Modelling study of the dispersal of pollutants at São Jacinto submarine outfall (Aveiro, Portugal)

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Abstract

The discharge of pollutants into the near shore waters over the continental shelf represents a source of water quality problems. In order to minimise the eventual impact of the discharge in the environment, submarine outfalls have been proposed. These systems avoid the direct contamination of the near shore waters by discharging the pollutants a few kilometres away from the coast, in the inner part of the continental shelf.

In this work a numerical study of the dispersion of pollutants at São Jacinto (Aveiro, Portugal) submarine outfall is presented. The 3D numerical model ROMS (Regional Oceanographic Modelling System) is used to simulate the flow and the evolution of a cloud of pollutants released at the outfall. This model is able to reproduce the main features of the coastal circulation in the neighbourhood of the submarine outfall.

The numerical experiments performed were conceived to establish the effect of different oceanographic conditions on the pollutants dispersion. This work represents the results when different wind conditions are considered.
1 Introduction

The discharge of domestic and industrial wastes into the near shore waters over the continental shelf represents a source of water quality problems. In order to minimise the eventual impact of these discharges in the environment, submarine outfalls have been proposed. These systems discharge the pollutants a few kilometres from the coast, in the inner part of the continental shelf, in order to avoid the direct contamination of the near shore waters (e.g. beaches). Therefore, the implementation of a submarine outfall system requires a previous study: the local characteristics of the outfall have to be established in order to achieve optimal rates of dilution of the pollutants released to the environment.

Within this work, we considered as a study case the pollutant cloud released at São Jacinto (Aveiro, Portugal) submarine sewer outfall. This submarine outfall is located about 3 km offshore and 3 km north of the Barra channel (see figure 1). The Barra channel is an artificial channel that connects the coastal lagoon (Ria de Aveiro) with the open ocean. One of the particularities of this outfall is its location near the entrance of the coastal lagoon, where the circulation is dominated by the tidal wave dynamics (Dias [1]). The Ria de Aveiro and its surrounding coastal zones, provides natural conditions for harbour, navigation and recreation facilities.

![Bathymetry, M2 tidal ellipse at the S. Jacinto outfall](image)

Figure 1: Geographic map of Ria de Aveiro and coastal region, illustrating the bathymetry and the M2 tidal ellipse component in São Jacinto outfall.

Only a few studies concerning the dispersion of the polluted plume originated in São Jacinto outfall have been done. In the Hidroprojecto report [2] the dispersion of the pollutants released at the sewer were simulated with a 2DH vertical integrated numerical model.
In the present study the 3D numerical ocean model, ROMS (Regional Oceanographic Modelling System) that solves the primitive hydrodynamic equations in a sigma coordinate system (Song and Haidvogel, [3]), is considered. This model is able to reproduce the main features of the coastal circulation in the shelf, namely wind driven and tidal flows, and simulates the evolution of a cloud of pollutants released at the outfall.

The wind and the tidal currents are one of the most important forcing mechanisms of the circulation in the continental shelf, in this region. In the simulations, different wind regimes are considered and the response of the effluent plume is analysed. The influence of tidal induced currents in the region close to the entrance of the lagoon and its interaction with the effluent plume is also studied.

2 Model and experimental configuration

The Regional Oceanographic Modelling System (ROMS) is a free surface, hydrostatic, primitive equation ocean model that uses stretched terrain following coordinates in the vertical (σ coordinate system) and orthogonal curvilinear coordinates in the horizontal.

In the present study, the ROMS model was configured to encompass the continental shelf up to 50 m isobath and the Ria de Aveiro lagoon. The dimensions of the computational domain are approximately 25 x 44 km, from longitude 8.60°W to 8.90°W, and latitude 40.50°N to 40.90°N (see figure 1). The computational domain is discretized into 222 by 126 grid cells, with a high resolution of 200 m. Due to limitations of sigma coordinate system, the depth in the coastal lagoon was assumed constant and equal to 5 m. Ten equally vertical sigma levels were considered, to solve the Ria de Aveiro circulation scale and their interaction with continental shelf circulation. To ensure stable numerical solutions the baroclinic time step was set to 20 s, and the barotropic to 1 s.

At the northern, western and southern open boundaries, the tidal wave is imposed, considering the harmonic semidiurnal components M2, K2, S2, N2 and the diurnal P1, Q1, O1, K1. In addition, the tidal ellipses corresponding to these frequencies were also imposed at the boundaries to improve the adjustment of the velocity field in the interior. These values were obtained from the application of the model to a larger domain. The M2 tidal ellipses in the inner shelf for the location of the São Jacinto outfall is represented in figure 1, with a scale of 5 cm s⁻¹ plotted in the lower right corner of the figure. A radiation condition was imposed to allow the model to radiate the perturbations due to the wind driven circulation.

