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Ocean outfalls as an alternative to minimizing risks to human and environmental health

Renato Castiglia Feitosa [1]

Abstract *Submarine outfalls are proposed as an efficient alternative for the final destination of wastewater in densely populated coastal areas, due to the high dispersal capacity and the clearance of organic matter in the marine environment, and because they require small areas for implementation. This paper evaluates the probability of unsuitable bathing conditions in coastal areas nearby to the Ipanema, Barra da Tijuca and Icaraí outfalls based on a computational methodology gathering hydrodynamic, pollutant transport, and bacterial decay modelling. The results show a strong influence of solar radiation and all factors that mitigate its levels in the marine environment on coliform concentration. The aforementioned outfalls do not pollute the coastal areas, and unsuitable bathing conditions are restricted to nearby effluent launching points. The pollution observed at the beaches indicates that the contamination occurs due to the polluted estuarine systems, rivers and canals that flow to the coast.*
Key words *Ocean outfalls, Coliform, Water pollution*

[1] Escola Nacional de Saúde Pública, Fundação Oswaldo Cruz. Av. Brasil 4365, Manguinhos. 21040-900 Rio de Janeiro RJ Brasil.
rcfeitosa71@gmail.com

Introduction

The coastal occupation of major Brazilian cities has been steadily increasing in recent years. Increased urbanization in coastal areas has not been followed by appropriate sewage networks. In recent decades the water quality in coastal areas has suffered an intense process of degradation due to domestic sewage that flows to the beaches without any treatment, either by direct dumps or through rainwater drainage networks.

Beach contamination occurs from point sources along the coastline, or indirectly through its connection with polluted rivers and tidal channels. This fact leads to the constant contamination of the beaches, which, in turn, compromise the water quality standards and consequently increase the risk of diseases through primary or secondary contact with polluted waters.

Sewage systems aim to mitigate or avoid the contamination of water bodies, in order to preserve the environment and promote good public health conditions. However, in coastal areas the increased urbanization leads to an unavailability of space for sewage treatment.

The sewage disposal of wastewater through submarine outfalls has been pointed to as an efficient alternative to the final destination of wastewater, due to high capacity of dispersion and decay of organic matter in the marine environment. This capacity lies in the available energy in the marine environment due to the action of ocean currents in effluent dispersion, availability of dissolved oxygen, and for being a hostile environment to the survival of microorganisms. Previous studies were performed by Feitosa[1,2] on the impact assessment of sewage discharge in coastal waters. According to Conama 274/2000 (Brazilian water quality regulation), water quality assessment is done from the concentration of indicator microorganisms of fecal contamination, which allows to evaluate the probability of contamination of the population by pathogenic microorganisms of enteric origin. The use of fecal coliform bacteria for monitoring of fecal pollution in coastal water is justified by the high density of these microorganisms in domestic sewage

The present work presents the likelihood of unsuitable bathing conditions in the coastal zone around the vicinities of the submarine outfalls of Barra da Tijuca, (SSOBT), Ipanema (SSOI) and Icaraí (SSOIC). The first two are located, respectively, at the West and South zones of Rio de Janeiro, whereas the last one belongs to Niterói city. This work aims to identify if the contamination of the coastal zone occurs by the aforementioned outfalls, and, in negative cases, identifying which ones are the main sources of contamination.

Theoretical basis

Submarine sewage outfalls: definition, selection criteria and mixing processes

The submarine outfalls are basically constituted from a pipeline that transports the effluents generated in the coastal cities for a final discharge into the ocean. In Rio de Janeiro, the main emissaries are located in Barra da Tijuca, Ipanema and Icaraí.

By the time the first ocean outfall (Ipanema) was set up in 1975, there was not a specific regulation regarding the level of sewage treatment should have before being launched into the sea. In this case, only a coarse screening is applied. Nowadays the Annapolis Protocol regulates the sewage disposal through submarine outfalls in the same way that the emission of gases is regulated by the Kyoto Protocol. Figure 1 below schematically illustrates the concept involving sewage ocean outfalls setup process. The collected sewage is sent to a preliminary treatment, and then is directed to marine environment through a submarine pipeline, where the effluent launching occurs by a multi-port diffuser that aims to maximize the effluent dilution.

