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Modeling of Coastal Water Contamination in Fortaleza (Northeast Of Brazil)

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Modeling of coastal water contamination in Fortaleza (Northeastern Brazil)

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Abstract
An important tool in environmental management projects and studies due to the complexity of environmental systems, environmental modeling makes it possible to integrate many variables and processes, thereby providing a dynamic view of systems. In this study the bacteriological quality of the coastal waters of Fortaleza (a state capital in Northeastern Brazil) was modeled considering multiple contamination sources. Using the software SisBaHiA, the dispersion of thermotolerant coliforms and *Escherichia coli* from three sources of contamination (local rivers, storm drains and submarine outfall) was analyzed. The models took into account variations in bacterial decay due to solar radiation and other environmental factors. Fecal pollution discharged from rivers and storm drains is transported westward by coastal currents, contaminating strips of beach water to the left of each storm drain or river. Exception to this condition only occurs on beaches protected by the breakwater of the harbor, where counterclockwise vortexes reverse this behavior. The results of the models were consistent with field measurements taken during the dry and the rainy season. Our results show that the submarine outfall plume was over 2 km from the nearest beach. The storm drains and the Maceió stream are the main factors responsible for the poor water quality on the waterfront of Fortaleza. The depollution of these sources would generate considerable social, health and economic gains for the region.

Keywords
Modeling, coastal water, bathing water quality, storm drains, submarine outfall

INTRODUCTION

Coastal waters receive pollution from many sources, including rivers, storm drains, effluent outfall, sewer overflow and diffuse source inputs (EPA, 2013). This may lead to the formation of a visible sewage field near the discharge points, depletion of dissolved oxygen, algae blooms and microbial pollution of bathing water. Pathogenic bacteria and viruses discharged into the sea constitute a potential health risk for bathers, especially in densely populated areas. Uncontrolled and excessive waste disposal tend to create unacceptable levels of seawater pollution, compromising local economic activities and the ecological balance of coastal waters (Esen et al., 2011).

Over the past decades, population and tourism have grown extraordinarily along Brazil's 8,000 km of coastline. With approximately 2.5 million inhabitants, Fortaleza is the fifth-largest city in the country and one of the most important economic and recreational hubs in Northeastern Brazil. During the 1970s, a submarine outfall with a flow capacity of 4.8 m^3/s was built to protect urban beaches from pollution with untreated sewage, although less than half this capacity is currently attained. Two rivers in the metropolitan region (the Ceará River to the west and the Cocó River to the east) flow into the sea near beaches used for bathing. Thirty-two storm drains along the city's 25 km of waterfront discharge stormwater mixed with untreated domestic sewage and drain a 35 km^2 basin formed by the marine slope of Fortaleza.

In order to protect the marine environment and public health, the impact of the discharge from rivers and storm drains on the quality of bathing water is monitored weekly by the local environmental agency (SEMACE), while the impact of the discharge from the submarine outfall on the quality of water, sediment and biota is monitored biannually by the local water company (CAGECE).

Environmental modeling is not only a helpful tool in the monitoring of coastal environments, but may be used to design projects and studies involving environmental management of complex environmental systems. For example, the use of mathematical models makes it possible to obtain the individual effect of a set of sources of bacteriological pollution and identify cause and effect relationships (López *et al*., 2013), integrating a large number of variables and processes into a dynamic whole and evaluating present and future conditions. Based on hydrodynamics and data on water quality variation, environmental modeling can also be used to optimize sewage disinfection dosages thereby minimizing the impact of undesirable chlorinated disinfection by-products on the marine environment and meeting beach water quality standards (Chan, 2013). In addition, environmental modeling has been successfully used in emergency response situations (*Ibid.*).

In bacterial modeling, the decay rates of indicator microorganisms are critical for quantifying biological hazards and predicting the distribution of bacterial concentrations. Bacterial decay is affected by a number of environmental factors such as solar radiation, temperature, salinity, adsorption, sedimentation, pH and nutrient deficiency (Yalcin and Muhammetoglu, 2011; Muhammetoglu *et al*., 2012; Thoe *et al*., 2012; Feitosa *et al*., 2013; López *et al*., 2013; Boye *et al*., 2014). Solar radiation has been found to be of particular importance in the assessment of the impact of sewage discharged in marine waters (Roberts *et al*., 2010; Chan *et al*., 2013; Feitosa *et al*., 201; Chan *et al*., 2014). The significance of factors affecting bacterial decay (e.g. solar intensity and temperature) may be expressed in empirical ratios, such as the time required to reduce a bacterial concentration by 90% (T_{90}) (Feitosa *et al*., 2013b).

The purpose of this study was to make an integrated assessment of the quality of the bathing water along the waterfront of Fortaleza. The distribution of bacterial indicators (thermotolerant coliforms) discharged from three major sources (submarine outfall, rivers and storm drains) was predicted with a depth-averaged 2-D integrated hydro-environmental model, considering local physical parameters and processes of bacterial decay. The model was calibrated with field data on currents and coliform concentrations gathered locally by government monitoring agencies.

METHODS

The resolution of equations involving hydrodynamics and transport of substances requires the establishment of initial and boundary conditions, including realistic values of bathymetry and geometry (Rosman, 2011). The initial conditions used in the hydrodynamic models were zero velocity and free surface elevation, corresponding to the elevation at the initial moment of each model. The boundary conditions were the affluence of rivers to the boundary, free surface elevation and differences in phase and angle.

Oceanographic monitoring over the last 10 years and surveys performed by Occhipinti (1976) prior to the building of the outfall both indicate very small density gradients and no thermohaline stratification in the area, justifying the use of a 2-D model in the present simulation.

Computing Tool

The software SisBaHiA® (Basic System of Environmental Hydrodynamics) was used to model the hydrodynamics, initial dilution, plume dispersion and bacterial decay in the study area. The tool can simulate hydrodynamic, eulerian or lagrangian transport processes of solutes and sediments in estuarine and coastal waters, model water quality (with up to 11 parameters), wave generation and propagation and to make analyses and predictions of tides. In this study only hydrodynamic and lagrangian transport models were used, the latter combined with the near-field model proposed by Roberts (1979) and Roberts *et al*. (1989) and the bacterial decay model developed by Mancini (1978). The software and the models were described in detail by Rosman (2011) and Feitosa *et al*.

(2013a).

Area of study

Figure 1 shows the bathymetry of the region covered by the hydrodynamic and transport models. The region encompasses 283 km^2 of sea, with 43 km of coastline of which about 29 km are beaches used for bathing (19 km in Fortaleza and 10 km in Caucaia, an adjacent municipality). The grid contains 1,783 quadratic elements and 7,564 nodes and was designed so as to allow for the highest possible level of detail in the main areas of interest, i.e. discharge points and areas characterized by complex circulation patterns (breakwaters and the harbor).

