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Article *in* Journal of Coastal Research · January 2011

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Journal of Coastal Research	SI 64	922 - 926	ICS2011 (Proceedings)	Poland	ISSN 0749-0208

Application of the Cormix model to assess environmental impact in the coastal area: an example of the ocean disposal system for sanitary sewers in the city of Fortaleza (Ceará, Brazil)

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ABSTRACT

L. P. Maia, M. O. Bezerra, L. Pinheiro, J. M. Redondo, 2011. Application of the Cormix model to assess environmental impact in the coastal area: an example of the ocean disposal system for sanitary sewers in the city of Fortaleza (Ceará, Brazil). Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 922 – 926. Szczecin, Poland, ISSN 0749-0208

Cornell Mixing Zone Expert System-CORMIX software was used to simulate the behavior of effluents discharged by the underwater emissary in Fortaleza (Ceará, Brazil). This software is used to analyze and predict the discharge design in bodies of water. Application of the CORMIX model was determined to simulate the tracer discharge using local environmental parameters and underwater emissary discharge data. Data on wind, current and position in relation to the coast were used in the chosen case to obtain the discharge flow classification from the model since the hydrodynamic dispersion fields are differentiated by the predominance of different physical processes responsible for the dispersion and mixture of effluents. The simulations carried out considering the characteristics of the underwater emissary, liquid effluents and receiving medium show a very high dilution capacity. The dilution is directly related to coastal current speed ranging between 1:45 and 1:278, respectively the minimum and maximum for the mixture's initial zone dilution, with diffuser distances between16 and 55 meters. This gives the system the characteristic of good dilution capacity compared to other installed systems. At the limit of the simulations, 5.000 m from the diffuser, dilutions reached values between X1:251 and 1:2.688. From the simulations, it is possible to observe that given the difference in density between the effluent (freshwater) and the sea, the plume presents strong positive buoyancy. Thus, if we consider the unfavorable speeds and currents (0,25-direction and 0,04 - speed) we would have a P = 0,25 x 0,04 or P =0,01 (1%) probability of occurrence. However, for the actual situation, this probability is near zero. The results obtained from using the CORMIX model helped in the environmental monitoring of the effluent disposal area.

ADDITIONAL INDEX WORDS: *CORMIX model, underwater emissary, dispersion and mixture of effluents, ocean disposal, environmental monitoring*

INTRODUCTION

An ocean disposal system for sewage is understood as being one that treats those effluents using the potential self-purification capacity of sea waters for reducing pollution concentrations to admissible levels before the sewage / sea water mixture field can, in the most adverse displacement conditions, reach areas of beneficial use, especially those related to bathing and water sports or aquiculture activities.

Thus, experiments aimed at determining the behavior of an effluent plume in the sea caused by sewage discharge is of utmost environmental, social and economic importance.

Studies involving the application of models such as the Cornell Mixing Zone Expert System-CORMIX offer a new perspective on the phenomena related to vertical dilution of the effluent mixture field in ocean waters from punctual or diffused sources, taking into account the effect of seasonal variations in ocean currents and other environmental parameters.

There are currently many models available for predicting dispersion in the coastal zone. The option for CORMIX has been well accepted by the scientific community because it has a good adjustment in near-field prediction models and because it can be applied for different types of discharge, resulting in a broad classification in flow classes. The program strongly emphasized initial dilution geometry and characteristics in the mixture zone, including the legal limits for discharging polluting substances, although it precisely simulates remote plume behavior.

CORMIX consists of a series of subsystems for analysis, prediction and design of water discharges in water courses with an emphasis on initial mixture zone dilution geometry and characteristics, and is applied to several environments, stratified or not, such as rivers, lakes, estuaries and coastal zones. The CORMIX system consists of three integrated subsystems: CORMIX1 for simple underwater discharges (ducts); CORMIX2 for underwater discharges with diffusers; CORMIX3 for subarea discharges. CORMIX 3.0 software consists of a system for analyzing, predicting and designing liquid effluent plumes containing toxic substances or conventional pollutants.

