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

S.P. Pereira[1], P.C.C. Rosman[2], C. Alvarez[3], R.S.Oliveira[4], C.A.F. Schetini[5], R.H.S.F.Vieira[4]

[1]Company of Water and Wastewater of Ceará State (CAGECE) / Federal University of Ceará (UFC), Tomás Lopes Street, 85, Fortaleza, CE, Brazil (silvanopereira@terra.com.br).
[2]Federal University of Rio de Janeiro (UFRJ), Brazil (pccrosman@ufrj.br).
[3]Environmental Hydraulics Institute (IHCantabria), University of Cantabria, Spain
[4]Federal University of Ceará (UFC), Brazil
[5] Federal University of Pernambuco (UFPE), Brazil

Abstract
The environmental modelling is an important tool to project design and to environmental management studying, because of its complexity. With this methodology, it is possible to integer a big number of variables and processes to obtain a dynamic vision of those systems and them evaluating the present and future conditions of it.
In this paper, are presented the results from the coastal water quality modelling of various bacterial input loads on the receiving waters in Fortaleza (Brazil). Faecal coliforms, used as the indicators for bathing water quality under the Brazilian law, were numerically modelled using the SisBaHiA (Environmental Hydrodynamic Base System) with contamination loads from three different fonts: rivers, storm drains and one submarine outfall. The models were used to represent the variable decay rate by solar radiation and others environmental factors. Relatively close agreement between model predicted and measured faecal coliform concentration distributions were obtained for two different scenarios. Results showed that the storm drains was the most significant input, and that under these conditions the bathing waters were likely to fail to comply with the Brazilian law, especially on the rainy scenarios. Moreover, there was not risk of the plume outfall touching the bathing area.

Keywords
Modelling, coastal water, discharges, storm drains, outfall,

INTRODUCTION

Several sources of pollution generally exist in coastal waters including: rivers, storm drains, effluent outfalls, sewer overflows and diffuse source inputs. Some of the more prominent adverse impacts include: formation of a visible sewage field near the discharge points; creation of extensive sea bed deposits; depletion of dissolved oxygen, especially in the bottom layers; algae blooms resulting in loss of transparency, fish kills due to toxins and enrichment of the sediments with dead organic matter; microbial pollution of bathing waters; accumulation of toxic substances in the sediments and the body of higher aquatic organisms (ANDREADAKIS, 1997).

Pathogenic bacteria and viruses discharged into the sea constitute a possible health risk for the beneficial uses especially in densely populated areas. The mortality of enteric bacteria, which are the indicators of faecal pollution, has been the subject of substantial research with regard to potential public health hazards resulting from the discharge of sewage to marine waters. Reduction in the concentration of indicators produced after disposal of domestic effluents into the sea has been related to physical (initial dilution and dispersion) and biological phenomena (CANTERAS et al., 1995).

Brazil has a 8.000 km long coastline where population and tourism has grown tremendously in the last years. Fortaleza is the fifth biggest city of Brazil, with near 3.5 million of habitants and an important economic, recreational and tourist area in the northeast country. In year's 70, a submarine outfall with 4.8 m3/s flow capacity was build to avoid that untreated discharges from urban sources polluted the beaches. Therefore, nowadays, less than half of this sewage is disposal.

The city has two rivers that flows by metropolitan region and arises near the beaches used for bath, the Ceará River at west side and Cocó River at east side. The first has a important affluent, the Maranguapinho River, that has 34 km long and 223 km² of basin area of which 29% is on Fortaleza. The Cocó River has about 50 km long, draining 60% of Fortaleza region and has an area about 485 km^2. At long the 25 km of costal city there are many storm drains that carry untreated domestic sewage and stormwater discharges. These storm drains were on the marine slope basin, the unique basin totally into the Fortaleza city, with about 35 km^2 (LGCO, 2009).

The impact of these three types of disposal is monitored, using evaluation of water quality for outfall, rivers and storm drains, over their sediments quality and biota diversity for outfall. Rivers and eleven principal storm drains flows was quantified in four years periods. The main objective of these monitoring program is to identify possible impacts of those discharges in the marine environment and to preserve the public health.

The environmental modelling is an important tool to project design and to environmental management studying, because of its complexity. The ability to predict bacterial concentration levels in coastal waters can aid environmental water managers and civil engineers in making effective and economic decisions in planning and designing new infrastructure works or refining existing wastewater treatment works (KASHEFIPUR *et al*, 2005). Numerical hydroenvironmental models have proved to be a valuable tool for predicting the flow and water quality distribution in coastal waters and they have been increasingly used in environmental impact assessment studies (*ibdem*). With it is possible to integer a big number of variables and processes to obtain a dynamic vision of that systems and them evaluating the present and future conditions of it.

In bacterial modelling the decay rate of a microbial indicator is a critical parameter for predicting its concentration distribution. This parameter, which controls the pathogen population in the coastal receiving waters, can be affected by a number of environmental and natural factors such as solar radiation, temperature, salinity, adsorption, sedimentation, pH and nutrient deficiency (MANCINI, 1978; SARIKAYA and SAATCI, 1987; SINTON *et al*., 1999). Among these, the effect of solar radiation has been found to be of particular importance for assessment of the impact of discharged sewage in marine waters (SARIKAYA and SAATCI, 1995; CANTERAS 1995; YAN *et al*., 2000). The significance of these factors such as solar intensity and temperature affecting the coliform decay is usually expressed using some empirical relationships in terms of T_{90}, time in which the concentration of a determined indicator is reduced by 90%.