The criteria for selecting the emissaries encompass population, geographic, oceanographic, hydraulic, economic and microbiologic aspects. From the population and geographic perspective, it is not only necessary to study the current and future populations to be served but also the selected area to be supplied by the system. The oceanographic aspects comprise the characterization of the currents that have a major role in the determination of the effluent launching point. In addition, it is extremely important to characterize how water density varies with depth, since it regulates the effluent mixing in the marine environment. The sanitation aspects comprise the level of treatment of the effluent prior the release in the environment that will depend on local regulations. The economic bias lies in the constructive methods, and the pipeline type to be adopted. The hydraulic design is not only characterized by the type of material used in the piping but also the aspects of the diffuser line responsible for the levels of effluent dilution. The microbiological aspect is related to the microbi-

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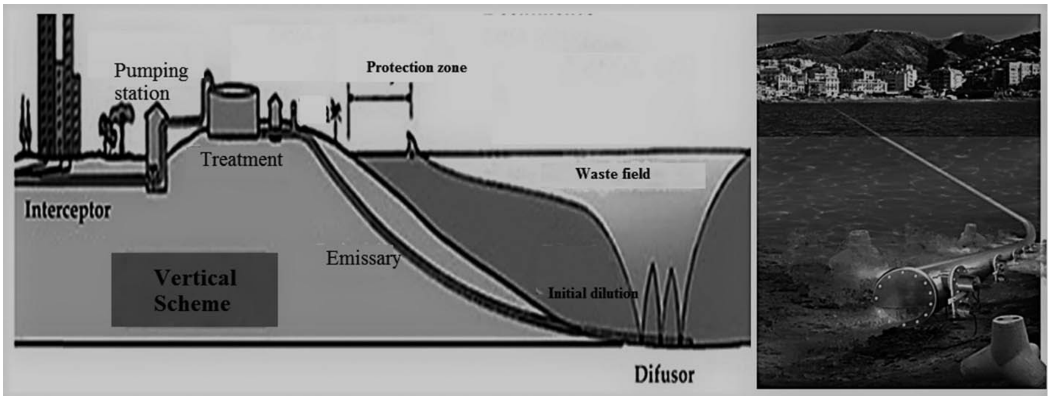

Figure 1. Scheme of effluent discharge through submarine sewage outfalls.

ological indicator selected in the water quality assessment, and are addressed separately in the bacterial decay topic below.

The criteria regarded to the aforementioned sewage outfalls were established along the time of their design, and thus are prior to the present work. Previous studies were performed in order to provide subsidies to Barra da Tijuca's ocean outfall setup. The Water and Sewage Company of Rio de Janeiro – Cedae[3] presented a report that took into account three different options regarding the effluent launching point. In Barra da Tijuca's case, Roberts[4] evaluated the sewage plume's dilution according to current patterns based on oceanographic campaigns.

Therefore, it should be noted that the results presented here are a post-evaluation study of the bathing conditions in the adjacent regions to the effluent discharge.

The mixing process between the sewage and the seawater encompasses two different regions according to their space and time scales. The first region so called near-field or active mixing zone occurs close to the diffuser. It comprises a turbulent region where the hydrodynamics is strongly influenced by the effluent jet. In the second region, named far-field or neutral mixing zone, the mixing process is less intense. The effluent is passively transported by ocean currents and the bacterial decay kinetics starts. The following paragraphs present a qualitative description for each of the mixing zones.

