Ciências Exatas e da Terra: Conhecimentos Estratégicos para o Desenvolvimento do País

Júlio César Ribeiro
(Organizador)

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APRESENTAÇÃO

O desenvolvimento socioeconômico do País está assentado primordialmente na inovação baseada no seu desenvolvimento científico e tecnológico.

É notado, principalmente nos últimos anos, que há grande necessidade de fortalecimento e expansão da capacidade de pesquisa e de inovação, bem como o aprimoramento dos conhecimentos já adquiridos pela sociedade.

Neste contexto, o E-book "Ciências Exatas e da Terra: Conhecimentos Estratégicos para o Desenvolvimento do País" foi composto por uma coletânea de trabalhos relacionados às Ciências Exatas e da Terra que contemplam os mais variados temas ligados ao desenvolvimento.

Os 20 capítulos que constituem a presente obra, elaborados por pesquisadores de diversas instituições de pesquisa, permitem aos leitores analisar e discutir assuntos tais como: importância das ondas eletromagnéticas e transmissão na camada da ionosfera, produção de filmes de polímeros a partir de diferentes complexos para aplicação em células solares, estudo de diferentes metodologias na caracterização de material polimérico, utilização de modelagem numérica na investigação da dispersão de plumas poluentes, aplicação de malhas computacionais para a verificação do transporte de doenças de plantas pelo ar, dentre outros assuntos de relevância para as Ciências Exatas e da Terra.

O organizador e a Atena Editora agradecem aos autores e instituições envolvidas nos trabalhos que compõe a presente obra.

Por fim, esperamos que este E-book possa proporcionar reflexões significativas que contribuam para o aprimoramento do conhecimento e desenvolvimento de novas pesquisas.

Boa leitura!

Júlio César Ribeiro

SUMÁRIO

CAPÍTULO 2

NUMERICAL MODELING OF SEWAGE OUTFALLS PLUMES IN THE COAST OF THE STATE OF PARANÁ – BRAZIL

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ABSTRACT: The present study aims to investigate the oceanographic characteristics and the dispersion of pollutant plumes in the coastal region of the State of Paraná, on the southeastern continental shelf of Brazil (25°S - 26.2°S, 49°W - 47.5°W), from the coast to the isobath of 50 meters, approximately. The numerical simulations were performed using the Delft3D modeling system, with the hydrodynamic module (FLOW) and the water quality module (WAQ). The dispersion modeling was implemented with the objective of evaluating possible construction sites for underwater sewage outfalls, considering that these outfalls constitute an excellent solution for an efficient and sustainable management of domestic effluents, in a region whose coastal cities suffer great environmental pressure due to growth of economic activities, especially tourism. The results of the models indicated the hydrodynamic characteristics of the coastal region and the most suitable locations for the construction of submarine outfalls, thus constituting an important subsidy in the treatment of sewage off the coast of the State of Paraná.

KEYWORDS: Numerical modeling, Delft3D, pollutant dispersion, submarine outfalls.

MODELAGEM NUMÉRICA DE PLUMAS DE EMISSÁRIOS SUBMARINOS NA REGIÃO COSTEIRA DO ESTADO DO PARANÁ - BRASIL

RESUMO: O presente estudo teve como objetivo investigar as características oceanográficas e a dispersão de plumas de poluentes na região litorânea do Estado do Paraná, na plataforma continental sudeste do Brasil (25°S

– 26.2ºS, 49ºW – 47.5ºW), desde a costa até a isóbata de 50 metros, aproximadamente. As simulações numéricas foram realizadas através do sistema de modelagem Delft3D, com o módulo hidrodinâmico (FLOW) e o módulo de qualidade de água (WAQ). A modelagem da dispersão foi implementada com o objetivo de avaliar possíveis locais de construção de emissários submarinos de esgotos, considerando que esses emissários constituem uma excelente solução para uma gestão eficiente e sustentável de efluentes domésticos, numa região cujas cidades litorâneas sofrem grande pressão ambiental devido ao crescimento das atividades econômicas, especialmente o turismo. Os resultados dos modelos indicaram as características hidrodinâmicas da região costeira e os locais mais adequados para a construção dos emissários submarinos, constituindo assim importante subsídio no tratamento de esgoto do litoral do Estado do Paraná.
PALAVRAS-CHAVE: Modelagem numérica, Delft3D, dispersão de poluentes, emissários submarinos.

1 I INTRODUCTION

The State of Paraná is located at the southern region of Brazil (25ºS - 26.2ºS, 49ºW - 47.5ºW), comprising two important estuarine systems, Paranaguá Estuarine Complex and Guaratuba Bay.

The climatology of the region and the circulation on the platform are defined by the Tropical South Atlantic Anticyclone High and the Polar Migratory Anticyclones. The former produces winds from NE and E directions that occur on the continental shelf, with an average intensity of 4 m.s-1 (CAMARGO and MARONE, 1995), so the currents on the platform have predominant S - SW directions (CASTRO, 2005). The occurrence of frontal systems in the region is associated to the Polar Migratory Anticyclones, which propagate to N and NE directions (QUADROS et al., 2007); during these meteorological events, winds from South may become strong and persistent enough to reverse the circulation on the platform, forcing Northeast currents (CASTRO, 2005). During the summer the cold fronts are less frequent, while in winter they are generally more frequent and stronger (SOARES and MÖLLER, 2001).

The dynamic of the Southeast Brazilian platform is therefore dominated by wind forcing. The tidal currents are weaker and rotating in time, whereas the currents generated by the winds are persistent and stronger, parallel to the coast, predominantly to the West-Southwest, but turning to East-Northeast (and usually more intense) under the influence of frontal systems. However, within the Paranaguá Estuarine Complex and Guaratuba Bay, and adjacent coastal areas, the hydrodynamics is governed by fluvial discharges and tides. Due to continuity, the tidal currents are very intense at the entry of these estuaries (RIBAS, 2004).

The discharge of domestic sewage is one of the most common types of ocean pollution, either through diffuse pollution in watercourses or through concentrated sources, such as submarine outfalls. A submarine emissary consists of a long pipeline, implanted on the seabed, from which the effluents are released in deeper regions, thus allowing effective dilution (LAMPARELLI, 2007).

In general, the amount to be disbursed in an emissary construction is much larger than in a sewage treatment plant. The latter can be built in stages, considering the populational demand, while the emissary must be built at once.

However, when comparing reference values between a sewage plant and an emissary, per capita costs are lower for the second (ARASAKI and ORTIZ, 2007). In addition, the advantages of a submarine outfall are numerous, including: high efficiency of sewage treatment and disposal, absence of visual pollution and odors, low energy expenditure, low maintenance requirements and less occupation of land (KNILL, 1984).