In this study a depth integrated two-dimensional numerical model, i.e. SisBaHiA, was used to predict the flow, initial dilution, decay rates and transporting of bacterial indicator. SisBaHiA was developed for simulating hydrodynamic, eulerian or lagrangean transport processes of solute and sediment in estuarine and coastal waters, water quality with until 11 water parameters, waves generation and propagation and tide analyses and prediction. It has been calibrated and validated against many practical field studies over the past 25 years.

The purpose of this paper was to assess the impact of tree tips bacterial input loads on the bathing water quality of the Fortaleza coast, northeast of Brazil. The distributions of total and faecal coliforms, used as pathogen bacterial indicators, were predicted using a 2D depth integrated hydro-environmental model. The model was comparated against the field data collected for the region study.

MATERIAL AND METHODS

The computing tool used to modelling the hydrodynamic, contamination transport and decay rate at the region was the SisBaHiA® (Environmental Hydrodynamic Base System). Information about this software was at www.sisbahia.coppe.ufrj.br.

Modeling region

The Figure 01 shows the grid and batimetric region used in the Hidrodinamic Model. This mesh has 1.790 elements and 7.579 nodes, the batimetric and rugosidity were purchased from nautical maps of the DHN ("Diretoria de Hidrografia e Navegação da Marinha do Brasil") numbers 701and 710.

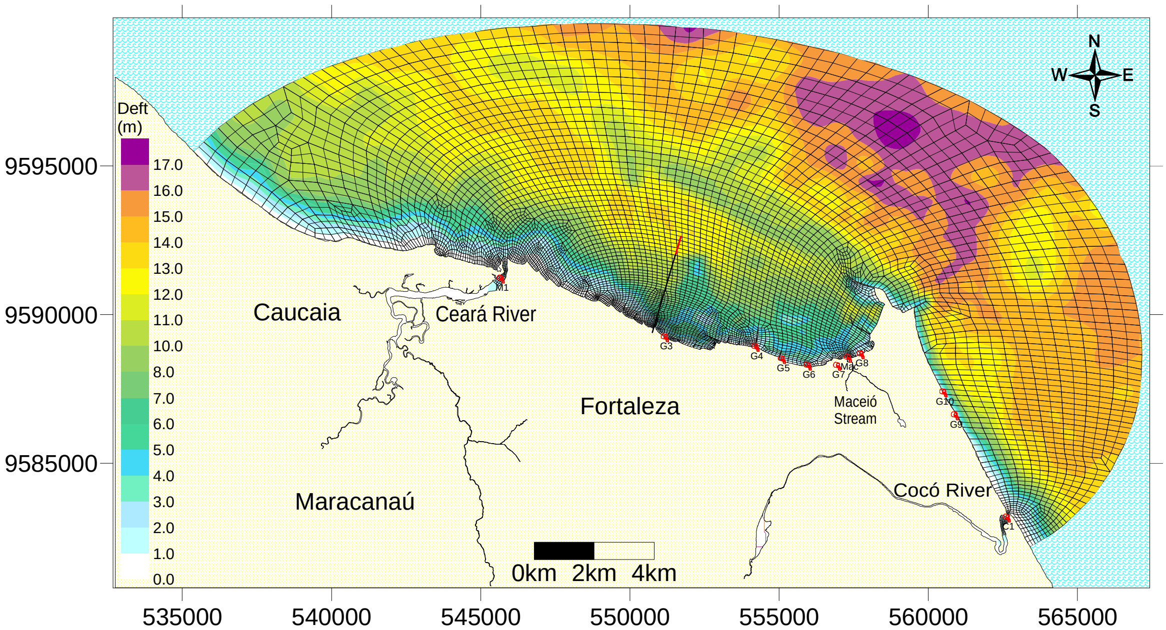

Figure 1. Grid, deft and outfall, rivers and storm drains locating, used in the models.

Choice of Scenarios

The city is on semiarid region at 3o south, with two seasonal periods, one with rain, between February and May and other one without rain (Figure 2). It observed too a seasonal variability of the wind, but opposite to the rain: at the dry month happen the highest wind intensity. About the surface solar radiation, this is higher at lass cloud cover, which occurred at dry month. To represent these conditions, we selected the months of April and November.

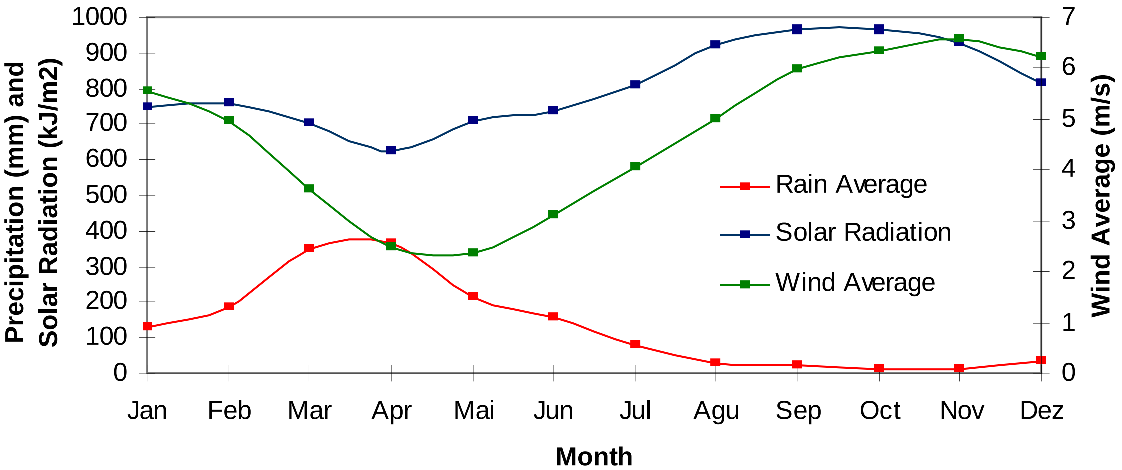

Figure 2. Average monthly of precipitation, wind intensity and surface solar radiation of Fortaleza. Precipitation between the years 1974 and 2008, wind average from 2008 to 2009 and solar radiation from 2007 to 2008. (font: www.funceme.br)

Contamination loads

Were used variable flows, purchased from the data acquired via local water company (CAGECE - Company of Water and Wastewater of Ceará State), corresponding to average hourly at November of 2008, which are showed on Table 1. For all hours was adopted a mean concentration of faecal coliform of 4×10^7 NMP/100mL, purchased from monthly analysis of the station plant effluent at 2007 year.