Near-field mixing zone: In this turbulent region the effluent is intensively mixed with seawater. The effluent tends to rise due to its lower density when compared to seawater. In the near-field are established the main characteristics of the effluent plume such as: initial dilution; rise height; and thickness. These characteristics strongly depend on the ocean currents condition and the density profile in the water column. Considering the same conditions of ocean currents, the higher the density variations along the water column between the surface and the effluent discharge point, the lower will be the dilution and the height of the sewage plume in the water column. Under homogeneous conditions of density the sewage plume will always reach the free surface. The position in the water column is extremely relevant in coliform bacteria die-off, since it regulates the solar radiation levels over the submerged plume.

Far-field mixing zone: In this zone located downstream of the discharge point the effluent, already established in a certain depth, is passively transported by the ocean currents, but with lower levels of turbulence if compared to the Near-field zone. In the Far-field mixing zone the sewage concentrations in water depend on bacterial decay kinetics.

Bacteria decay

The decay rates of fecal indicator bacteria are extremely relevant in the determination of the concentration of these microorganisms in coastal waters. Several experimental and field studies have been carried out aiming to quantify the decay rates of these microorganisms in the marine environment. Feitosa e Rosman[5] verified in a compilation of different studies the influence of temperature, salinity and solar radiation on bacterial decay rates.

Temperature: According to Oliveira[6] the temperature variations can affect the growth, nutritional demands, enzymatic activity and chemical composition of microorganisms.

Studies[7-10] showed that coliform bacteria die-off is directly proportional to temperature variations. Noble et al.[10] also verified a significant effect of temperature on enterococcus die-off.

The temperature has shown to have importance on bacterial decay in the absence of solar radiation. Under solar radiation, the temperature effect becomes less relevant[11-13].

Osmotic effects – salinity: Enteric bacteria in contact with seawater are subjected to a sudden osmotic shock. Thus, variation in salinity levels will affect the survival of these microorganisms in the marine environment[8]. According to Oliveira[6], salinity influences the speed of growth, physiology and reproduction of the microbial flora.

In salt waters the concentration of salts is higher than in microbial cells. As a result it will cause plasmolysis which is the process of shrinkage of the cell as a result of loss of water from the protoplasm to the environment. The importance of this phenomenon lies in the inhibition of growth at the moment when the plasma membrane is separated from the cell wall[14].

Based on works[9,15-17] it was observed that there is an increase in bacterial decay rates with higher salinity levels.

Photo-oxidation: Solar radiation has a fundamental role in bacterial decay in marine environments. A significant correlation has been found between coliform decay rates and solar radiation levels[7,9-13,15-24]. Pathogenic microorganisms such as *Giardia*, *Cryptosporidium*, *Poliovirus* e *Salmonella* presented a higher survival in the absence of solar radiation[25].

Studies performed by Chamberlin & Mitchell[15] produced convincing evidence that coliform decay rates vary with the light intensity in the free surface and other factors that affect its penetration in the water column.

Factors affecting solar radiation levels

The incoming solar radiation that reaches the sewage plume depends on the following factors as follows:

Variations in the solar constant: The solar constant depends on the Earth-Sun distance that varies over the year due to Earth's elliptical orbit around the sun. However it is important to highlight that these distance variations are not significant once this orbit is almost circular.

Latitude and seasons of the year: The latitude and seasons of the year influence the amount of radiation incident to a particular location on the earth's surface. These two factors basically identify the angle of incidence of solar radiation. The higher amount of solar energy occurs when the sun rays strikes Earth perpendicularly.

Earth's axis of rotation around the sun is tilted with respect to its orbital plane by an angle of approximately 23.5 degrees. The effect of the axial tilt leads to changes in day length and altitude of the sun at noon over the year. At any time of year, the conditions that occur in the southern hemisphere in terms of luminosity are opposite to those occurring in the northern hemisphere and vice versa.

Meteorological and oceanographic conditions: are responsible for light attenuation through the atmosphere and water column until reaching the effluent plume that can be at the surface or submerged. The cloud cover conditions are responsible for attenuating solar radiation through atmosphere. Under clear sky conditions the intensity of solar radiation is three times higher than overcast sky conditions[1]. The light attenuation through water column is regulated by oceanographic conditions represented by turbidity, and the density profile in the water column that will regulate the sewage plume submersion.