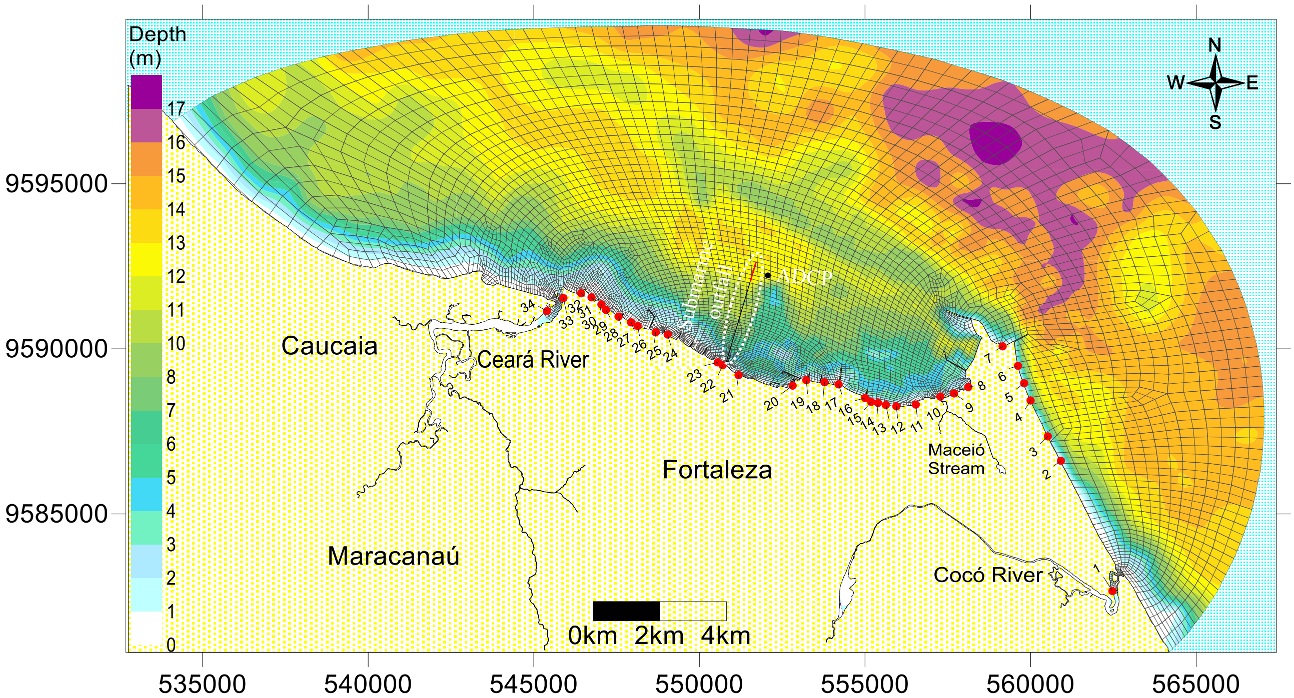

Figure 1. Area of study, showing grid, depth and 35 points of discharge of fecal pollution (rivers, storm drains and submarine outfall) on the coast of Fortaleza, Ceará, Brazil and the ADCP.

Bathymetric and surface roughness data were retrieved from charts DHN #701 (1:13.0000) and DHN #710 (1:50.000) produced and updated in 2011 by the department of hydrography and navigation of the Brazilian Navy.

The bathymetric map in Figure 1 was based on 2,395 depth points of the nautical charts, producing a 30x30m grid for interpolation with the Kriging method (Andriotti, 2004). The depth at each node was subsequently entered into the SisBaHiA database. The roughness chart was based on 143 points comprising different soil types converted into rugosity.

Choice of scenarios

At three degrees south of Equator, Fortaleza has a tropical, semiarid climate. Rainfalls are practically restricted to the rainy season (essentially from February to May) (Appendix, Figure A1). In contrast, during the dry season, when skies are mostly cloudfree, wind speeds (Figure A1) and solar radiation levels increase. To represent these two scenarios, the months of March and October were selected for simulation.

Bacterial concentrations and loads

The model was fitted with variable submarine outfall flow rates corresponding to hourly averages throughout November 2008 (Appendix, Figure A2) retrieved from the database of the local water company (CAGECE). A mean *E.coli* concentration of 4×10^7 MPN/100mL was adopted for all hourly flows based on monthly sewage treatment analyses conducted in 2007 by CAGECE.

The bacterial loads of the two other sources of discharge (storm drains and rivers) were based on data from a 2009 monitoring program by the Ceará State University. An overview of the bacterial concentrations and loads used in each scenario is given in the Appendix (Table A2).

Bacterial decay rates

The model assumed a variable cloud cover calculated from the incidence of solar radiation in order to obtain thermotolerant coliform and *E. coli* decay rates. This information and wind data were obtained from a weather station installed on the coast near the submarine outfall. Light attenuation in the water column was estimated based on Secchi depths for October (2.5 m) and March (4 m) and using the methodology described by Feitosa *et al*. (2013a).

Tides and winds

The model was forced with harmonic tides along the open boundaries and wind stress over the domain. Fifty tidal harmonic constituents were calculated based on a 6-month (1 June 2008 to 30 Nov 2008) water level record from an IBGE tide gauge installed in the harbor of Fortaleza. Local tides are fully semi-diurnal (tidal form number: 0.2). The mean spring and neap tides in the area are 1 m and 3 m, respectively.

Wind data were recorded every 10 minutes by a 15-m high weather station close to the beach (-3.718º and -38.536º). The tides are similar in March and October, but wind patterns differ: winds are less intense and more breeze-like in March (~3 m/s), and stronger and steadier in October (~6.5 m/s). The sea breeze effect is less perceptible in October than in March. In both seasons the wind clearly intensifies around noon. The modal direction is east-southeast in March and southeast in October.

The wind was measured simultaneously near the outfall diffusers (ocean wind) and at the weather station (land wind) to help calibrate the hydrodynamic model. In addition, gust wind speeds were measured on land.

Currents

An acoustic Doppler current profiler was anchored near the outfall diffusers in October 2011 at a depth of ~15m in order to obtain a vertical profile of current speeds. The device also recorded changes in pressure, temperature, conductivity and sea level. Some of these parameters were used to calibrate the hydrodynamic model.

Bathing water quality

The results produced by the models were compared with data on coastal water quality provided by a state environmental agency (SEMACE) conducting weekly samplings at thirty points along the waterfront of Fortaleza. The percentage of samples exceeding maximum acceptable concentrations of thermotolerant coliforms (1,000 MPN/100mL) in 2009 is shown in the Appendix (Table A3).

RESULTS

The correlation between observed and modeled sea levels was satisfactory in terms of both amplitude and phase (Figure A3), suggesting the model is a reliable tool for the prediction of this parameter.

The modeling results and measurements of currents show that the hydrodynamics off Fortaleza are primarily determined by wind patterns, with tides playing a minor role. Figure 2 shows the mean current intensities in the water column modeled for three different wind types and measured with a current profiler anchored near the outfall diffusers. The results obtained with the model using gust winds were closest to actual values. Therefore, gust winds were adopted in the hydrodynamic and transport models analyzed below.