Submarine emitters represent an extremely efficient way of managing effluents resulting from large population centers. Both Paranaguá Estuary and Guaratuba Bay have enormous urban pressure due to the rapid and disorganized development of their cities, mostly due to tourism, fishing and maritime transport activities. An excellent option to improve the existing flaws in the region's basic sanitation system is the construction of sewage emissaries given that the region's sewage treatment system is increasingly suffering from high demand for quality services, especially during summer season, due to an enormous affluence of tourists.

The detailed study of hydrodynamics in the coastal region is necessarily the first step in the decision making of the emissary implementation process. Without this information, the construction may not be efficient in recycling discharged organic material, resulting in considerable environmental damage.

Considering that submarine sewage outfalls constitute an excellent solution for an efficient and sustainable management of domestic effluents, the question to be addressed in present study is on the indicative of the best sites for the construction of submarine emissaries.

2 I MATERIAL AND METHODS

The hydrodynamics and dispersion of pollutants simulations along the coast of the State of Paraná were carried out using the Delft3D modeling system (DELTARES, 2019), considering its hydrodynamic module (FLOW) and water quality module (WAQ). To form a full analysis of the processes that occurs in the study area, simulations were performed for the month of January 2016, representing summer conditions, and for the month of July 2016, representing winter conditions.

The hydrodynamic model implemented in this study used an Arakawa Type C grid, built in spherical coordinates, with grid spacing around 350 m, containing 300 points both in the directions parallel and perpendicular to the coast, as shown in Figure 1.

In this study, data of mean sea level and tidal elevation, together with currents, temperature and salinity profiles, were used as forcing at the open contours of the grid. In addition, the wind shear stress and radiation fluxes were applied at the sea surface of the whole study area. All the boundary conditions were taken from validated global models, frequently used in the most diverse studies, and recognized for their reliability. Both meteorological and oceanographic boundary data were interpolated into hourly intervals.

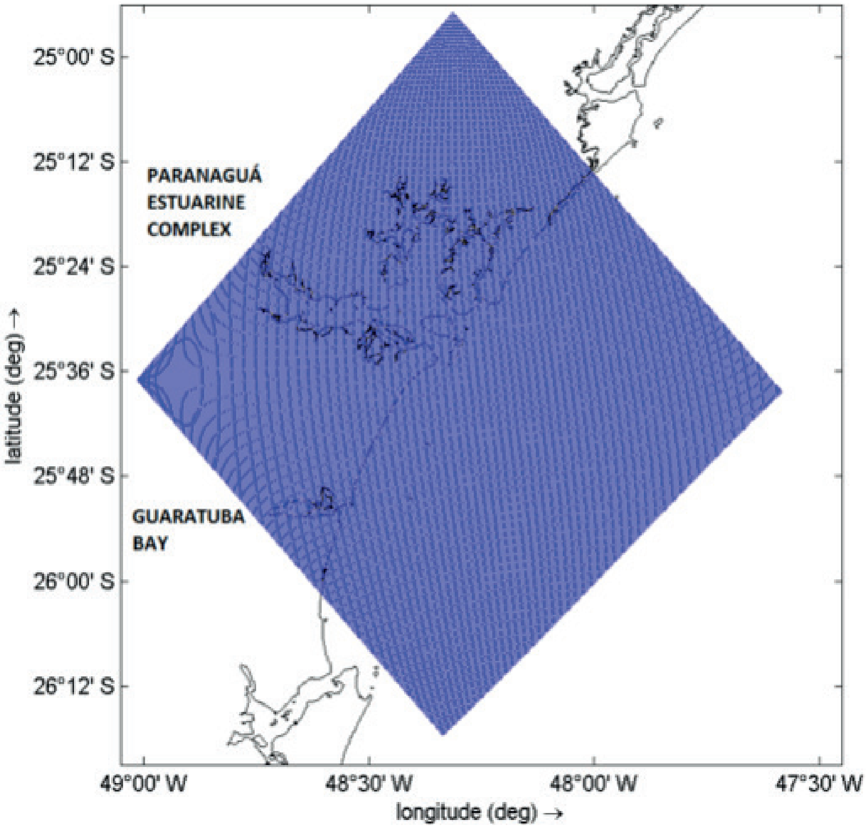

Figure 1. Study area and computational grid used for the hydrodynamic and water quality modeling.

Surface wind and radiation data were extracted from the global atmospheric model of National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) (SAHA et al, 2011), being interpolated in space and time, for grid points and for hourly intervals.

Tidal data for the open contours of the grid were obtained through the Oregon State University TOPEX/Poseidon Global Inverse Solution (TPXO) database (EGBERT et.al ., 1994), for constituents M2, S2, N2, K2, K1, O1, P1, Q1, Mf, Mm, M4, MS4, MN4.

Vertical profiles of temperature and salinity at the open contours of the study area were extracted from outputs of global models of CMEMS - Copernicus Marine Environment Monitoring Services (Copernicus, 2019) (NOUEL, 2018). These models also provided current profiles and mean sea level oscillations at the open boundaries, associated to meteorological and density effects. Finally, the Riemann invariant, which combines water level and current data, was used at the open boundaries of the grid as flow forcing. CMEMS ocean models have horizontal resolution of approximately 9 km.

The bathymetry of the region was obtained through the digitalization of nautical charts, available on the website of the Marine Hydrographic Center of the Brazilian Navy, in raster format, with maximum depth around 50 meters. Figure 2 presents the bathymetry of the grid, ten monitoring points of model results on the continental shelf (P1 to P10) and seven monitoring points for the discharge points of possible submarine outfalls to be constructed along the coast of the State of Paraná (EM1 to EM7).