An important aspect of this software consists of the orientation system used, where its characterization and understanding are fundamental for simulation success. Alignment Angle (GAMMA) – Corresponds to the angle measured in the counterclockwise direction between the current to be simulated in the receiving environment and the diffuser axis; Horizontal Angle (SIGMA) - Corresponds to the angle measured in the counterclockwise direction between the current to be simulated in the receiving environment and the projection plane of the center of diffuser piping; Vertical Angle (THETA)- Corresponds to the angle between the center of the diffuser piping and the horizontal plane. In this study, diffuser piping is aligned to the diffuser axis (GAMMA = SIGMA).

For more details about the CORMIX model we refer to Akar and Jirka (1991), Akar and Jirka (1993), Akar and Jirka (1994), Akar and Jirka (1995), Bezerra el al (1995), and EPA (2010).

One example is Davies, Mofor and Neves (1997), who applied CORMIX to assess remote observation image data of wastewater plumes along the coasts of Scotland and Spain.

Cornell Mixing Zone Expert System-CORMIX (Jirka, 1991) software was used to simulate the behavior of effluents discharged by the underwater emissary in Fortaleza (Ceará, Brazil) (Figure 1). This software is used to analyze and predict the discharge design in bodies of water.

This study aims to assess the marine area under the influence of effluents discharged by Fortaleza's underwater emissary, using the simulation obtained by CORMIX to examine whether this system is capable of reducing concentrations of pollutants for environmental quality control.

Application of the CORMIX model was determined to simulate the tracer discharge using local environmental parameters and underwater emissary discharge data. Data on wind, current and position in relation to the coast were used in the chosen case to obtain the discharge flow classification from the model since the hydrodynamic dispersion fields are differentiated by the predominance of different physical processes responsible for dispersion and mixture of effluents.

In the vast majority of cases, final disposal systems that use underwater emissaries represent the most effective means to reduce coastal pollution in the most densely inhabited and visited areas.

According to Gonçalves and Souza (1997), an ocean disposal system for sanitary sewage is understood as one that promotes treatment of these effluents using the seawater's potential capacity for self-purification to reduce concentrations of pollutants to acceptable levels, before the sewage / seawater mixture field can, in the most adverse displacement conditions, reach those areas of beneficial use, especially bathing and water sport areas or those for aquaculture activities.

The implementation and perfect functioning of ocean disposal systems for sanitary sewage is important for countries like Brazil, whose coastline stretches eight thousand kilometers (Brazil, 2005), with nearly two thousand beaches and coastal islands.

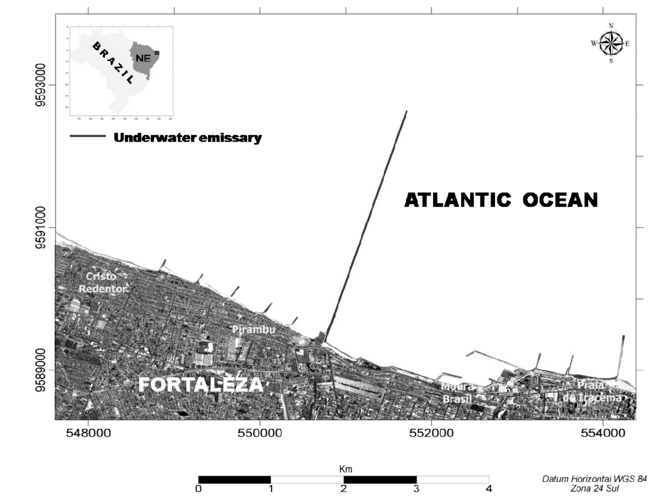


Figure 1. Study area with indication of location of the Ocean Disposal System for Fortaleza Sewage's ("Sistema de Disposição Oceânica de Esgotos de Fortaleza" –SDOES) underwater emissary (Ceará, Brazil).

From an economic perspective, this coastline has extraordinary worth as a source of foods and support for leisure and tourism activities and undertakings, used all year round, as in the case of the city of Fortaleza.