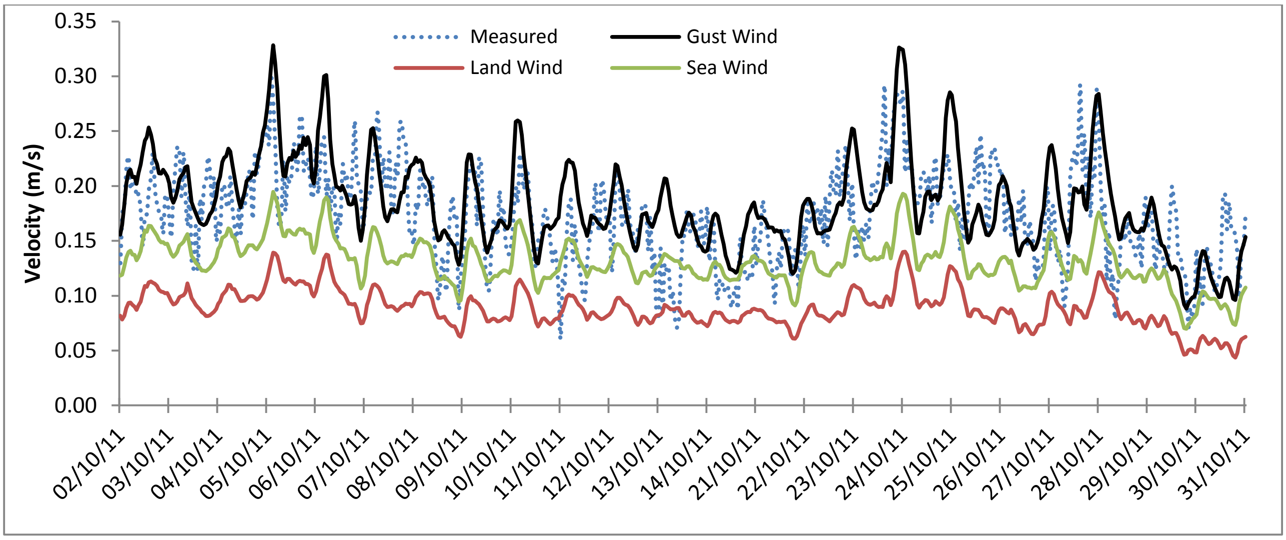

Figure 2. Depth-averaged current speeds, modeled for three different wind types (continuous lines) and measured with ADCP anchored near the outfall diffusers (dotted line).

Behavior of currents

Figure 3 shows the behavior of the currents off Fortaleza at low and high spring tide. The main direction of the currents is westward, but a more complex pattern is observed near the shore, especially along the urban beaches closest to the long breakwater protecting the harbor. Several smaller breakwaters have been installed in this area to reduce the erosive action of waves and coastal currents. Note the formation of counter-clockwise vortexes in the harbor and around the breakwaters on the central and eastern beaches, reducing current speeds and water renewal rates.

Our coastal current frequency distribution maps show that currents tend to follow the coastline in north-northwestern direction in the western and eastern sectors, east-northeastern and west-southeasten direction in the central sector (where the mouth of the Maceió stream is located), especially in March (Figure 3), and in west-northwestern direction near the outfall, at an average angle of 278°.

Near the outfall diffusers, the average current speed at spring tide in October was 0.15 m/s (maximum: 0.24 m/s). The corresponding figures for March were 0.07 and 0.15 m/s. The average current speed at the mouth of the Maceió stream was 0.05 m/s (maximum: 0.12 m/s) in October. The corresponding figures for March were 0.04 and 0.10 m/s. This trend is most likely due to seasonal variations in wind patterns, as explained above.

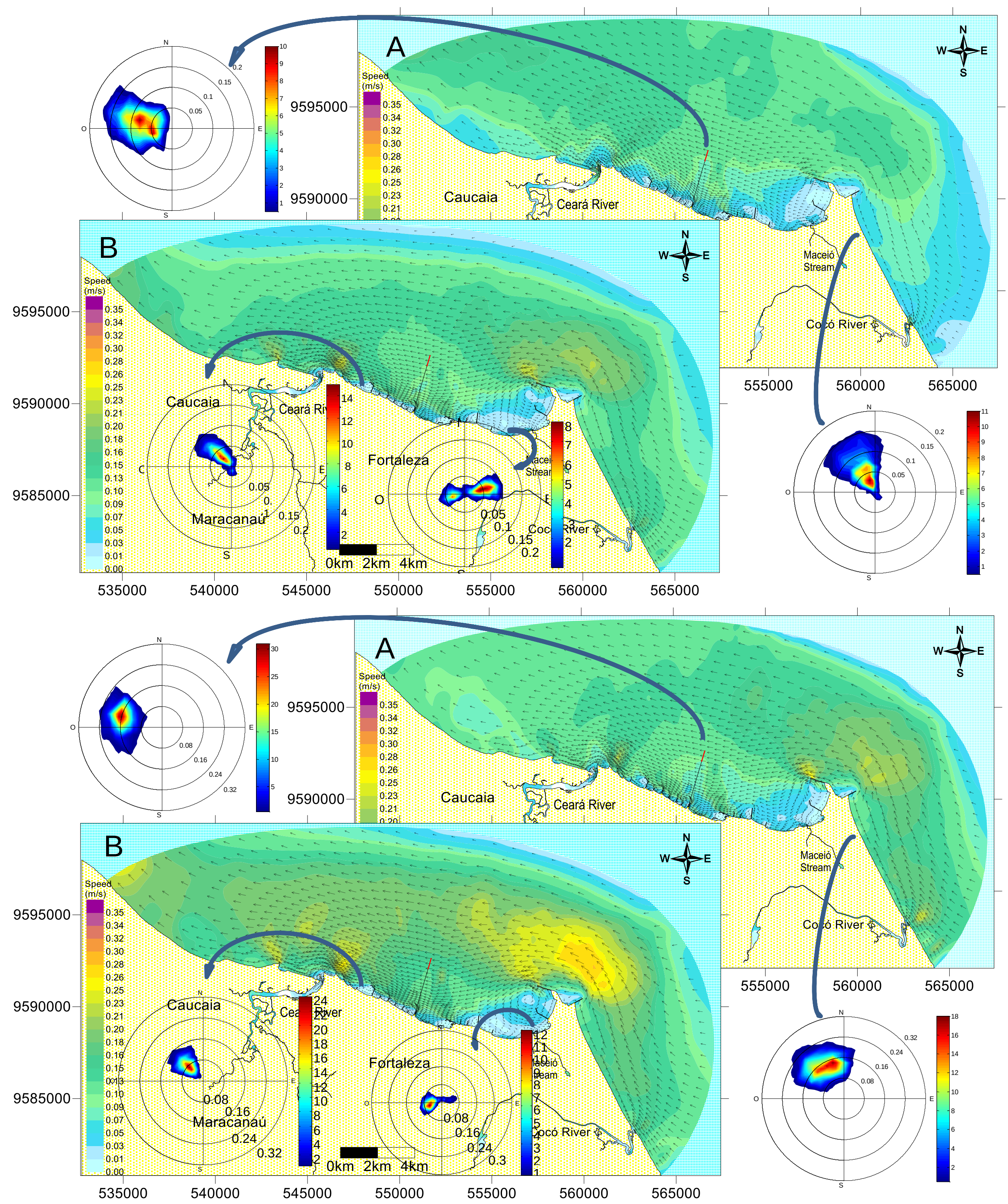

Figure 3. Snapshots of modeling results for ocean currents at low (A) and high (B) spring tide in March (above) and October (below), 2009. The inserted polar frequency distributions of currents represent one tidal cycle period for each month and place.