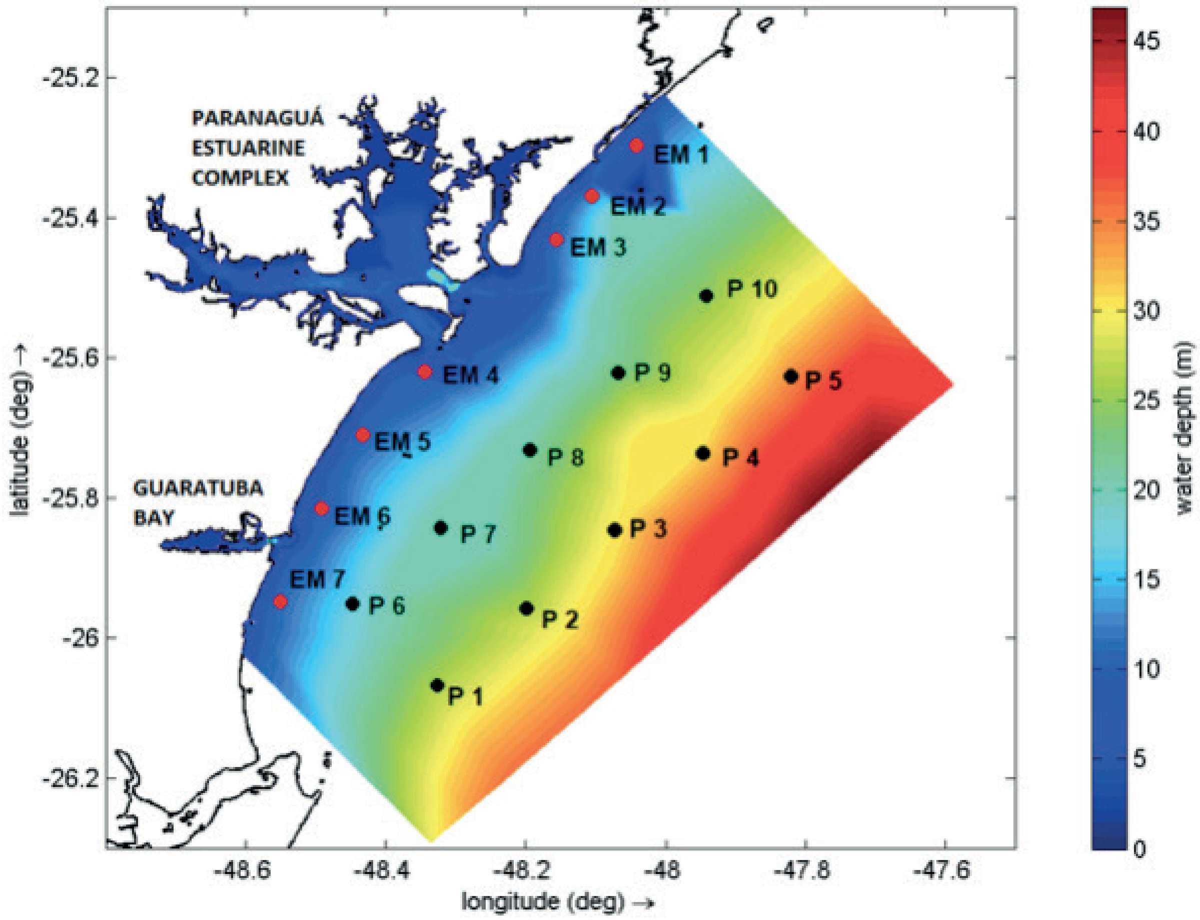

Figure 2. Bathymetry of the grid, selected points for monitoring the model results at the continental shelf (P1 to P10) and selected points for possible submarine outfalls (EM1 to EM7).

2.1 FLOW module

The FLOW module simulates transport phenomena resulting from tide, river discharges and meteorological effects, including the effect of density difference due to horizontal gradients of temperature and salinity fields. The Delft3D - FLOW may be used for flow simulations in seas, coastal regions, estuaries, reservoirs and rivers. This module provides the hydrodynamic conditions used by the other modules, being the first step for any simulation to be developed by the Delft3D program.

Fluvial discharges were considered for both Paranaguá Estuary (eight discharge points) and Guaratuba Bay (one discharge point), with corresponding values of temperature, salinity and flow. For Paranaguá the total river discharges ranged from 63.23 $m^3.s^{-1}$ in January to 26.44 $m^3.s^{-1}$ in July, while in Guaratuba from 126.08 $m^3.s^{-1}$ in January to 50.88 $m^3.s^{-1}$ in July (TCP, 2008; RIBAS, 2004 *apud* MANTOVANELLI, 1999).

2.2 WAQ module

The water quality module (WAQ) is a three-dimensional model used for representing water quality in natural and artificial environments. This module solves the advection-diffusion-reaction equations for a predefined computational grid and several different substances, using the finite element method. In present case, the dispersion of fecal coliforms was simulated, discharged in hypothetical positions for the construction of submarine outfalls, in order to support their construction, based on the premise of minimum influence of contaminants at the coast and adjacent waters.

When the effluent is discharged in the marine environment through a submarine outfall, a mixing process takes place. This process presents three distinct zones: near-field, intermediate field and far-field (GREGORIO, 2009; DELFIM, 2011; SUBTIL, 2012). Near-field models are used to simulate the blending processes in the region of the initial discharge, for this, they rely on specific information about the effluent discharge. Far-field models are important for simulations of dispersion of pollutants regardless of how they are released into the marine environment. Therefore, they are commonly used for coastal or estuarine regions or in situations aiming to simulate the dispersion of effluents from previous results of the near field models. In this study, only far-field simulations were performed.

Coliform bacteria have been commonly used in the evaluation of the microbiological quality of the environment (TALLON et al., 2005). In addition to meeting the requirements of a good indicator of fecal contamination, *Escherichia coli*, one of the species of the coliform group, presents thermotolerant characteristics and habitat restricted exclusively to the intestinal tract of humans and warm-blooded animals. Thus, as they do not occur naturally in the environment, this species constitutes an excellent indicator for the presence of fecal contamination in the environment (CETESB, 2012). According to the Brazilian Council CONAMA, Resolution No. 274/2000, concerning "freshwater, brackish and saline waters intended for bathing (primary contact recreation)", waters considered proper for human use can be subdivided according to Table 1 (CONAMA, 2001).

Saline Water (Salinity ≥ 30 PSU) – Class 1 (primary contact recreation)	
Escherichia coli	**MPN/100mL**
Proper (Excellent)	200
Proper (Very good)	400
Proper (Satisfactory)	800

Table 1. CONAMA Resolution N.º 274/2000 – Limits for *Escherichia coli.* (MPN: "most probable number").

In this study, values referring to a nearby outfall, the Praia Grande Submarine Emissary - Subsystem 1 in Sao Paulo State, were used as base for the initial discharge's concentration in Parana State. Information on the concentrations of pollutants discharged by Praia Grande emissary, during summer and winter seasons, was obtained from SABESP (2006) and, Yang and Harari (2016). Thus, in the simulations of the far field model, the following values of *E. coli* were used for hourly discharges, 3.17×10^5 MPN/100mL and 1.36×10^5 MPN/100mL, for summer and winter respectively, in five levels equally spaced along the vertical, for the seven emissaries proposed in this study. Standard values were used for other Delft3D-WAQ parameters. In order to identify the pollution of the marine environment exclusively from the proposed submarine emissaries, zero concentration of fecal coliform was defined as the initial condition for all the grid points.

