DETERMINATION OF A SUBMARINE OUTFALL DISCHARGE LOCATION BASED ON A 3D HYDRODYNAMIC-LAGRANGIAN HIGH RESOLUTION MODEL IMPLEMENTED FOR THE RÍO DE LA PLATA IN SOUTH AMERICA

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CHAPTER SYNOPSIS

Background
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 chapter, 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 modelled using two models; a 3D-hydrodynamic-baroclinic model and a lagrangian tracer transport model that simulates the movement of the submarine discharge plume.

Results
The hydrodynamic model was implemented using a nested domain approach with four 3D grids of increasing horizontal resolution. The particles evolution was simulated in a high resolution grid. A net of control boxes was defined to evaluate the evolution of the plume in the coastal areas of interest, specially the beaches. Two submarine outfall locations for the projected discharge were evaluated. The numerical results were processed statistically in order to compare them with the standards of the local legislation for water quality.

Conclusions
The final result of the process is a submarine outfall design that verifies the economic and environmental requirements by minimizing the environmental impact.

1 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. Since the 1990's a first submarine outfall exists in the area covering the main part of the city (the *Punta Carretas* outfall). Nevertheless the city's growth has required the planning and design of a second submarine outfall.

Montevideo's municipality requested the Institute of Fluid Mechanics and Environmental Engineering (IMFIA) to undertake an evaluation of different discharge alternatives based on the use of numerical models. In this chapter, the methodology and main results of these studies are presented. Different outfall locations, lengths, and geometries were modelled 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.

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. During the last few years several modelling studies in the Río de la Plata River and the Atlantic Ocean have been done using the MOHID [1, 2].

In this book chapter we present the main characteristics of the modelling study developed in order to solve the management issue of sewage disposal in the sea water. The characterization of the study area, the main tasks for the implementation of the model, the overall and site specific methodology applied, and finally the results are showed. In addition to the long history of MOHID's successful applications to oceanic, coastal, lagoons, and estuarine waters and previous applications in Río de la Plata [1, 2], this model was selected mainly for its capacity to integrate the near and the far field solutions for a submarine jet discharge. Also, due to the big area and high resolution requirements the nested domain approach included in the MOHID system was a determining factor in order to capture the dynamics of the submarine outfall discharge plume in an affordable CPU time.

The design of Montevideo's outfall discharge is presented here. The study was made during the 2008 year. The same methodology and base tools were used for the design of the other submarine discharge in Uruguay (Punta del Este city). Nowadays the outfall discharge for Punta del Este is in construction and in the next year the construction of the new submarine outfall for Montevideo will start. Both designs were developed considering the environmental results obtained in this modelling study.

2 THE 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 34^{o}00' - 36^{o}10' South latitude and 55^{o}00' - 58^{o}10' West longitude, and has the second largest basin of South America (3,170,000 km^2) after the Amazonic (Figure 1, left panel).

The flow dynamic in the Río de la Plata and adjacent Atlantic Ocean is very complex due to the topographic variation of the river (Figure 1, right panel) and the influence of continental flows, astronomical and meteorological tides coming from the ocean, and the local winds. The Río de la Plata behaves as a micro-tidal estuary in the central zone, i.e. the river level variations produced by astronomical tides are much lower than those generated by the wind action and oceanic waves. The Paraná and Uruguay rivers provide more than 97% of the continental water inlet with an annual mean flow of 22,000 m^3 s^{-1} [3]. The fresh water mixes with the oceanic water creating a zone of brackish waters. Montevideo is located at the central estuarine zone of the Río de la Plata river where the salinity shows significant seasonal fluctuations [4].