Initial dilution and bacterial decay

The dilution near the submarine outfall diffusers varied according to the currents and the water column (Roberts *et al.*, 2010). This explains the large variations observed (126-910 in March and 208-1,047 in October) (Figure 4). Dilution was greatest at high tide and when effluent flow rates were low and the currents were strong (in October).

Bacterial decay is faster during the day than at night (Figure A4). In the absence of solar radiation, decay is determined mostly by variations in temperature and salinity. In daylight, T_{90} values were between 2 and 15 h (March) and between 3 and 12 h (October). At night, T_{90} was approximately 22.5 h. Due to particularly favorable environmental conditions (intense solar radiation and high temperature and salinity), decay was faster in our study than in other similar studies such as Boye *et al*. (2014) (T_{90}: 20 h during daytime and 100 h at night), Rodrigues (2011) (T_{90}: 12 h to 13.2 h), and Yalcin and Muhammetoglu (2011) (T_{90}: 17 h to 88 h). Our diurnal T_{90} values are close to those suggested by Roberts (2010) for use in submarine outfall projects.

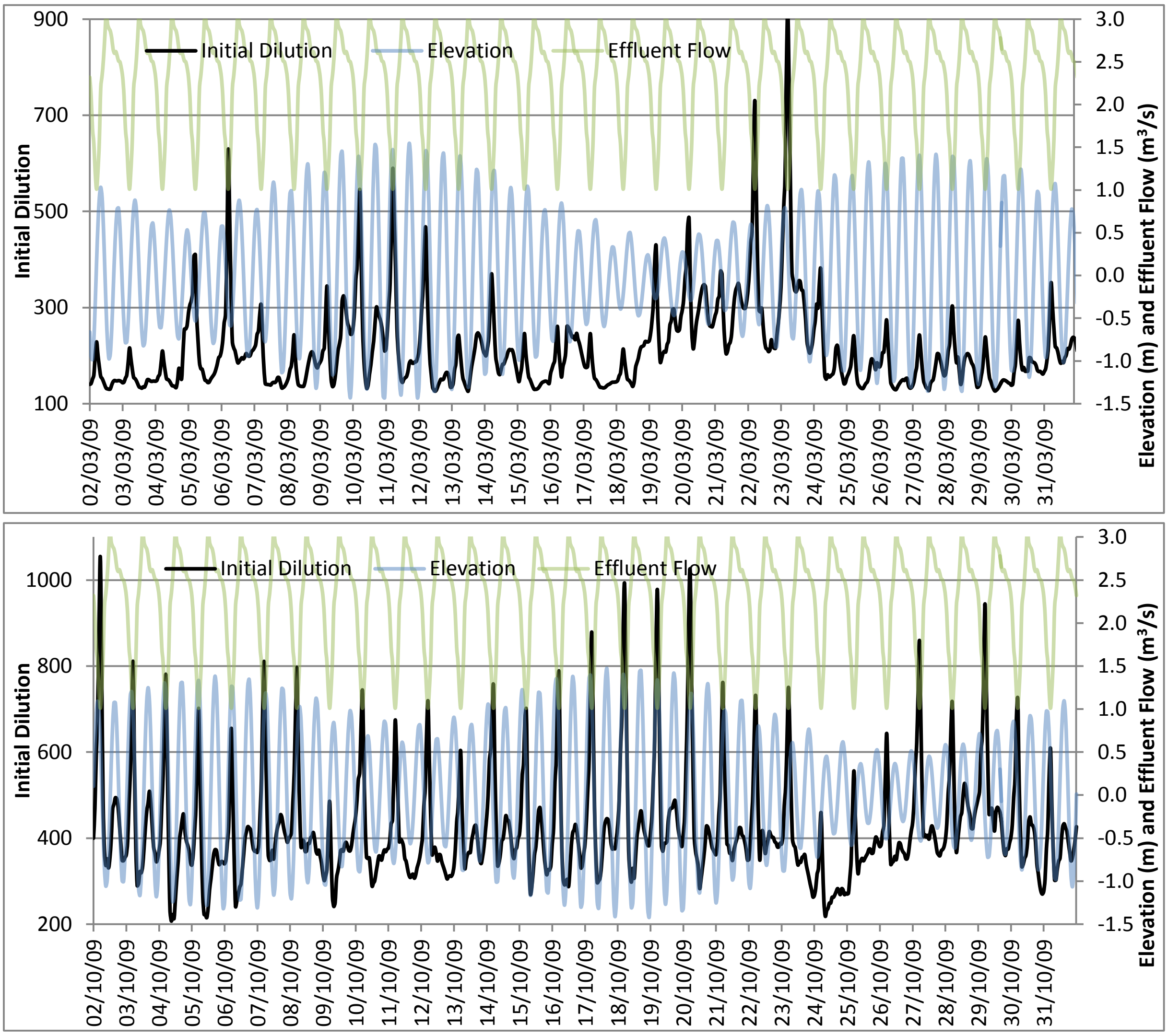

Figure 4. Initial dilution of the submarine outfall effluents, elevation of the free surface and effluent flow in March and October, 2009.

Dispersion of contaminants

Figure 5 shows the impact of thermotolerant coliform loads on coastal water quality in each model scenario. The extension of the plume was strongly influenced by solar radiation and currents. Bacterial decay rates were very high during the day due to strong UV radiation, unlike the early morning hours when salinity, temperature and predation were the main factors determining the much lower decay rates observed.

The outfall plume was shorter in March (when the currents are less intense) than in October (Figure 3), but the lateral dispersion and the concentration were greater. This trend was confirmed by an analysis of the probability of thermotolerant coliform concentrations exceeding maximum limits, as shown in Figure 6 which illustrates the percentage of time each month in which the water was unsuitable for bathing (>800 MPN/100mL for *E. coli*). The collected water quality data were similar to the results of the model with regard to the frequency with which thermotolerant coliform concentrations exceeded maximum limits, but the values obtained with the model were slightly lower because not all sources of discharge were considered.

As shown in Figure 6, the plume was over 2 km from the nearest beach—a very favorable situation for recreation and bathing. Brazilian legislation does not specify the minimum distance required to protect areas of human recreation from marine sources of pollution, but in the Mediterranean the reference value is 300 m (UNEP 2004). Thus, the water in the recreational areas along the waterfront of Fortaleza is not contaminated by the outfall.