2.3 Model validation

In this study, time series from the Copernicus Marine Environment Monitoring Service (CMEMS) database were used for validation of the Delft3D model, by comparing mean sea level elevation, and surface values of temperature (TEMP), East-West component (EW) and North-South component (NS) of currents. The validation used data from the observational points on both the continental shelf and emissary points (Figure 2).

The following statistical parameters were used: the means of the differences between the results of the two models (M_D), the standard deviation of these differences (DP_D), the correlation coefficient between Delft3D and CMEMS time series (CC), the significance of the correlation coefficient (SIGN_CC), the mean absolute error (MAE), the absolute error in relation to the amplitude (RMAE), the percent absolute error in relation to the amplitude (RMAE%), and the Willmott (1982) index of agreement (IOA).

3 I RESULTS

To analyze the model results for the months of January and July 2016, the model was processed starting from rest in the months of December 2015 and June 2016, respectively, to avoid the influence of a resting state initial condition.

3.1 Validation

For the comparison between the results from the Delft3D model and the values obtained through the CMEMS database, statistical calculations and graphs of the respective time series were performed, for points P1 to P10 and EM1 to EM7. As an example, the comparison between the time series of sea level elevation for the P5 position, located on the continental shelf, are shown on Figure 3. Table 2 presents the mean statistical parameters for all the analyzed positions (P01 to P10 and EM1 to EM7).

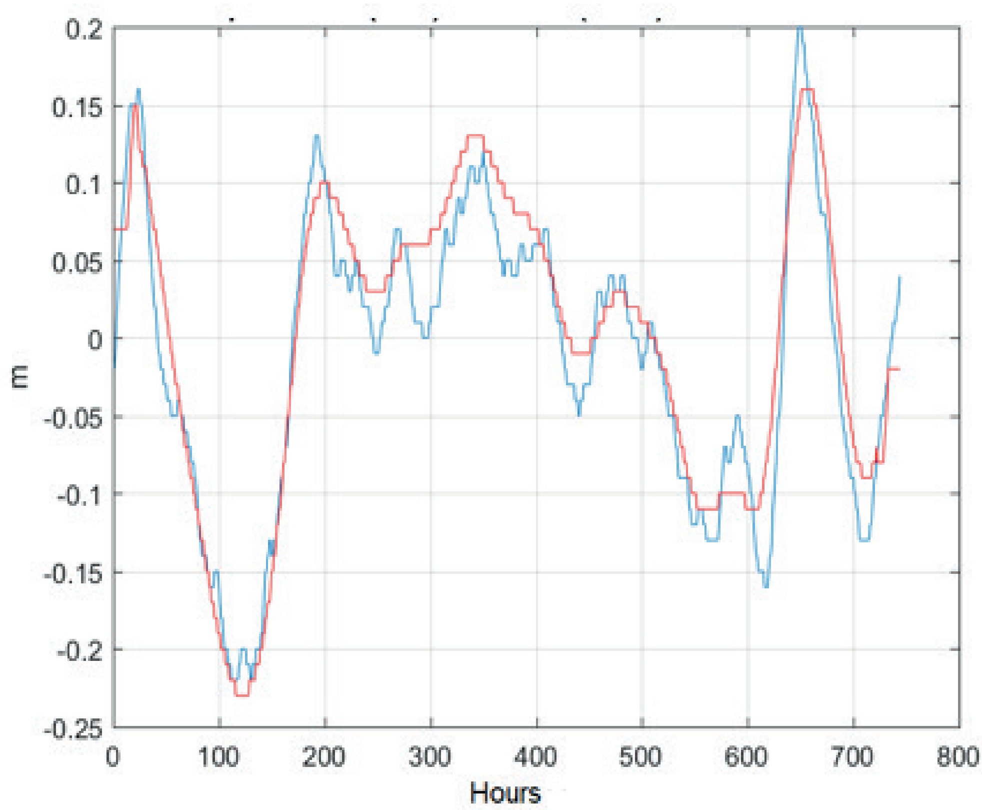

Figure 3. Comparison between mean sea surface elevation time series for Delft3D (red) and CMEMS (blue), throughout January 2016, at the P5 location.

Based on the hydrodynamic simulation's results, time series and thematic maps from different parameters, such as temperature, salinity, surface elevation and current velocity and magnitude were created through MATLAB, version R2016a. Some of these results are shown below.

		M_D	DP_D	CC	SIGN_CC	MAE	RMAE	RMAE%	IOA
JANUARY 2016	**Elevation (m)**	-0.01	0.04	0.95	0.01	0.03	0.06	6.00	0.98
	TEMP (ºC)	0.32	0.66	0.68	0.04	0.62	0.17	17.44	0.76
	EW ($m.s^{-1}$)	0.01	0.10	0.50	0.05	0.09	0.19	18.50	0.82
	NS ($m.s^{-1}$)	-0.03	0.11	0.57	0.05	0.10	0.15	14.88	0.89
JULY 2016	**Elevation (m)**	0.08	0.04	0.95	0.01	0.08	0.14	13.88	0.90
	TEMP (ºC)	-0.13	0.38	0.54	0.05	0.42	0.24	24.12	0.64
	EW ($m.s^{-1}$)	-0.01	0.07	0.65	0.04	0.06	0.17	16.88	0.73
	NS ($m.s^{-1}$)	0.01	0.10	0.48	0.05	0.08	0.17	17.06	0.82

Table 2. Mean comparative statistical parameters obtained for January and July 2016. M_D: Mean difference; DP_D: Difference standard deviation; CC: Correlation coefficient; SIGN_CC: Significance of the correlation coefficient; MAE: Mean absolute error; RMAE: Absolute error in relation to the amplitude; RMAE %: RMAE percentage; IOA: Index of Agreement.

3.2 Hydrodynamic model

An example of the circulation model output is given on Figure 4, with the angular histograms of the surface currents at point EM4, on January and July 2016.

Examples of surface current distributions computed by FLOW module are given on

Figure 5, referent to times of maximum current intensity for EM4, with corresponding values of 0.62 and 0.61 m.s^{-1}, which occurred on January 25th at 23:00, and on July 21st at 11:00.

3.3 Water quality model

Using Delft3D-WAQ module, *E. coli* concentration time series were obtained for all emissary points, for several depth levels. The results for point EM4, at the surface, in January and July 2016, are shown on Figure 6. These results are relative to OBS1, the precise location of the emissary, and at OBS5, at a distance of 1400 m from EM4 towards the coastline, including the levels of satisfactory, very good and excellent water quality, following the limits of CONAMA Resolution No. 274/2000 (Table 1).

