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EDIÇÃO ESPECIAL

Seminário Internacional Qualidade das Águas Costeiras

(International Workshop Coastal Water Quality)

November 3th-4th, 2016

São Paulo, Brasil

ARTIGOS TÉCNICOS

- Economic, Regulatory and Social Aspects Related to Wastewater Ocean Disposal through Submarine Outfalls
- Treatment Options for Marine Wastewater Discharges
- Wastewater Marine Disposal through Outfalls on the coast of São Paulo State – Brazil: An overview
- Seawater Monitoring under the Influence of SABESP Sea Outfalls in Baixada Santista (South Coast) and North Coast - São Paulo State- Brazil
- Submarine Outfalls are an Effective Solution for the Disposal of Properly Treated Sewage of Coastal Cities
- Sanitation and microbiological water quality in the watershed of Santos - São Vicente Estuary
- Modeling Extreme Conditions of Sewage Plumes in Central – South Coastal Region of São Paulo State – Brazil
- Combining measurements, models and decision support systems to optimize outfall sitting
- Prior environmental characterization strategies for outfall systems

editorial

A Secretaria de Saneamento e Recursos Hídricos do Estado de São Paulo, em parceria com a Escola Politécnica da Universidade de São Paulo, Prefeitura Municipal de Santos e Agência Metropolitana da Baixada Santista – AGEM, promoverá no Município de Santos –SP, nos dias 03 e 04 de novembro de 2016, o Seminário Internacional Qualidade das Águas Costeiras.

O principal objetivo do evento é promover uma ampla discussão dos principais aspectos relacionados ao assunto em questão, permitindo a formulação de programas e políticas públicas, em nível municipal estadual e federal, que respondam às necessidades de desenvolvimento econômico, social e ambiental da região costeira do Estado de São Paulo.

A revista DAE, ciente da relevância do tema, decidiu apoiar essa iniciativa através da edição de um número especial com os principais artigos técnicos que serão apresentados no evento.

A análise e seleção dos artigos, apresentados a seguir, foram realizadas por um Conselho Científico especialmente constituído para esse fim e presidido pelo professor doutor Jayme Pinto Ortiz, da Escola Politécnica da Universidade de São Paulo. São eles:

- **Economic, Regulatory and Social Aspects Related to Wastewater Ocean Disposal through Submarine Outfalls**
  Menahem Libhaber
- **Treatment Options for Marine Wastewater Discharges**
  Philip J. W. Roberts
- **Wastewater Marine Disposal through Outfalls on the coast of São Paulo State – Brazil: An overview**
  Jayme Pinto Ortiz, Antonio Braulio Neto, Jacqueline Pedrera Yanes
- **Seawater Monitoring under the Influence of SABESP Sea Outfalls in Baixada Santista (South Coast) and North Coast - São Paulo State- Brazil**
  Silene Cristina Baptistelli, Edward Brambilla Marcellino
- **Submarine Outfalls are an Effective Solution for the Disposal of Properly Treated Sewage of Coastal Cities**
  Eduardo Pacheco Jordão, Paulo Cesar Colonna Rosman

  Sanitation and microbiological water quality in the watershed of Santos - São Vicente Estuary

  Alexandra Franciscatto Penteado Sampaio, Eloísa Helena Cherbakian, Fabio Giordano, Francisco Correa Ramos Júnior, Renan Braga Ribeiro
- **Modeling Extreme Conditions of Sewage Plumes in Central – South Coastal Region of São Paulo State – Brazil**
  Samuel Hora Yang, Joseph Harari
- **Combining measurements, models and decision support systems to optimize outfall sitting**
  Tobias Bleninger, Alex Falkenberg, Alexandre Trevisan, Maria Olívia Maranhão, Mayra Ishikawa, Pedro Ribeiro, Rodrigo Barletta
- **Prior environmental characterization strategies for outfall systems**
  Alexandre Bach Trevisan, Ricardo Kazuo Furuya, Vanessa dos Santos

Americo de Oliveira Sampaio

EDITOR-CHEFE

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Missão

A Revista DAE tem por objetivo a publicação de artigos técnicos e científicos originais nas áreas de saneamento e meio ambiente.

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Economic, Regulatory and Social Aspects Related to Wastewater Ocean Disposal through Submarine Outfalls

Dr. Menahem Libhaber

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Abstract

The receiving body of wastewater and effluents of coastal cities is, in most cases, the ocean or the sea. For the most part, two wastewater management strategies are applied in coastal cities: (i) provision of secondary level wastewater treatment followed by effluent discharge to the sea via a short submarine outfall; and (ii) provision of preliminary level wastewater treatment followed by effluent discharge to the sea via an effective submarine outfall. A comparison between the two strategies is presented in the article, leading to a conclusion that Strategy (ii) of preliminary treatment followed by an effective outfall is economically, environmentally and socially superior. A preliminary treatment plant followed by an effective outfall is simple to operate and presents a low public health risk and a low level of negative environmental impacts. Many outfalls systems of this type are successfully functioning and have a proven track record in many coastal cities all over the world. For developing countries it is the essential solution since such countries cannot afford executing high investments in complex and unnecessary wastewater treatment plants. This strategy should be coupled with a sea water quality monitoring program beginning prior to and continuing after the construction of the outfall system, to verify the performance of the system and to determine if a higher than preliminary treatment level is necessary. This is a logical approach which prevents costly investments in unnecessary treatment installations.

***Keywords**: Submarine Outfalls, Marine Wastewater Outfalls, Wastewater Treatment*

Sumário

Na maioria dos casos, o corpo receptor de esgotos e efluentes de cidades costeiras é o oceano ou o mar. Duas estratégias para a gestão dos esgotos em cidades costeiras são geralmente aplicadas: (i) tratamento secundário do esgoto seguido por descarga do efluente ao mar através de um emissário curto; ou (ii) tratamento preliminar do esgoto seguido por descarga do efluente ao mar através de um emissário eficaz. Neste artículo é apresentada uma comparação entre as duas estratégias, concluindo-se que a segunda Estratégia (ii) é superior em termos econômicos, ambientais e sociais. Uma Estação de Tratamento de Esgotos (ETE) de nível preliminar seguido por um emissário eficaz é simples de operar e apresenta um baixo risco para a saúde pública, bem como um baixo nível de impactos ambientais negativos. Muitos sistemas deste tipo estão em operação em cidades costeiras no mundo, com um histórico comprovado. Para países em desenvolvimento é uma solução essencial posto que este tipo de países não podem se permitir executar altos investimentos exigidos por complexas e desnecessárias ETEs. Esta estratégia deve ser executada em paralelo com um programa de monitoramento da qualidade da água do mar, iniciando antes e continuando depois da construção do sistema do emissário, para verificar o desempenho do sistema e para determinar se um nível maior que tratamento preliminar é necessário. Este e um enfoque lógico que previne a realização de altos investimentos em instalações de tratamento desnecessárias.

Palavras-chave: Emissários Submarinos, Tratamento de Esgoto.

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THE DILEMMA OF SELECTING THE STRATEGY FOR WASTEWATER MANAGEMENT IN COASTAL CITIES

South and Central America are bordered by two oceans, the Pacific in the east and the Atlantic in the west, with very long shorelines and coastal zones. The Caribbean Islands are surrounded by seawater. The American continent is also crossed by some very large rivers with a high autopurification capacity. Many cities in Central and South America are coastal cities, as are most of the cities in the Caribbean Islands. About 30% of the urban population of cities with more than 100,000 inhabitants in Latin America resides near the coast or near estuaries (UN 2003). The receiving bodies of wastewater and effluents of coastal cities are the ocean or the sea, except in cases where effluents are needed for reuse purposes (and those are few in Latin America).

In broad terms, two wastewater management strategies are applied in coastal cities:

i. Provision of secondary level wastewater treatment or superior followed by effluent discharge on the beach or to the sea via a short submarine outfall

ii. Provision of preliminary level wastewater treatment followed by effluent discharge to the sea via an effective submarine outfall (an effective outfall being defined as an outfall which provides a near field dilution of at least 1:100)

Preliminary treatment preceding a submarine outfall consists of coarse screening, grit removal and fine screening. Such treatment is sometimes referred to as advanced preliminary treatment because it contains the fine screening unit, which is not included in preliminary treatment that forms part of a secondary treatment plant (and is not necessary in such case).

In most countries in Latin America and the Caribbean (LAC), environmental legislation enforces application of Strategy (i). In spite of such legislation, in several cases coastal cities have applied Strategy (ii). Ways for achieving legal authorization for such an approach are discussed below.

In most LAC countries, legislation referring to effluent quality is defined by two independent norms: (i) effluent quality defined by the maximum permissible limits of certain contaminants in the effluent; and (ii) receiving bodies' water quality, which defines the quality of various types of surface water which cannot be surpassed when effluents are discharged into these receiving bodies. There is no direct relation between the two norms. Norm (i) can be complied without complying with norm (ii) and vice versa. The requirement is to comply with both simultaneously. Norm (i) is a message that wastewater must be treated before it is discharged to the environment. Norm (ii) is the important norm which ensures the protection of surface waters and indirectly defines the level of wastewater treatment required in each case for protecting the quality of those waters.

In most cases, the seawater quality defined by norm (ii) can be achieved by applying management strategy (ii): preliminary level treatment followed by effluent discharge to the sea via an effective submarine outfall. Complying with norm (i) which requires a higher than preliminary level of treatment is not necessary for achieving the seawater quality accepted by norm (ii), but the requirement to comply with both norms simultaneously renders the application of the management strategy of providing only preliminary treatment as being unacceptable (or illegal).

A comparison between the two strategies (preliminary treatment followed by an effective outfall versus secondary treatment) is presented below; leading to a conclusion that Strategy (ii) of preliminary treatment followed by an effective outfall is economically, environmentally and socially superior. The economic superiority is of special importance for developing countries because developed countries have the economic capacity to finance higher than preliminary treatment plants even if it is unnecessary, while developing countries cannot afford such a behavior.

WASTEWATER CONTAMINATES AND THEIR FATE IN THE SEA AFTER BEING DISCHARGED THROUGH A SUBMARINE OUTFALL

Municipal wastewater contains 99.9% water and 0.1% other materials, part of them contaminants. Effluents of wastewater treatment plants (WTP) contain less than 0.1% of other than water materials. The principle contaminants in municipal wastewater and effluents are: floating matter, suspended solids, organic matter represented by Biochemical Oxygen Demand (BOD), pathogenic organisms represented by the indicator organism fecal coliform, nutrients (nitrogen and phosphorous) and a variety of persistent toxic contaminants (toxics organics and traces of metals).