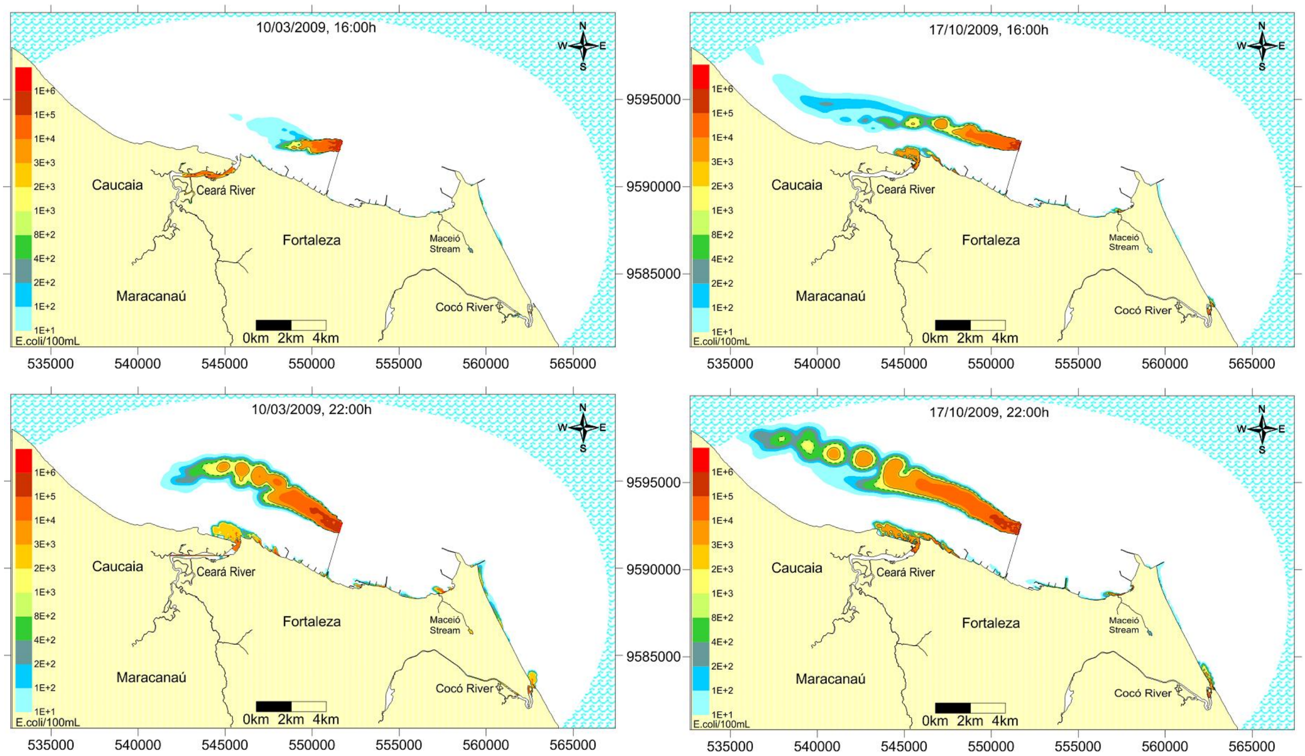

Figure 5. Dispersion of *E.coli* discharged by storm drains, rivers and the submarine outfall at low (A) and high (B) spring tide in March (left) and October (right), 2009. The dotted line indicates the maximum acceptable concentration of *E.coli* (800 NMP/100mL) according to Brazilian legislation.

However, the situation is less favorable with regard to the impact produced by other sources. Discharge from the Cocó river in the eastern sector, from five storm drains (#7, 9, 10 and 14) and the Maceió stream in the central sector, and from all the storm drains in the western sector was found to have a significant impact on the bathing water quality in Fortaleza regardless of the season. Wind, tide and currents spread fecal coliforms from these sources to recreational areas. Low radiation levels during the night favor the persistence of plumes, extending their influence along the urban waterfront.