The underwater discharge installations are used for the appropriate penetration of effluents to be discharged into the ocean and the formation of an initial and optimized mixture field (dilution) in order to take utmost advantage of the receiving body's potential capacity to promote the diffusion, dilution and subsequent dispersion and bacterial decline of pollutant loads and contaminants launched into it to preserve water quality standards established for the diverse zones of the receiving body.

The Ocean Disposal System for Fortaleza Sewage ("Sistema de Disposição Oceânica de Esgotos de Fortaleza" - SDOES) is responsible for treating and disposing of sewage of part of the city of Fortaleza, encompassing the maritime watershed's water basins. SDOES is responsible for treating and disposing of sewage from part of the city of Fortaleza (Ceará, Brazil). After removal of sand and solid waste from the Pre-Conditioning Station, the sewage is sent to Fortaleza's underwater emissary where they are discharged at a depth of around 16 meters and 3.2 kilometers from the coast by a series of 120 diffusers, at a flow of 2.5 m3s-^{1}.

A mutual technical-scientific cooperation agreement was signed for the environmental monitoring of SDOES between the Ceará Water and Sewer Company ("Companhia de Água e Esgoto do Ceará" - CAGECE) and the Sea Sciences Institute ("Instituto de Ciências do Mar" - LABOMAR) of the Federal University of Ceará ("Universidade Federal do Ceará" - UFC), in compliance with the demands by the Inter-American Development Bank (IDB). The main objective of this agreement is to raise oceanographic data and conduct physical-chemical, sedimentological, biological and bacteriological analyses, as well as assess ocean current speeds and directions to simulate the sewage dispersion plume. LABOMAR has been monitoring this for more than 14 years.

In the following items, we shall explain the methodology employed to obtain oceanographic information needed to run the CORMIX model and describe the model's application with the objective of getting to know the potential of its applications for the case in question. The model must be able to identify the physical processes and project effluent diffusion along the coast of Fortaleza.

METHODS

CHARACTERISTICS OF THE RECEIVING BODY

The mixture process for any effluent are governed by the relations between the receiving body of water's environmental conditions and the discharge characteristics. Therefore, in order to apply the CORMIX dispersion model it is necessary to know the characteristics of the receiving body, in this case, the seawaters into which the effluent will be launched.

CORMIX is an interactive program, and each parameter of the maritime environment can be defined by the user using the hydrodynamic characteristics that prevail in the near-field of effluent emissions as well as the far-field. The basic data required for the program are: dispersion depth (bathymetry), density of the contaminant and the receiving environment, temperature, wind speed at a height of 10 meters, current speed and the region's geometric characteristics.

Climatic Conditions: Knowledge of weather conditions is of fundamental importance for analyzing the behavior of coastal dynamic agents. Weather, wind and wave conditions in the region have a close relationship with the displacement process or migration of the Intertropical Convergence Zone (ITCZ) and the meteorological conditions in the Northern Hemisphere. In tropical latitudes, the biggest climatic variations are associated with seasonal changes of the intertropical convergence zone (ITCZ) and summer monsoons, which are responsible for a great part of summer precipitation in the region (Clivar/Brasil, 1998). The region's climate is defined as semi-arid. Only two well-defined seasons stand out in the region: a rainy season, which begins in January, with maximum rainfall in April, and the dry season, which begins in July, with maximum dry weather in November. The annual pattern for rain distribution in the region reaches its peak in March and April.

Winds: Average wind speeds were obtained from measurements at the Cearense Meteorology Foundation ("Fundação Cearense de Meteorologia" - FUNCEME) station and the Federal University of Ceará (UFC) in Fortaleza (Ceará, Brazil), are range from 2,62 to 4,56 ms-^{1}, and an overall average of 3,64 ms-^{1}. They have a seasonal distribution with lower values distributed from January to June, and minimal values in March and April. The highest speed values occur between July and December, with peaks between August and October. The most effective winds are admittedly those from the E and E/SE quadrants, whereas those from the N and NE are more active in months with higher rainfall rates (January to June). However, during the year, its importance as a coastal dynamic agent is quite reduced in comparison to the effective winds.