Methodology

The assessment of coliform concentration levels in the vicinities of the outfall effluent discharge is based on computational modelling, that comprises hydrodynamic and water quality models. The steps of model implementation aiming to characterize the current's patterns and the coliform waste field of Barra da Tijuca, Ipanema

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and Icaraí outfalls is presented as follows. The hydrodynamic and water quality modelling was performed by SisBaHiA model (Sistema Base de Hidrodinâmica Ambiental), developed at the Coastal and Oceanographic Engineering program – Federal University of Rio de Janeiro[26]. Considering the influence of solar radiation as one of the most important factors in determining bacterial decay rates, the NRFIELD[27] model was used to establish the depth and the plume's thickness. The intensities of solar radiation were calculated by the formulations proposed by Martin e McCutcheon[28].

Hydrodynamic modelling

The hydrodynamic modelling consists of determining the current patterns of natural or artificial water bodies, such as rivers, canals, bays, estuaries, seas and oceans.

The modelling procedure allows the hydrodynamic prognosis, considering predetermined scenarios that provide, for example, the pattern of currents in a bay during the flood or ebb tide, under different conditions of wind and other environmental parameters. In addition it is useful in environmental diagnosis when field data are not available, and is essential for water quality modelling.

Coliform plume modelling

In the present work fecal coliform bacteria are considered for delimiting the coastal areas that meet the bathing water quality standards. According to regulation Conama n° 274/2000, fecal coliform levels higher than 1000 MPN/100 ml are considered not suitable for bathing.

The Coliform plume modelling is divided into two different steps. In the first step, data of currents calculated by hydrodynamic model and the density profile of the water column are provided as an input for the near-field model, which in turn determines the depth and thickness of the sewage plume. These characteristics are extremely relevant in far-field modelling, since they regulate the income solar radiation on the plume. The second step comprises the dispersion and the decay of coliform wastefield in the far-field. The decay rates are estimated according to environmental levels of temperature, salinity and solar radiation. Considering that the solar radiation has the most relevant role in bacterial decay, it is necessary to include in the modelling all data that attenuate directly or indirectly the solar radiation levels on the plume. This attenuation occurs not only through the light propagation in atmosphere, but also in the water column. The percentage of cloud cover and the turbidity levels are the main responsible for light attenuation in the atmosphere and in the water column respectively. In bacterial decay modelling, the decay rates are commonly represented by the parameter T_{90}, which corresponds to the time required to reduce the bacterial population by 90% of its original amount.

The bacterial decay rates were estimated based on formulation proposed by Mancini[9] that considers the simultaneous variation of temperature, salinity and solar radiation over the sewage plume. According to Feitosa et al.[29] this methodology presents good estimates of coliform decay rates in the marine environment.

The solar radiation levels included in the modelling were calculated by the methodology proposed by Martin e McCutcheon[28]. The input data for simulation comprise: day, month and year; latitude; turbidity levels of seawater; dew point temperature; and percentage of cloud cover.

Characteristics of the area of study and effluent discharge

Ipanema outfall receives a higher sewage contribution, followed by Barra da Tijuca and Icaraí outfalls. Based on this, the flow rates of 7.5, 5.0 and 1.0 m^3/s are considered, respectively, to the aforementioned outfalls.

One of the most important assumptions to be considered in the modelling is the initial concentration of coliform of the effluent discharge. The present work considered for Ipanema outfall an initial coliform concentration of 7.10^7 MPN /100ml, typical of raw sewage, because at the time of the setup of Ipanema outfall, there were no legal requirements regarding standards for effluent discharge in coastal waters. Currently a state regulation requires a primary treatment of the effluent prior to discharge in coastal waters. In this case, considering a reduction of 40% in the initial coliform concentration due to this level of treatment, it was considered for outfalls of Barra

Table 1. Characteristics used in simulated scenarios.