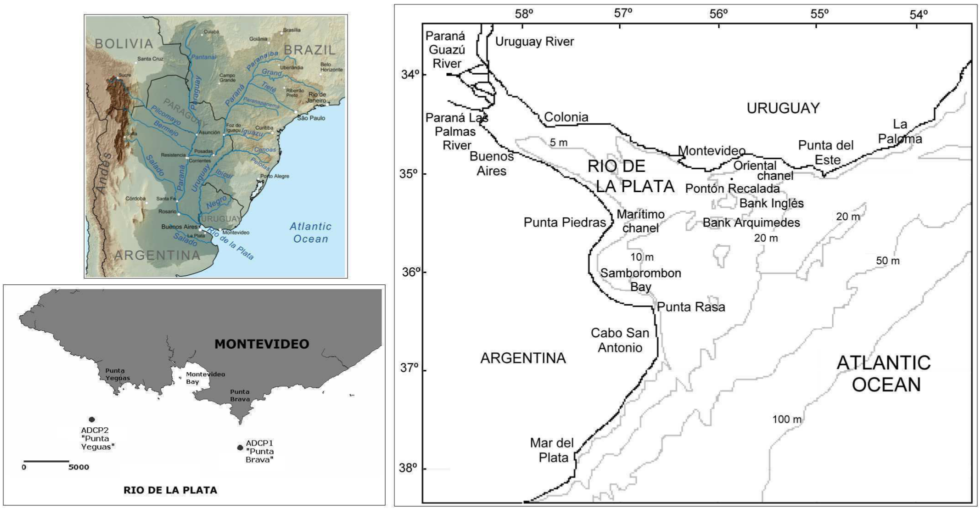

Figure 1. *Río de la Plata and Montevideo city location and morphology.*

3 NUMERICAL MODELS

3.1 Hydrodynamic model implementation

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. A system of four rotated 3D grids of increasing horizontal resolution was defined to describe the system. We used Cartesian coordinates in the horizontal direction with the x direction, following the axis of the river (almost southeast). Sigma coordinates with 10 layers equally spaced were used in all nested levels in order to obtain an adequate representation of turbulence in vertical.

The computational domain is shown in Figure 2, left panel. The larger domain has been extended in the oceanic limit in order to avoid boundary effects inside the Río de la Plata area. The study area is approximately of 250,000 km^2, bounded by the city of Mar del Plata to the South, the coast of Brazil to the North, the continental shelf to the East, and Uruguay and Paraná rivers to the West. The open boundary extends into the continental shelf to approximately the 2,000 m isobath and approximately 350 km from the coastal points. The alignment of the South and North oceanic boundaries is perpendicular to the coast and follows the continental shelf slope. This alignment simplifies numerically the income of the astronomical and meteorological wave tides which travel northward along the coast of Argentina entering the estuary from the South. On the other hand, the offshore boundary is almost parallel to the continental shelf avoiding strong bathymetry gradients along the model limit.

The first level of nested grid corresponds to the largest domain with a regular grid of 5,941 active cells. The resolution in both x and y directions is 5 km in the fluvial and estuary zone and 9 km in the oceanic zone (Figure 2, right panel). The second level focuses on the estuarine

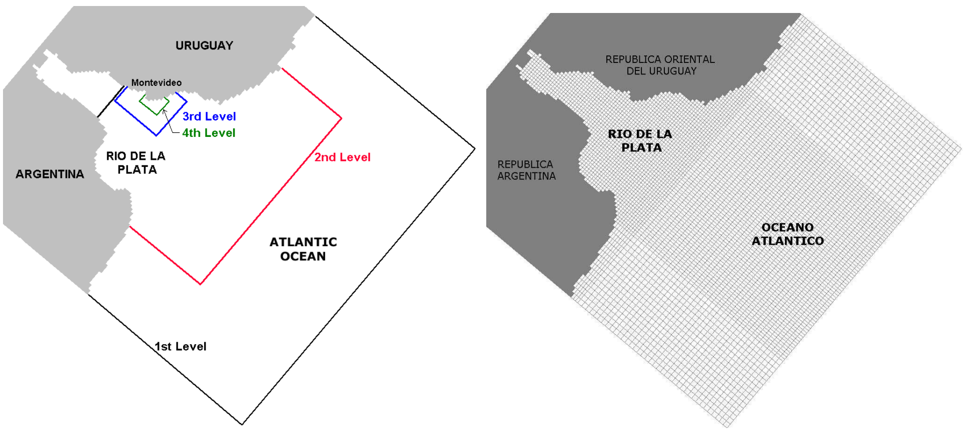

Figure 2. *Domains of the 4 resolution levels (left panel) and grid of the first level (right panel).*