Hydrodynamic Parameters

Tides: Tides in the region can be characterized as mesotides with semi-diurnal periodicity (Morais 1980). In studies conducted by Maia (1998), in which 14 monthly analog records were analyzed of an LNG-15 tide graph installed at the Porto of Mucuripe, he verified that from May 1995 to June 1996, maximum tide range was 3,23 m, which occurred during spring tide in December 1995, whereas the minimal range was 0,75 m, occurring during neap tide in March 1996. This author also observed that in June and December both neap and spring tide ranges increase, with the opposite occurring in September and March, when temporal differences of 0,30-0,40m and 0,40-0,50m were verified in spring and neap tide ranges, respectively.

Waves: Maia (1998) studied a 4-year sequence of wave measurements taken at the Port of Mucuripe (Fortaleza), by the Waterway Research Institute (INPH), using a Waverider (Datawell) buoy installed at an average depth of 16 m east of the Futuro beach ridge crest in Fortaleza. With the data obtained, he determined an average wave height of 1,15 m and mode of 1,14 m, with a most frequent average wave period of 5,70 seconds, associated with significant height and an average of 5,89 seconds. This same author identified a predominance of sea waves, representing 94,2 %, compared to swell waves, which corresponded to 0,28 %, and the rest (5,52 %), could not be defined because they were situated between the two limits.Wave period were grouped in 1 to 9 and 10 to 20 s, respectively assuming sea and swell wave intervals. During the evaluated time interval (March 1997 to March 1998), 27 % of the peak periods are encompassed between intervals (10 to 16 s), whereas 0,4 % correspond to the (17 and 19 s) interval. This type of wave is seen from December to May. The existence of strong control of wave characteristics by wind speed and direction was also verified, determining a dominance of ESE and ENE octant, E waves and secondarily NE. These observations confirm Morais' (1980) conclusions, who verified that the predominance of E-SE quadrant waves and a secondary occurrence of NE waves for the same region.Analysis of the annual wave pattern in the region reveals a predominance of NE in the first 4 months of the year, and starting in May, the waves are distributed with a great incidence in the ESSE direction until November. In December, there is a tendency for a return of NE waves. (Maia 1998).

Ocean currents: In order to study the behavior of coastal currents in the Fortaleza region and to determine the factors of greatest importance in the configuration of the coastal circulation, an initial study of the general characterization of currents in 7 stations distributed along the coast was conducted during the dry (September to November) and rainy (March to May) season. Current direction and speeds were measured at each station using a Hydrocean current meter in vertical depth profiles at 1 meter intervals and during a complete spring and neap tide cycle. Wind speed/direction and water column salinity/temperature were recorded simultaneously. Due to the persistence of current characteristics until December, in the simulations we used the same critical direction, but with a maximum speed of 0,51 ms-^{1} , compared to 0,46 ms-^{1} in September.

Hydrographic Parameters: Observations of the parameters that control density, salinity and temperature show that the water layer is homogeneous, with salinity ranging between 35 e 3l,37 during the study's two periods (dry and rainy season) and temperature between 25 and 28ºC. In general, salinity increases with depth at an average rate of 0,015 per meter, 0,2 between the surface and bottom, whereas temperature falls 0,3ºC along the entire water column. Temperature varies with diurnal heating and can reach a total variation of 1ºC.

RESULTS AND DISCUSSION

Application of The Cornell Mixing Zone Expert System (Cormix)

Surface current measurements show that speed varied during the dry season between 0,22 ms-^{1} and 0,68 ms-^{1}, with an average value of 0,34 ms-^{1}, whereas during the rainy season average speed is slightly lower (0,25 ms-^{1}) and has greater variation (0,08 and 0,58 ms-^{1}).

Throughout the study period, surface current speed presents a good correlation with wind speed recorded simultaneously. With regard to direction characteristics, it was observed that the

Table 1: Set of speed data and respective directions used in the simulations for September and December for Fortaleza's underwater emissary (Ceará, Brazil).