	Outfall characteristics		Maximum solar radiation at water surface (W/m²)			Turbidity	Maximum solar radiation within the sewage plume (W/m²)		
Outfall	**Flow rate (m^3/s)**	**Fecal coliform concentration (MPN/100ml)**	**Summer clear sky**	**Summer overcast**	**Winter clear sky**	**Secchi depth (metres)**	**Summer clear sky**	**Summer overcast**	**Winter clear sky**
Barra da Tijuca	5	$4,2.10^7$	991	345	593	8	378	132	227
Ipanema	7,5	$4,2.10^7$	991	345	593	8	378	132	227
Icaraí	1	7.10^7	991	345	593	4	207	72	124

da Tijuca and Icaraí a coliform concentration of $4.2.10^7$ MPN/100 ml.

Results

The assessment of beach contamination by submarine sewage outfalls lies on results of probabilistic modelling, where three different scenarios that comprise seasonal (summer and winter) and meteorological (clear and cloudy skies) are considered.

Table 1 presents the maximum levels of solar radiation on water surface and within the sewage plume for each scenario.

All aforementioned scenarios comprise 14 days of simulation. The summer and winter conditions refer to solar radiation levels from January and June respectively. The meteorological conditions of clear and overcast skies refer to cloud cover percentage of 5% and 100%, respectively. All scenarios considered homogeneous density conditions in the water column, which result in plumes reaching the water surface. Thus, the incoming solar radiation varies with the time of the day and cloud cover conditions.

In addition to the aforementioned seasonal and meteorological characteristics, regarding the light penetration in the water column, it was considered in the present work surfaced sewage plumes whose thickness was 10 metres. The turbidity levels are determined by the Secchi disk depth (The Secchi disk depth provides a method for assessing turbidity. A Secchi disk is a circular plate attached to a rope and lowered into the water until it is no longer visible [Secchi depth]) that quantifies the light penetration in the water column. The Secchi depth adopted for the regions surrounding Barra da Tijuca and Ipanema outfalls was 8 meters. In the case of Icaraí outfall a Secchi depth of 4 meters was considered due to the higher turbidity levels of the waters of Guanabara Bay.

The results presented in Figure 2, Figure 3 and Figure 4 show the percentage of time over 14 days of simulation under unsuitable bathing conditions according to Brazilian regulation Conama 274/2000. It is worth to highlight that all the scenarios present the same hydrodynamic condition. Thus, the differences observed in the aforementioned figures lie on the different levels of solar radiation that occur in each scenario.

Among the presented scenarios the combination of summer and overcast conditions (Figure 3) comprises the worst condition, being observed most of the time unsuitable fecal coliform conditions between Barra da Tijuca and Ipanema outfalls.

The best and intermediate conditions occurred for clear skies during the summer and

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winter time respectively. Due to effluent discharge from the Icaraí outfall, the Guanabara Bay mouth presented unsuitable bathing conditions in the majority of the time in all scenarios.

Discussion

The microbiologic degradation in the marine environment has shown a direct correlation with the increasing levels of solar radiation. Field studies[10,11,19,24] showed a deleterious effect of solar radiation in bacterial decay in marine waters, reinforcing the observed results in the present work.

In all scenarios the effluent discharge in the marine environment occurred exclusively by the referred outfalls, and it was not considered sources of pollution along the coast, such as polluted rivers, lagoons and storm water runoff. Thus, based on presented results there was not an observation of the impairment of the water quality in bathing zones, which indicates that the sewage discharged by the outfalls did not reach the coastline.

In the surrounding regions of effluent discharge, significant percentages of unsuitable bathing conditions were observed. This trend is also observed in the zones between Barra da Tijuca and Ipanema outfalls due to the combination of their respective effluent plumes.

Comparatively it was observed a higher occurrence of unsuitable bathing conditions around Icaraí submarine outfall. It occurred because of the higher levels of turbidity in Guanabara Bay's water when compared to offshore waters in the vicinities of Barra da Tijuca and Ipanema outfalls.

