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3D Lagrangian Modeling of Montevideo's Submarine Outfall Plume

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Abstract
Waste water treatment and the disposal of its residuals is one of the most important aspects of coastal management. The usage of preliminary waste-water treatment plants and subsequent ocean disposal via submarine outfalls for domestic sewage is one option that needs to be carefully studied. In this paper, the evaluation of different alternatives of sewage disposal through submarine outfalls for the city of Montevideo is presented. Different outfall locations, lengths, and geometries were modeled using two models; a 3D-hydrodynamic-baroclinic model and a lagrangian tracer transport model that simulates the movement of the submarine discharge plume. The hydrodynamic model was implemented using a nested domain approach with four 3D grids of increasing horizontal resolution. A net of control boxes was defined to evaluate the evolution of the plume in the coastal areas of interest. The numerical results were processed statistically in order to be compared with the standards of the local water quality legislation. The final result of the process is a submarine outfall design that verifies the economic and environmental requirements by minimizing the environmental impact.

Keywords
Submarine outfall; Lagrangian model; MOHID

INTRODUCTION

Uruguay's capital city, Montevideo, has one million and a half inhabitants. Along Montevideo's coast there are several beaches that are visited by the city's residents and tourists during the summer. Over the last few years an improvement plan for the sewage systems of Montevideo has been under study. This project considers the discharge of treated effluents into the Rio de la Plata River through a submarine outfall.

Montevideo's municipality requested the IMFIA to undertake an evaluation of different discharge alternatives based on the use of numerical models. In this paper, the methodology and main results of these studies are presented. Different outfall locations, lengths, and geometries were modeled using two models; a 3D-hydrodynamic-baroclinic model and a lagrangian tracer transport model. These models were applied in the coastal zone of Montevideo obtaining the temporal variation of currents, water levels, salinity, and concentration of the discharged substance at every point of the analyzed domain. The numerical results were processed statistically and compared with the standards of the local water quality regulation. Following this methodology, a submarine outfall design that verifies the economic and environmental requirements by minimizing environmental impacts, was obtained.

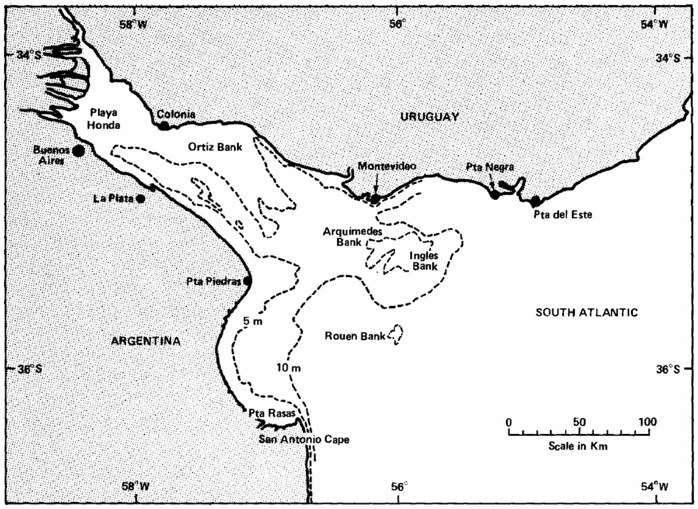
STUDY AREA

Uruguay is located in the east coast of South America between Argentina and Brazil. It has an area of 176.215 km^2 and a population of 3.46 million. To the southwest, in the border with Argentina, lies the estuary of Río de la Plata. This water body is located between 34º 00´ - 36º 10´ South latitude and 55º 00´ - 58º 10´ West longitude, and has the second largest basin of South America (3.170.000 km^2) after the Amazonic one (Figure 1). Montevideo is located on the central estuarine zone of the Rio de la Plata River where the salinity shows significant seasonal fluctuations.

The flow dynamic in the Rio de la Plata and the Maritime Front is very complex due to the topographic variation of the river (Figure 2) and the influence of continental flows, astronomical and meteorological tides coming from the ocean and the local winds. The Rio de la Plata behaves as a micro-tidal estuary, i.e. the river level variations produced by astronomical tides are much lower than those generated by the wind action and oceanic waves. The Parana and Uruguay rivers provide more than 97% of the continental water inlet with an annual mean flow of 22.000 m^3/s. The fresh water mixes with the oceanic water creating a zone of brackish waters.