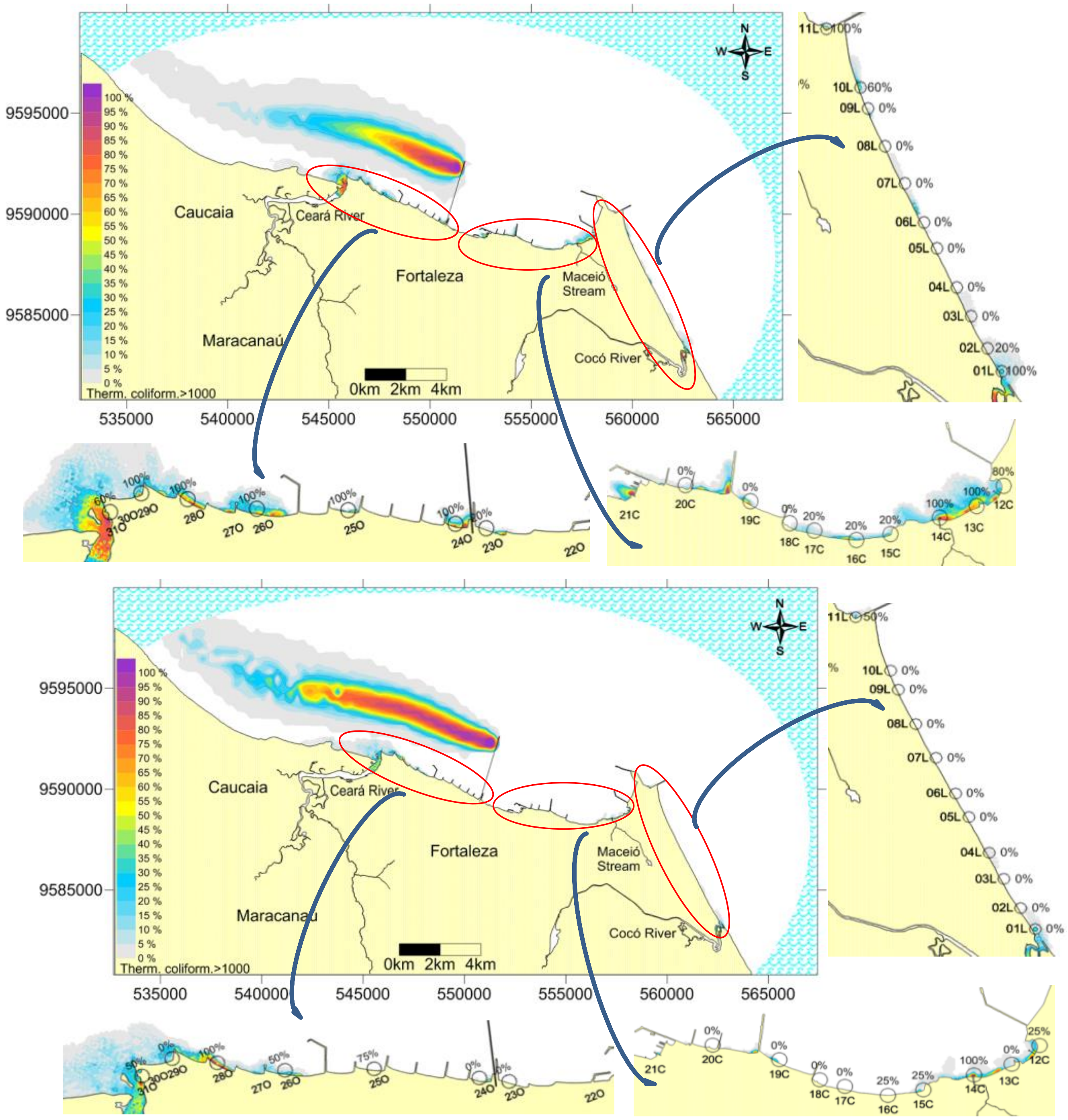

Figure 6. Probability of the concentration of thermotolerant coliforms exceeding maximum acceptable levels (1,000/100mL) according to the results of the model (colors) and data from a government monitoring program (circles) for March (A) (above) and October (B) (below), 2009. The dotted line indicates the maximum acceptable probability (20%) specified in the Brazilian legislation.

CONCLUSION

The local hydrodynamic and environmental conditions (including intense sunlight) protect the beaches of Fortaleza from the influence of the submarine outfall. As shown by the model, the outfall plume remains at least 2 km from the recreational areas on the shore.

Unfortunately, the same is not true for pollution discharged by rivers, streams and the local stormwater network. Although this discharge is punctual, it is eventually propagated westward by ocean currents and longshore drift, contaminating strips of beach water to the left of each storm drain or river. An exception to this condition occurs only in the area protected by the long breakwater of the harbor where counterclockwise vortexes reverse this behavior.

Bacterial decay is much slower at low levels of solar radiation, such as in the early morning hours. At this time of day, the beach is often used by bathers looking to avoid exposure to harmful UV rays. Thus, unfortunately, the protection against skin cancer afforded by bathing in the early morning hours is offset by an increased exposure to fecal contaminants.

Discharge from the Cocó river (east sector), from storm drains #7, 9, 10 and 14 and the Maceió stream (central sector) and from all the storm drains in the western sector is responsible for the poor bathing water quality along the waterfront of Fortaleza. The depollution of these sources would greatly improve the quality of the bathing water and generate considerable social and economic gains for the region.

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APPENDIX

Table A1. List of abbreviations.

Abbreviation	
ADCP	Acoustic Doppler Current Profiler
CAGECE	Companhia de Água e Esgoto do Ceará
CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
DHN	Diretoria de Hidrografia e Navegação da Marinha do Brasil
IBGE	Instituto Brasileiro de Geografia e Estatística
LABOMAR	Laboratório de Ciências do Mar
LGCO	Laboratório de Geomorfologia Costeira
SEMACE	Superintendência de Meio Ambiente do Ceará
SisBaHiA	Sistema Base de Hidrodinâmica Ambiental

Table A2. Flow rate (m^3/s) and bacterial concentration and load (thermotolerant coliforms) at each point of discharge (outfall, rivers, storm drain) according to season (March vs. October).

Source	March 2009			October 2009		
	Flow (m^3/s)	Concentration (TC/100mL)	Load (TC/s)	Flow (m^3/s)	Concentration (TC/100mL)	Load (TC/s)
1	4	5.0E+04	2.0E+09	2	5.0E+04	1.0E+09
2	0.4	1.6E+04	6.4E+07	0.017	1.6E+04	2.7E+06
3	0.0016	1.0E+04	1.6E+05	0.001	1.0E+02	1.0E+03
4	0.1	1.6E+04	1.6E+07	0.005	1.6E+04	8.0E+05
5	0.05	1.6E+05	8.0E+07	0.03	1.6E+04	4.8E+06
6	0.02	1.6E+04	3.2E+06			
7	0.1	1.6E+04	1.6E+07	0.05	1.6E+04	8.0E+06
8	0.01	1.6E+06	1.6E+08	0.01	1.6E+06	1.6E+08
9	0.1	1.6E+05	1.6E+08	0.05	1.6E+05	8.0E+07
10	1.5	1.6E+04	2.4E+08	0.15	6.0E+04	9.0E+07
11	0.001	1.6E+05	1.6E+06	0.0038	1.6E+05	6.1E+06
12	0.16	1.6E+04	2.6E+07	0.002	1.6E+04	3.2E+05
13	0.001	1.6E+03	1.6E+04	0.001	1.6E+03	1.6E+04
14	0.002	1.6E+04	3.2E+05	0.002	1.6E+03	3.2E+04
15	0.65	1.6E+02	1.0E+06	0.006	1.6E+03	9.6E+04
16	0.01	1.6E+05	1.6E+07	0.001	1.6E+06	1.6E+07
17	1	1.6E+04	1.6E+08	0.078	1.6E+04	1.2E+07
18	0.1	1.6E+04	1.6E+07	0.02	1.6E+04	3.2E+06
19	0.02	1.6E+04	3.2E+06	0.02	1.6E+04	3.2E+06
20	0.2	1.6E+05	3.2E+08	0.02	1.6E+04	3.2E+06
21	0.02	1.6E+05	3.2E+07			
22	0.1	1.6E+05	1.6E+08	0.05	1.6E+04	8.0E+06
23	0.02	1.6E+05	3.2E+07	0.02	1.6E+04	3.2E+06
24	0.01	1.6E+05	1.6E+07	0.001	1.6E+05	1.6E+06
25	0.01	1.6E+04	1.6E+06	0.001	1.0E+03	1.0E+04
26	0.1	1.6E+06	1.6E+09	0.05	1.6E+05	8.0E+07
27	0.01	1.6E+04	1.6E+06	0.08	1.6E+03	1.3E+06
28	0.005	1.6E+06	8.0E+07	0.001	1.6E+05	1.6E+06
29	0.05	1.6E+06	8.0E+08	0.05	1.6E+06	8.0E+08
30	0.08	1.6E+04	1.3E+07	0.01	1.6E+04	1.6E+06
31	0.05	1.6E+05	8.0E+07	0.005	1.6E+04	8.0E+05
32	0.01	1.6E+05	1.6E+07			
33	0.25	1.6E+04	4.0E+07	0.08	1.6E+05	1.3E+08
34	12	5.0E+04	6.0E+09	8	5.0E+04	4.0E+09

TC=thermotolerant coliforms.

Table A3: Percentage of water samples exceeding maximum acceptable concentrations of thermotolerant coliforms (1,000 MPN/100mL) at 31 sampling points monitored by SEMACE. Fortaleza, Ceará, Brazil. 2009.