Table 1. Efluent flow carring to Fortaleza submarine outfall.

Time	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00
Flow (m3/s)	2.32	2.10	1.72	1.54	1.20	1.01	1.23	1.58	2.19	2.34	2.53	2.80
Time	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Flow (m3/s)	3.08	2.94	2.89	2.86	2.78	2.65	2.60	2.62	2.57	2.51	2.50	2.43

To the others punctual fonts, were used loads obtained by field measurement campaign was then undertaken during March and October 2009 by Laboratory of Coastal Geomorphology (LGCO) from State University of Ceará. The contamination load was calculated multiplying the discharge (m^3/s) by concentration (faecal coliforms /100mL) and 10^4. A summary of the contamination load discharged into costal water during the scenarios is highlighted in Table 2. VIEIRA *et al*. (2002), analyzing three of that storm drain, sorted that out of 180 strains isolated from 15 samples, 118 were *E. coli*, and that organisms *Enterobacter aerogenes* and *Citrobacter* sp. were also isolated.

Table 2. Loads contamination of punctual fonts, on March and October of 2009, in faecals coliforms per second, used to April and November scenarios, respectively.

Font	G3	G4	G5	G6	G7	G8	G9	G10	Maceió String	Ceará River	Cocó River
March	3.2E+06	3.2E+08	1.6E+08	2.6E+07	1.2E+05	1.6E+07	3.8E+06	2.4E+05	2.7E+08	4.2E+08	1.8E+08
October	0.0E+00	1.2E+08	9.6E+05	3.2E+05	6.1E+06	0.0E+00	2.7E+06	0.0E+00	2.4E+06	3.2E+07	2.0E+07

Decay rates

To calculate the decay rates of faecal coliforms, was suppose a variable cloud cover calculate from the solar radiation (Figure 3). This information, and the winds one, was purchased from an Onset weather station installed at the beach near the outfall. To estimate the light extinction in water, was used the Secchi profundity of 3.5m in November and 5m in April, according to FEITOSA and ROSMAN (2007).

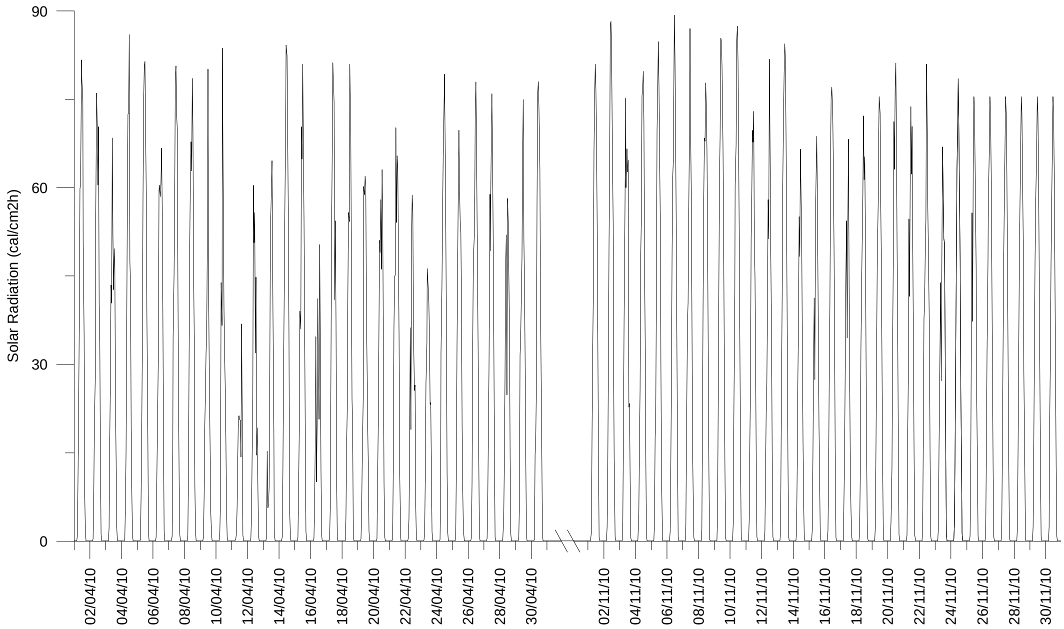

Figure 3. Solar radiation used in the decay model.

Water Bathing Quality

To compare de results produced by the models, were used information about the coastal water quality monitoring by the “Superintendência Estadual do Meio Ambiente” (SEMACE), which weekly conducts sampling at twelve points along the Fortaleza coastline. Table 3 shows the sample percentage of 28 of them, that exceeding the concentration limit to faecal coliform (1000/100mL).

Table 3. Sample percentage that exceeding the concentration limit for Faecal coliforms (1000/100mL).