The importance of each contaminant in terms of its environmental impact depends on the type of the wastewater or effluent receiving body. If the receiving body is a river, the critical contaminants are BOD (which can deplete the oxygen from the river water) and pathogens. If the receiving body is a lake, the critical contaminants are nutrients, which may cause eutrophication. In the case of the sea as a receiving body, the critical contaminants are pathogens, floating material and large diameter suspended solids. This conclusion results from the fate of the contaminants in the seawater.

What is the fate of the mentioned contaminants in seawater? Non-degradable floating matter continues to float. BOD is diluted and decomposes in the oxygen saturated marine environment, mainly through biological decomposition. Suspended solids of small diameter are diluted and their organic fraction, which is BOD, undergoes biological decomposition. Bacteria are dilutes, float and are destroyed by the ultraviolet radiation of the sun. Nutrients are diluted but do not decompose, and the persistent micro-contaminants are diluted and do not decompose.

Considering the above, it becomes clear that the critical contaminates related to wastewater discharge to the sea are: (i) bacteria, which in spite of the dilution remain in high concentration due to their very high concentration in the raw wastewater (of about 10^6-10^7 MPN/100ml); (ii) non-degradable floating matter which continues to float and does not decompose; and (iii) large diameter suspended solids which continue to float for a long time. Other contaminants such as BOD are diluted to very low levels and decompose with time. Nutrients and micro-contaminants do not decompose but are diluted to very low concentrations.

Since BOD is not a critical contaminant, it is not necessary to remove BOD prior to discharge of effluent to the sea. Given that the main function of secondary or higher level of treatment is removal of BOD, it is doubtful that secondary or higher level of treatment is necessary prior to effluent discharge to the sea.

Based on the considerations presented above, the strategy for the management of wastewater when the effluent receiving body is the sea is surging to be the following:

- Removal of the following contaminants from the wastewater is required prior to the discharge of the effluent to the sea: (i) floating matter; (ii) coarse suspended solids; and (iii) toxic micro contaminants.
- The discharge of effluent into the sea needs to be done in such a manner that ensures a high level of dilution of the effluent in the seawater.

With the application of this strategy floating matter, coarse suspended solids and toxic micro contaminants do not reach the sea, the BOD is diluted and decomposed in natural process at sea, pathogens are reduced to acceptable levels by dilution and solar radiation, and nutrients are diluted to levels that do not present risks to the marine environment.

The main source of toxic micro contaminants in municipal wastewater is industrial wastes. These toxics are not removed even by secondary treatment. and must be treated in the source by the industries that generate them.

The level of treatment which is compatible with the management strategy presented above is the advanced preliminary treatment. A higher level of treatment such as secondary or higher is not required and would not have any positive effect if the effluent is discharge through an effective outfall, because the main achievement of secondary treatment is BOD removal, and in this case, BOD removal is unnecessary.

THE SUBMARINE OUTFALL AS A WASTEWATER TREATMENT UNIT

The density of municipal wastewaters and effluents is close to that of water and is lower than that of the saline seawater. Due to this density difference, wastewater or effluent which is discharged at the bottom of the sea floats up to the surface (like oil in water) creating an up-cone which causes entrainment of seawater into it and results in a high dilution of the effluent. The dilution of the up flowing effluent is termed the near field dilution or initial dilution. Once the effluent reaches the sea surface, the action of the waves and sea currents causes a second type of dilution, the far field dilution. The resulting total physical dilution of the effluent is the multiplication of the near and far field dilution values. It is not possible in this article to get into the details of the hydrodynamic models of the near and far fields but ample information on this subject can be found in the book by Roberts, Libhaber et al (2010). The near field dilution depends on the depth of the effluent discharge point (i.e. on the slope of the bottom of the sea in front of the wastewater generating city) and on the sea current field characteristics (velocity and direction) in the effluent discharge zone. Most of the submarine outfalls discharge the effluent at a depth of at least 20 meters. A near field dilution of 1:100 is usually achieved at such a depth, and frequently a much higher dilution. The length of most of the existing outfalls in the world is usually in the range of 0.5-4 Km. The far field dilution is usually in the range of 3-10. The resulting overall physical dilution caused by discharge of an effluent from a well-designed outfall is between one to several hundreds and one to several thousand. In the case of bacteria contained in the effluent, in addition to the physical dilution, they undergo biological decay due to their extinction in the seawater, mainly as a result of the UV radiation of the sun. The decay of the bacteria is very fast. In most cases ninety percent die out in less than an hour. So the total dilution of bacteria is much higher than the dilution of other constituents in the effluent. This is very important because the concentration of bacteria in the effluent (if disinfection is not applied before the discharge to the sea) is much higher than that of the other constituents. The near field dilution of an effective outfall is equivalent to at least 99% removal of all contaminants, and with far field dilution it can reach 99.9% removal of all contaminants.

Secondary treatment (activated sludge or equivalent) usually provides for BOD and Total Suspended Solids (TSS) a dilution of 1:5 to 1:10 (usually the inflow BOD and TSS concentrations are around 200 mg/l each and effluent BOD and TSS concentrations are 2030 mg/l each). For other constituents of non-organic nature secondary treatment provides a lower level of dilution because they are not removed by the activated sludge process. As to bacteria, the activated sludge process itself practically does not remove bacteria. It removes about half an order of magnitude, which in terms of dilution translates to a dilution of 1:2 for bacteria. Considering the high concentration of bacteria in wastewater, such a level of removal is meaningless. Usually an activated sludge effluent undergoes disinfection, and with that, a high level of bacteria dilution is achieved. However, in emergency cases (which may occur quite frequently) disinfection installation go out of operation due to lack of chlorine or malfunctioning of UV lamps, and in such cases, the bacteria dilution of activated sludge plants is practically nonexistent. In terms of design safety, secondary treatment needs to be considered as a process which does not remove bacteria. In fact, the effluent of a secondary treatment plant needs necessarily to be discharged to the sea through an effective outfall (and not through a short outfall) as a protective measure against bacteria contamination during disinfection failure periods.

Comparing the performance of an activated sludge treatment plant to that of an effective submarine outfall system (which includes the preliminary treatment unit, the outfall and the dilution in the nearfield zone surrounding the outfall discharge area) it becomes clear that an outfall system is not just a pipe which transports liquid **but rather a very effective treatment unit**. The mechanisms of performance of the outfall system as a treatment unit are: (i) the preliminary treatment installations eliminate the contaminants which the sea cannot process: floating matter, gross solids and toxic micro-contaminants (which are in fact eliminated in the source); (ii) the effective outfall causes a high physical dilution of all contaminants, most of them to level acceptable by seawater quality standards; (iii) the marine environment causes further decay of bacteria and decomposition of organic matter (BOD). Consequently, removal on shore of BOD, fine suspended solids and pathogenic bacteria by a treatment plant more advanced than preliminary is unnecessary.

Unfortunately, the outfall system is considered by laymen to be just a pipe, and usually the decision makers in charge of selecting the wastewater management strategy are laymen.

BENEFITS OF THE STRATEGY OF PRELIMINARY TREATMENT FOLLOWED BY AN EFFECTIVE SUBMARINE OUTFALL

Strategy (ii) based on preliminary level treatment followed by an effective submarine outfall has several advantages in relation to Strategy (i) which is based on secondary level treatment. These advantages include economic, environmental, sustainability and social aspects.

In terms of investment cost Strategy (i) is usually much more expensive than Strategy (ii), in a ratio ranging from 6 to 15, depending on the marine characteristics. The specific ratio in each case depends to a large extend on the bathymetry of the sea at the vicinity of the coastal city. As the slope of the sea bottom is steeper, an effective outfall can be shorter and the economic benefit of strategy (ii) becomes higher.

But the economic benefit of Strategy (ii) is not manifested only by the investment cost benefit. Perhaps more important is its O&M (Operation and Maintenance) benefit. The O&M annual cost of Strategy (i) is 10 to 20 times more expensive than that of Strategy (ii). Usually the O&M cost of an activated sludge plant is about 10 US$/Year/Capita while data from several Strategy (ii) schemes (Cartagena in Colombia and Taboada in Lima, Peru) indicate that the O&M costs of an effective outfall system is in the range of 0.5-1.0 US$/Year/Capita. A water and sanitation utility can, in many cases, mobilize investment costs for wastewater treatment installations through government investment subsidies and soft loans. But O&M costs are usually not subsidized, so the adoption of Strategy (i) imposes a continuous heavy financial burden on a utility, while Strategy (ii) is much more convenient from the financial standpoint.

Strange as it may sound, Strategy (i) is also advantageous from the environmental standpoint. As explained, Strategy (ii) is equivalent, in terms of its impact on the seawater quality, to strategy (i) if both include an effective outfall, and is superior to strategy (i) if strategy (i) includes only a short outfall or no outfall at all. But in terms of on-land environmental impact Strategy (ii) is advantageous. First, the preliminary treatment plant of Strategy (ii) has a foot print of about 2-5% of that of a secondary treatment plant of Strategy (i). That in itself represents a significant environmental benefit. A secondary treatment plant also generates large quantities of excess biological sludge, which presents a serious environmental problem, while the preliminary treatment plant of Strategy (ii) generates a small quantity of mostly inert solids that are easy to handle. Secondary treatment plants also generate unpleasant odors in their vicinity; while preliminary treatment installations can be (and usually are) located within closed structures with odor control, so that they do not impose any problem to the environment. As an example, Figure 1 shows the preliminary treatment plant of the city of Cartagena, Colombia, with a capacity of serving a population of about 1.3 million, located inside a modern-style building, posing no nuisance to the environment.

The adoption of strategy (ii), which means operation of an on-land preliminary treatment plant contributes significantly to improving the sustainability of the utility in charge of wastewater management, in several forms: (a) by improving the financial sustainability of the utility due to reduced investment and reduced O&M costs of the wastewater management installations; (b) by improving the technical and operational sustainability of wastewater treatment installations through the use of a process simple to operate and maintain, based on simple equipment, mostly locally manufactured; and (c) by improving the institutional sustainability of the utility, since as a result of the limited economic demand and technical efforts required for operating the installations, which do not require significant managerial attention, wastewater management does not impose additional administrative efforts in the utility and therefore reduces the burden on the utility's management, thus improving its sustainability.

Figure 1: Photo of the Preliminary Treatment Plant of Cartagena, Colombia, Located Inside a Modern-Style Building, Posing no Nuisance to the Environment

The use of preliminary treatment helps, in fact, in alleviating the principal problems of the water and sanitation sector in developing countries, which are: financial weakness, low technical capacity and institutional weakness, thus contributing to improving sector sustainability.