The environmental impact study during the setup of Barra da Tijuca outfall carried out by Roberts[4] concurred with the results here presented, where it is not observed the contamination of the coastline by the referred outfall. This fact is also evidenced by the study performed by

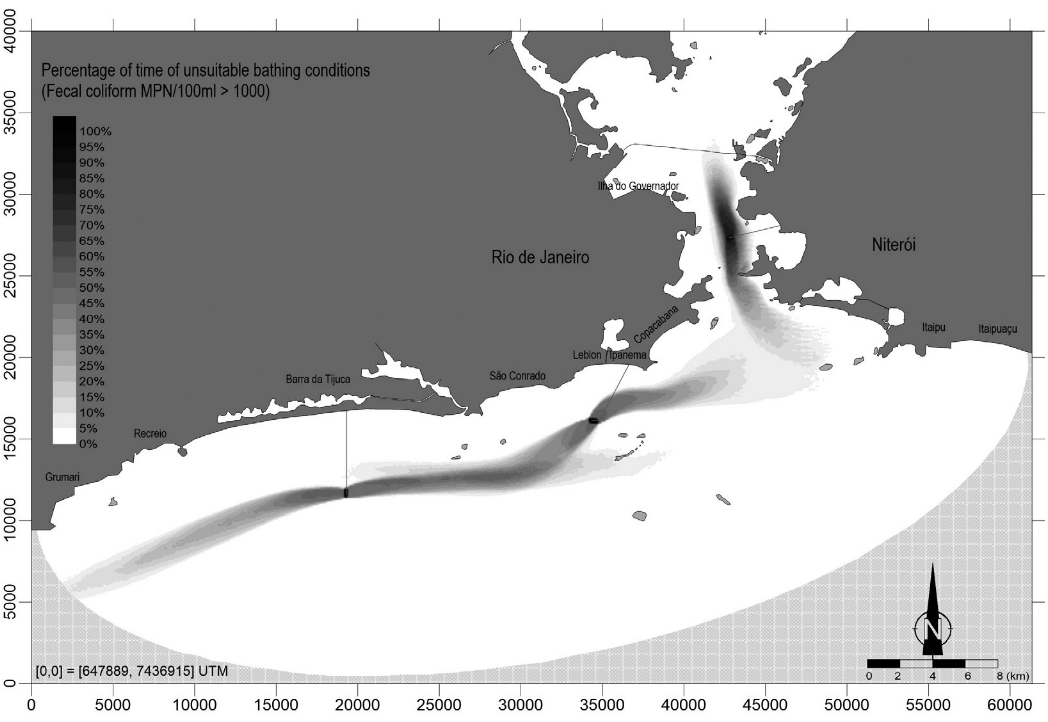

Figure 2. Scenario 1 – Summer and clear sky conditions. Percentage of time under unsuitable bathing conditions.

