MONITORING AND MODELLING FOZ DO ARELHO SUBMARINE OUTFALL PLUME

CÁTIA ALVES

Águas do Oeste, S.A., Águas de Portugal SGPS, S.A., Convento de S. Miguel das Gaeiras 2510-718 Gaeiras, Portugal

SANDRA CARVALHO

Águas do Oeste, S.A., Águas de Portugal SGPS, S.A., Convento de S. Miguel das Gaeiras 2510-718 Gaeiras, Portugal

MADALENA SANTOS

Maretec – Instituto Superior Técnico,Universidade Técnica de Lisboa, Av. Rovisco Pais 1049-001Lisboas, Portugal

JOSÉ H. S. ZENHA

Águas do Oeste, S.A., Águas de Portugal SGPS, S.A., Convento de S. Miguel das Gaeiras 2510-718 Gaeiras, Portugal

RAMIRO NEVES

Maretec – Instituto Superior Técnico,Universidade Técnica de Lisboa, Av. Rovisco Pais 1049-001Lisboas, Portugal

Águas do Oeste, S.A. (AdO) is the company responsible for the Multimunicipal System of Water Supply and Wastewater Treatment of the denominated West region of the Portuguese Continent. One of its most important projects is the tentative to protect the Óbidos Lagoon from the constant threats of pollution, primarily due to the discharge of wastewater directly in to this wetland, through the renewing and construction of Wastewater Treatment Plants, directing the wastewater to a submarine outfall. AdO has started on July of 2004 a Monitoring Program in the Óbidos Lagoon and Foz do Arelho Submarine Outfall. This work pretends to simulate the impact of the implementation of the submarine outfall using a fully three-dimensional, time-dependent hydrodynamic model, MOHID.

INTRODUCTION

The Óbidos Lagoon is a small and shallow coastal lagoon located in the western coast of Portugal, approximately 80 km north of the capital Lisbon, as shown on Figure 1, with a hydrographic basin that covers an area of 440 km^2. The communication with the sea is trough a narrow and deeper channel which currently tends to move south.

Figure 1. Location of the Óbidos Lagoon.

In the upstream zone the lagoon is branched off in two arms: Barrosa at north edge and Bom Sucesso at the south, being the main receptors of the rivers Cal and Arnóia. The fresh water discharges of the rivers have a secondary importance in terms of hydrodynamics but are really important in the water quality at the upstream zones, where the residence time is high (around one month). Therefore, the lagoon was recently classified sensible according to the eutrophication criteria. This classification was based on European WWTP Directive 91/271/CEE.

Being aware of the fact that water protection requires complete water quality monitoring and assessment information to verify the effectiveness of the management activities, AdO has started on July of 2004, under it's direct supervision, a Monitoring Program in the Óbidos Lagoon and Foz do Arelho Submarine Outfall, with the support of Instituto Superior Técnico (IST) from the Universidade Técnica de Lisboa (IST) and Instituto de Investigação das Pescas e do Mar (IPIMAR).

The main purpose of this study was to establish a reference situation in Óbidos Lagoon and study the dispersion of the plume at coastal area, before the implantation of the Foz do Arelho submarine outfall. The Foz do Arelho Submarine Outfall (-9.24 West and 39.44 North) extends into the Atlantic Ocean, perpendicular to the coast line, with a length of 2 000 m. It's diffuser has 91,5 m of length which incorporates ten holes with 110 mm of diameter each, and is responsible for the discharge of the treated wastewater (the treatment is processed in the Wastewater Treatment Plants of Óbidos, Carregal, Charneca, Caldas da Rainha e Foz do Arelho) into the sea, at roughly 30 m deep. The volume estimated, of treated wastewater to be sent to the submarine outfall, per second is approximately 0,3 m^3.

Achieving this goal requires modeling work combined with field work in order to understand the physical and ecological processes between the two study areas. To simulate the ecological processes was used a hydrodynamic, ecological and water quality model (MOHID) and for the dispersion of the plume was used the MOHIDJET model. The modeling task presented here use nested models that includes different domains with different resolution.

After shifting the discharge zone, which occurred in October of 2005, the impact in Óbidos Lagoon water quality continues to be a case study supported for AdO, in order to characterize the effects of this change. This project represents a strong investment for AdO in a total of 226 900 €(from the year 2004 to 2006), value that is in part supported by the Cohesion Fund.