Wastewater management Strategy (ii) also provides social benefits. It enables reaching a solution to the wastewater problem of a city in an expedited form (sine a requirement of a much larger investment might delay the provision of a solution) and it saves a lot of investment funds, enabling directing the saved funds to solve other social problems, such as providing to the poor improved housing, education etc.

For coastal cities, wastewater disposal by preliminary treatment followed by an effective submarine outfall is an affordable, effective, and reliable solution. It is simple to operate and presents a low public health risk and a low level of negative environmental impacts. Many outfalls systems of this type are successfully functioning and have a proven track record in many coastal cities all over the world. For developing countries it is the essential solution since such countries cannot afford executing high investments in complex and unnecessary wastewater treatment plants. Coastal communities and authorities in developing countries need to accept that the concept of wastewater disposal by preliminary treatment followed by an effective submarine outfall is an excellent start which is superior to doing nothing.

This strategy should be coupled with a sea water quality monitoring program beginning prior to and continuing after the construction of the outfall system, to verify the performance of the outfall system and to determine if a higher than preliminary treatment level is necessary. This is a logical approach which prevents costly investments in unnecessary treatment installations.

THE POSITION OF THE WORLD HEALTH ORGANIZATION

The issue of human health risk caused by discharge of wastewater to the sea depends on how the wastewater is discharged. This issue was addressed by the World Health Organization (WHO, 2003) in its guidelines for recreational water quality. The WHO findings are summarized in Table 1 for the major types of treatment and disposal practiced by coastal communities around the world. The table clearly shows that secondary treatment without an outfall or with a short outfall poses a high risk to human health. Secondary treatment followed by an effective outfall poses a low risk, the same as preliminary treatment followed by an effective outfall.

Table 1: Risk to human health from exposure to sewage (Including storm water runoff and combined sewer overflows) (WHO, 2003)

Treatment Process	Human health risk		
	Discharge directly on beach	Discharge from short outfall[a]	Discharge from effective outfall[b]
None[c]	Very high	High	NA[d]
Preliminary	Very high	High	Low
Primary (including septic tanks)	Very high	High	Low
Secondary	High	High	Low
Secondary plus disinfection[e]	-	-	-
Tertiary	Moderate	Moderate	Very low
Tertiary plus disinfection[e]	-	-	-
Lagoons	High	High	Low

[a]The relative risk is modified by population size. Relative risk is increased for discharges from large populations and decreased for discharges from small populations.

[b]Assumes the design capacity has not been exceeded and that climatic and oceanic extreme conditions are considered in the design objective (i.e., no sewage on the beach zone).

[c]Includes combined sewer overflows if active during the bathing season (a positive history of total non-discharge during the bathing season can be treated as "Low")

[d]NA = not applicable

[e]Additional investigations recommended to account for the likely lack of prediction with faecal index organisms.

This clearly demonstrates that: (i) an effective outfall is a prerequisit for obtaining a low level of risk to public health; and (ii) from the public health risk standpoint, more advanced treatment than preliminary does not significantly lower the risk. The WHO does not present an opinion regarding secondary treatment followed by disinfection. But as mentioned, the risk of secondary treatment with disinfection is similar to the risk of secondary treatment without disinfection due to the exposure during instances of failures of the disinfection systems (which in developing countries are quite frequent). That means that even if secondary treatment is provided, it should be followed by an effective outfall, however, if an effective outfall is installed, secondary treatmet is not required.

The above referres to public health risks, but it applies also to risks to the marine environment imposed by effluent discharge to the sea, since when taking into consideration the high dilution achieved outside the mixing zone, the discharged contaminants concentrations comply with most of the existing seawater quality standards.

EXAMPLES OF WASTEWATER OCEAN DISCHARGE IN LATIN AMERICA

Some examples of projects of wastewater discharge to the sea and to large rivers in Latin America are presented in this section, for the purpose of providing information on: (a) the impact of Strategy (ii) on the seawater quality; and (b) economic comparison of Strategy (i) and Strategy (ii).

In Chile, legislation allows discharge to marine waters of an effluent of a quality compatible with that of a preliminary treatment effluent, if the discharge site is located outside the coastal protection zone. As a result, the wastewater management strategy of all the Chilean coastal cities is based on preliminary treatment followed by an effective outfall. About 40 systems of this type are spread along the Chilean coast, the largest being the system which serves jointly the cities Valparaiso and Viña del Mar. A five years comprehensive monitoring program of the seawater quality around the discharge point of two outfalls, Penco (serving a population of 40,000 0) and Tome (serving a population of 50,000), in the Concepcion Bay in Chile was carried out by the local water utility. The Tome outfall has an internal diameter of 450 mm and is 1,200 m long, equipped with a 25 meter long diffuser zone discharging the effluent at a depth of 25 m. The Penco outfall has an internal diameter of 580 mm and is 1,300 m long, equipped with a 25 m long diffuser zone discharging the effluent at a depth of 22 m. The location of the penco outfall and the sampling points around this outfall are shown in Figure 2. The results of the monitoring program of the Penco outfall based on information provided by Leppe and Padilla (1999) are presented in Table 2. The marine water quality composition at 100 meters from the discharge points refers to averages of six measuring points around the outfalls. The results are averages of five years of measurements.

For all quality parameters measured around the Penco outfall, except fecal and total coliforms, concentrations at a distance of 100 meters from the discharge point are the same as background levels. This demonstrates the high treatment capacity of the outfall systems.

Figure 2: Sampling Points around the Penco Outfall

The concentrations of coliforms in the raw sewage and preliminary treated effluents are extremely high. Even so, their concentrations are markedly reduced at a distance of 100 meters from the discharge point, to levels that meet the most stringent bathing water standards, although they are still a little higher than the background. With decay, the concentrations reduced to background levels within a short additional distance. The monitoring results of the Tome outfall are similar.

The uniqueness of the Penco and Tome outfalls is that: (i) a comprehensive monitoring program of their performance has been in effect for a long period of 10 years (of which only the resultsof 5 years are reported here); and (ii) water quality was measured not only near the shore, which is the common practice, but also near the discharges at several points located on circles with a radius of 100 meters difference centered at the discharge point. A summary and conclusions of the study of the Penco and Tome outfall is presented in Roberts, Libhaber et al, (2010) PP 428-434, and it includes important material on the prformance of an effective submarine outfall system.

The wastewater management system of the city of Cartagena, Colombian, a city with a population of over one million located on the coast of the Caribbean Sea, consists of an advanced preliminary treatment plant (located inside a closed building as shown in Figure 1) followed by a submarine outfall of 1,800 mm diameter discharging the effluent at a distance of 2.8 Km from the shoreline, at a depth of about 20 meters. The Colombian legislation requires secondary treatment for wastewater discharged to the sea, but in the case of Cartagena, a license for discharging preliminary effluent was approved for a fixed period of several years, after which the treatment level will have to be upgraded (see below). Detailed information on the Cartagena project is presented in Roberts, Libhaber et al, (2010) PP 414-428, and in Browder and Duvi (2014). A scheme of the Cartagena wastewater management system is presented on the right hand side of Figure 3. The Cartagena wastewater management system went into operation in 2013. Performance results of the system based on water quality monitoring undertaken in 2014 are presented in the left hand side of Figure 3 (source: Browder and Duvi, 2014).

The results show the marked improvement in the quality of the water bodies surrounding Cartagena, including the beaches, the Cienaga de la Virgen coastal lagoon and the Cartagena Bay. Monitoring carried since 2014 show similar results and confirms the positive impact of the system of preliminary treatment followed by the effective outfall on the quality of all the water bodies surrounding Cartagena.

The construction cost of the Cartagena preliminary treatment plant was 15 Million US$ (MUS$) and the construction cost of the submarine outfall was 22 MUS$, resulting in a total investment cost of 37 MUS$ for the wastewater management system. The O&M cost of the system amounts to 0.7 MUS$/year. The investment per capita is about 28.5 US$/Capita, which is a low investment for a wastewater management scheme of a large city. If upgrading the preliminary treatment plant to secondary treatment is imposed, an additional large investment will be required, which according to our estimates, would amount to about 260 MUS$ for an upgrade to activated sludge. The operation and maintenance cost of the upgraded system would initially be about 10 MUS$/Year and would increase to about 13 MUS$/Year after 20 years.

Table 2: Marine water quality near the Penco outfall, Concepción, Chile (Average of 5 Years Monitoring)

Parameter	Effluent discharged into outfall	Maximum according to local standards	At the discharge point	At 100 m from the discharge point	Typical back-ground values
pH	7.4	5.5 - 9.0	7.6	7.6	8.0
Temperature °C	18.4	-	11.5	13.2	13.8
Oil and grease mg/l	48.8	150	4.0	5.6	3.2
TSS (Total suspended solids) mg/l	216	300	3.5	3.7	3.8
BOD5 (Biochemical oxygen demand) mg/l	236	-	2.5	2.8	2.5
TOC (Total organic carbon) mg/l	142	-	2.5	3.5	1.4
DO (Dissolved oxygen) mg/l	1.1	-	5.1	7.9	7.9
Detergents mg/l	15.4	15	0.05	0.07	0.06
Nitrogen Kjeldal mg/l	49.3	-	0.5	0.36	0.4
Nitrites mg/l	0.01	-	0.02	0.01	0.01
Nitrates mg/l	0.15	-	0.18	0.21	0.16
Total Phosphorus, mg/l	12.9	-	0.2	0.25	0.2
Phosphate, mg/l	39.6	-	1.0	1.0	1.0
Sulfur, mg/l	0.8	5	0.18	0.25	0.22
Phenol	<0.002	1	<0.002	<0.002	<0.002
Fecal Coliforms, MPN/100 ml	$1.1x10^8$	-	5420	172	3.0
Total Coliforms, MPN/100 ml	$1.4x10^8$	-	7317	223	5