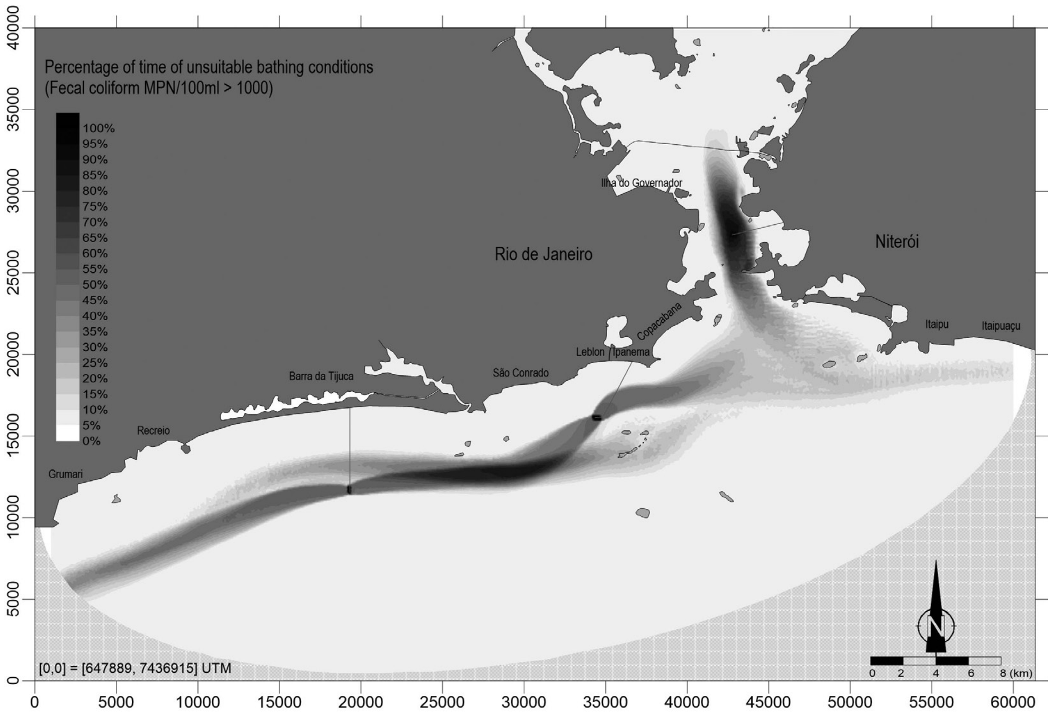

Figure 3. Scenario 2 – Summer and overcast sky conditions. Percentage of time under unsuitable bathing conditions.

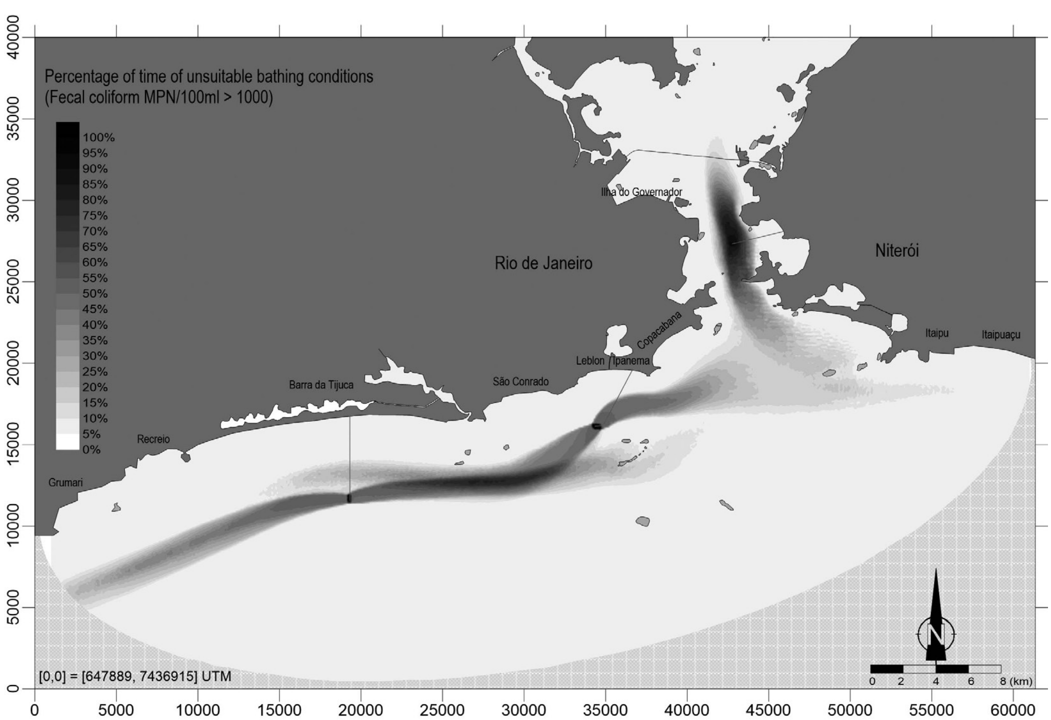

Figure 4. Scenario 3 – Winter and clear sky conditions. Percentage of time under unsuitable bathing conditions.