zone of the Río de la Plata in an area of approximately 92,000 km^2. The South boundary has an extension of 163 km and the North boundary has an extension of 137 km from the coastal points. The horizontal grid is uniform with a grid cell of 2 km generating a total of 22,978 active cells. The third and fourth levels defined in this exercise are focused in Montevideo's coastal zone, covering an area of 5,100 km^2 and 900 km^2 approximately, respectively. Both are uniform grids with 1 km and 100 m grid size in both directions. The total number of active cells is 5,166 and 90,000 respectively.

The bathymetry was generated using mapping information from nautical charts for the Río de la Plata and the continental shelf. Figure 3 shows bathymetry in the first and four levels. The coastal zone of Montevideo includes approximately 13 km with several sandy beaches and a big bay (Montevideo's Bay) covering an area of 12 km^2 and navigation channels. Navigation channels are about 11 m deep, the rest of the area is 8 m deep with a slow slope shoreward. The hydrodynamic model was calibrated and validated considering the main forces: fresh water flow, astronomical and meteorological tides in the oceanic boundary, and wind acting on the ocean surface.

The boundary conditions are specified for the open ocean, the place of discharge of the major tributaries, and the free surface. The water surface elevation was specified for the ocean open boundary condition. The surface elevation results from the addition of astronomical oscillations and non-astronomical oscillations due to meteorological effects. The astronomical oscillations at the open boundary were obtained from the FES2000 astronomical tide atlas and correspond to the overlap of the main harmonic components M2, O1, Q1, N2, and S2 for the selected time period. The non-astronomical oscillations were calculated as the difference between measured and astronomical hourly levels at two coastal stations, Mar del Plata and La Paloma (Figure 3). To extend the water level series information to the entire ocean boundary, an interpolating strategy was used and validated. Density in the area is controlled by salinity [5] so only salinity variations are considered in the density equation of state. The free

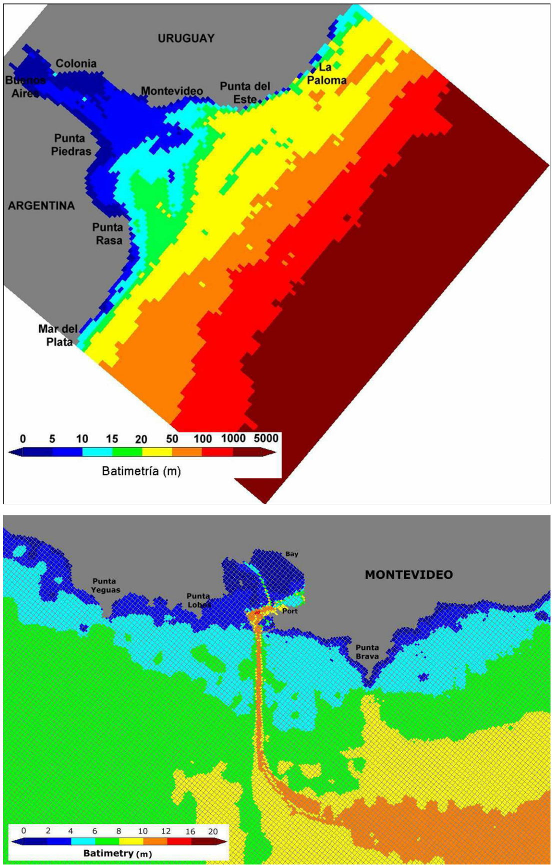

Figure 3. *Bathymetry of the first (left panel) and four (right panel) level.*

surface wind effect was included using measurements from the area (Montevideo). In this way the wind effect was considered time varying but uniform in space. A constant salinity value of 38 ppt was imposed in the ocean boundary. The characteristics of the hydrodynamic model implementation are presented in Table 1.

