spot will progress further inland along those channels.

When the rivers inflow is considered, the oil spill has more difficulty in progressing into the area where the Vouga River drains and it only reaches a smaller area than that reached in the simulation without rivers inflow. This pattern is induced by the larger flow from the Vouga River compared to those from the northern rivers of the lagoon, which means that the particles (oil spot) are pushed up due to the influence of the Vouga River, reaching further compared with the simulation without the rivers inflow.

CONCLUSIONS

The particle-tracking Lagrangean model applied in this work has some limitations concerning the reproduction of the oil characteristics dispersion. However, it accurately reproduces the advective processes in the Ria de Aveiro, which are fundamental in driving the transport processes in this kind of environment. Therefore, it can be considered a useful tool to estimate the oil spill dispersion in the Ria de Aveiro lagoon. Its results give valuable information regarding the areas that will be most affected, as well as about the time that an oil spill takes to spread along the lagoon main channels. These results may be used by the local authorities for planning prevention and cleaning missions.

The results show that some lagoon channels are more affected by the possible oil spill than others, regardless of the type of tide or rivers inflow assumed. The northern area of the lagoon is much more affected comparing with the southern area. The S.Jacinto and the Espinheiro channels are strongly affected, particularly the first one. In these two channels there are important ecological and economic sensitive areas, namely the Reserva Natural das Dunas de São Jacinto and the Aveiro port, which will be affected by the oil spill. Only the beginning of the Ílhavo channel is affected by the oil spill described, and just in the average and spring tide simulations. The Mira channel was not affected by the oil spill studied.

The areas of the lagoon affected by the oil spill will be strongly dependent on the characteristics of the tide when the potential accident will occur. If it takes place during spring tide the lagoon will be much more affected than if it happens during neap tide. The influence of the freshwater inputs was found less determinant.

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