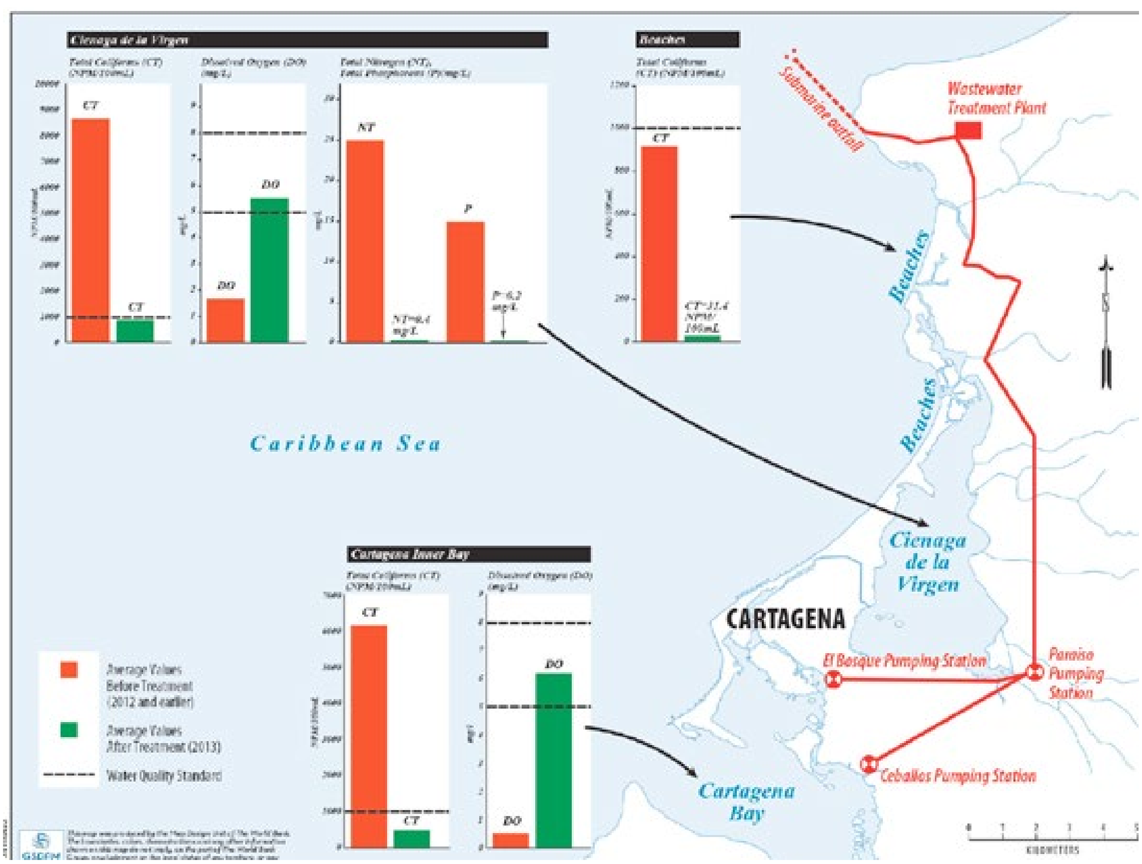

Figure 3: The Cartagena Wastewater Management Installations and Indicative Water Quality Data

An economic comparison between the two management strategies (the implemented strategy and the strategy of upgrading the existing treatment plant to an activated sludge plant while using the same already constructed outfall) is presented in Table 3.

The results show the meaningful economic benefit of the adopted strategy. In terms of investment cost, the secondary treatment alternative is 7.6 times more expensive than the adopted strategy of preliminary treatment. But the real economic comparison refers to comparison of the net present value (NPV) of the two alternatives, which is the comparison of the life cycle costs of both.

The NPV of the operation of the current Cartagena system is about 52 MUS$. The NPV of the secondary treatment alternative is about 540 MUS$, i.e., about 10.5 times higher than that of the current alternative.

Table 3: Economic Comparison of Two Wastewater Management Alternatives for Cartagena

Wastewater Management Strategy	Source Cost Data	Cost (Million US$)			
		Constrution		O&M (per year)	Net Present Value (NPV) (20 years, 6%)
		Outfal	Treatment Plant		
Applied Strategy of preliminary treatment followed by an Effective Outfall (Strategy ii)	Actual construction and OM cost	22	15	0.7	51.7
Potencial Upgrade Strategy of Activated Slugde Treatment followed by an Effective Outfall (Strategy i)	Author's estimate	22	260	10 during initial years 13 during final years	541.7

If forced to upgrade the treatment plant at an investment of 260 MUS$, Aguas de Cartagena, the water utility of Cartagena, would financially collapse. Even if the additional investment would be provided by the government as an investment subsidy (which is not likely to happen) the additional O&M cost of the activated sludge system would worsen the financial standing of the utility. But most importantly, the upgrade would not provide any public health and environmental benefits.

In Lima, the capital of Peru, a city with a population of over 8 million, two submarine outfall systems were recently constructed: (i) the Taboada system which entered into operation in 2013 and serves a population of about 5 million; and (ii) the La Chira system which is planned to initiate operating in 2016 and is designed to serve a population of about 2.7 million. Both systems are based on an advanced preliminary treatment plant followed by an effective outfall. The investment cost of the Taboada system was about 150 MUS$, of which 90 MUS$ refer to the outfall and 60 MUS$ to the preliminary treatment plant. The O&M cost of the Taboada system is about 4 MUS$/Year. The investment per capita is about 30 US$/Capita, which is similar to that of Cartagena and is also a low investment for a wastewater management scheme of such a large city.

Buenos Aires, the capital of Argentina, a city of about 12 million people located on the bank of the La Plata River, represents an interesting case. AYSA, the city's water and sanitation utility is implementing a wastewater management project consisting of constructing two preliminary treatment plants followed by two long subaquatic outfalls of about 10 km long each (at two different locations) for discharge of the effluents to the La Planta River. The same river is also the water supply source of the city. Using water quality modeling, the location and length of the outfalls was established in such a way that the discharged effluents will not affect the water quality at the withdrawing points for the water supply system. If this approach was adopted in the case of discharge of effluent into a water body which serves as the potable water source for such a large city, it can most probably be applied in cases where the waster body serves for bathing and recreation.

The city of Montevideo, the capital of Uruguay, discharges its wastewater to the La Plata River through two systems, each consisting of a preliminary treatment plant followed by a subaquatic outfall. In Brazil, several systems of preliminary treatment plants followed by an outfall discharging the effluent to the ocean are in operation. Those include the Ipanema outfall system in Rio de Janeiro, The Santos, Guaruja and Praia Grande outfalls in the Baixada Santista, and a large outfall in the state of Bahia.

The outfall systems of Santa Marta in Colombia and of Sosua in the Dominican Republic represent special cases. The sea bottom slope in front of these cities is steep so at a short distance from the shoreline the water depth is over 50 meters and in such conditions an effective outfall can be short. The Santa Marta outfall is 500 meters long (see Roberts, Libhaber et al, 2010, PP 434-438) and the Sosua outfall is 780 meters long. The treatment level in both cases is preliminary and the investment in the wastewater management systems was small.

Recent examples of projects which are based on higher than preliminary level of treatment prior to discharge of the effluents to large receiving bodies are the following:

A large city in Latin America located on the bank of a large estuary is now implementing a wastewater management project for a population of about 1.1 million (about half of the city's population). The adopted strategy is construction of a chemically enhanced primary treatment (CEPT) plant on the bank of the estuary and discharge of the effluent to the estuary through a 650 meters long outfall made of a 2.4 meters diameter pipe trenched in the bottom of the river, with a diffuser section at the last 90 meters of the outfall.

An alternative strategy of using a preliminary treatment plant followed by the same outfall was also studied. Based on modeling of the estuary water quality it was found that the impact of the two alternatives on the estuary water quality was identical and both complied with the country's estuaries and marine waters quality standard. However, the preliminary treated effluent does not comply with the country's effluent quality standard, which requires that all treatment plants produce an effluent containing no more than 100 mg/l of BOD and TSS and no more than 1,000 MPN/100 ml total coliforms. Coincidently, the raw water is quite diluted, containing about 125 mg/l BOD and about the same concentration of TSS.

The estimated cost of the adopted CEPT treatment plant is about 90 MUS$ and the estimated O&M cost of the plant is about 7 MUS$/Year, while the estimated cost of an advanced preliminary treatment plant is about 30 MUS$ and its O&M cost is about 0.6 MUS$/Year. The economic advantage of the preliminary treatment alternative is significant, but it was rejected for the purpose of obtaining an effluent quality which conforms to the effluent quality standard. What is the environmental benefit induced by the standard in this case? The effluent will flow inside a section of a land pipe about 500 meters long before entering the outfall. The CEPT treatment will ensure that the effluent flowing in the pipe will not contain more than 100 mg/l BOD and TSS. But there will be no negative impact on the pipe or on the environment if the BOD and TSS concentrations inside the pipe were to be a little higher than 100 mg/l. However, to comply with the standard (an act which has no benefit in this case) an additional investment of about 60 MUS$ and an additional annual cost of about 6.4 MUS$/Year will be spent. On top of its economic disadvantage, the selected alternative will also generate a severe environmental problem by producing 94 ton/day of raw CEPT primary sludge, which required a lot of efforts for adequate treatment and safe disposal.

In another city with a population of 500,000 located on the bank of the Amazon River (not in Brazil), the construction of the new wastewater management system was recently completed. The system consists of a complex secondary treatment plant whose effluent will be discharged to a large tributary of the Amazon through a subaquatic outfall, through a discharge point located at a distance of 3.3 Km from the confluence of this tributary with the Amazon. The cost of this system was about 110 MUS$, all of it provided as an investment subsidy from various government agencies. A preliminary treatment plant would have been sufficient in this case, saving about 80 to 90 MUS$, which could have been invested in urban upgrading in the large poor neighborhoods of this city. It is also doubtful that the local water and sanitation utility will be able to finance the O&M costs of the treatment plant. Unfortunately, there is no bypass from the preliminary treatment unit to the pumping station which conveys the effluent to the outfall. It might be a good idea to provide, for operational purposes, in each coastal treatment plants of higher than preliminary treatment level, a bypass connecting the preliminary treatment unit's effluent to the final effluent discharge point of the plant.

Roughly, it is estimated that the ratio of investment cost in the strategy of secondary treatment followed by an effective outfall to investment cost in the strategy of preliminary treatment followed by an effective outfall is in the range of 6 to 15. The low value refers to the condition of a mild bottom sea slope (which requires a long outfall) and the high value refers to the condition of a steep bottom sea slope (which requires a short outfall).

The ratio of investment cost in a strategy of less than secondary treatment (but higher than preliminary) followed by an effective outfall to investment cost in the strategy of preliminary treatment followed by an effective outfall is in the range of 3 to 7. The low value refers to the condition of a mild bottom sea slope (which requires a long outfall) and the high value refers to the condition of a steep bottom sea slope (which requires a short outfall).