Figure 1. Rio de la Plata location

Figure 2. Rio de la Plata morphology



MODEL DESCRIPTION

The numerical model used in this study was the MOHID, a three-dimensional water modelling system developed by MARETEC - IST (Marine and Environmental Technology Research Center - Instituto Superior Técnico), from the Technical University of Lisbon [1]. During the last few years several modeling studies in the Rio de la Plata River and the Atlantic Ocean have been done using the MOHID [2, 3, 4].

The MOHID is a three-dimensional hydrodynamic model based on the Navier Stokes equations including the Boussinesq and hydrostatic approximations. The basic equations, with appropriate boundary and initial conditions, are integrated numerically using the finite volume method. The grid can be set up using the sigma vertical coordinate, cartesian or others which allow a good representation of the topographical effects. The temporal implicit discretization ADI (Alternating Direction Implicit) uses a non centered grid solving stability problems usually found with explicit methods. The ADI discretization also simplifies the resolution of the water levels and the horizontal velocities reducing the system to a tridiagonal matrix. The Coriolis force and the horizontal transport terms are solved explicitly while the pressure and vertical transport terms are solved using an implicit algorithm. The MOHID has been applied to different coastal and estuarine areas, and it has showed its ability to simulate complex features of the flows [5, 6].

Hydrodynamic Model

In order to capture the dynamics of the submarine outfall discharge plume in an affordable CPU time, the hydrodynamic model was implemented using a nested domain approach. Four 3D grids of increasing horizontal resolution were defined to describe the system using cartesian coordinates in the horizontal direction and 10 sigma layers in the vertical direction. The first level represents the flow of the Rio de la Plata and its Maritime Front. The second level simulates the flow in the estuarine area of the Rio de la Plata. The third and fourth levels of resolution are focused on Montevideo's coast.

The hydrodynamic model was forced with astronomical and meteorological tides at the oceanic boundary, wind stress on the ocean surface, and fresh water flow at the western boundary. Series of water levels measured in six coastal stations and vertical profiles of current velocity measured in 4 different locations in the Rio de la Plata were used for calibrating and validating the hydrodynamic model. The characteristics of the hydrodynamic model implementation are presented in Table 1.

Figure 3. Domains of the 4 resolution levels

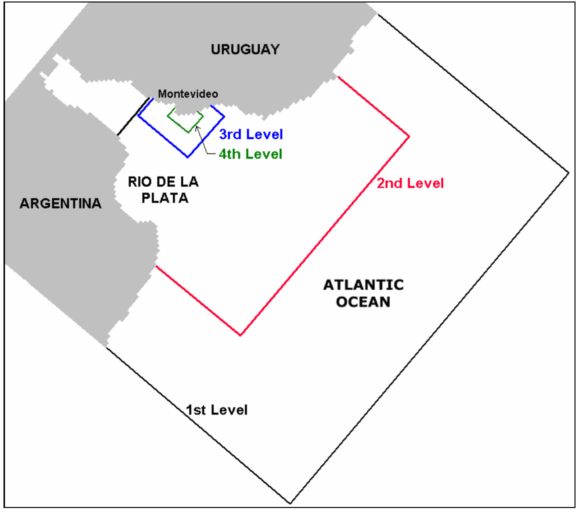


Figure 4. Bathymetry of the fourth level

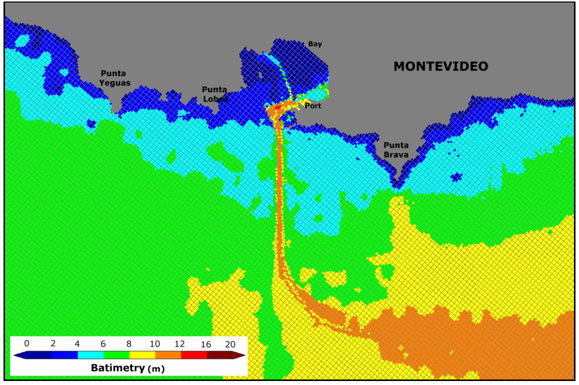


Table 1. Main characteristics of the hydrodynamic nested models

Resolution Level	Domain Area (km^2)	Spatial Resolution Dx=Dy (m)	Time step (s)	Boundary Conditions	
1st level	250,000	3000 to 9000	40	Continental	Freshwater discharge
				Open boundary	Astronomical and Meteorological tide
				Free surface	Uniform wind
2nd level	92,000	2000	20	Open boundary	η, U, V and S from 1st level solution
				Free surface	Uniform wind
3rd level	5,100	1000	10	Open boundary	η, U, V and S from 2nd level solution
				Free surface	Uniform wind
4th level	900	100	5	Open boundary	η, U, V and S from 2nd level solution
				Free surface	Uniform wind