MATERIAL AND METHODS

Field data and management
The need to gather historic data was essential in order to characterize the study area in the beginning of the Monitoring Program and to run the model. The data was acquired in two Portuguese institutional organizations that had already monitored the Óbidos Lagoon, the Instituto da Água (INAG) and the Instituto Hidrográfico (IH).

The monitoring plan proposed for AdO encloses five monitoring stations in the Óbidos Lagoon (the water samples are collected in high and low tide) and two monitoring stations in the coastal area (the water samples are collected considering three water levels: surface, middle and bottom). Associate to the classical sampling, it was used a multiparametric sounding lead with the purpose of acquiring data in a continuous way. The main goal of the monitoring program is the study of the lagoon and coastal area before the shifting of the treated wastewater to the submarine outfall and consequently after the submarine outfall started functioning, in order to evaluate the changes in the system over time.

Due to enormous volume of existing data, it was developed a data base WEBGIS (www.mohid.com/gis) with the intention of storing and organizing the field data. This data base simplifies the way the field data is arranged, allowing a more effective search and handling of the data.

Model Description
The model used in the study is the MOHID (www.mohid.com). The Mohid system is composed by a free surface three dimensional baroclinic hydrodynamic module, a eulerian transport module, a lagrangian transport module, a turbulence module, a zero-dimensional water quality module and an oil dispersion model. Parameters and processes involving non-conservative properties are object of specific modules (e.g. turbulence module, water quality, ecology and oil transformation).

The hydrodynamic model solves the three-dimensional incompressible primitive equations, as in, Martins *et al.* [7]. Hydrostatic equilibrium is assumed as well as

Boussinesq approximation. The model uses a finite volume approach. This method makes the solution independent of the mesh geometry, allowing the use of a generic vertical mesh. The turbulence module uses the well known General Ocean Turbulence Model (GOTM, www.gotm.net/). The model also solves a transport equation for salinity and temperature in order to compute the specific mass.

The eulerian transport module used to transport these properties is based in the same finite volume method of the hydrodynamic model and is independent of the property transported.

The lagrangian transport model tracks the trajectories of selected water masses using the transport fields from the hydrodynamic model in an explicit procedure. Dispersion is computed using the results from the turbulent model.

The ecological model uses a zero-dimension formulation that enables the application of the same model with both the lagrangian and the eulerian transport models, as in, Pina [8]. In this method the model equations are implemented in the form of source and sink terms of the transport models. Those terms are written in a generic form and can be applied both to eulerian cells and to lagrangian particles. The ecological model simulates the nitrogen cycle, the dissolved oxygen concentration, the BOD, the zooplankton and the phytoplankton population dynamics. The nitrogen species include the three main inorganic forms: ammonia, nitrate and nitrite and also three organic fractions: dissolved refractory fraction (DRON), dissolved non-refractory fraction (DNRON) and particulate fraction (PON).

Another integrated module developed was the MOHIDJET module, as in, Leitão [6]. The MOHIDJET module is useful to compute the dispersion of submarine outfall plumes. The MOHIDJET integral model aims to simulate the initial dilution associated to outfalls jets. The model is used as an initial condition of the MOHID system Lagrangian tracers module. The MOHIDJET is a very helpful tool to simulate the impact of outfalls water bodies integrating the near field (MOHIDJET) with the far field (MOHID). A Lagrangian approach was used in the MOHIDJET similar to the one use in the JETLAG model, as in, Lee and Cheung [4] (www.aoe-water.hku.hk/visjet/index.htm). Basically is simulated the trajectory and volume variation of a tracer with a cylindrical geometry. However, for the entrainment parametrization was used the work of Jirka [3]. This author is one of the main contributors to the development of CORJET (Cornell Buoyant Jet Integral Model) the buoyant jet model of CORMIX (Cornell Mixing Zone Expert System).

Model simulations for the Óbidos Lagoon
The simulations performed include the calculus of the residence time and also ecological simulations. The same methodology describe here is also applied in several Portuguese estuaries, as in, Saraiva *et al.* [9].