The initial condition in the first nested model is a hot start solution obtained by spinning up the model through six months run forced by freshwater river runoff and astronomical tide with a constant salinity value at its open ocean boundary. During this simulation the salinity field is generated. The lateral boundary condition at coastal boundaries is a free slip condition, imposed by specifying a zero normal component of mass and momentum diffusive fluxes at cell faces in contact with land. No fluxes at the surface and bottom were considered. The initial conditions in the second, third, and fourth nested models were interpolated from the previous level. The flow and salinity boundary conditions are interpolations of the calculation obtained in the previous level. The wind is also added in each level as an external forcing on the free surface.

Table 1. *Characteristics of the hydrodynamic nested models.*

Resolution Level	Domain Area (km^2)	Spatial Resolution (m)	Time step (s)	Boundary Conditions
1st level	250,000	3000 to 9000	40	Continental, Freshwater discharge Open boundary, Astronomical and Meteorological tide Free surfasse, Uniform wind
2nd level	92,000	2000	20	Open boundary, U, V and S from 1st level solution Free surfasse, Uniform wind
3rd level	5100	1000	10	Open boundary, U, V and S from 2nd level solution Free surfasse, Uniform wind
4th level	900	100	5	Open boundary, U, V and S from 2nd level solution Free surfasse, Uniform wind

This study was performed with the 4.9 MOHID parallel version using a computer with 4 processors and a 4GB memory ram. The parallelized code allows running the 4 nested models simultaneously, each one in one processor with a restriction in the time interval relations. Since the time interval for any nested model has to be a submultiple of the previous grid level, the time intervals for the final configuration were 40 sec, 20 sec, 10 sec, and 5 sec for the first, second, third, and four nested grid respectively.

3.2 Calibration and Validation

In previous studies [1] the hydrodynamic model MOHID was implemented to solve the main dynamic at the Río de la Plata and the adjacent Atlantic Ocean using only one grid for the entire domain (the first level described before). Thus the main calibration parameters (bed roughness, wind stress, horizontal and vertical turbulence schemes) were determined. During this calibration-validation process the same parameters were defined as start parameters in all nested levels and the model results were controlled in comparison with data mainly from the coastal zone of Montevideo. January and March of 2004 were used as periods of calibration and validation respectively.

In Figure 4, upper panel, the comparison between the measured water level elevation in Montevideo's costal station and the modelled water level elevation obtained in the 3rd nested grid for January 2004 is presented. The model correctly follows the main variability of water level reproducing the low waters (as in day 20) and the high waters (day 15).

The currents in the model were controlled using currents measurements with two 1200 kHz ADCPs of the Teledyne RD Instruments Company (called Punta Brava and Punta Yeguas) located approximately 3,500 m away from Montevideo's coast (Figure 1, lower panel). The equipment was installed specially for these submarine outfall study and the data was analyzed to improve the coastal zone circulation knowledge [6]. The Punta Brava ADCP was programmed to collect current intensity and direction with a vertical resolution of 0.35 m and the Punta Yeguas with 0.5 m. Both ADCPs collected data every 30 minutes. Figure 5, upper panel, shows the measured and modelled currents in bottom, mid depth, and surface at Punta Brava station during the first eight days of January 2004. The model correctly reproduced the main direction and intensity of the measured currents in PB.