OVERCOMING RESTRICTIONS OF NORMS AND REGULATIONS

The political economy favors imposing the application of a complex and expensive wastewater management strategy. Ministries of the environment, which formulate and enact the effluent quality standards, always prefer adopting the most stringent standards (considering it to be safer) and they do not take into account financial implications of overly stringent standards. Usually they copy the most stringent standards from developed countries. Universities teach students the cutting edge technologies of wastewater treatment, and the graduates' tendency is to prefer such technologies. Consulting firms prefer larger and more complex projects, and decision makers have sometimes their own reasons to prefer more expensive projects. In spite of all that, surprisingly, there are many cases in Latin America of implementation by coastal cities of the strategy of preliminary treatment followed by an effective submarine outfall.

A condition for succeeding to implement the strategy of preliminary treatment followed by an effective submarine outfall is the existence of a champion who favors this strategy. That can be the managing director or the chief engineer of the water and sanitation utility, or the politician in charge of making the decision, or the representative of the institution which provide financing for the project (in case this person has knowledge and understanding in the matter). A champion supporting the strategy of preliminary treatment followed by an effective outfall can try and convince the authorities to approve this strategy in one of the following ways:

(a) convince the authorities that complying with effluent quality standards should take into account the need for staged development of the treatment systems. Wastewater management must be developed in stages in accordance with the availability of financial resources and capacity, while taking into account in the first stage the assimilation capacity of the receiving bodies, so that the stringent effluent standard are achieved after time, at the ultimate project stage, while maintaining reasonable environmental standards at the first stages. Even developed countries went through such a staged process. It is better to start with a first stage that does not fully comply with the regulation than to delay, because of lack of sufficient funding, the initiation of works well into the future while subjecting the population (especially the poor) to many additional years of severe health risks, and the environment to high levels contamination. If the staged approach is accepted, then after operating the first stage it can be proved through environmental monitoring that upgrading the preliminary treatment to secondary treatment is unnecessary. This approach was taken in the projects of Cartagena, Colombia and Bella Vista, Asuncion, Paraguay. In Cartagena, the Colombian legislation required secondary treatment prior to discharge of effluent to any surface water receiving body. After a lot of efforts on part of the water and sanitation utility, the local environmental authority issued the environmental license for the wastewater management project permitting the construction of a first stage consisting of preliminary treatment followed by an effective outfall and operating it until 2015, a year in which the treatment level needs to be upgraded to higher than preliminary. As happens with most wastewater management projects of large cities, project construction took a long time because it included construction of the secondary sewage networks, some large pumping stations, the main wastewater collection and conveyance system and the treatment plant. Consequently, the construction of the treatment plant and of the outfall was completed in 2013, the year in which the system went into operation. Since then the environmental authority is monitoring all the water bodies surrounding Cartagena, and as shown above, the quality of all the water bodies, including the Caribbean Sea, significantly improved since the treatment plant went into operation. It became clear that upgrading the treatment plant to secondary treatment will not further improve the quality of the water bodies. The requirement for upgrade is currently on hold.

(b) convince the authorities to provide a waiver to a specific project without modifying the environmental legislation. Modifying legislation can be a difficult task but obtaining a waiver for a specific project can be easier. This was the case in the Taboada and La Chira large outfalls of Lima, Peru. The government decided to obtain financing for the Taboada project from the private sector through a BuildOperateTransfer (BOT) contract. The proposals received in response to the bidding process were all based on preliminary treatment followed by a long outfall, while only one was based on secondary treatment followed by a short outfall, and it was much more expensive than the others. The government had to confront the dilemma and consulted with several experts. Based on the advice received it decided to approve the lowest cost proposal which referred to preliminary treatment followed by a long outfall. In order to accept the lowest cost proposal, a waiver was given to outfall projects in Lima. Based on this waiver, the La Chira system was constructed under the same principle.

Arranging for authorities a demonstration tour to other countries in which projects of preliminary treatment followed by an effective outfall are in operation may also help in convincing that this strategy is viable. This was also part of the strategy in Cartagena.

MANAGING SOCIAL RISKS

As mentioned, Wastewater management Strategy (ii) also provides social benefits by enabling resolving wastewater problems expeditiously and with a lot of savings, thus liberating the saved funds to solve other social problems. However, as in any wastewater disposal project of a large city, an ocean disposal wastewater project may generate opposition from various interest groups. In this type of projects, opposition occurs during the preparation and construction stages, resulting from misunderstanding of the project, especially of the hydrodynamic concepts. At the operation stage opposition dissipates because no damages or damaging environmental effects occur.

Opposition in developing countries to wastewater disposal through a submarine outfall preceded by preliminary treatment will often prevent any progress at all towards improving wastewater management and disposal. This is because treatment above and beyond preliminary would render most projects financially non-viable. Avoidance of actions towards solving wastewater disposal problems is the worst option of all, and usually leaves the most vulnerable population (mostly the poor) under the worst conditions.

While considering the use of submarine outfalls for wastewater disposal, the possibility of opposition of the public and of other interest groups, as well as other social risks to the project, should not be ignored. Actions to control social risks need to be part of project planning and need to be implemented at the outset. A project component should be designed to address public opposition by providing and disseminating to the community and other stakeholders project information and project studies results, especially the environmental studies, to inform them about the project benefits and the absence of negative environmental impacts, and to gain public acceptance.

As an example, social activity actions undertaken in the Cartagena project were the following:

- Expansion of the participatory approach and working with the community to provide information regarding the impact of the outfall and its benefits (about 250 events were carried out);
- Execution of a publicity campaign regarding the outfall, including publicity in the media (articles in newspapers, advertisements in radio and on TV), preparation and distribution of brochures, etc.;
- Implementation of the social community development program of the project including: (i) support for urban rehabilitation, improvement of sanitary conditions and cleanup activities; (ii) strengthening and development of community organizations to promote participation and social control; and (iii) promotion of community development to consolidate communities, and avoid or reduce conflicts, and to recover cultural heritage, mainly by rehabilitating the Cienaga de la Virgen coastal lagoon;
- Organization of a study tour for community leaders and representatives of the media, the municipality, the environmental authorities, and other stakeholders to similar outfalls sites

operating in Latin America. The group included about 30 persons that visited outfalls in Chile (Viña del Mar, Valparaiso, and Concepción,), Montevideo in Uruguay and Guaruja in Brazil. All these outfalls are of comparable size to that which was proposed for Cartagena and have the same type of preliminary treatment. Unlike Cartagena, all of them are located in front of the most desirable residential areas and beach resorts, whereas in Cartagena the outfall is located about 20 km north of the city in a zone which is not a beach resort. In all sites visited the outfalls are functioning successfully, to the complete satisfaction of all the local stakeholders;

- Utilization of a panel of five international experts (hired to review the project), with broad experience in wastewater management, design and construction of ocean outfalls, water quality and oceanographic modeling and environmental impact assessment. The panel provided valuable support in clarifying the technical issues to the various stakeholders.
- Execution of a series of workshops with the opposition groups to explain the scientific, technical and engineering aspects of the selected alternative and its advantages over all others; and
- Financing the participation of representatives of the key stakeholders in an international course on the submarine outfall alternative for final disposal of sewage in coastal cities in the Caribbean, organized at the time by PAHO/WHO in Barbados.

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Treatment Options for Marine Wastewater Discharges

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ABSTRACT

Some aspects, especially environmental impacts and costs, of wastewater disposal through marine outfalls are discussed. It is argued that the scheme should be thought of as a system, comprising the treatment plant, the outfall and diffuser, and the near field where rapid dilution is achieved. Environmental impacts should be regulated by a mixing zone approach that accounts for the very rapid initial mixing. "End-of-pipe" limitations or specification of arbitrary treatment levels should be discouraged. Water quality requirements, including those for toxics and bacteria, can be met by an effective outfall, i.e. one that discharges far from shore with high dilution, and preliminary treatment such as milliscreening. Secondary or other advanced treatment is rarely necessary. This is illustrated by the Cartagena, Colombia, outfall. The cost of disposal by an effective outfall and preliminary treatment is of the order of one tenth that of secondary treatment when amortized over 25 years.

Keywords:*Outfalls; Marine; Wastewater treatment; Environmental impacts*

RESUMO

São discutidos alguns aspectos, especialmente os impactos e custos ambientais, de saneamento de águas residuais através de emissários submarinos. Argumenta-se que o esquema deve ser pensado como um sistema, compreendendo a estação de tratamento, o emissário e difusor, e o campo próximo onde a rápida diluição é alcançada. Os impactos ambientais devem ser regulados por uma abordagem de zona de mistura que leva em conta uma mistura inicial muito rápida. Limitações "end-of-pipe" ou especificação de níveis de tratamento arbitrários devem ser desencorajados. Requisitos de qualidade da água, incluindo os de produtos tóxicos e bactérias, podem ser atendidos por um emissário eficaz, ou seja, aquele que descarrega longe da costa, com alta diluição e tratamento preliminar, como milipeneiras. Tratamento secundário ou outro tratamento avançado raramente é necessário. Isto é ilustrado pelo emissário de Cartagena, Colômbia. O custo da disposição por um emissário eficaz e tratamento preliminar é da ordem de um décimo do tratamento secundário quando amortizado em 25 anos.

Palavras-chave: Emissários; Marinho; Tratamento de água poluída; Impactos ambientais

INTRODUCTION

Appropriate treatment levels for marine wastewater discharges have long been contentious and the source of vigorous debate. In this paper we discuss some of the issues involved in wastewater disposal through outfalls into a coastal environment.

A typical disposal scheme, Figure 1, consists of a treatment plant and an outfall. The outfall is a pipeline or tunnel, or combination of the two, which terminates in a diffuser. Outfalls typically range from 1 to 4 km long and discharge into waters 20 to 70 m deep, although they may be longer or shorter if the seabed slope is unusually flat or steep.

The disposal scheme should be thought of as a system, comprising the treatment plant, outfall, diffuser, and also the region round the diffuser (known as

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the near field) where rapid mixing and dilution occurs. This is illustrated schematically in Figure 1.

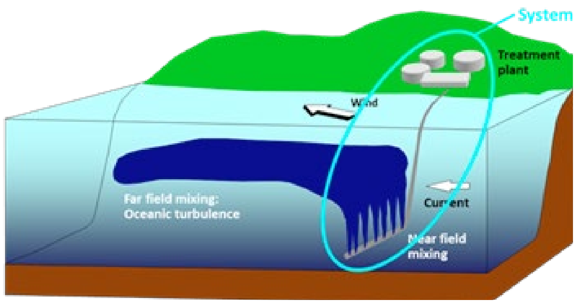

Figure 1: A marine wastewater disposal scheme: Treatment plant, outfall pipe, and diffuser.