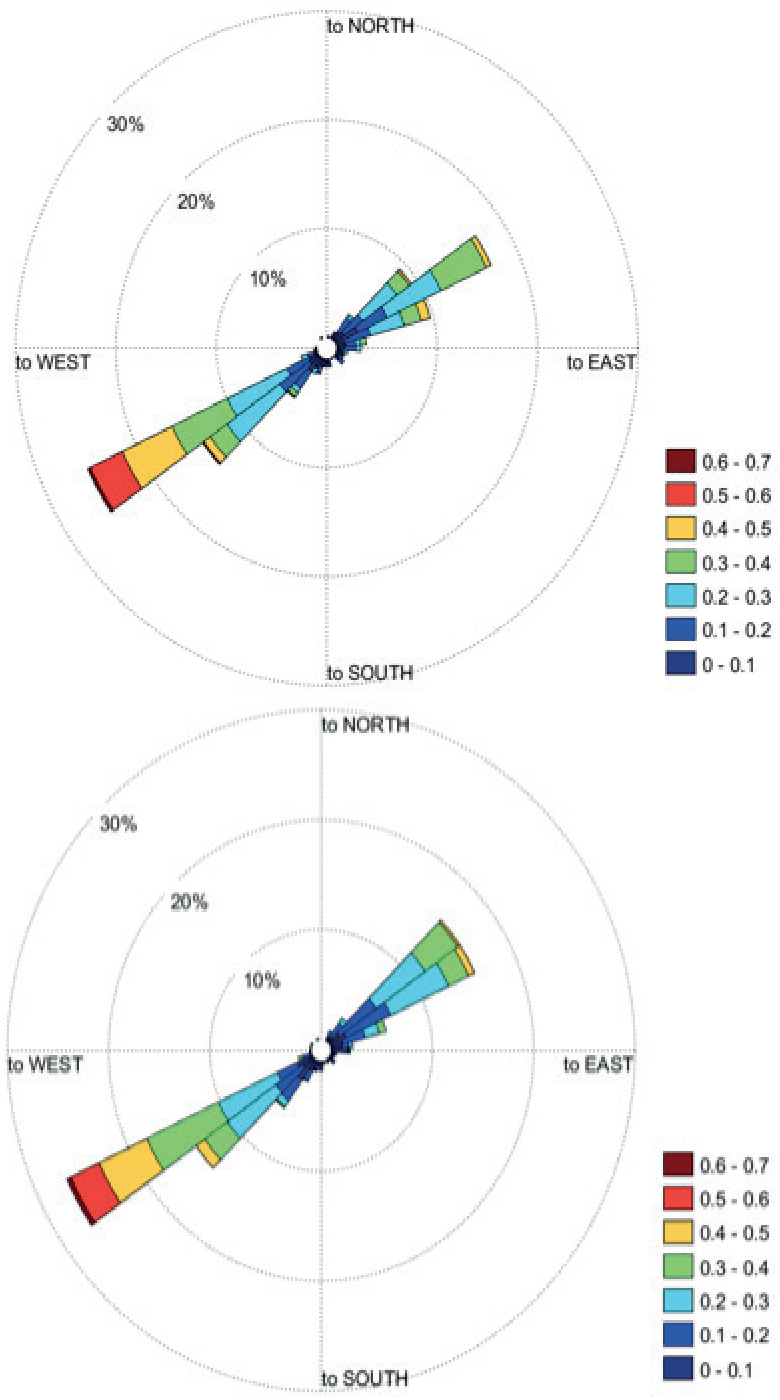

Figure 4. Angular histograms of surface currents (m.s_^{1}), for the EM4 position, in January 2016 (above) and July 2016 (below).

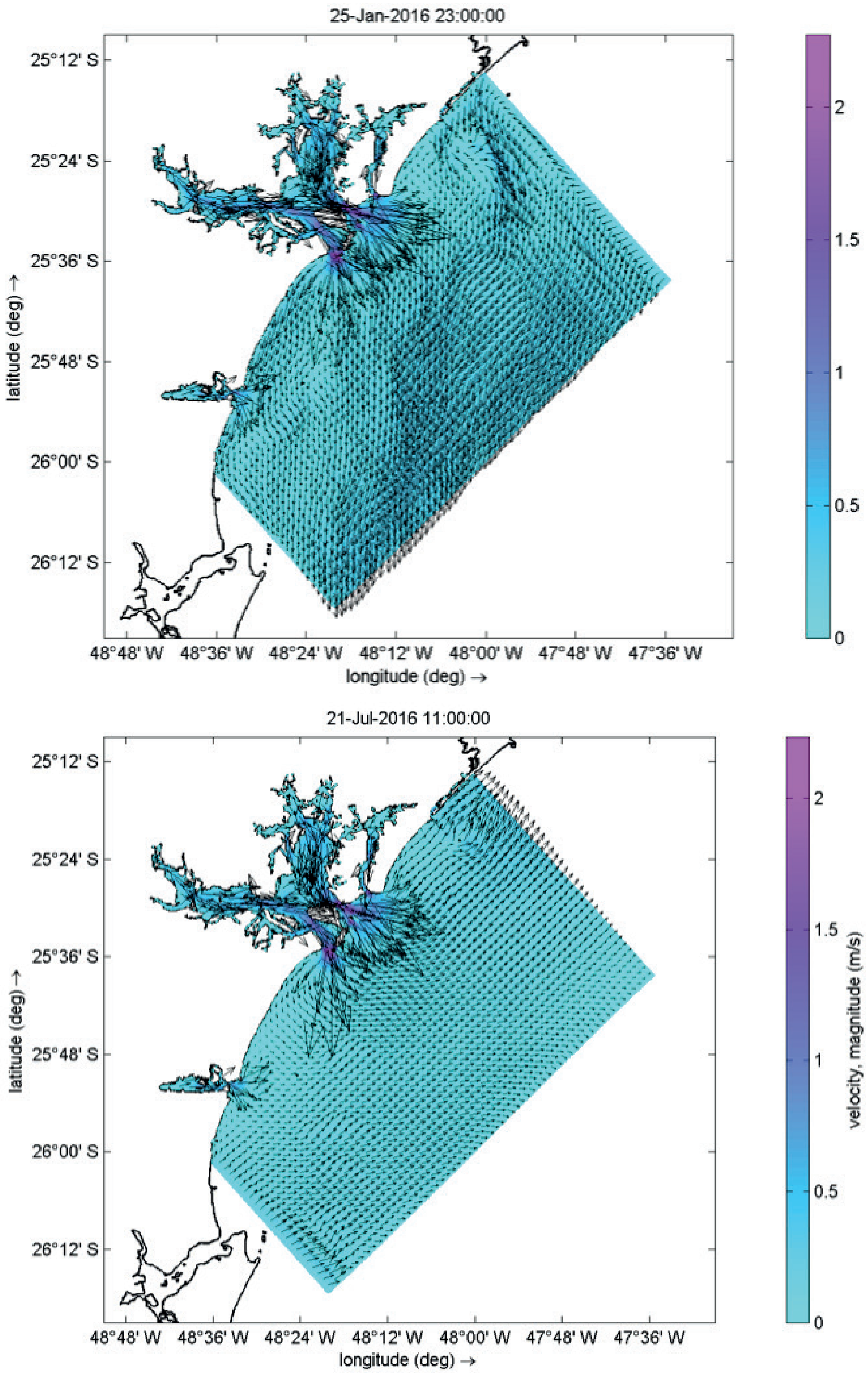

Figure 5. Surface current distributions (m.s^{-1}), at times of maximum current intensity for EM4, on January 25th 23:00, and on July 21st 11:00.