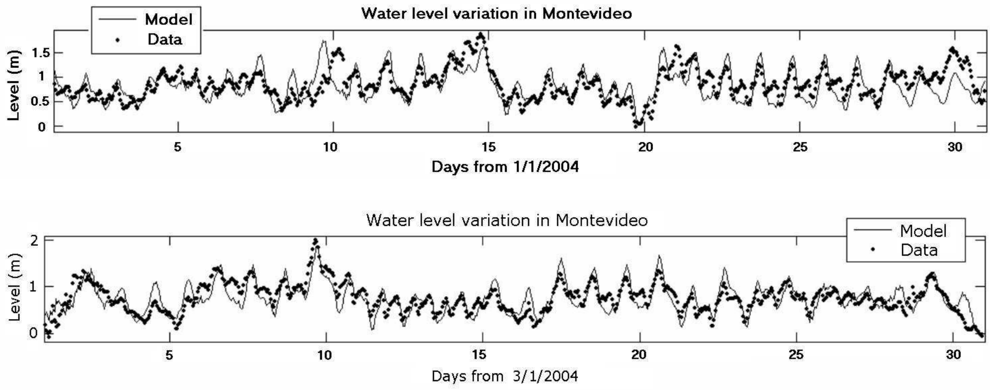

Figure 4. *Water level modelled and measured in Montevideo station. January 2004 (upper panel) and March 2004 (lower panel).*

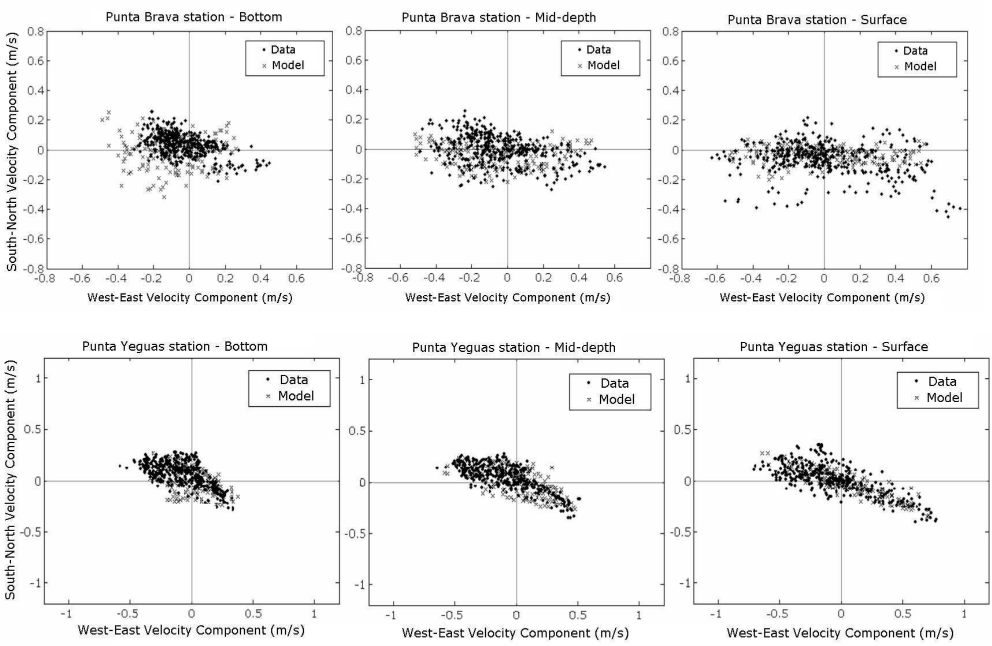

Figure 5. *Comparison of measured and modelled currents at bottom, mid-depth, and surface. Period from 1/1/2004 to 1/8/2004 at Punta Brava station (upper panel) and period from 3/11/2004 to 3/18/2004 at Punta Yeguas station.*

The obtained results for the validation period March 2004 are presented in Figures 4 and 5, lower panels. The water level series reproduced by the model in Montevideo show the same fluctuations (in amplitude and phase) as the measured water level elevation. The comparison between the measured and modelled currents in bottom, mid depth, and surface at Punta Yeguas station show that the model represents the main measured currents behavior.

The hydrodynamic simulation of a relevant period of time, representative of the average conditions of flow, was made in order to be used on the submarine outfall studied. A period of 53 days during the summer of 2004 (27 December 2003 to 17 February 2004) was simulated using the four nested levels in order to represent the conditions of use of the beaches. These are the most restrictive conditions due to water temperature and the duration of the sunlight.

3.3 The lagrangian model

In order to analyze the disposal alternatives and evaluate their potential impacts, the water quality module of MOHID 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 a permanent discharge of polluted particles using the currents fields calculated with the hydrodynamic module. The near field model (MOHIDJET) was used to simulate the dynamic of the plume close to the discharge.