In the inner continental shelf the density field variations are not considered in the scope of this work. Therefore, in the main simulations we have considered a well-mixed ocean with a salinity of 35 PSU and a temperature of 14°C. These values were also considered inside the lagoon.

A study of the response of the coastal circulation patterns to different wind regimes has been done. Steady winds with different directions in each simulation
were considered: northerly, westerly and northwesterly winds with a wind stress of 0.07 Pa (corresponding approximately to winds of 7 ms$^{-1}$ in those directions).

To simulate the polluted plume released at São Jacinto outfall, a conservative passive tracer was injected. The rate flow, salinity and temperature of the injected polluted water set in the model correspond to the conditions observed at the São Jacinto submarine outfall. At the location of discharge the polluted plume has 1 unity of concentration and is produced through the discharge of 3 m$^3$s$^{-1}$ of freshwater into the ocean. The lighter water injected near the bottom mixes with the environmental water, upwells due to its high buoyancy, and spreads in the surface layer in accordance with the forcing. Thus, and in order to avoid salinity numerical instabilities near the bottom, the discharge was made in the middle levels of the water column.

In addition to the sewage outfall in São Jacinto, another independent passive tracer has been considered. At the beginning of the numerical simulation, a tracer with value of 1 unity has been initialised in the interior of the Ria de Aveiro, and 0 in the ocean coastal region. The evolution of the tracer is driven by the water exchange between the coastal water and the Ria, due to the effect of the tides and wind forcing.

3 Results

The aim of the present study is to establish the dependence of the dispersion of a tracer with the wind direction and to study the conditions in which the strong tidal induced currents produced near the entrance of the lagoon affect this dispersion.

All the simulations were made during a 14 day period, conditioned by two forcing mechanisms: one relative to tidal wave, and another relative to different wind conditions (North, West, and Northwesterly winds). As an example, figure 2 illustrates the free surface elevation computed at the point of the discharge for the whole simulation period. The pollutant dispersion analysis is focused on the first five-day period, corresponding to spring tide conditions.

The results of each simulation are represented in the form of contour plots of the tracer's concentration at the surface level on the third day of simulation, corresponding to maximum ebb tide current (see figure 2). Also, during the first five days of the simulation, surface floats were released every three-hours at the São Jacinto outfall location. Additionally clusters of floats are released along the N-S direction in the initial stages as indicated in the figures. The representation of the paths of the floats enables us to analyse the preferential paths of particles released at the sewer and, to a greater extent, establish the domain of influence of the coastal lagoon circulation.
Figure 2: Free surface elevation computed at the point of discharge.

3.1 Northerly winds

Figure 3 represents the results obtained with a northerly wind forcing. Figure 3(a) illustrates the concentration tracer contours. The contours depicted at 8.78W and 40.67N refer to the submarine sewer outfall. The minimum value of the contour is $10^{-4}$ and the contour interval is $5 \times 10^{-4}$. With the analysis of similar figures along the wave tidal cycle (not shown), we observe that the pollutant cloud injected at São Jacinto outfall, remains almost stationary with little advection due to tidal currents. It is noted that the plume shape is related with the tidal ellipse at that point, as illustrated in figure 1. The maximum concentration values are observed at the point of discharge and strong concentration decay occurs within approximately 1 Km from the point source, where the observed concentration is 0.01% of the injected value.

Figure 3(a) also displays the contours for the tracer introduced in the Ria: in this case the values of the contour lines range from 0.01 to 0.35. This picture gives a clear indication of the water exchange between the Ria de Aveiro and the ocean, and the advection of the tracer in the shelf as result of the wind forcing. If the tidal forcing dominates the exchange of waters between the Ria and the ocean, by means of an offshore jet in Barra channel, the wind forcing reveals as the main forcing in the shelf, as it controls the shelf circulation by means of the alongshore southward coastal current. The dynamics of this flow is well studied (Allen et al., [4]). It results from the response of the ocean to the offshore Ekman transport, coastal divergence, and hence the generation of a pressure gradient (water level gradient) with lowers values of sea level at the coast. This generates a southward geostrophic jet, which advects the tracer in that direction, as seen from the figure.
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Figure 3: Northerly wind forcing: (a) contour lines of tracer’s concentration on the third day of simulation; (b) the contour paths for the floats released at the submarine sewer outfall.

Figure 3(b) shows the particles paths released at the sewer outfall. During flood tide conditions the floats are advected towards the coastal lagoon entrance and afterwards move southward and some floats are impinging on the coast. Only few floats enter into the lagoon through the channel. During ebb tide conditions, the floats are driven offshore due to the strong offshore ebb flow at the channel, and are advected southward responding to the northerly wind forcing afterwards, as described before. Note, the ebb and flood induced circulations near the entrance of the coastal lagoon, lead to different paths of the floats as they move southward.