The objectives of the system are to dispose of wastewater in a safe, economical, and reliable way with minimal impacts to the receiving water. This means that the local ecosystem and the health of the public that are swimming and using nearby beaches are protected, and that the outfall functions reliably with minimal maintenance. These objectives can be usually achieved by an effective outfall that has sufficient depth to ensure high initial dilution and sufficient length to prevent contamination of beaches.

ENVIRONMENTAL AND WATER QUALITY ASPECTS

Environmental and human health impacts of marine discharges are controlled by water quality standards set by some regulatory authority. They should ensure that:

- Concentrations of bacteria are reduced to safe levels to protect human health;
- Concentrations of toxics and other contaminants are reduced to safe levels to protect the local ecosystem;
- Ecosystem products of the effluent (organic carbon, nutrients, etc.) are kept within allowable limits to prevent eutrophication;
- Dissolved oxygen concentrations and biochemical oxygen demand (BOD) are kept within allowable limits;
- Local particulate deposition is not excessive;
- The wastefield is not visible on the water surface.

According to the National Research Council (NRC, 1993), a wastewater constituent may be considered to be of high concern if it:

> *"...poses a significant risk to human health and ecosystems (e.g. if it contaminates fish, shellfish and wildlife, causes eutrophication, or otherwise damages marine plant and animal communities) well beyond points of discharge and is not under demonstrable control. A wastewater constituent may be generally considered to be of lower concern if it causes only local impact or is under demonstrable control."*

Using these criteria, the NRC developed a list of anticipated priorities for wastewater constituents in coastal urban areas as shown in Table 1.

Table 1: Pollutants of major concern for Coastal Discharge (NRC, 1993)

Priority	Pollutant groups	Examples
High	Bacteria and Pathogens	Enteric viruses
	Toxic organic chemicals	PAHs
	Nutrients	Nitrogen
Intermediate	Selected trace metals	Lead
	Others hazardous materials	Oil, chlorine
	Plastics and floatables	Beach trash, oil, and grease
Low	Biochemical oxygen demand	
	Solids	

The high priority pollutants can be readily controlled by an effective outfall combined with appropriate wastewater treatment. Although nutrients are listed as high priority, they are actually not usually a concern for discharges to open coastal waters with good flushing.

They are more of a problem in enclosed water bodies with poor flushing such as lakes, bays, or estuaries, where eutrophication may occur. Pathogens are microorganisms that can cause disease in humans. They are assumed to be controlled if the level of an indicator organism (an organism that indicates the presence of sewage) is below some specified standard or guideline. They can be controlled by a combination of initial dilution, oceanic diffusion, and mortality, as discussed in Roberts et al. (2010). Toxic organic chemicals and trace metals can cause adverse effects in aquatic organisms and humans. They can be addressed by, for example, applying the limitations prescribed in the California Ocean Plan, as discussed below. This can usually be accomplished by initial dilution alone for regular domestic sewage, but source control may be needed for industrial discharges.

Intermediate level constituents can also be controlled by treatment and dilution. Plastics and other particulate floatables should be removed by treatment such as screening. Other floatables, especially grease and oil, are of more concern since they may contain pathogens and may be blown onshore by winds (see Figure 1). As discussed below, milliscreening, especially when combined with other forms of treatment such as flotation, can remove substantial quantities of grease and oil and other floatables.

It may seem surprising that biochemical oxygen demand (BOD) is low priority in Table 1. This is because high initial dilution and the large surface area available for re-aeration generally results in negligible depletion of dissolved oxygen. Solids are also ranked low priority due to the ability to control them with treatment and high dilution. The potential for accumulation on the seabed, and their possible association with toxic organic chemicals, metals, and pathogens should be addressed, however.

Mathematical modeling and monitoring of operating outfalls show that their effects are generally limited to a small area, typically a few hundred meters around the discharges. This is true even for substantial discharges of essentially raw sewage, for example the Ipanema outfall in Rio de Janeiro.

The key parameters in the design of municipal wastewater systems are generally bacteria, floatables, and grease and oil. Toxics are readily controlled by dilution. Bacteria are best controlled by locating the outfall so that transport of wastewater to beaches or other water contact areas is virtually eliminated. The outfall should be designed, however, that, in the unlikely event that transport to beaches does occur, the combination of initial dilution, oceanic diffusion, and bacterial mortality reduces the bacteria to very low levels. Chlorination of the effluent is then unnecessary. As discussed above, other parameters such as nutrients, BOD, and dissolved oxygen will not usually be a concern unless the sewage is discharged to a shallow, poorly flushed coastline, or embayment.

REGULATORY ASPECTS

Because of the unique behavior of wastewaters discharged from an outfall into a coastal environment, defining and specifying regulations and how to apply them is quite difficult. Probably the first major attempt to do so was the California Ocean Plan (*The Plan*). It was first published in 1972 and has been updated several times since, most recently in 2015 (SWRCB, 2015). *The Plan* specifies beneficial uses of the ocean and requirements for water quality and discharges to protect them. *The Plan*, or parts of it, has been adopted by many environmental agencies around the world.

High near field dilution is often a specific design requirement. It can be readily achieved by a multiport diffuser that discharges the effluent as high velocity turbulent jets that rise through the water column. They entrain substantial quantities of seawater that can dilute the effluent to at least 100:1 within a few minutes after discharge and within a few hundred meters from the diffuser (Figure 1).

This high dilution and the rapid and very substantial contaminant reduction that it provokes are recognized by regulatory authorities through the concept of a mixing zone. Understanding mixing zones is the key to understanding the environmental impacts of an ocean outfall and how they are regulated.

The mixing zone is a region of limited water use. For example, the US EPA regulations for toxics defines a mixing zone as:

> *"An area where an effluent discharge undergoes initial dilution and is extended to cover the secondary mixing in the ambient water body. A mixing zone is an allocated impact zone where water quality criteria can be exceeded as long as acutely toxic conditions are prevented."*

Mixing zone water quality standards are usually limited to parameters for acute toxicity protection. Toxics can be readily controlled by, for example, satisfying the requirements of Table 1 (formerly Table B) of *The Plan*. For regular domestic sewage, this will usually be accomplished if an initial dilution of order 100:1 is maintained, although source control may be needed for industrial discharges.

It is important to note that these limits are specified at the mixing zone boundary rather than at the "*end-of-pipe*". For example, *The Plan* does not generally specify effluent limitations or treatment levels, instead it specifies effluent limits that will achieve water quality objectives after near field dilution. To emphasize this, it states that:

> *"Waste effluents shall be discharged in a manner which provides sufficient initial dilution to minimize the concentrations of substances not removed in the treatment."*

Prevention of microbial contamination in order to protect human health is an essential part of outfall design; indeed, the main reason for an outfall project is often to solve a microbial contamination problem.

Bacterial standards are not normally imposed within or at the boundary of mixing zones unless the diffuser is located near areas of shellfish harvesting or recreational use. In that case, advanced treatment and chlorination of the effluent will probably be required. Instead, they are specified at water contact areas, such as the shoreline.

Meeting these bacterial standards is a major driver of outfall design. Various standards have been set by International and other agencies for protection of human health. For example, The World Health Organization (WHO, 2003) presented Guidelines for Safe Recreational Water Environments using intestinal enterococcus as the indicator organism. Because of the wide variations that always occur in bacterial sampling, the standards are generally expressed in statistical terms such as geometrical means or exceedance frequencies rather than instantaneous values.

Bacteria are best controlled by locating the outfall so that transport of wastewater to beaches or other water contact areas is virtually eliminated. The outfall should be designed, however, that, in the unlikely event that transport to beaches does occur, the combination of initial dilution, oceanic diffusion, and bacterial mortality reduces the bacteria to very low levels.

All water quality, health, and environmental objectives can be readily achieved by a suitable combination of outfall and diffuser location, effective dispersion and dilution of the effluent, and treatment. To achieve them, it is necessary for the designer to understand how wastewaters mix in coastal waters, to design the outfall and diffuser to promote efficient mixing, and to match the treatment level accordingly.

APPROPRIATE TREATMENT FOR OCEAN OUTFALL DISCHARGES

Wastewater treatment for ocean discharges is a contentious issue and is often arbitrarily specified. According to the WHO, the level of treatment has little bearing on the human health risk of discharge from an effective outfall. The risk from any effluent discharged through an effective outfall is low, even if only treated to preliminary or primary levels. Conversely, if a short (ineffective) outfall is used, even secondary treatment will not reduce the health risk to acceptable levels. Effluents discharged directly on the beach or from a short outfall constitute a high health risk; unfortunately, this commonly occurs in developing countries.

Preliminary treatment alone will usually suffice with an effective outfall. For domestic sewage this consists of milliscreens with apertures around one mm.

To understand why advanced treatment is usually unnecessary, consider an outfall with a diffuser that effects an initial dilution of 100:1 (which can usually be easily accomplished). This corresponds to a 99% reduction in contaminant concentrations in the receiving water, which is far beyond the capabilities of even advanced conventional treatment processes. Diffuser mixing is therefore usually much more important than treatment in mitigating environmental impacts. This is why the diffuser and near field are included in the "system" in Figure 1.

RELATIVE TREATMENT COSTS

For coastal cities, especially in developing countries, the strategy of wastewater disposal through an effective outfall with preliminary treatment is an affordable, effective, and reliable solution that is simple to operate and with minimal health and environmental impacts. Mandating more advanced levels of treatment that are unaffordable often results in "no action," with continued contamination of water bodies and their associated health risks.

The lifetime cost of a typical urban wastewater scheme with advanced, for example secondary, treatment is much higher than one with primary treatment and an effective long ocean outfall. If the treatment is limited to removal of floatables and grease and oil, the economic comparison is even more favorable for the outfall. Also, increasing use of High Density Polyethylene (HDPE) makes outfalls even more attractive, especially for small to intermediate communities.

The reason for the large discrepancy in costs can be seen in the summary of relative costs for typical treatment processes and their removal efficiencies in Table 2, in which the processes are presented in increasing order of sophistication. This table includes some other processes, such as milliscreening and CEPT. Some of the treatment processes are unit processes that would be combined with others to constitute a treatment plant. For example, primary treatment may include screening, grit chambers, and sedimentation tanks. Onsite treatment systems commonly use subsurface disposal, especially septic tanks. It can be used as a high-density treatment system if the soil is permeable enough and there is no significant risk of groundwater contamination.