Points	01L	02L	03L	04L	05L	06L	07L	08L	09L	10L	11L	12C	13C	14C	15C	16C	17C	18C	19C	20C	23O	24O	25O	26O
April	100	50	0	0	50	50	50	25	50	75	100	100	100	75	50	50	50	50	50	25	75	100	100	100
Nov.	20	0	0	0	0	0	0	0	0	0	40	80	0	20	0	0	0	0	0	0	0	60	80	100

Tide and Wind

The model was forced by prescribed harmonic tides along its open boundaries, and wind stress over the domain. Tidal harmonic constituents were calculated based on a 6-month water level record from a tide gauge of Brazilian Institute of Geography and Statistics (IBGE), installed at the Port of Fortaleza. Local tides are pure semi-diurnal with form number ([O1+K1]/[M2+S2) = 0.2), with mean spring and neap tides of the order of 1 and 3 m, respectively. Figure 4 shows the harmonic tidal signal for the study area.

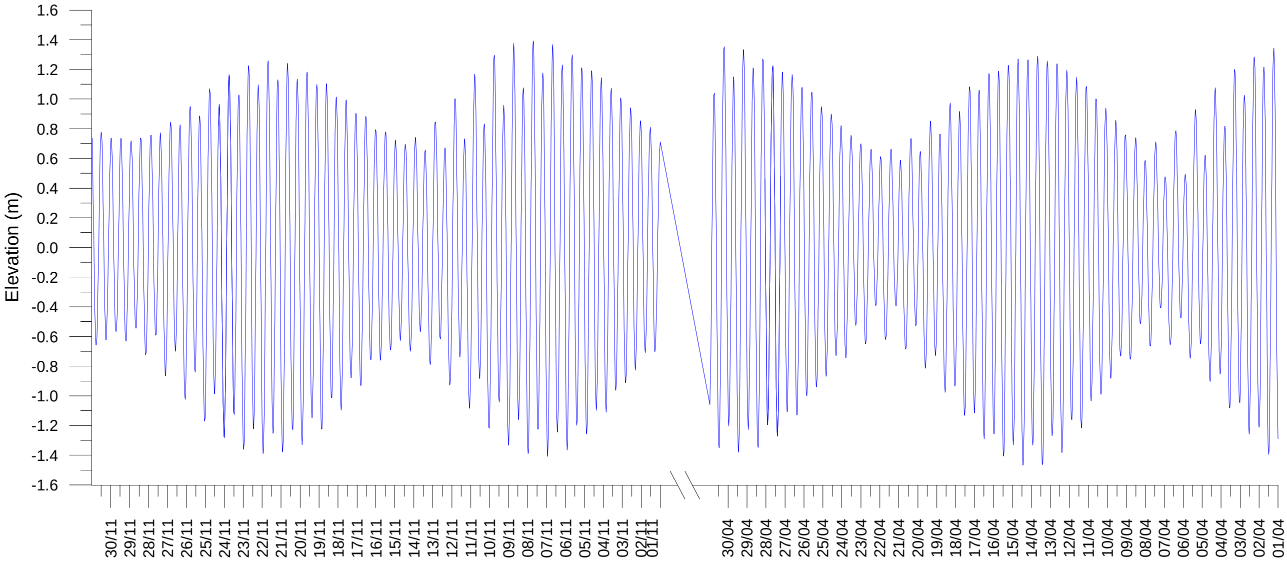

Figure 4. Water level calculated with harmonic constituents for April (right) and November (left), 2010.

Wind data was obtained from a meteorological station installed in land just 600 m away, in front the outfall (ONSET weather station, model HOBO), at 15 m above the sea in the water front, recording at 10-minute intervals. The Figure 5 shows vector diagrams of hourly wind for the months April and November, 2010, and Figure 6 shows the polar frequency distributions.