In this implementation the discharged particles are modelled as passive substances and therefore they do not affect the currents field or the density of the receiving water body. The discharged substance is faecal coliform and the processes included in the far field evolution are advection, diffusion, and bacterial natural decay. The particles evolution was simulated in the grid 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. The currents, water levels and salinity field were used in the calculation of the pollutant evolution.

In addition to Montevideo's future submarine discharge, the existing coastal submarine outfall must be included in the simulations. In this way two points of discharge were defined in each simulation and the particles coming from each outfall were followed to identify the source of contamination for each beach.

One of the most relevant processes involved in the evolution of a pollutant discharged in a water body is the bacterial decay rate with is represented by the T90 (time for a 90% decay in concentration). A formulation that integrates salinity, temperature, and solar radiation is used to calculate the T90 [6]. This formulation was calibrated by adjusting the minimum daily (20 hours) and the maximum daily (72 hours) value of T90 for Montevideo's coastal zone. Instead of the bacterial decay rate, the advection and diffusion of the discharged substance controlled the evolution of the plume. The advection process is related with the main flow (calculate in the hydrodynamic model). The diffusion process is related to the turbulent movement in two different scales: eddies larger than the particles and eddies smaller than the particles. In the simplification used in the model the turbulent flow component is represented proportional to the mean flow with a coefficient. In this way the proportional coefficient represents the turbulence intensity of the flow. Because there are no measurements of pollutants dispersion for Montevideo's coastal zone, a value of 20% was supposed for the turbulence intensity. In order to guaranty the quality of the final solution at the end of the study, a sensibility analysis to these parameters was made.

4 SUBMARINE OUTFALL LOCATION STUDY

4.1 Methodology

Firstly, the simulation of two alternatives for disposal was carried out (Figure 6) using the lagrangian transport model that reads the current fields obtained with the hydrodynamic model. Both alternatives have a length of 2,000 m with different alignments, North - South for the first alternative (called PY2000 alternative), and 41^{o} to westward from the North-South alignment for the second alternative (called PY2000W alternative). The average water depth is 7 m for 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 6). However, the model can determine the source of the contaminant at each beach for the processing and analysis.

A preliminary diffuser design (Figure 7) was defined to simulate the submarine discharge: 200 m of diffuser with 40 horizontal (α=0 in Figure 7) 0.2 m diameter ports aligned with the main pipe (β=0 in Figure 7) and discharging in single ports at 1.5 m of the bottom. The effluent characteristics defined for the year 2050, for the projected submarine outfall, are 2.89 $\mathrm{m\,s^{-1}}$ of flow rate and 10^7 UFC/100ml of faecal coliform concentration. The flow rate value for the existing Punta Carretas submarine outfall implemented in the model is 3.29 $\mathrm{m\,s^{-1}}$ with the same faecal coliform concentration. In order to analyze the results of the plume dispersion model, a net of monitoring boxes was defined in the bathing beaches (Figure 6). These boxes include several grid cells in the horizontal plane and 10 layers in the vertical direction. Every instant, the model computes the concentration of faecal coliforms in each box. Using this information, the concentration of pollutant frequency curve was calculated for every beach.

The model results should be compared with the water quality standard for recreational proposes. There is wide range of criterion when it comes to water quality standards [7]. The local legislation on water quality of beaches uses a classification based on the geometric average of 5 samples of faecal 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 modelled 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 entire period is calculated, obtaining a number of 48 MG5 values for each beach, for 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.