Table 2: Typical Treatment Plant Removal Capabilities and Costs (NRC, 1993)

Constituent	Treatment process						
	Preliminary	Primary	Enhanced primary (CEPT)			Secondary plus	
			Low dose	High dose	Primary	CEPT	Nutrient removal
Suspended solids	22±7	55±14	71±11	92±6	93±4	93±5	94
BOD Nutrients	N/A	20±11	55±10	78±11	92±6	95±4	94
As mg/l TN	N/A	15±13	37±11	N/A	32±32	N/A	84±4
As mg/l TP	N/A	38±19	63±19	93±3	38±28	87±4	97±2
Relative cost (US$/MG)	150	500	600	700	1.100	1.200	1.400

Capital costs vary widely for different plants of the same type and in different countries for two main reasons. First, each process can be designed over a wide range of different criteria. The choice of design criteria affects the effluent quality and investment costs. For example, secondary treatment by activated sludge can be designed as high rate activated sludge with a detention time of 2-4 hours in the biological reactor, or as an extended aeration activated sludge with a detention of 10-24 hours. The cost of an extended aeration reactor is much higher than that of a high rate reactor. Second, labor, material, and equipment costs, land costs as well as taxes and duties, vary in different countries. O&M costs also vary due to different design criteria, and costs of labor, energy, chemicals and spare parts. Because of this uncertain variability, only typical values and not ranges are presented in Table 2 for O&M costs.

The costs rise very rapidly as the level of treatment (and contaminant removal) increases. This is shown by the estimated annual costs to treat 100 mgd (4 m^3/s) of raw wastewater in Figure 2 where the level of treatment is expressed by the percentage BOD removed. These costs include recovery of investment plus O&M costs.

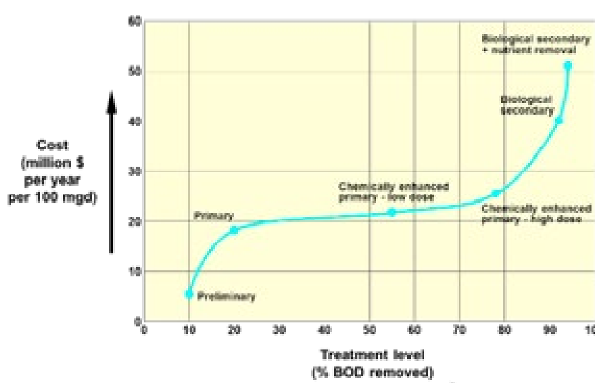

Figure 2: Relative costs of wastewater treatment

CASE STUDY

A recent case study that illustrates the relative costs and impacts of various treatment options is Cartagena, Colombia, Figure 3.

The scheme consists essentially of preliminary treatment by milliscreening without chlorination followed by discharge through a long outfall. The preliminary treatment plant was designed to remove floatable material such as oils and plastic bags, as well as sand and grit particles.

Figure 3: Cartagena, Colombia, outfall

The outfall extends approximately four km into the Caribbean Sea and terminates in a diffuser 520 m long in water depth of 20 m.

The design flow rate is about 4 m^3/s (~100 mgd). Extensive measurements of currents and density stratification were made near the diffuser and used in mathematical modeling of the initial plume behavior and wastewater fate and transport (Roberts and Villegas, 2006).

It was found that dilutions should be very high, ranging from 84 to 860 with a median value of 230. Dilutions were greater than 100:1 for 85% of the time. Because of the weak stratification, the plume almost always surfaces, but when it does surface, the dilution is always greater than 85:1.

Far field modeling was performed to estimate the bacterial impacts, especially at the shoreline. Predictions of bacterial impacts are shown in Figure 4 expressed as areas where the WHO guidelines for Enterococci are exceeded. The outer contour corresponds to WHO classification "A". This range is below the "no-observed-adverse-effect" (NOAEL) level for human health impacts.

It can be seen that bacterial impacts decrease rapidly with distance from the diffuser and bathing water standards will be met far from the shoreline and at the shoreline with a large margin of safety. This conclusion also applies to other bacterial criteria such as in the California Ocean Plan.

Figure 4: Bacterial simulation results compared to WHO (2003) guidelines

It was also found that all requirements for toxics of the California Ocean Plan would be met.

Since the outfall became operational and began discharging, a monitoring campaign has been under way and field observations have been regularly made such as at the stations shown in Figure 5. These include stations over the outfall and at shore. In addition, water quality monitoring at other key locations around the city have been performed.

The outfall is operating satisfactorily. Extensive water quality monitoring around the discharge area following international standards indicates that outside of the prescribed mixing zone there is no discernible impact on seawater quality.

Outside of the 500 meter mixing zone around the diffuser, BOD and suspended solid concentrations are equal to ambient seawater quality levels, and total coliform levels are less than 5 MPB/100 ml - an extremely low level considered suitable for human contact.

Figure 5: Field study locations for the Cartagena outfall.

The project has had many other benefits in cleaning up previously polluted areas. Cartagena's Caribbean beaches are now essentially free of contamination from sewage and the "red-flag" days of beach closures are history. Coliforms are a broad class of bacteria found in the environment, including the feces of man and other warm-blooded animals. The presence of coliform bacteria in water may indicate possible presence of harmful, disease-causing organisms. The Colombian standard for safe bathing is 1000 MPN/100 ml and was frequently exceeded in the past. Total coliform concentrations on beaches and in the Cienega and Bay have declined dramatically after the wastewater treatment system has been commissioned.

The wastewater generated in the western part of the city, accounting for approximately 35% of the total pollution load, is now conveyed to the wastewater treatment plant and disposed through the submarine outfall. Pollution levels in the Bay, particularly alongside Cartagena in the "Inner Bay," are now significantly reduced.

The removal of wastewater discharges into the Lagoon, coupled with improved water circulation produced by the La Bocana project, has transformed the estuary. All key parameters, including coliforms, dissolved oxygen, biochemical oxygen demand, and suspended solids are now within regulatory standards and odor problems have been eliminated. The city is planning to transform the Lagoon and its surrounding area into a protected ecological park.

RELATIVE COSTS

Table 3 shows the relative costs of two outfall schemes: outfall plus preliminary treatment versus secondary treatment for the Cartagena outfall and also for the Taboada outfall in Lima, Peru.

Clearly, preliminary treatment is much less expensive. The savings can allow funds to be used for more pressing environmental and societal needs.

Table 3: Typical comparative costs of two outfall schemes with different treatment levels

Location	Treatment Level	Cost (million US$)			
		Constrution		O&M	Total Cost
		Outfal	Plant	(per year)	Over 25
Taboada, Lima, Perú	Preliminary	90	60	4	250
	Advanced	50	400	18	900
Cartagena, Colombia	Preliminary	22	12	0.7	52
	Advanced	22	150	13	97

CONCLUSIONS

Wastewaters can be disposed of safely and economically into coastal waters with minimal economic impact. Water quality objectives and protection of human health can usually be met with an effective outfall, defined as one that has sufficient length and depth to ensure high initial dilution and to prevent sewage from reaching areas of human usage, with preliminary treatment only. The combination of an effective outfall and preliminary treatment is particularly applicable to developing countries, where reliability and low cost are paramount. The science and technology of marine wastewater disposal is advancing rapidly on all fronts, from oceanographic instrumentation, mathematical modeling, and construction techniques that ensure reliable and economical systems.

Because domestic sewage is degradable, potential problems are, at most, local, and not regional or global. Mathematical modeling and monitoring of operating outfalls generally show that their effects are limited to a small area, typically a few hundred meters around the discharges.

Mixing zone regulations rather than effluent limitations are recommended, and arbitrary levels of treatment prior to discharge should be discouraged.

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Wastewater Marine Disposal through Outfalls on the coast of São Paulo State – Brazil: An overview

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Abstract

According to the water's fitness for bathing/swimming Report of 2011, São Paulo state coast has a population of over two million people, which can be duplicated in the summer and only reaches a wastewater collection rate of 56% on average. In the recent years, the investments of São Paulo government and of the Japan Bank have allowed a significant improvement in the collection rates and in the treatment of wastewater in the São Paulo coast. However, it remains necessary to improve the technical alternatives with a more wide vision of problem. The aim of this work is to present an overview of sewage disposal through submarine outfalls in the coast of São Paulo state, as well as, discuss new alternatives to be considered, to help the decision makers in the choose among wastewater treatment systems alternatives, taking into consideration the technical solutions, the cost benefit analysis, the environmental impact and the current environmental legislation, looking maximizing sustainable development in the region.

Keywords: *submarine outfalls, domestic wastewater, computational simulation, environment preservation, modeling.*

Sumário

De acordo com o Relatório de balneabilidade de 2011, o litoral de São Paulo tem uma população de mais de dois milhões de pessoas, que pode ser duplicada no verão e só atinge uma taxa de coleta de águas residuais de 56% em média. Nos últimos anos, os investimentos do governo de São Paulo e do Banco do Japão têm permitido uma melhora significativa nas taxas de coleta e no tratamento de águas residuais na costa de São Paulo. No entanto, continua a ser necessário melhorar as alternativas técnicas, com uma mais ampla visão do problema. O objetivo desse trabalho é apresentar uma visão geral de disposição de esgoto através de emissários submarinos na costa do estado de São Paulo, bem como, discutir novas alternativas, para ajudar os tomadores de decisão na escolha entre alternativas de sistemas de tratamento de águas residuais, levando em consideração as soluções técnicas, a análise de custo-benefício, o impacto ambiental e da legislação vigente, procurando maximizar o desenvolvimento sustentável na região.

Palavras-chave: emissários submarinos, águas residuais domésticas, simulação computacional, preservação do meio ambiente, modelagem.

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INTRODUCTION

According to the Brazilian Association of Sanitary and Environmental Engineering (Associação Brasileira de Engenharia Sanitária e Ambiental - ABES 2005) there is the need for investing of 4.5 billions of dollars yearly over the next 20 years in country-wide sanitary services which, nowadays only attend to the needs of 42% of the population, in terms of sewage collection (SNIS 2007). In coastal cities where several forms of human activity are involved like tourism, nautical sports, fishing, navigation, aquaculture, and water quality control it must follows the development of these cities to preserve the human activities mentioned above.

In 2007, the Clean Wave Program (Programa Onda Limpa) was launched by São Paulo Government State with the objective to improve the wastewater collection and treatment in the São Paulo coast. São Paulo government and Japan Bank-JBIC investments has been allowing a significant improvement in the collection and treatment rates of waste, although still far from levels of developed countries. The program foresees, in the period that began in 2007 and should be completed by the end of this decade, investments of R$ 4.4 billion. (SABESP, 2014)

These investments must increase the levels of wastewater collection and treatment in São Paulo coast, minimizing the morbidity rates and children hospitalization by water contamination; improving the beach water quality; recovering coastal rivers water quality as well as improve the environmental quality and the social development in these regions. Table 1 shows the collection and treatment wastewater index in the main municipalities of São Paulo coast before and after Clean Wave Program.