The residence time is the time required for the water inside the lagoon to leave it or, in other words, is the time required for renewing the water in the lagoon. Residence time is a key aspect for understanding the fate of loads, since processes with time scales larger than the residence time can not take place in its interior. From an ecological point of

view, lagoons with a short transit time will export nutrients from upstream sources more rapidly than lagoons with longer transit times and as consequence lagoons with short residence time are expected to have much lower algae blooms than lagoons with higher residence time, as in, Braunschweig *et al.* [1]. The residence time determination uses, in this study, the concept of lagrangian tracers to label the water inside coastal lagoon and assumes residence time as the time required by 80% of the water to leave the coastal lagoon. Residence time was computed performing the following steps, using the methodology described by Braunschweig *et al.* [1]: *(i)* computation of hydrodynamics forced by tide and mean annual river inflow of rivers Arnóia (2.8 m^3/s) and Cal (0.14 m^3/s.); *(ii)* division of the lagoon into 5 boxes that are filled with lagrangian tracers, and *(iii)* calculation of residence time considering the ratio between instantaneous tracers volume and the initial tracers volume in each box over time.

For the ecological simulations was performed a reference simulation which represents the conditions of Óbidos Lagoon before the submarine outfall discharging. Results obtained in this simulations aim to explain the functioning of the system. The main forcing conditions are the tide at the open boundary and the seasonal discharge of the River Arnóia and Cal at the land boundaries. To evaluate the effects of the discharges of Wastewater Treatment Plants that will be connected to the outfall, was performed one simulation to be compared with the reference situation. In this scenario was considered the connection of all the treatment plants mentioned earlier to the submarine outfall.

Model simulations for the Coastal Area
The simulations in the coastal area were performed using a 3D nested hydrodynamic model. The incased of four level models allowed the integration of processes with different scales. The communication between models is made one-way, that is, the higher scale models can influence the lower scale models, but the contrary is not valid.

The higher resolution model (level 1) covers the entire Portuguese coast. The model was forced with wind gathered in the MAMBO Project surveys [2] and the FES95.2, global tidal solution, as in, Le Provost *et al*. [5]. The grid used in this model is made up of 324 cells horizontally and 218 cells vertically, with a variable spatial step of 0.04ºx0.04º (~4kmx4km) in the open border and 0.02ºx0.02º (~2kmx2km) close to the ending border. The level 2 model covers the whole coastal area from the port of Nazaré to the port of Peniche (the Óbidos Lagoon is still not shown in this model). The grid used in this second level is composed of 107x278 cells of calculus with the variable spatial step of 0.01º (~1.4km) in the open border and 0.008º (~800m) near the ending border. The third level, with a 50 meters resolution grid, already includes the Óbidos Lagoon and the coastal area including the calculus of the salinity and temperature Óbidos Lagoon plume. The fourth nested model includes a bathymetry of 25 m and allows the simulation of the plume resulting of the discharge of the submarine outfall.

The simulations were performed simulated under different wind scenarios. To study the behavior of the plume in the study area the fecal coliforms were used s as the perfect indicator.

RESULTS

Óbidos Lagoon

Ecological Simulations

MOHID Water Modelling System is able to produce several types of results. To validate models simulation, point time series are usually used comparing data field values and model results. However, this method raise two questions *(i)* which area is a point representing and *(ii)* which field data should be compared with a point time series computed by a model.

In these study an integrated boxes approach was used. In these approach is possible to associate time series to large boxes and therefore computing the fluxes across the boundaries of those boxes, simplifying the analysis of results. With this approach it is possible to compute the net fluxes across boundaries and trough the boxes for the lagoon.

The Figure 2 represents the input and output for phytoplankton, ammonia and nitrate in the reference situation. The output was computed integrating spatially results of cells inside the boxes and fluxes trough those boxes. The total annual balance in the lagoon for reference and future situation is presented, in Table 1. The balance was computed as the difference between output and input annual fluxes of properties.
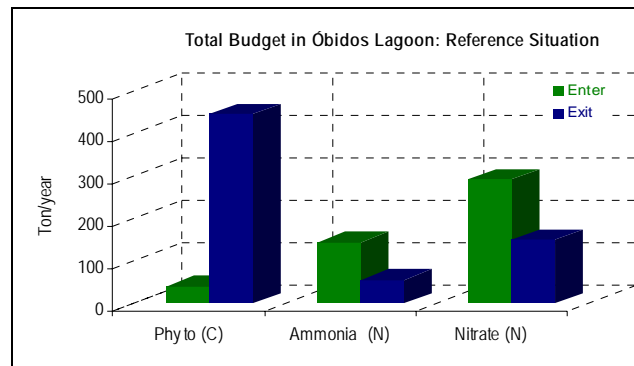

Figure 2. Total budgets for phytoplankton, ammonia and nitrate in Óbidos Lagoon.