Figure 6. *Monitoring boxes representing the beaches and location of the outfalls discharges.*

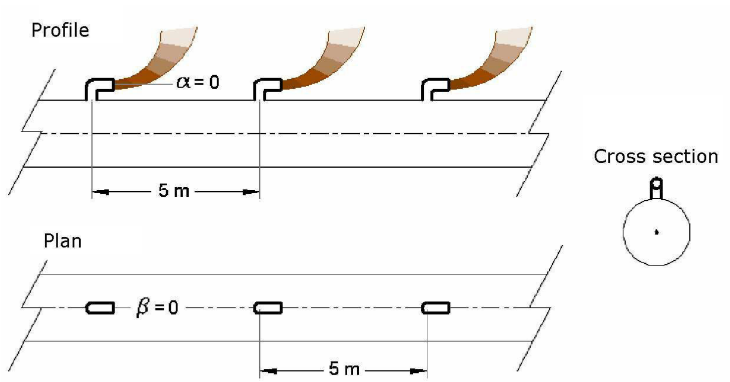

Figure 7. *Plan view, profile and cross section of the preliminary diffuser design.*

5 RESULTS AND DISCUSSION

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. This means that the 10 controlled beaches would be classified as very good quality beaches for bathing if the outfall is built. 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 8, 9, and 10 show examples of the results obtained from the outfall location analysis. Figure 10 presents the outfalls plumes obtained with the lagrangian transport model for one particular instant (PY2000W alternative). It is possible to see that the location of the

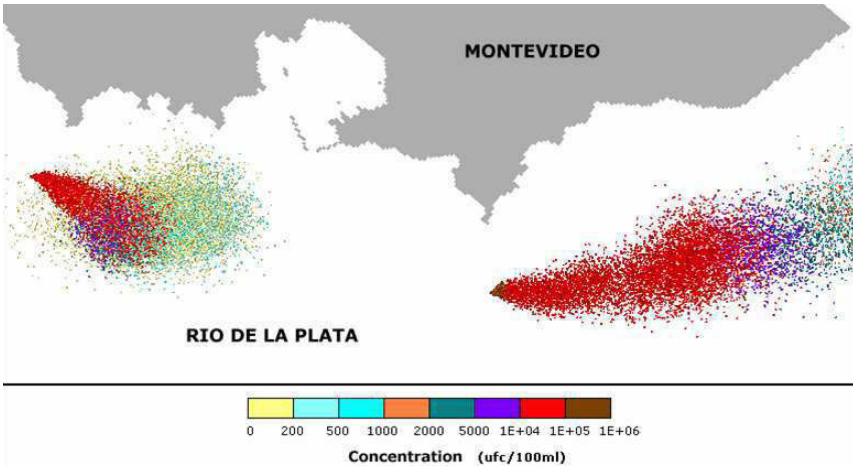

Figure 8. *Example of the result obtained with the lagrangian transport model for one instant. PW2000W alternative discharge.*

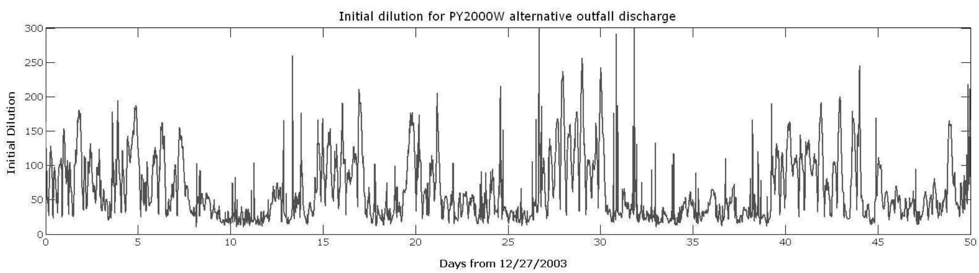

Figure 9. *Initial dilution time series for the PY2000W alternative.*

discharged particles for both outfalls follow a seaward current flow. Figure 11 shows the initial dilution time series obtained with the MOHIDJET model for the PY2000W alternative. Finally, Figure 10 shows the coliform concentration time series obtained for the Santa Catalina beach generated by both alternatives PY2000W and PY2000. The fluctuation between non zero concentration values with high concentration values responds directly to the main flow direction variation in Montevideo's coastal zone, from East to West and from West to East.