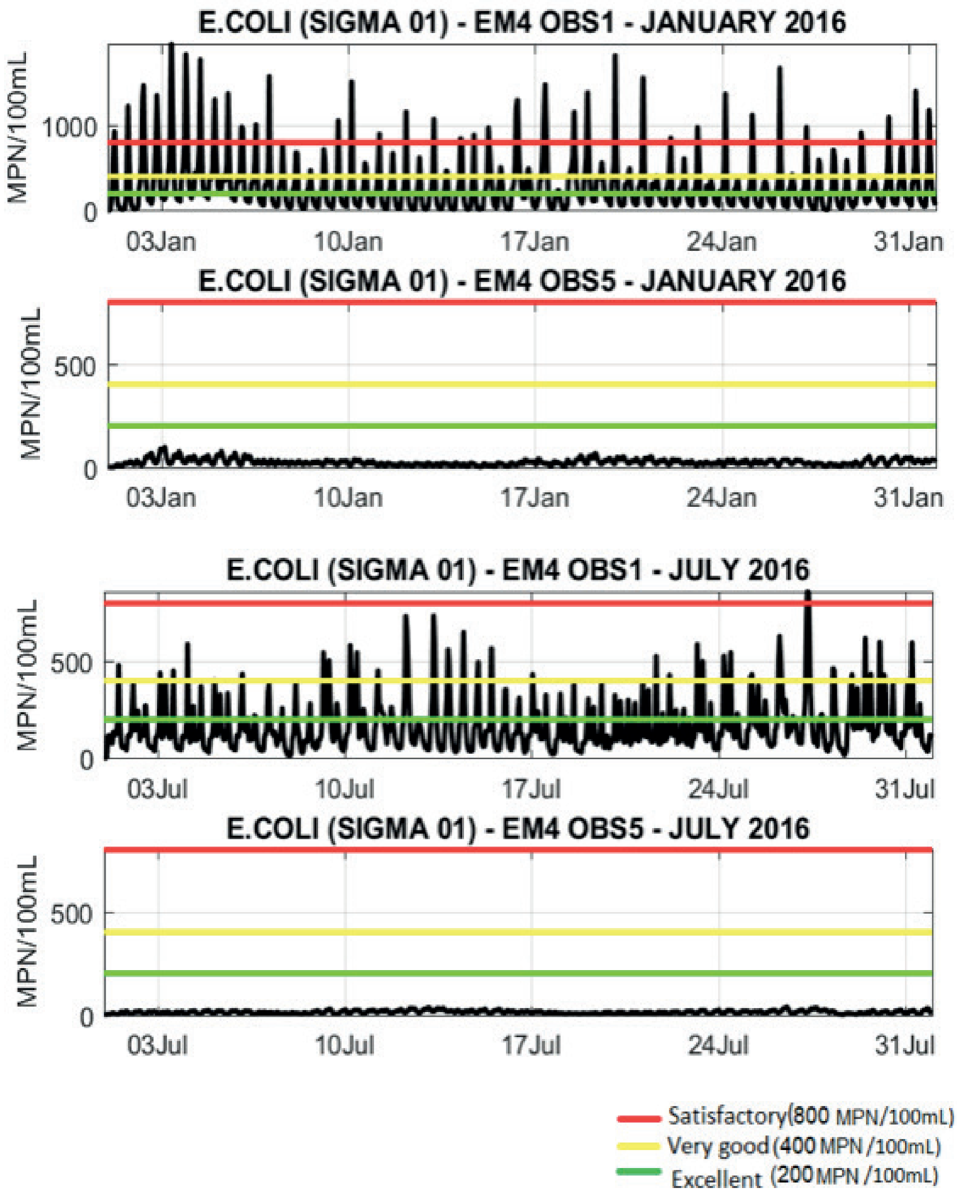

Figure 6. Time series of *E.coli* surface concentration, at the precise location of the emissary EM4 (OBS1) and 1400 m from EM4 towards the coastline (OBS5), throughout January 2016 (above) and July 2016 (below).

Figures 7 and 8 show the distribution of *E. coli* plumes at the times of maximum concentration and maximum dispersion from emissary EM4, in January and July 2016. At the times of maximum concentration, the limit for satisfactory water quality was exceeded, respectively on January 3rd 09:00 and July 27st 08:00 (see Figure 6); the times of maximum dispersion were January 25st 23:00 and July 21st 11:00. Finally, an example of *E. coli* distribution map in the modeled region, considering the operation of all hypothetical emissaries simultaneously, is provided in Figure 9.