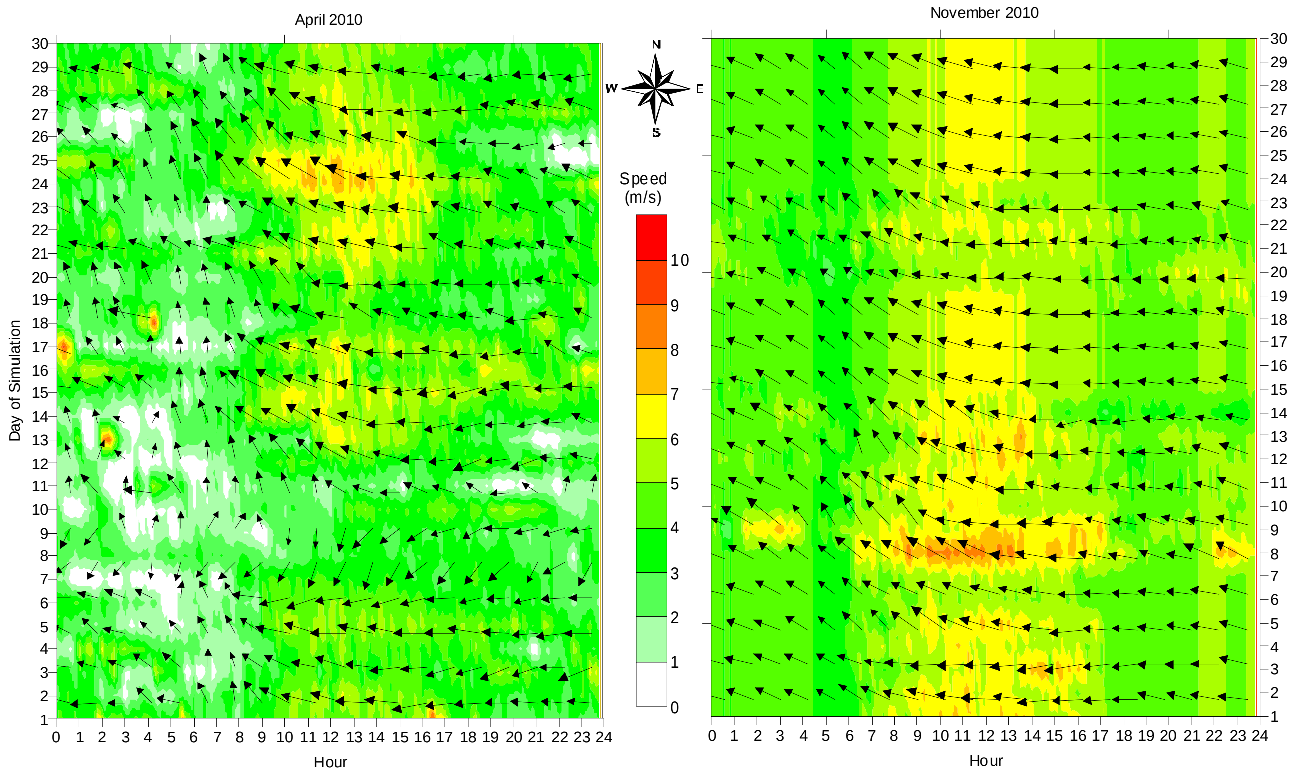

Figure 5. Hourly wind direction (vectors) and magnitude (colours) for April and November, 2010.

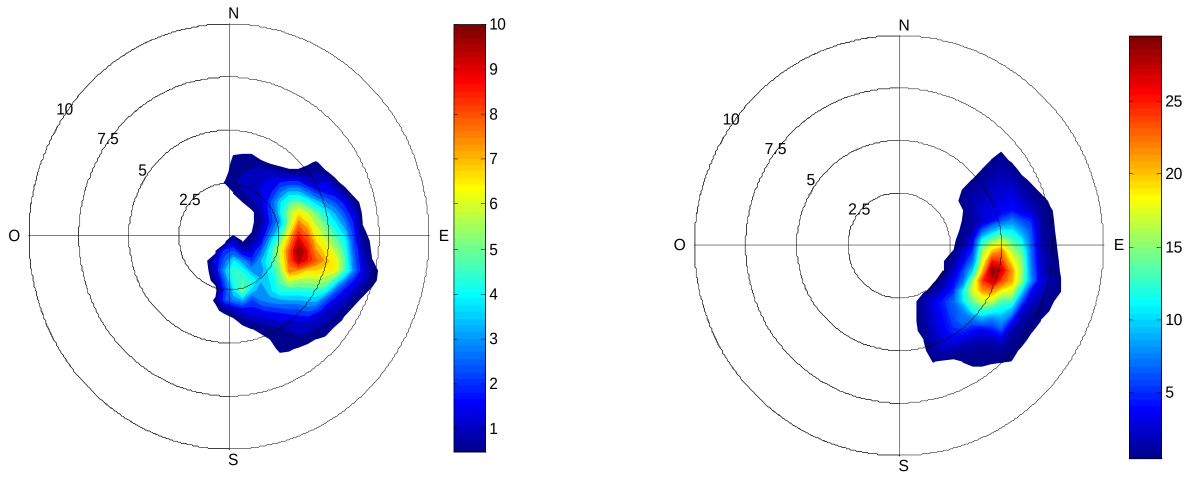

Figure 6. Polar frequency distribution of the wind at April (left) and November (right), 2010.

Meanwhile the tides are quite the same for April and November, the wind pattern changes slightly. The wind magnitude is smaller in April, about of 3.5 m/s, with more noticeable effects of sea breeze. The wind in November is steadier, with mean magnitude bout of 5 m/s. Still there is the effect of sea breeze, although less noticeable than April. In both cases is clear the wind intensification during the noon period. The modal direction in April is E/ESE, and in November is ESE/SE.

Data of currents in the study area are scarce. The best current data available is two sets of 15-day long periods, recorded using propeller-vane current meters in the vicinity of Port of Fortaleza, in May/June and November, 1998. The currents data were used for semi-quantitative comparison with model results, since there was not tide and wind synoptic data. Currents offshore the Port of Fortaleza are mainly wind-driven, and almost steadily westwards, with average magnitude of 0,25 m/s (May/June) and 0,15 m/s (November).

RESULTS

From the previous current measurements of 1998 and from our modeling results, it was highlighted that the hydrodynamic regime offshore Fortaleza is firstly driven by wind, with minor role of tides. The regional hydrography indicated very weak density gradients, suggesting that the barotropic mode prevail over the baroclinic, which may be important only very close to the estuarine inlets.

The Figure 7 shows a sequence of maps with of depth averaged currents at spring tide. The currents main direction is westwards, therefore with more complex pattern near the shore and towards the harbor area. Nearby the outfall area the averaged currents were of 8 cm/s, with maximum of 13 cm/s during spring tide in November, and 6 and 10 cm/s (average/maximum) in April. In the Maceió stream the averaged were 3 cm/s, with maximum of 8 cm/s in November, and 2 and 8 cm/s (average/maximum) in April. This trend is explained by the wind change, as seen in the Figure 4 and 5.