The presented comparison shows different levels of contamination in this beach with more affectation with the PY2000 alternative than the PY2000W alternative located farther to the beach than the previous one. For the same cause the PY2000W alternative generates more affectation in Pajas Blancas beach than the PY2000 alternative. In Punta Espinillo and La Colorada beaches both alternatives plumes arrive occasionally. In relation to the eastern beaches, neither PY2000 nor PY2000W discharges arrive to Pocitos, Malvin, Verde, and Carrasco beaches. Also, the PY2000W alternative discharge arrives occasionally at Cerro and Ramirez beach while PY2000 plume reaches these beaches several times.

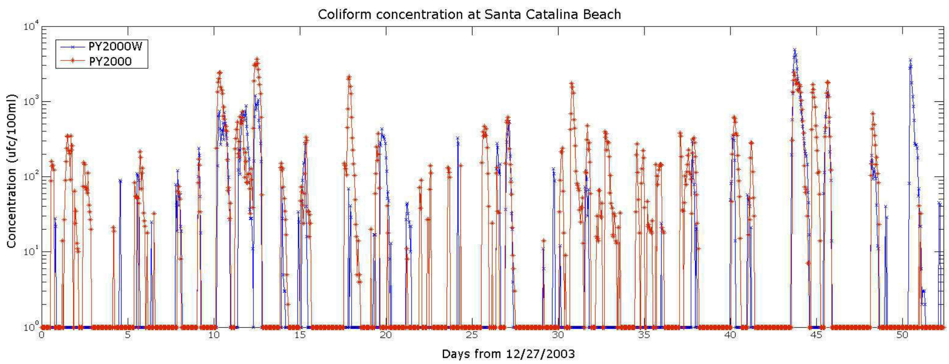

Figure 10. *Coliform concentration time series at Santa Catalina for the PY2000 and PY2000W alternatives discharges.*

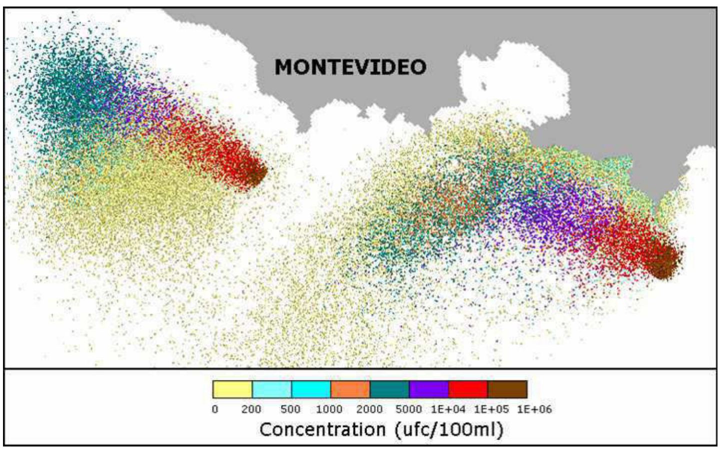

Figure 11. *Example of the result obtained with the lagrangian transport model for one instant at the sensitivity analysis. PW2500W alternative discharge.*

A sensitivity analysis of the model results to the assumed lagrangian model parameters was made. It is a recommended practice when we based the results in assumed parameters. Both alternative options, PY2000 and PY2000W, were analyzed with a turbulence intensity of 40% representing more substance diffusion than the original study and consequently a more exigent condition for the design. The results show higher particle dispersion everywhere when compared to the normal dispersion conditions presented before.

The obtained results show that the PY2000W, in extreme conditions, will affect more the coast than the PY2000 alternative. Finally, the possibility of a larger length, 2500 meters, was evaluated in both alignments (PY2500W and PY2500) using only the extreme dispersion conditions (Figure 11). The beaches quality classification obtained for both alternatives are equal to the corresponding discharge in a 2000 m. This means that the elevation of the cost resulting in an increase in the length of discharge is not worth from an environmental point of view.

6 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 and the near field calculated with a jet plume model. The numerical results were processed statistically in order to evaluate different sewage disposal alternatives considering the standards of the local water quality regulation.

The progress made on computer resources and numerical tools as 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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