3.2 Westerly winds

Figure 4 (a,b) are identical to the ones represented above but are considered for a westerly wind forcing.

It is seen in figure 4(a) that the pollutant plume released at the outfall is now advected in the coastward direction and does not show any interaction with the circulation at the lagoon entrance. Also note in figure 4(b) that the floats released at the sewer outfall are all advected shoreward and arrive at the beach. Other floats, released in a N-S line at 8,82°W and between 40,6°N and 40,68°N, converge to Barra channel and enter in the Ria. A strong asymmetry between ebb and flood flows is observed. Thus, during ebb the flow consists of a jet (with approximately 2-3 m/s), that extends to some kilometres offshore; during flood flow, a region of suction can be identified (in figure 4b), that feed the Ria. We can also observe that during flood conditions the particles deviates towards clockwise direction due to the action of the Coriolis force. For the northerly wind simulation, all the floats released at the same point, were advected southward and did not interact with the Ria flow. On the other hand, it may also be seen from
the shape of the plumes in figure 4(a), the westerly wind does not induce a significant flow in the north/south direction. This means that westerly wind forcing is not favourable to a renewal of the waters within the Ria.

Figure 4: Westerly wind forcing: (a) contour lines of tracer’s concentration on the third day of simulation; (b) the contour paths for the floats released at the submarine sewer outfall.

3.3 North-westerly winds
The contour plots for the tracer’s concentration released at the sewer and at Ria, represented in figures 5(a), do not show significant differences to those represented in figure 3(a). The main differences are observed in figure 5(b) that illustrates the path of the floats released at the outfall. It is observed that with a northwesterly wind almost all the floats injected are driven into the lagoon through Barra channel but during ebb flow, are advected offshore and southeastward.

Figure 5: Northwesterly wind forcing: (a) contour lines of tracer’s concentration on the third day of simulation; (b) the contour paths for the floats released at the submarine sewer outfall.
4 Discussion and conclusions

A study of pollutant dispersion released at the location of the sewer outfall in Sao Jacinto, Aveiro, (Portugal) was done. The main concern was to establish the hydrodynamic conditions, in which the pollutant release might affect the coastline, (beaches and the coastal lagoon, Ria de Aveiro).

A set of numerical experiments was done, in order to study the typical oceanographic and meteorological conditions, by means of a 3D ocean numerical model, ROMS. Even if the model resolves adequately the hydrodynamic equations, it has some shortcomings when it is applied to a very shallower domain as the Ria de Aveiro lagoon. A minimum constant depth of 5 m was considered in the interior of the Ria. This affects the characteristics of the tidal wave propagation inside the lagoon and therefore, the interior circulation is not properly resolved. However, the main interest of this work was to study the circulation patterns in the coastal domain, and this could be achieved as far as the exchange between Ria and the coastal shelf waters is concerned, as described in this study.

The water exchanges between the Ria and the ocean depends on the coastal circulation at the inner shelf, which as it has been shown, depends strongly on the wind direction and magnitude.

This fact may be important to the pollutant dispersion coming from Sao Jacinto sewer that eventually enters in the lagoon, or arrives at the coast (where a large number of beaches and recreation facilities exist).

In what concerns the concentration of the tracer released at the S. Jacinto outfall, the simulation has shown that for Northerly and North-westerly winds, the polluted plume is diluted to a small distance from the source (at a scale of 1-2km), and does not seem to interact with the Ria de Aveiro nor with the coastal beaches. For the westerly wind conditions the tracer reaches the coastal beaches with a non-negligible concentration (0.02% of the concentration at the sewer).

This study also had a Lagrangian component, in which particles were released at different points of the coastal domain in study, and at the S. Jacinto outfall. By following the track of the particles released, we can take some conclusions concerning the possibility of pollution originating at the sewer.

In the case of Northerly wind these particles are mainly advected in the southward direction, and may affect the beaches located southward of the Barra channel. For the Northwesterly wind conditions, most particles enter in the Ria, and leave during ebb flow. Afterwards they follow the Southeast direction until they reach the coast, about 20km south of Barra channel. In addition, for Westerly winds, all the particles released at the sewer reach the beach located 3km away.

The present study shows that the tracer concentration to a great extent is limited to the source. However the particulate material released at the sewer may affect, through the mechanisms described above, some critical zones in the shore. More studies including stratification, originated by river runoff and heat fluxes,
should be done to improve the degree of understanding of the present simulations.

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References