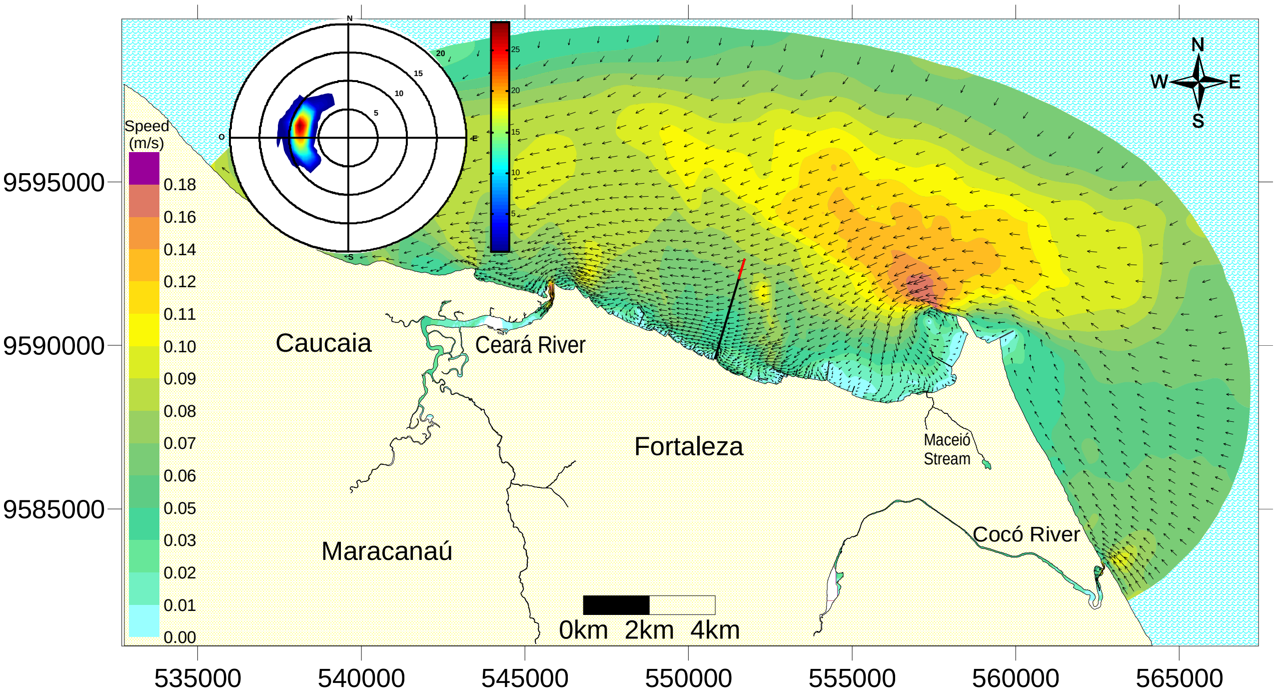

Figure 7. A snapshot of currents results at spring tide. The polar frequency distribution inside represents a tidal-cycle period for the region nearby the outfall.

Initial dilution and Coliform decay

According to TIAN *et al*. (2004), the dilution on near field depends on the ocean currents and, of course, the water column above the diffusers. These are the reasons why was observed such larges variation of dilution on Figure 8. The highest dilutions occurred during high tide and in presence of currents of greater intensity, as observed in November.

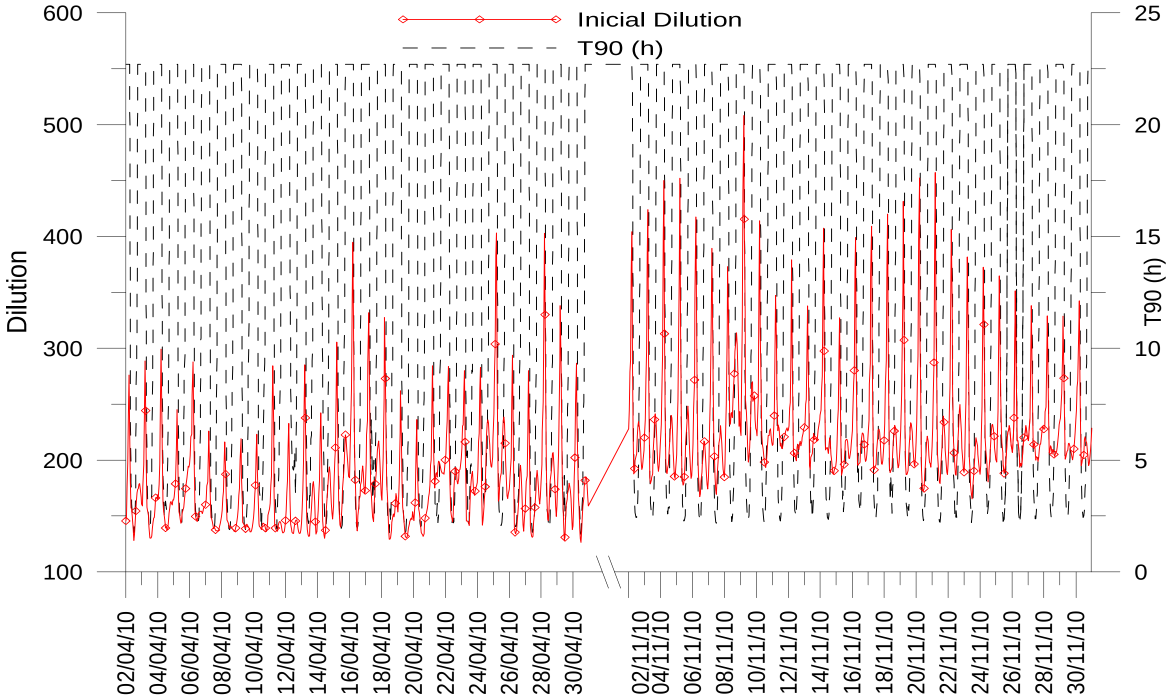

Figure 8. Initial dilution and T_{90} of April and November 2010.

Transport of Contaminant

Figure 9 shows the relevant impacts from the loads contamination of faecal coliform on the coastal water, at the distinct modeling scenarios. With observed the plume extension is hardly influenced by the solar radiation and currents.