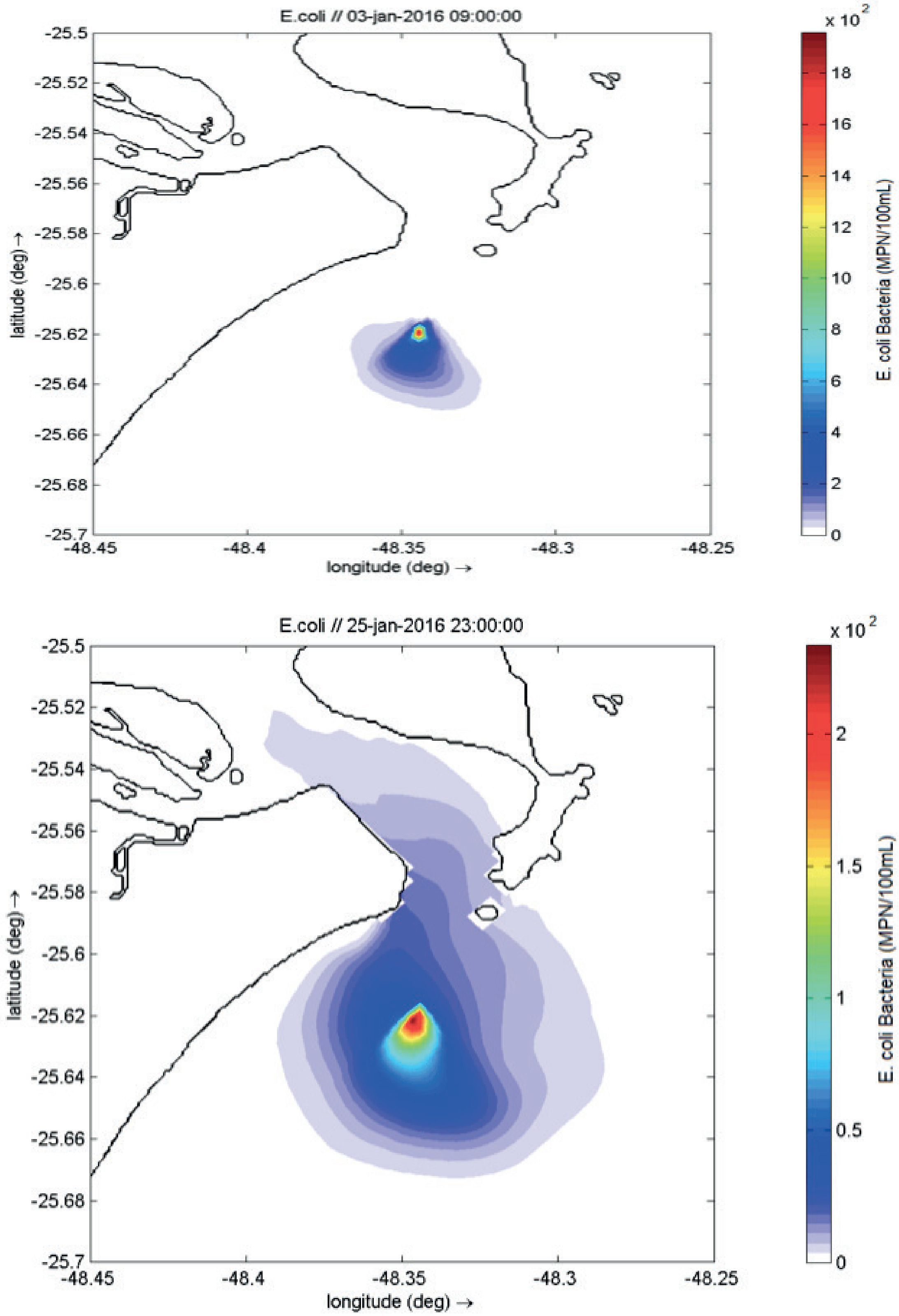

Figure 7. *E. coli's* surface pollutant plumes from submarine outfall EM4 in January 2016: maximum concentration (above) and maximum dispersion (below).

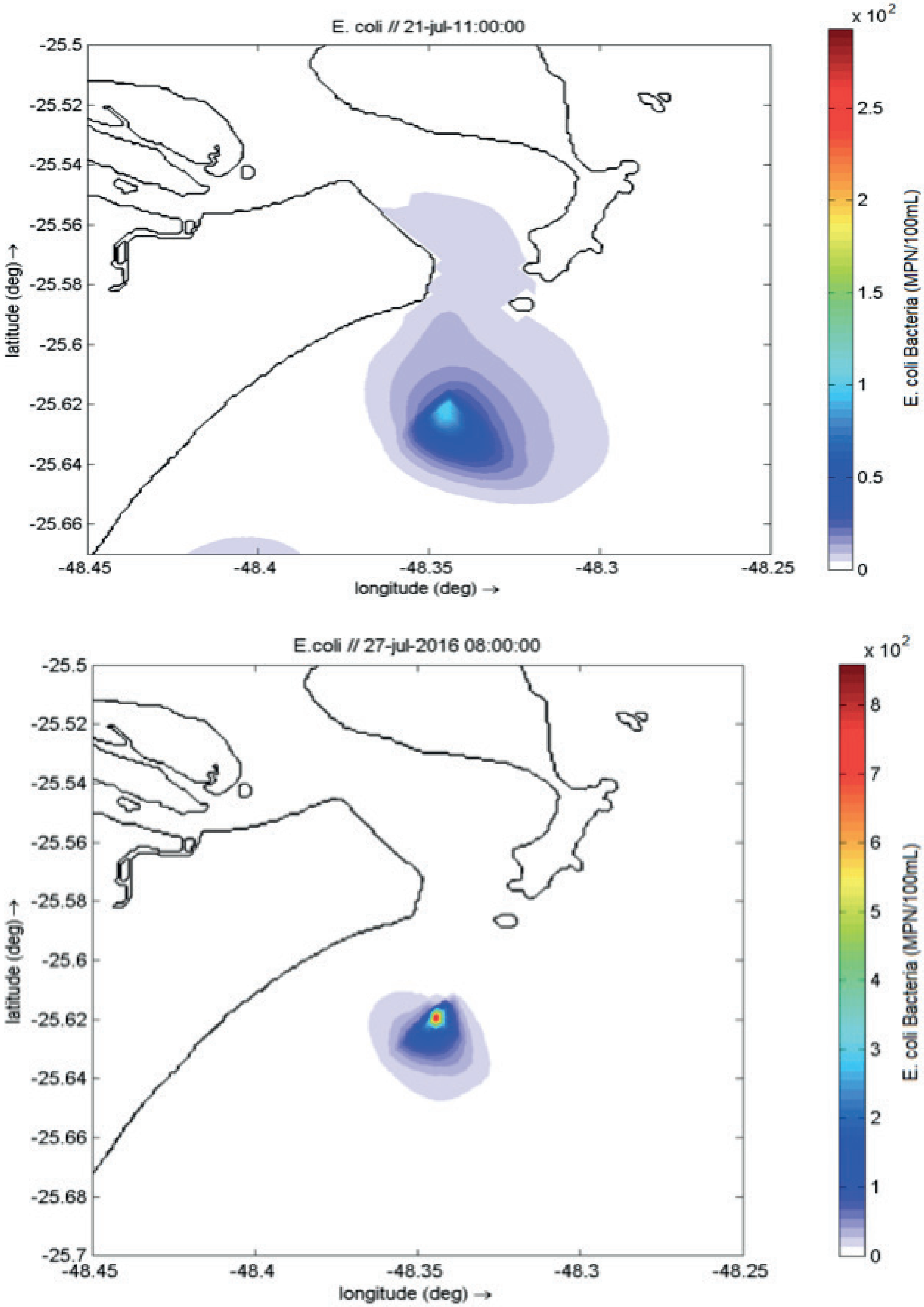

Figure 8. *E. coli's* surface pollutant plumes from submarine outfall EM4 in July 2016: maximum dispersion (above) and maximum concentration (below).