Table 1. Annual phytoplankton and nutrient budgets for the lagoon, in reference and future situation. (Positive => Inflow+Production>Outflow+Consuption).

Óbidos Lagoon	Mean Residence Time (days)	Ammonia (TonN/y)	Nitrate (TonN/y)	Phytopl. (TonC/y)
Reference Situation	12	-89	-141	+405
Future Situation	12	-43	-65	+310

The results show that the lagoon behaves as phytoplankton exporters to the coastal area having a positive total balance. The lagoon has a high residence time (particularly in the upstream zones) because the fresh water flows are not important, when compared with the tidal prism. The tide is the mains responsible for renewal inside lagoon. Therefore, the residence time can be on the order of one day in the downstream zones near the inlet, to 26 days in the arms of the lagoon. The mean residence time of the water inside lagoon (12 days) is enough to permit the development of the main ecological processes. To support this production the lagoon is a net consumer of nutrients (ammonia and nitrate), which presents a negative annual budget.

Comparing the reference situation with the future situation, the phytoplankton exports reduce, because the entrance of nutrients is lower than in the reference situation. In this case, because fresh water influence is low and residence time is high, a reduction in nutrients will produce a significant reduction in phytoplankton concentration and, therefore, in primary production. Comparing the budgets for both scenarios it is possible to see a reduction of about 24% of the primary production in the future situation.

Dispersion of the plume simulations
The currents in the study costal area are almost parallels to the coast line with a magnitude about of 15 to 20 cm/s at the surface. The currents are influenced by the local winds which are predominantly from north with a mean intensity of 6 m/s. In north winds conditions the plume is dragged far away from the coast to the south and to north at south winds (Figure 3).

The initial dilution promoted is in the order of a 1/500, with a concentration of fecal coliforms around $1x10^4$ CFU/100 ml at the surface, for a concentration of fecal coliforms, in the treated wastewater, of $1x10^7$ CFU/100 ml. As shown in the figure, the distance necessary for the concentration on bacteria of the plume to fall to 100 CFU/100 ml is around 2 km.
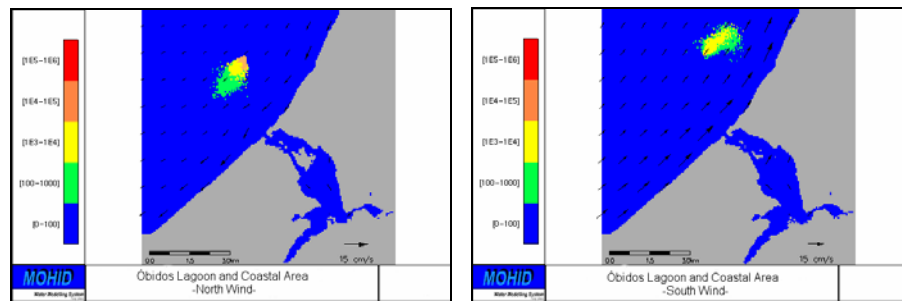

Figure 3. Submarine outfall plume under north (left) and south (right) wind conditions.

MAIN CONCLUSIONS

With this work it was shown that primary production at Óbidos Lagoon is vulnerable to nutrients input. In the future situation, it will be expected that primary production diminish and therefore demonstrates an improving in the system. However it is necessary time for the system to recover, due to the organic matter accumulated in the sediments. The monitoring program is important to follow the behavior of the system along the time.

At the coastal area the microbiological impact of the plume shows that the maximum concentration ate the surface will be around $1x10^4$ CFU/100 ml. The field data gathered after the discharging of the submarine outfall will be helpful to validate the values simulated by the model. The simulations performed under different wind conditions suggest that the plume probably will never reach the coast, because the transport at the surface is conditioned by the wind, which in the Portuguese coast frequently comes from the north.

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