Lagrangian Model

In order to analyze the different disposal alternatives and evaluate their potential impacts, the water quality module of MOHID [7] was used. Lagrangian transport models are very useful to simulate localized processes with sharp gradients, as it is the case of submarine outfalls. The lagrangian transport module of the MOHID simulates the movement of the plume generated by the discharge of polluted particles using the currents fields calculated with the hydrodynamic module. The lagrangian model simulates the movement of the discharged pollutant, considering advection and diffusion processes as well as bacterial natural decay processes in the case of fecal coliforms. A near field model (MOHIDJET) was used to simulate the dynamic of the plume close to the discharge. This module calculates the initial dilution of the outfall jet with higher accuracy and works together with the lagrangian module of the far field. The discharged particles are modeled as passive substances and therefore they do not affect the currents field or the density of the receiving water body.

When the transport of a substance is calculated using a lagrangian approach, it is possible to solve the equation of transport independently of the momentum balance equations. This basically means that the lagrangian module can “read” the hydrodynamic information of the system and update the calculations without having the need to solve all the variables at the same time. The lagrangian model computes the position and concentration of the discharged particles in every instant using the currents, water levels, and salinity fields calculated for the detail level by the hydrodynamic model. This methodology reduces the computational cost allowing studying various designs in a reasonable time.

Implementation and calibration of the lagrangian model was done in the detail level (high resolution grid centered in the zone of the discharge). The limits of the high resolution grid are defined reasonably far from the point of discharge in order to guarantee mass conservation of the discharged pollutant.

A formulation that integrates salinity, temperature, and solar radiation is used to calculate the T90. This formulation was calibrated by adjusting the minimum daily (20 hours) and maximum daily (72 hours) value of T90 in the Montevideo’s coastal zone. The diffusion coefficients were selected according to bibliography.

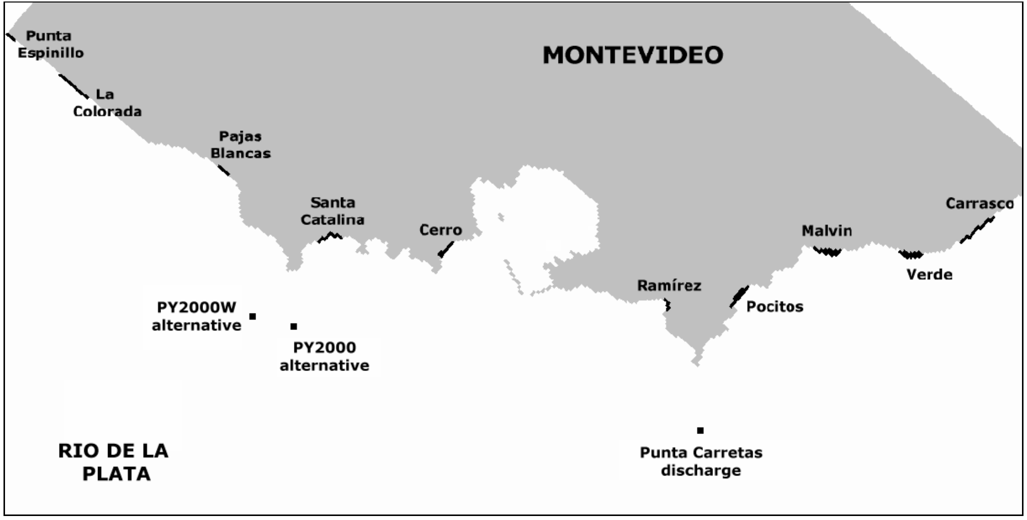
METHODOLOGY

The numerical modelling process was divided in two stages. First, the calibrated hydrodynamic model was run over a relevant period of time, i.e. representative of the average conditions of flow. A summer period (January, February, and March in the Southern Hemisphere) was simulated in order to represent the beaches conditions of use. Second, the simulation of two alternatives for disposal was carried out (Figure 5) using the lagrangian transport model that reads the current fields obtained with the hydrodynamic model. Both alternatives have a length of 2000 m with different allineation, North-South for the first alternative (called PY2000 alternative), and 41° to westward from the North-South allineation for the second alternative (called PY2000W alternative). The average water depth is 7 m in both locations. The existing outfall discharge of Montevideo, called Punta Carretas, was included in the simulation in order to represent the combined effect in the city beaches (Figure 5). However, the model can determine the source of the contaminant at each beach.