Point	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dez
01L	0	0	100	100	100	50	25	20	0	0	20	0
02L	0	0	20	50	25	50	25	20	0	0	0	0
03L	0	0	0	0	25	25	0	40	0	0	0	0
04L	0	0	0	0	25	25	0	20	0	0	0	0
05L	0	0	0	50	75	50	0	0	0	0	0	0
06L	0	0	0	50	75	25	25	0	25	0	0	0
07L	0	0	0	50	50	25	50	0	0	0	0	0
08L	0	0	0	25	50	0	0	0	0	0	0	0
09L	0	50	0	50	75	25	50	20	0	0	0	0
10L	0	0	60	75	100	25	25	20	0	0	0	0
11L	50	100	100	100	100	75	25	20	100	50	40	75
12C	100	75	80	100	100	75	50	100	75	25	80	50
13C	25	25	100	100	75	25	25	0	50	0	0	0
14C	50	50	100	75	100	50	50	40	50	100	20	0
15C	50	75	20	50	100	25	0	0	0	25	0	25
16C	25	50	20	50	75	50	25	0	50	25	0	0
17C	0	25	20	50	75	50	0	0	0	0	0	0
18C	0	0	0	50	0	0	0	20	0	0	0	0
19C	0	0	0	50	50	0	0	0	0	0	0	0
20C	0	0	0	25	0	0	0	0	0	0	0	0
21O	0	0	20	100	75	0	0	0	0	0	0	0
22O	25	25	0	75	100	0	0	0	0	0	0	0
23O	0	0	20	75	50	0	0	0	0	0	0	0
24O	25	100	100	100	100	75	25	60	50	0	60	100
25O	100	100	100	100	100	75	100	100	25	75	80	50
26O	100	100	100	100	100	100	100	100	100	50	100	100
27O	100	100	100	100	100	50	75	80	50	25	0	0
28O	100	100	100	100	100	75	100	100	100	100	100	100
29O	50	100	100	100	100	50	50	60	50	0	0	0
30O	25	100	100	100	100	25	50	60	50	50	0	0
31O	50	75	60	100	100	50	50	80	25	50	20	0

SEMACE=Superintendência Estadual do Meio Ambiente. L=East; C=Central; O=West

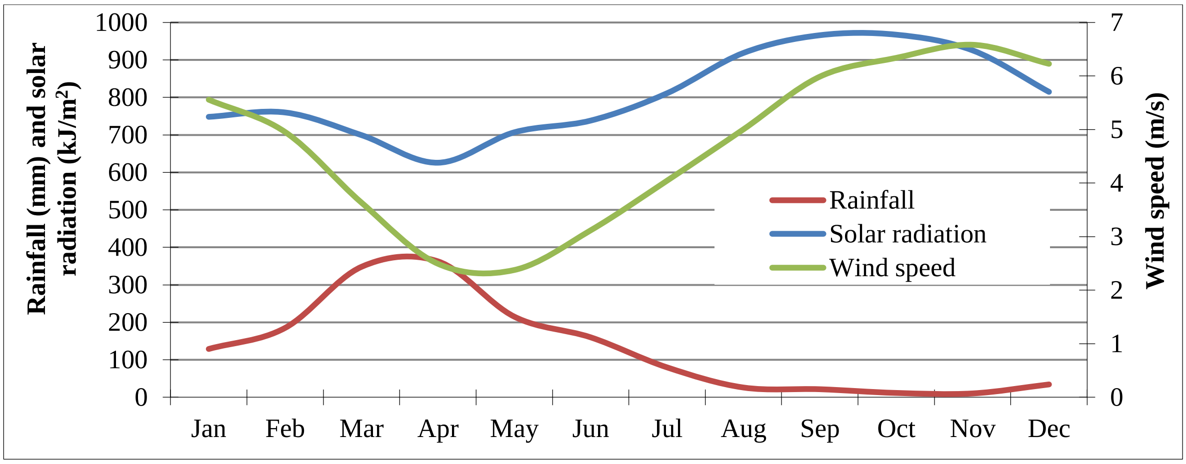

Figure A1. Monthly average rainfall (1974-2008), wind speed (2008-2009) and solar radiation levels (2008-2009) in the study region (Fortaleza, Ceará, Brazil).

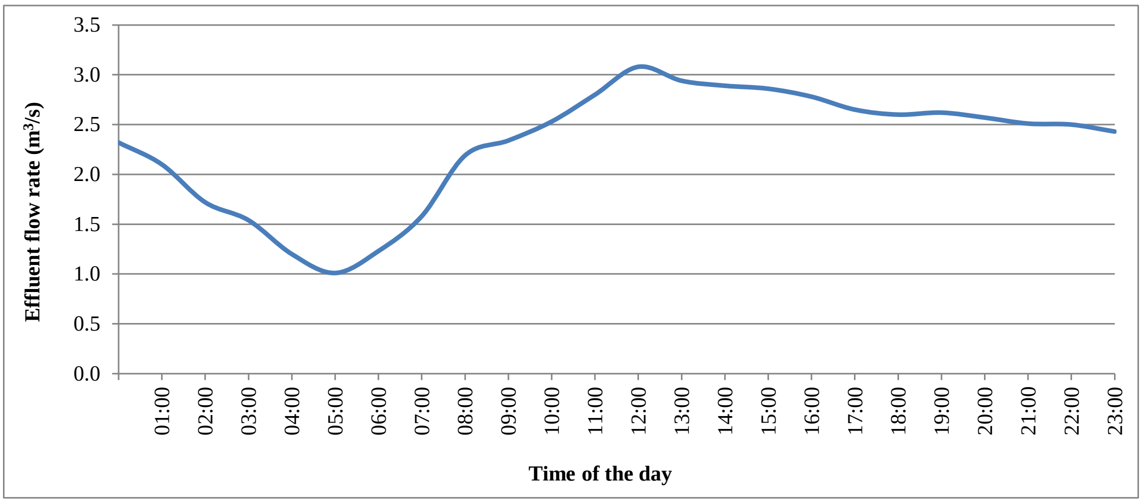

Figure A2: Average hourly submarine outfall flow rates used in the models.