SEPTEMBER			
Dir/Speed m^{-s}	Minimum	Average	Maximum
Divergent	WNW–0,078	WNW–0,246	WNW–0,460
Convergent	WSW–0,078	WSW–0,246	WSW– 0,460
Convergent	SSW– 0,078	SSW–0,246	SSW– 0,460
DECEMBER			
Dir/Speed m^{-s}	Minimum	Average	Maximum
Divergent	WNW–0,068	WNW-0,243	WNW–0,510
Convergent	WSW–0,068	WSW-0,243	WSW– 0,510
Convergent	SSW– 0,068	SSW– 0,243	SSW– 0,510

predominant surface current direction is WNW (parallel to the coast), ranging between WSW and NNW.

In general, and as predicted, speed decreased with depth, had less dispersion in speed values at the upper (16%) and lower (10%) portions of the water column and greater dispersion in the intermediate portion (20% to 39%). Speeds at the bottom ranged between 0,07 and 0,12 ms-^{1}, with an average value of 0,09 ms-^{1} .

In relation to the distribution of current directions, it was observed that in 70% of the cases the current parallel to the coast predominates, followed by the divergent (16%), convergent (11%) and normal (3%).

Measurements made over the underwater emissary diffuser in September revealed a certain homogeneity of current directions observed along the water column. At the surface, direction WNW , divergent in relation to the coast, totaled 75% of the recordings, followed by direction WSW which converges to the coast (19%) and the direction parallel to the coast W (6%). In relation to measurements at the bottom, there was also a predominance in direction WNW (50%), followed, and with the same frequency, by directions WSW (19%) and NNE (19%), SSW (6%) and W (6%).

Measurements made over the underwater emissary in December behaved in a similar manner to the previous study. At the surface, direction WNW, divergent in relation to the coast, totaled 75% recordings, followed by direction WSW which converges to the coast (25%). Direction WNW (56%), followed by direction NNW (25%), NW (13%) and SW (6%) predominated in bottom measurements.

In order to simulate the behavior of effluent discharged by Fortaleza's underwater emissary, we used Cornell Mixing Zone Expert System (Cormix) software, especially developed by the School of Civil and Environmental Engineering at Cornell University, USA, for the Environmental Protection Agency (EPA-U.S).

According to CAGECE (2010), the underwater emissary was made in 1987 of steel coated in concrete with a diameter of 1500mm and length of 3205 meters, and with the following technical characteristics: API-5Lx steel pipes, X-42 plate; nominal outer diameter: OD = 1524 mm; nominal inner diameter: ID = 1487 mm; thickness of CA plate 18.26 mm. Sewage is discharged into the sea through 120 holes called diffusers located at the far end of the emissary at a flow of 2.5 m^3s^{-1} and an approximate depth of 16.0 m. Values of 1023 kg/m^3 and 999.5 kg/m^3 were used in simulations for density of the medium (sea) and the effluent, respectively.

The table for the conditions to be simulated was elaborated considering the values for the most frequent WNW directions observed, and divergent in relation to the coastline, and the most unfavorable directions, being convergent to the coast, WSW and SSW, and the characteristic speeds (Table 1).

Due to the homogeneous sea conditions observed in terms of characteristic speeds, it was possible to simplify the number of simulations to 9 cases. The alignment angles used were WNW (112.5º), WSW (67.5º) and SSW (22.5º).

Simulation results are shown in Table 2. On the left, we have the simulated situation (e.g. WNW – 0.510), mixture zone characteristics in the field near the diffuser's area of influence and the dilution achieved in this zone. The next part shows the limits and dilution in the expansion zone, whether there is torque in the coastal zone and the final simulation characteristics with limits and dilution levels.

The results are also shown in graphs contained in Figure 2, showing the simulation plume represented by CORMIX software.

CONCLUSIONS

The CORMIX model was used because it has a considerable mathematical/physical formulation regarding the interaction between environmental conditions with dispersion. However, in some cases, such as flows influenced by tides and waves, its application should be used with precaution since the model does not take into account these parameters. In that case, the model will underestimate the diffusive coefficient, and in practice, the result is a reduction in the concentration of discharged contaminants.