During the Day, the UV radiation of the strong solar radiation (Figure 3), killed the bacteria quickly, which is observed with the little T_{90} (Figure 8). However, at dawn and during the early morning, the reduction or absence of radiation causes a persistence of those microorganisms. At these moments, the salinity, temperature and predation respond for the decay.

On April, because the less current intensity (Figure 7), the long plume is shorter then November but there is a bigger lateral dispersion and concentration into the plume. Looking at the probability map of exceeding the limit (Figure 10), this trend is confirmed.

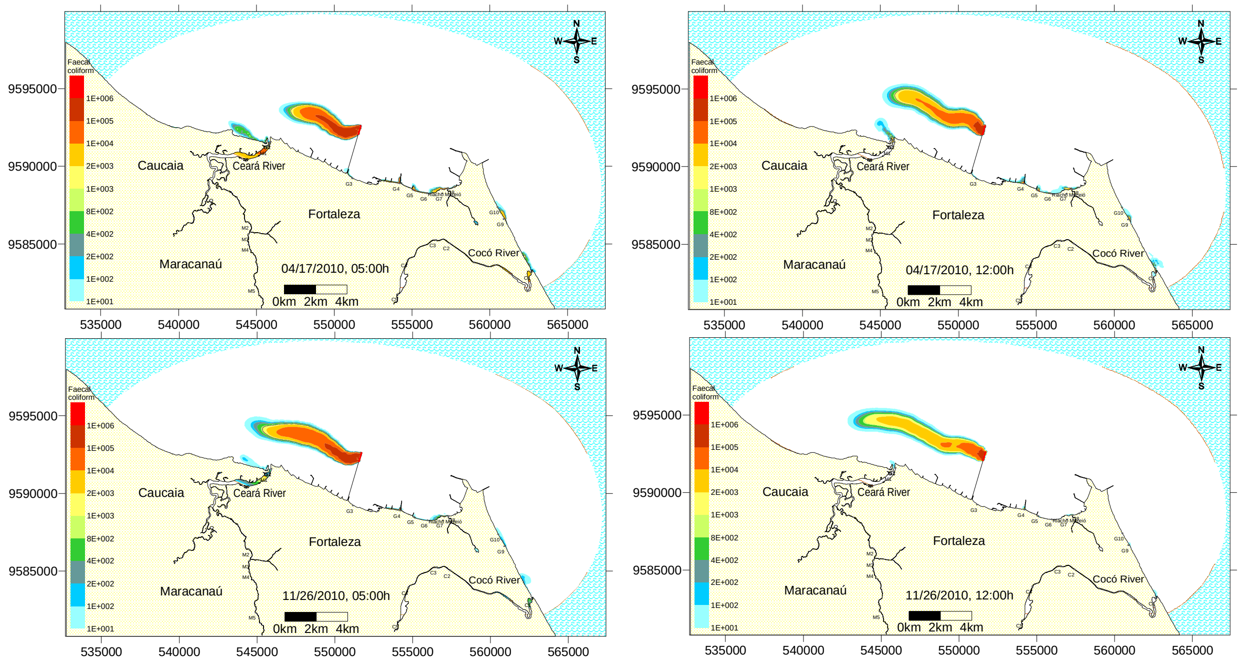

Figure 9. Plume of faecal coliforms dispersion on outfall effluent and others punctual fonts, corresponding to marine currents conditions shows at Figure 7.

About the risk of plume beach touch, as observed at Figure 10 and 11, there is not one and the most near area without recreation conditions is more them 2 km to the beach.

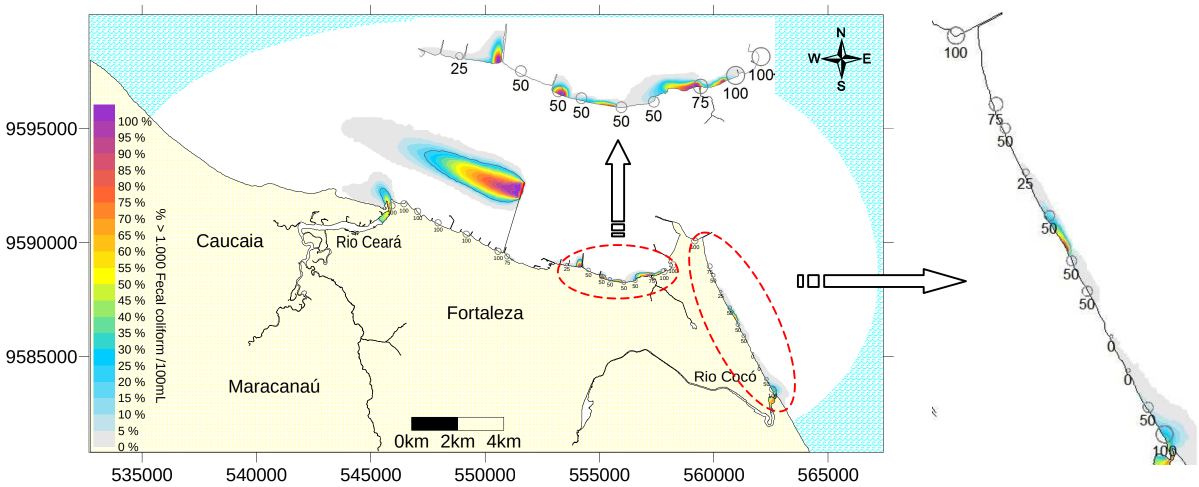

Figure 10: Probability to cross the limit of concentration for Faecal coliforms (1000/100mL), produced by model (colors) and resulting from monitoring program (cicles), both during April 2009. Dashed line mark the acceptable percent (20%) by the Brazilian law.