A preliminary diffuser design was defined to simulate the submarine discharge: 200 m of diffuser with 40 horizontal 0.2 m diameter ports aligned with the main pipe and discharging at 1.5 m of the bottom. The effluent characteristics defined for the year 2050, for the projected submarine outfall, are 2.89 m^3/s of flow rate and $1x10^7$ ufc/100ml of fecal coliform concentration. The flow rate value for the existing Punta Carretas submarine outfall implemented in the model is $3.29m^3/s$, maintaining the same fecal coliform concentration.

In order to analyze the results of the lagrangian model, a net of monitoring boxes was defined in the bathing beaches (Figure 5). These boxes include several grid cells in the horizontal plane and the 10 layers in the vertical direction. Every instant, the model computes the concentration of fecal coliforms in each box. Using this information, the concentration of pollutant frequency curve was calculated for every beach.

Figure 5. Monitoring boxes representing the beaches and location of the outfalls discharges.



The local legislation on water quality of beaches uses a classification based on the geometric average of 5 samples of coliform concentration (MG5) extracted daily from the beach. The legislation defines the following categories: *excellent* (MG5 < 250 ufc/100ml), *very good* (250 ufc/100ml < MG5 < 500 ufc/100ml), *barely acceptable* (500 ufc/100ml < MG5 < 1000 ufc/100ml), and *not acceptable* water quality for recreational purposes (MG5 > 1000 ufc/100ml). Considering this normative, the requirement for the chosen alternative will be to, at least fall in the *very good* quality category for all the beaches. From the modeled results, the beach water quality category was defined using the following methodology. First, a daily coliform concentration for each beach is calculated by finding the average of model results between the hours when the beach is in use, from 8am until 8pm. Second, the MG5 for the whole period is calculated, obtaining a number of 48 MG5 values for each beach, from the 53 days of the simulation. Finally, the value corresponding to the 95% limit, taken from the frequency curve, is the final value which is compared with the normative.

RESULTS

The main results after the simulation of the two alternatives for the new outfall discharge was that both alternatives, PY2000 and PY2000W, meet the quality criteria imposed on the new outfall. Nevertheless, the interaction of the new outfall plume with the plume of the existing outfall of Punta Carretas, is lower for the PY2000W alternative. Also, the mean initial dilution obtained for the PY2000W alternative (60) is greater than the obtained for the PY2000 alternative (40), due to more intense currents in the PY2000W discharge location.

Figures 6, 7, and 8 show examples of the obtained results. Figure 6 presents the outfalls plumes obtained with the lagrangian transport model for one particular instant. Figure 7 shows the initial dilution time series obtained with the MOHIDJET model for the PY2000W alternative. Finally, Figure 8 shows the coliform concentration time series obtained for the Santa Catalina beach generated for the PY2000W and Punta Carretas simultaneous outfalls discharges.

Figure 6. Example of the result obtained with the lagrangian transport model for one instant.

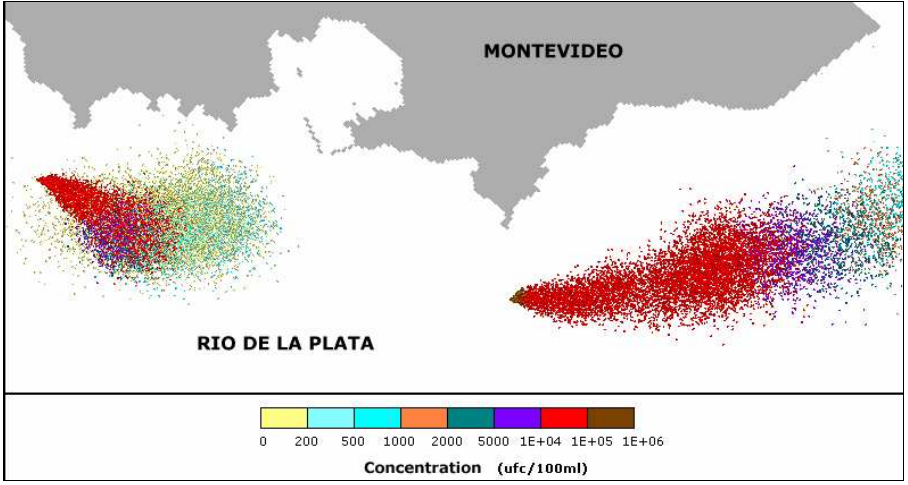


Figure 7. Initial dilution time series for the PY2000W alternative.