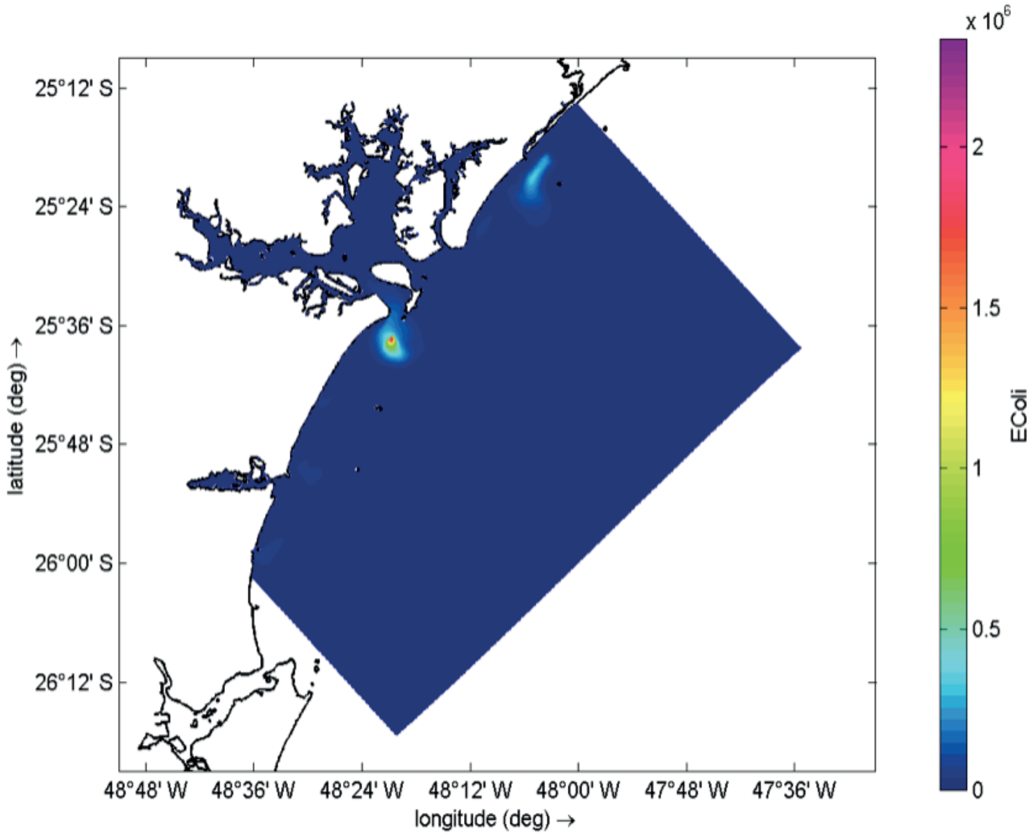

Figure 9. Distribution of E. coli in the modeled region, on January 25, 2016 at 23:00, considering the simultaneous operation of the seven submarine outfalls.

4 I DISCUSSION

The results for both the FLOW (hydrodynamic) and the WAQ (water quality) modeling, at the different points selected along the coast and on the adjacent continental shelf, allowed a complete analysis of the hydrodynamic conditions and dispersion of pollutants in the coastal region of the State of Paraná, especially in relation to the proposed sites for the construction of submarine emissaries (Figure 2). The results obtained in the research and analyses are discussed below, especially for emissary EM4, located near the Paranaguá Estuarine Complex, with biggest population involved and most important economic region of the study area.

4.1 Validation

The comparison between the results from the Delft3D coastal model (with horizontal resolution of 350 m) and the values obtained through the CMEMS global database (with horizontal resolution of about 9 km) suggest that the coastal model can be considered as fully validated. In terms of dispersion analysis, the most important hydrodynamic parameter is the horizontal current, which presented Index of Agreement IOA above 0.73 and percent absolute error in relation to the amplitude below 20% (Table 2).

4.2 Hydrodynamic model

Results from the hydrodynamic simulation reproduced well known characteristics of the shelf circulation, especially the influence of the meteorological conditions. The general features do not differ from summer to winter, as the angular histograms of January and July are very similar (Figure 4). On the other hand, frontal systems significantly change the current patterns at the continental shelf, as presented on Figure 5, which represents the standard circulation and the circulation under the effect of a cold front, although within Paranaguá Estuary and Guaratuba Bay, and adjacent areas, the tides act as primary effect. It is worth noting that cold fronts occur both on summer and winter months, and although being in general stronger and more frequent in winter, for the simulated months of 2016, the cold system at the beginning of January had stronger effect than that at the end of July.

4.3 Water quality model

For the analysis of the dispersion of pollutant's plumes, the focus is on the pollutants concentration between the discharge points and the coastline, by comparing the model results to the CONAMA limits of water quality.

When dealing with submarine emissaries, the "Legal Mixture Zone" is defined as a region where the parameters of the contaminants are above the limits established by legislation. In practice, this region is admittedly a zone of sacrifice. The better the emissary, the smaller the mixture zone will be (ALFREDINI, 2005).

The *E. coli* concentration time series for EM4 and nearby point (1440 m towards the coastline), for January and July, present several periods with very high values at the discharge point, exceeding the limit established for the satisfactory quality (800NMP/100mL); however, more than 1 km away from the discharge point, the concentrations are negligible (Figure 6).

Figures 7 and 8, corresponding to the *E. coli* plumes in the vicinity of EM4, at the times of maximum concentration and maximum dispersion, in January and July respectively, show that for the position of the proposed emitter, high concentrations are limited to regions close to the points of effluent discharge, without reaching deeper areas or the coastline.

The characteristics of the pollutants dispersion here presented and analyzed for EM4 were also observed for the remaining emissaries (see Figure 9).

5 I CONCLUSION

The hydrodynamic results obtained are consistent with previous studies carried out in the region. The analysis of the dispersion associated to all seven emissaries proposed along the coast of the State of Paraná, through the representation of the *E. coli* distributions, indicates that high concentrations are limited to the regions very close to the effluent discharge points, proving that the local current systems do not cause the return of pollution towards the coast. It is important to remember that the use of submarine emissaries is associated with a

Legal Mixing Zone, where concentrations of pollutants are still high, and constitute an area of environmental sacrifice.

The use of submarine outfalls for the efficient treatment of sewage has become increasingly common around the world. Effluent disposal in the ocean is an efficient, rapid and sustainable way to manage effluents. When considering the alternatives to improve the sewage treatment system in Paraná State, submarine outfalls are an excellent choice, due to their high efficiency, low cost and limited environmental impact. But the implementation and management of submarine outfalls must be done with suitable modeling of both hydrodynamics and dispersion, together with monitoring programs based on field measurements, to validate the models.

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