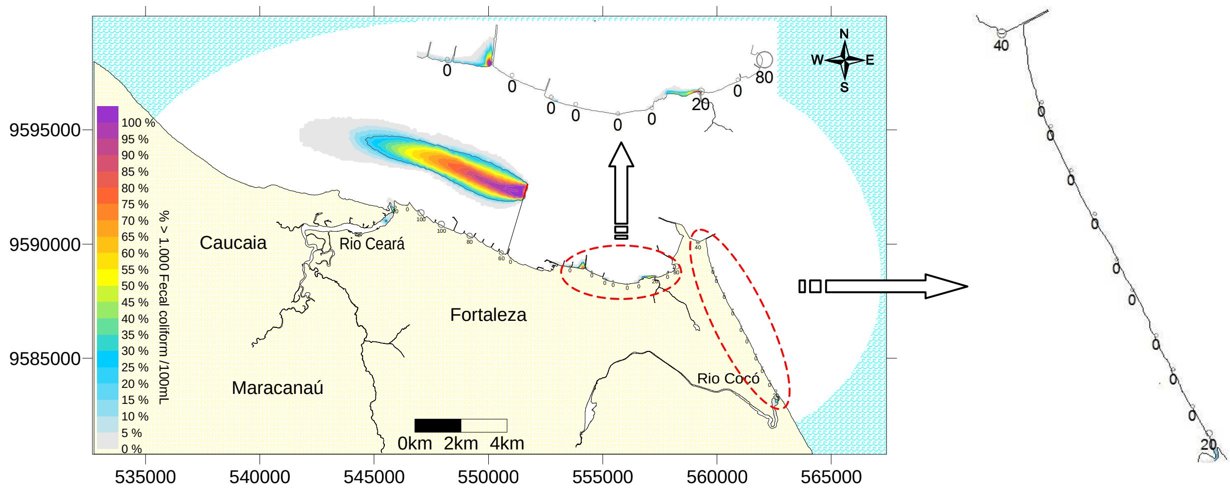

Figure 11: Probability to cross the limit of concentration for Fecal coliforms (1000/100mL), produced by model (colors) and resulting from monitoring program (cycles), both during November 2009. Dashed line mark the acceptable percent (20%) by the Brazilian law.

As show at Figure 10 and 11, there are three inputs were found to have a significant impact on the Fortaleza beach bathing water quality: the Maceió stream, and the 2 storm drain (G4 and G5), for both base and high flow scenarios. However, the dynamic movement of the contaminated plume due to the tidal current and wind action also had an important impact on the water quality at the compliance point, located along the beach of Fortaleza.

When comparing the results from water bath monitoring program and the models one (Figure 10 and 11), there is a similarity in the percentage of exceeding the limit. The model results were less then monitoring one because was not used all the punctual fonts.

CONCLUSION

Favored by intense sunlight, the local hydrodynamic and environmental conditions protect the beaches of Fortaleza from the influence of the submarine outfall. According to the defined model, contamination occurs 2 km offshore. However, the same is not true for the local stormwater network. Due to clandestine connections with sanitary sewers, stormsewers discharge untreated sewage directly on urban beaches, especially in the rainy season. Although this discharge is localized, it is eventually propagated westward by ocean currents and longshore drift.

BIBLIOGRAPHY

1. ANDREADAKIS, A.D., 1997. Wastewater treatment and disposal for the preservation of bathing and coastal water quality in touristic areas. *Marine Chemistry*, 58, 389-395.
2. CANTERAS, J.C., JUANES, J.A., PÉREZ, L., KOEV, K. N. (1995). Modellin the coliforms inactivation rates in the cantabrian sea (bay of Biscay) from in situ and laboratory determinations of T90. *Water Science and Technology*, 32(2), 37-44.
3. FEITOSA, R.C., ROSMAN, P.C.C, 2007. Emissários Submarinos de Esgoto: Aspectos de Qualidade de Água e Modelagem Computacional. *Métodos Numéricos em Recursos Hídricos* – 8, Associação Brasileira de Recursos Hídricos, Cap. 1, 209 pp, (www.abrh.org.br).
4. KASHEFIPUR, S.M., LIN, B., FALCONER, R.A., 2006. Modelling the fate of faecal indicators in a coastal basin. *Water Research*, 40, 1413-1425.
5. LGCO, 2009. Monitoramento dos indicadores de desempenho ambiental do programa SANEAR II nos rios Siqueira/Mranquapinho, Cocó e praias da zona oeste e leste de Fortaleza. Relatórios I e II Laboratório de Geologia e Geomorfologia Costeira e Oceânica, Universidade Estadual do Ceará.
6. MANCINI, J.L., 1978 Numerical Estimates of Coliform Mortality Rates Under Various Conditions. *Journal Water Pollution Control Fed.*, 50(11), 2477-2484.
7. SARIKAYA H.Z., SAATÇI A.M., 1995. Bacterial Die-away Rates in Red Sea Waters. *Water Science technology*, 32(2), pp 45-52.
8. TIAN, X., ROBERTS, P.J.W., DAVERO, G.J., 2004. Marine Wastewater Discharges from Multport Diffusers II: Unstratifield Flowing Water. *Journal of Hydraulic Engineering*, 130(12), 1147-1155.
9. VIEIRA, R.H.S.F., CATTER, K.M., SAMPAIO, S.S., RODRIGUES, D.P., THEOPHILO, G.N.D., FONTELES-FILHO, A.A., 2002. The stormwater drain system as a pollution vector of the seashore in Fortaleza (Ceará State, Brazil). *Brazilian Journal of Microbiology*, 33, 294-298.
10. YANG L., CHANG W., HUANG M, 2000. Natural Desinfection of Wastewater in Marine Outfall Fields. *Water Research*, 34(3): 743-750.