Schaffel et al.[30] that evaluates the fecal contamination of Ipanema beach by the sewage effluent discharge from the Ipanema outfall. In both cases it was observed that the water contamination occurs only in the vicinities of Barra da Tijuca and Ipanema outfalls, and the unsuitable bathing conditions in the coastline must be due to the contamination by polluted canals that flow to the coast and urban drainage systems.

The results observed for Icaraí submarine outfall showed a good agreement with studies presented by Coelho[31] where it was noted that there was a worsening in water quality between 2000 a 2005 in the monitoring station located in the central canal of Guanabara Bay. This fact seems to be related to the start of operation of Icaraí outfall in 2001 as a part of Guanabara Bay Clean-up Program, which started to discharge the effluent in the entrance of the bay. However, it is important to highlight that it was observed an improvement in the water quality of Icaraí Beach[31].

Conclusion and recommendations

In the present work the water quality assessment is based on coliform bacteria concentration in coastal waters. Solar radiation has shown to be the most relevant factor on bacterial decay in the marine environment. Temperature and salinity behave as secondary factors and are relevant only in the absence of solar radiation.

The coliform concentration levels in water have shown high dependence on solar radiation levels in the sewage plume. That is, all meteorological and oceanographic parameters that affect directly or indirectly the solar radiation are extremely relevant in determining the fecal coliform concentration in seawater.

The modelling of sewage plumes discharged by submarine outfalls, has a major relevance not only in impact assessment of sewage discharges from marine outfalls, but also in making decisions regarding the best position for effluent discharge, in order to avoid the contamination of bathing zones. The present study aimed to evaluate the contamination of bathing zones by the effluent discharge from the outfalls of Barra da Tijuca, Ipanema and Icaraí. The results have shown that the outfalls do not contaminate the coastal zone, and indicated that this contamination occurs by polluted rivers and sewers outflows

In order to corroborate this statement, a study performed by Vieira et al.[32] attested that the bathing conditions of Leblon beach have shown to be dependent on the water quality observed in the adjacent canals of Jardim de Alah and Visconde de Albuquerque. As for the Barra da Tijuca, the beach contamination occurs mainly due to its connection to the lacunar system of Jacarepaguá. According to the State Environmental Institute (INEA)[33] report of April 2016 this lacunar system presented high levels of microbiological contamination, showing an advanced stage of water degradation. In addition to the above, Coelho[31] also cites rainwater drainage galleries as additional coastal pollution agents.

Currently actions have been adopted in order to mitigate the pollution. As an example, a pollution control is performed at Visconde de Albuquerque Canal beach by means of dam. Under dry weather conditions it remains closed and the water that would flow to the Leblon beach is pumped to the Ipanema submarine outfall.

An example of improving previous polluted conditions was reported in Sydney (Australia). After the opening of three major sewage outfalls there was an observation of a significant improvement in the water quality of coastal waters (Sydney Water)[34].

No matter how comprehensive the sewage collection networks are, the high pollutant loads resulting from increasing population is capable of impacting coastal ecosystems, increasing the health risks through eventual contact with contaminated waters. The World Health Organization (WHO) co-sponsored by USEPA (United States – Environment Protection Agency) published in 1999 Health-Based Monitoring of Recreational Waters: The Feasibility of a New Approach (The Annapolis Protocol). According to this document submarine outfalls are assumed to be properly designed to ensure a low probability of the sewage plume reaching the designated bathing zones. As such, submarine outfall is an alternative of very low human health risk in that the bather is unlikely to come into physical contact with the sewage, whether treated or untreated. However there is an impact in the point of the effluent discharge, the use of submarine sewage outfalls has been an efficient alternative in the preservation of coastal environments.

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