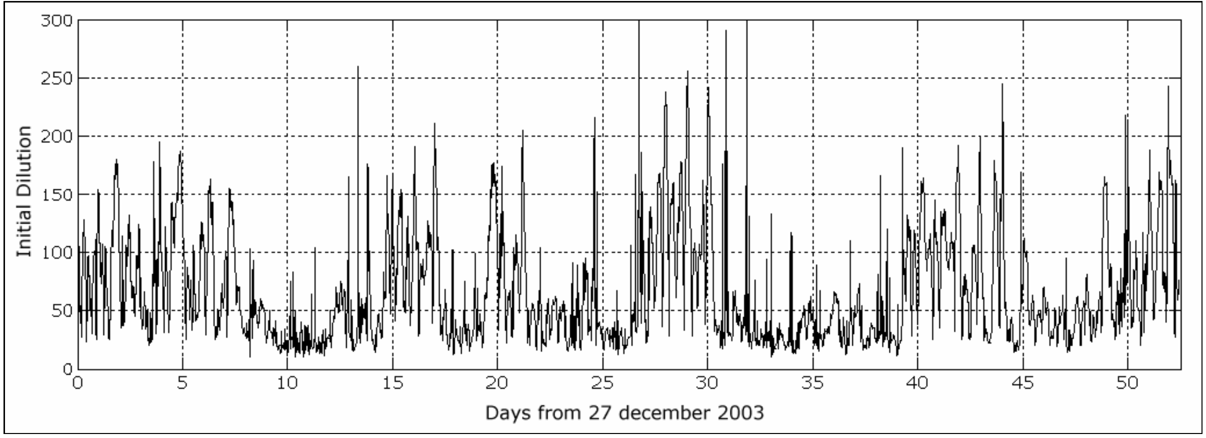
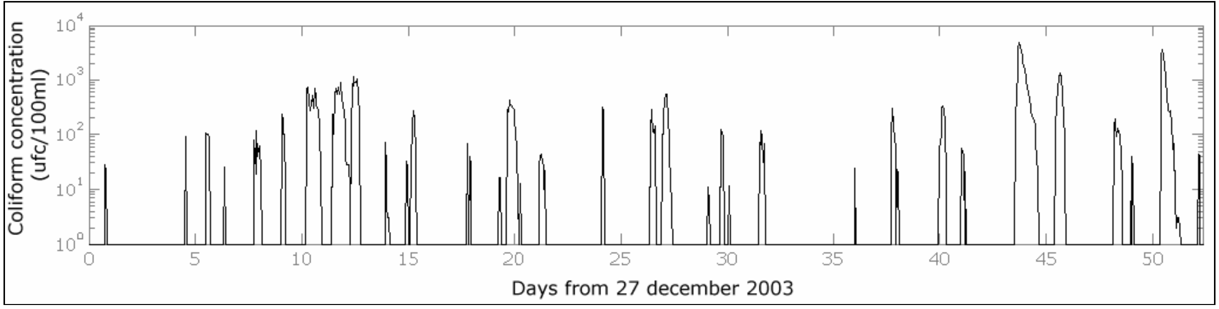


Figure 8. Coliform concentration time series for the PY2000W alternative discharge.



CONCLUSIONS

The final disposal of wastewater in coastal zones is a solution frequently implemented by developing countries. To design this type of solutions several aspects need to be considered, one of these aspects is the water body assimilative capacity for receiving the discharge without affecting other uses of the water body on the area. In this work a lagrangian tracer transport model has been used based on the current fields previously calculated with a 3D hydrodynamic model. The numerical results were processed statistically in order to evaluate different swage disposal alternatives considering the standards of the local water quality regulation.

The progress made on computer resources and numerical tools like the MOHID model makes it possible to analyze different solutions for this problem in an integrated way. Moreover, this approach provides elements that are important when making decisions, minimizing the environmental impact. The good results obtained in these studies validate the used methodology and show us the value and great utility of these numerical tools for use in similar projects.

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