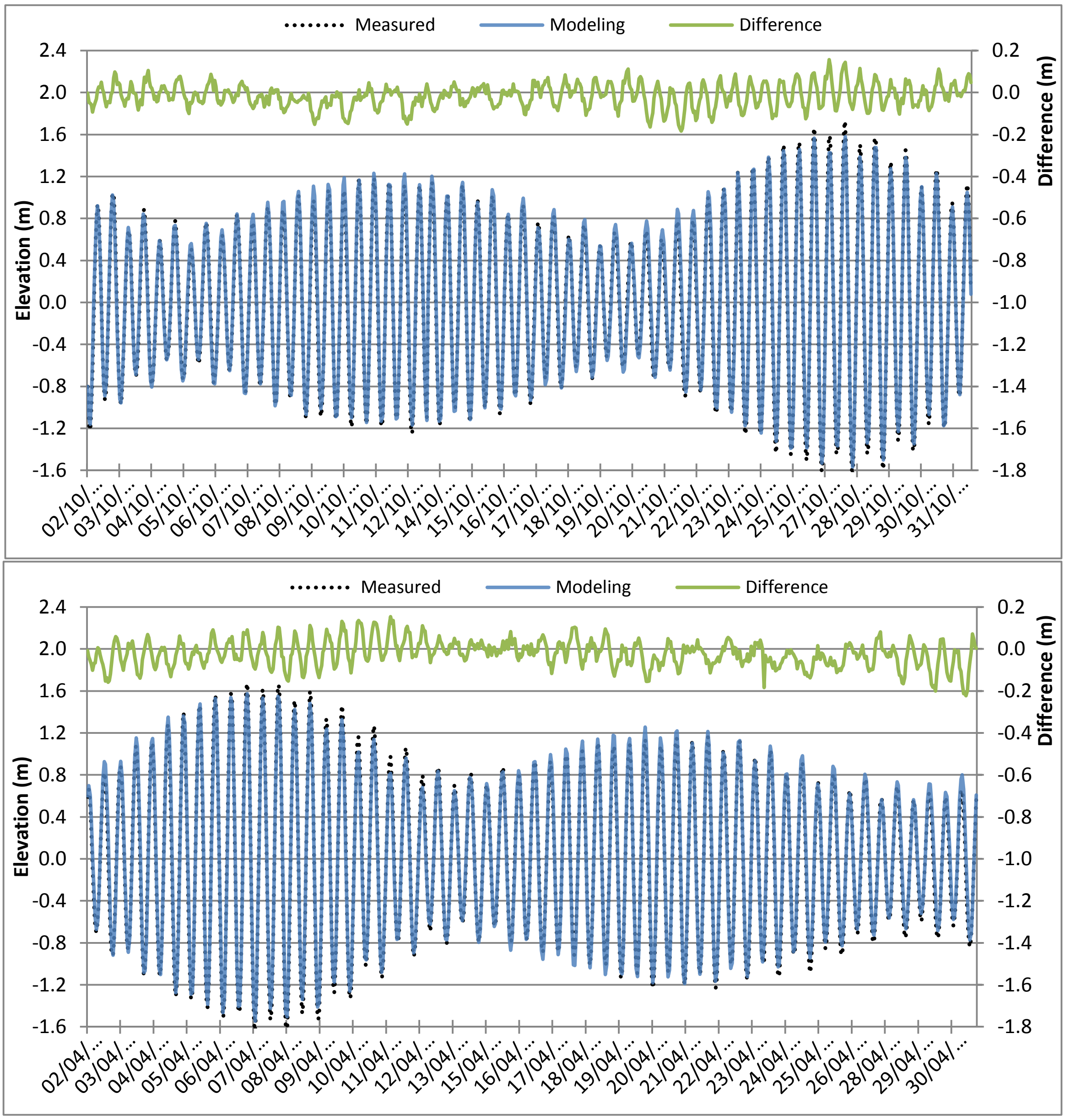

Figure A3: Water elevation according to the models and measurements in October 2011 (above) and April 2012 (below).

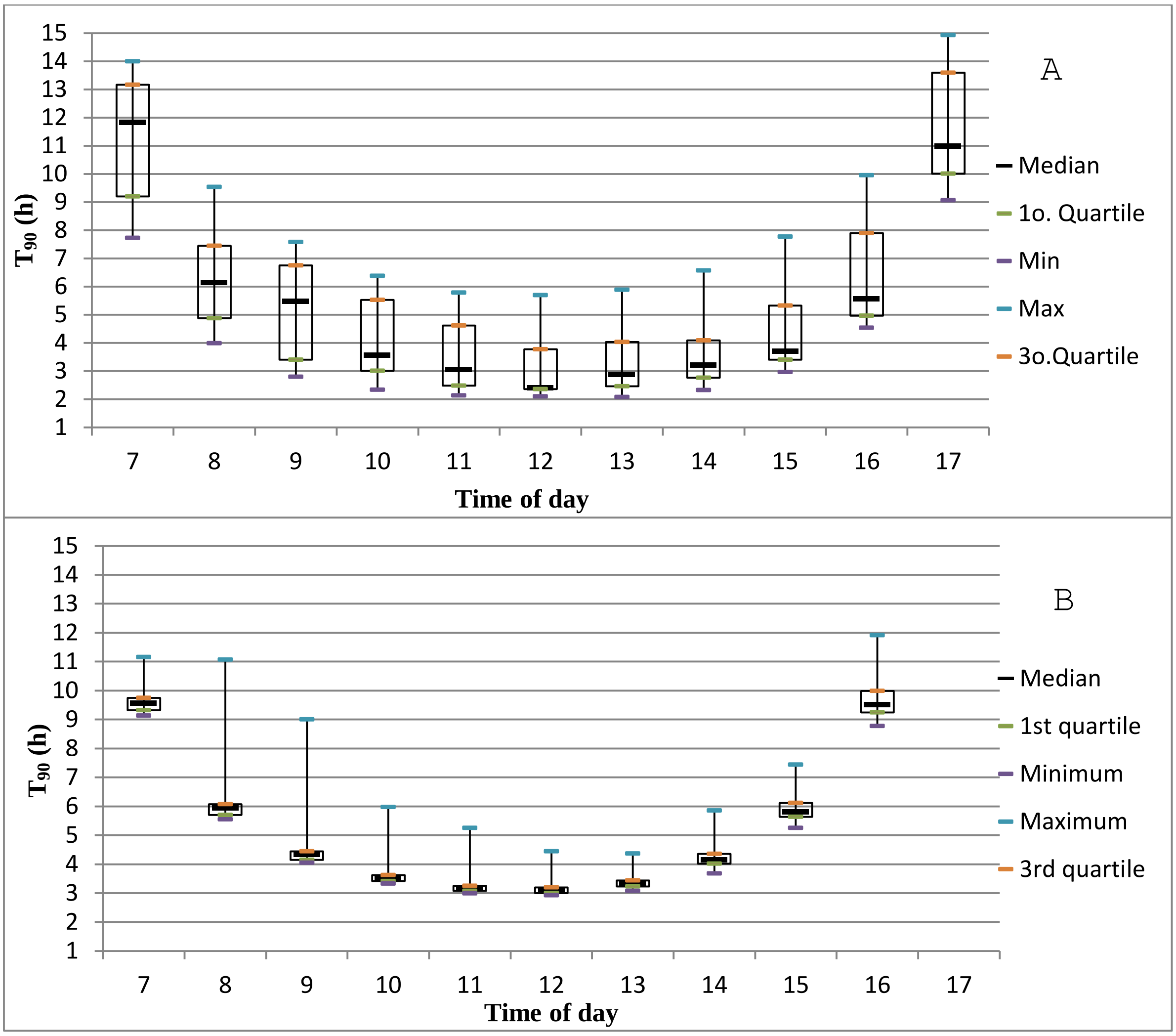

Figure A4: Statistics of daylight T_{90} values for the area near the outfall in March (A) and October (B), 2009.