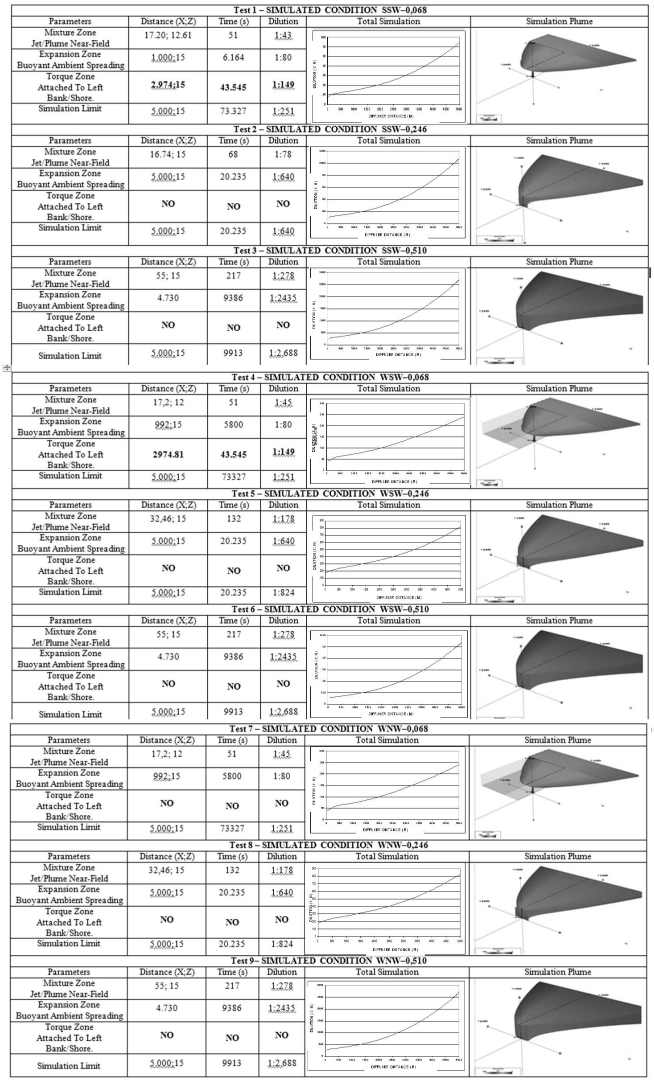
With regard to the simulations carried out by CORMIX considering the characteristics of the underwater emissary for liquid effluents operated by CAGECE and the receiving medium, they show a very high dilution capacity. The dilution is directly related to coastal current speed ranging between 1:45 and 1:278, respectively the minimum and maximum.

It is worth underscoring that these values are associated with dilution of the initial mixture zone and diffuser distances between 16 and 55 meters. This gives the system the characteristic of good dilution capacity compared to other installed systems. At the limit of the simulations, i.e. 5000 m from the diffuser, dilutions reached values between 1:251 and 1:2.688.

In the simulated conditions, where the most unfavorable situation of the analyzed system was sought, the effluent can only reach the coast during minimal speeds and with SSW and WSW currents.

In that case, dilution is around 1:149 and the time elapsed is 43.545 seconds (12 hours). Time for torque is important in the study of Escherichia Coli pathogenic bacteria, which in an interval of 8 hours and depending on environmental conditions (insolation) may be reduced to zero, without taking into account the dilution.

In relation to the probability for these situations to occur, September's records were taken into consideration, where at the surface the WNW direction, divergent in relation to the coast, totaled 75% of the record, followed by the WSW direction, which converges towards the coast (19%) and the direction parallel to the coast W (6%)



Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Test 1 – SIMULATED CONDITION SSW–0,068					
Mixture Zone Jet/Plume Near-Field	17.20; 12.61	51	1:43		
Expansion Zone Buoyant Ambient Spreading	1.000;15	6.164	1:80		
Torque Zone Attached To Left Bank/Shore.	**2.974;15**	**43.545**	**1:149**		
Simulation Limit	5.000;15	73.327	1:251		
Test 2 – SIMULATED CONDITION SSW–0,246					
Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Mixture Zone Jet/Plume Near-Field	16.74; 15	68	1:78		
Expansion Zone Buoyant Ambient Spreading	5.000;15	20.235	1:640		
Torque Zone Attached To Left Bank/Shore.	**NO**	**NO**	**NO**		
Simulation Limit	5.000;15	20.235	1:640		
Test 3 – SIMULATED CONDITION SSW–0,510					
Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Mixture Zone Jet/Plume Near-Field	55; 15	217	1:278		
Expansion Zone Buoyant Ambient Spreading	4.730	9386	1:2435		
Torque Zone Attached To Left Bank/Shore.	**NO**	**NO**	**NO**		
Simulation Limit	5.000;15	9913	1:2.688		
Test 4 – SIMULATED CONDITION WSW–0,068					
Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Mixture Zone Jet/Plume Near-Field	17,2; 12	51	1:45		
Expansion Zone Buoyant Ambient Spreading	992;15	5800	1:80		
Torque Zone Attached To Left Bank/Shore.	**2974.81**	**43.545**	**1:149**		
Simulation Limit	5.000;15	73327	1:251		
Test 5 – SIMULATED CONDITION WSW–0,246					
Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Mixture Zone Jet/Plume Near-Field	32,46; 15	132	1:178		
Expansion Zone Buoyant Ambient Spreading	5.000;15	20.235	1:640		
Torque Zone Attached To Left Bank/Shore.	**NO**	**NO**	**NO**		
Simulation Limit	5.000;15	20.235	1:824		
Test 6 – SIMULATED CONDITION WSW–0,510					
Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Mixture Zone Jet/Plume Near-Field	55; 15	217	1:278		
Expansion Zone Buoyant Ambient Spreading	4.730	9386	1:2435		
Torque Zone Attached To Left Bank/Shore.	**NO**	**NO**	**NO**		
Simulation Limit	5.000;15	9913	1:2.688		
Test 7 – SIMULATED CONDITION WNW–0,068					
Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Mixture Zone Jet/Plume Near-Field	17,2; 12	51	1:45		
Expansion Zone Buoyant Ambient Spreading	992;15	5800	1:80		
Torque Zone Attached To Left Bank/Shore.	**NO**	**NO**	**NO**		
Simulation Limit	5.000;15	73327	1:251		
Test 8 – SIMULATED CONDITION WNW–0,246					
Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Mixture Zone Jet/Plume Near-Field	32,46; 15	132	1:178		
Expansion Zone Buoyant Ambient Spreading	5.000;15	20.235	1:640		
Torque Zone Attached To Left Bank/Shore.	**NO**	**NO**	**NO**		
Simulation Limit	5.000;15	20.235	1:824		
Test 9– SIMULATED CONDITION WNW–0,510					
Parameters	Distance (X;Z)	Time (s)	Dilution	Total Simulation	Simulation Plume
Mixture Zone Jet/Plume Near-Field	55; 15	217	1:278		
Expansion Zone Buoyant Ambient Spreading	4.730	9386	1:2435		
Torque Zone Attached To Left Bank/Shore.	**NO**	**NO**	**NO**		
Simulation Limit	5.000;15	9913	1:2.688		

Figure 2. Results of CORMIX simulations for Fortaleza's underwater emissary.

In December, the WNW direction, divergent in relation to the coast, predominated in 75% of the records, followed by the WSW direction, which converges to the coast (25%). In relation to speeds, values under 0,100 ms-1 occurred at a frequency of 4% and still associated to currents measured at the bottom.

From the simulations, it is possible to observe that given the difference in density between the effluent (freshwater) and the sea, the plume presents strong positive buoyancy. Thus, if we consider the unfavorable speeds and currents (0,25 Direction and 0,04 - Speed) there is a probability of P = 0,25 x 0,04 or P = 0,01 (1%) for this to occur. However, for the actual situation, this probability is near zero.

The results obtained from using the CORMIX model helped in the environmental monitoring of the effluent disposal area, contributing towards appropriate sanitary disposal, since from the simulations it is possible to predict the purification capacity of the seawater around the emissary in terms of space/time and thus control discharges of pollutant load concentrations to maintain desirable water quality standards in the receiving body zone.

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ACKNOWLEDGEMENTS

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