However, it is necessary to improve the technical solutions and, although the decision makers should follow the state of art, they should also follow the benefit coast alternatives analysis, looking the cost and the environmental impact of each alternative technically possible, to be adopted in São Paulo and Brazilian coast.

Table 1: Collection and treatment wastewater index evolution with Clean Wave Program (SABESP, 2014).

Region	Municipality	year 2007	2010	2012	2015
North Coast	Caraguatatuba	35%	70%	78%	85%
	São Sebastião	44%	46%	76%	91%
	Ubatuba	28%	36%	60%	84%
	Ilhabela	4%	36%	62%	86%
Region	**Municipality**	**prior to the program**	**1st Stage (2007 - 2012)**	**complementary works (2013 - 2016)**	**2nd Stage (2015 - 2020)**
Baixada Santista	Bertioga	28%	35%	55%	95%
	Guarujá	57%	74%	84%	95%
	Mongaguá	21%	74%	85%	95%
	Praia Grande	46%	67%	84%	95%
	São Vicente	61%	75%	83%	95%
	Cubatão	31%	51%	73%	95%
	Itanhaém	11%	31%	59%	95%
	Peruíbe	17%	71%	72%	95%
	Santos	96%	97%	97%	95%
	RMBS	53%	72%	82%	95%

OBJECTIVE

The objective of this work is to present an overview of wastewater marine disposal through outfalls in the coast of São Paulo state and to present a discussion of new alternatives to be considered, to help the decision makers in the alternatives choose of wastewater treatment systems, taking into consideration technical solutions, cost benefit analysis, environmental impact and legislation, looking maximizing sustainable development in the region.

COAST OF SÃO PAULO STATE

In São Paulo State, the most populous and developed, located in southeastern Brazil, the predominant treatment process is treatment through activated sludge. Marine disposal although representing only 2% of all SABESP (São Paulo Basic Sanitation Company) installations in the state, accounts for 22% of total waste disposal for treatment, occupying the second place in terms of installed capacity. The reason is that the outfalls in operation in Baixada Santista serve large populations.

To date, the option for sea disposal, with preliminary inland treatment for sanitary discharge (see Figure 1), has competed with inland treatment through activated sludge. Although, improvement are required, the option for marine outfalls offers certain advantages considering the high capacity for sea dispersion, when compared to exclusively inland treatment plants, with the abiding scarcity of both areas and receiving bodies with sufficient capacity for adequate auto-depuration of the effluent, and difficulties in the transportation and disposal of the sludge generated from the treatment process.

Nowadays, for new projects, CETESB is enforcing advanced primary inland treatment.

Monitoring campaigns in specific areas are under way aimed at discerning sea outfall impact on aquatic biota and the quality of bathing water, while also subsidizing both the environmental agency responsible for checking standards of water quality and effluent concentration, and CETESB, in the environmental licensing process. Another very useful instrument in the control and management of generated impacts will be a state law for coastal management of ecological and economic zoning, this constituting the main territorial-wise tool for establishing norms in the occupation and use of coastal resources, besides indicating the most appropriate economic activities per zone.

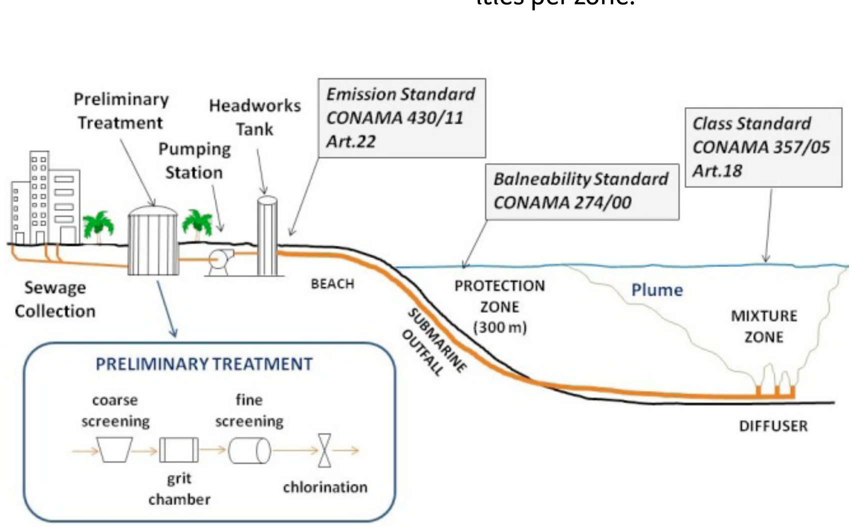


Figure 1: Scheme of a marine outfall coupled with preliminary treatment including grit chamber, screening and chlorination normally used in the SABESP outfalls.

CURRENT OPERATION AND NEW SEA OUFALLS OF SABESP

SABESP operates 8 sea outfalls for sanitary disposal with preliminary plants in São Paulo coast (figure 2 and table 2).

The main design characteristics of those in operation are summarized in Table 2.

In table 3 are summarized the maximum flow discharge, the inland treatment characteristics and the begin of operation.

OUTFALLS IN THE "BAIXADA SANTISTA"

Marine outfalls in "Baixada Santista" have been designed for large populations, as is presented in table 2.

Table 2: Main characteristics of submarine outfalls on the coastal region of São Paulo (Source: Adapted from http://www.mma.gov.br/port/conama/processos/EFABF603/Emissarios.pdf)

Municipality/ Location	Maximun Population (inhab)	Discharge Depth (m)	Outfall/ Difuser Length (m)	Outfall Diameter (m)	Ports number	Port spacing (m)	Port diameter (m)
Praia Grande/ Praia do Forte	253,755	12.5	3,300/ 25 (435)	1	5 (174)	16	0.175 (0.06)
Praia Grande/ Vila Tupi	348,635	13	3,300/ 25 (570)	1	5 (228)	14	0.175
Praia Grande/ Vila Caiçara	559,103	13	4,095/ 420	1	105	5.67	0.06
Santos/ José Menino	1,322,100	10	4,425/ 425 (200)	1.75	40	5	0.011 (0.06)
Guarujá/ Praia da Enseada	445,858	14	4,500/ 300	0.9	150 2 per riser	4	0.06
São Sebastião/ Praia das Cigarras	1,600	8.5	1,600/ 3.5	0.16	7	0.5	0.05
São Sebastião/ Araçá	21,396	17	1,215/ 24.3	0.4	6	4.2	0.09
Ilhabela/ Itaquanduba	30,536	36	941/ 32	0.45	16 2 per riser	4.5	0.075
Ubatuba/ Enseada	4,437	5	4,437/ 8	0.2	4	2.5	0.075

Note: in brackets original design

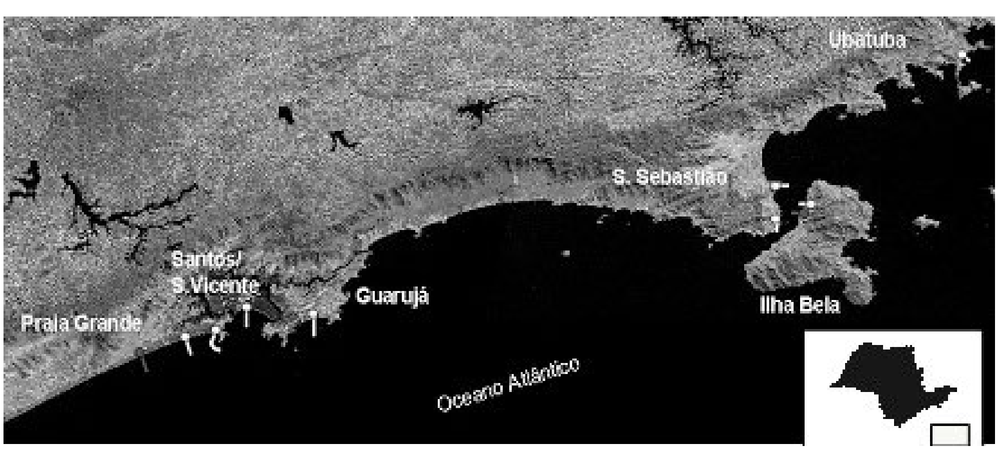


Figure 2: Location of SABESP sea outfalls in operation (Source: Adapted from http://www.mma.gov.br/port/conama/processos/EFABF603/Emissarios.pdf)

Table 3: Main characteristics of submarine outfalls inland preliminary treatment
(Source: Adapted from http://www.mma.gov.br/port/conama/processos/EFABF603/Emissarios.pdf)

Municipality	Location	Preliminary Treatment	Maximun flow (m3/s)	Began operation
Praia Grande	Praia do Forte	CS, CH (in the future + GC, FS)	1.041	1996
Praia Grande	V. Tupi	CS, CH (in the future + GC, FS)	1.047	1996
Praia Grande	V. Caiçara	CS, GC, FS, CH	1.400	2010
Santos	José Menino	CS, GC, FS, CH	5.3 (7.267)	1979
Guarujá	Praia Enseada	CS, GC, FS, CH	1.447	1998
São Sebastião	Praia Cigarras	CS, CH (in the future + GC, FS)	0.012	1985
São Sebastião	Araçá	CS, FS, CH	0.140	1991
Ilhabela	Itaquanduba	CS, GC, FS, CH	0.154	2010
Ubatuba	Enseada	CS, CH	0.015	-

Note: in brackets original design
CS - Coarse Screening, CH – Chlorination, GC - Grit Chamber, FS - Fine Screening (static and rotating screens (1,0 or 1,5 mm))

Santos Outfall. The System's Historical Conception

Santos is the oldest marine outfall system in operation along the São Paulo coast serving both Santos itself and the neighboring São Vicente, with a combined population showed in Table 2. Original planning of the system dates from 1969. From additional studies of the SBS - Baixada Santista Sanitation Company, as coordinated by Professor Garcia Occhipinti (Hidroconsult, 1975 apud CETESB, 2006) more precise design and construction criteria for this system were defined, this including the preliminary treatment at José Menino Beach, and a submarine outfall of steal, covered by concrete, starting on the beach with a length of 4 km.

On considering the lack of an adequate waste collection network system in the region, with wastewater flowing into the numerous channels of both towns, these were connected to the oceanic interceptor thereby making it possible, within a certain flood limit, to direct the channel flows to the preliminary treatment plant.

Use of Models to Support Decision Making

Although the Santos outfall substantially contributed to improving beaches, sea-bathing availability and touristic aspects of the region, its location in the center of the bay caused a certain impact on the mixing zone within the bay itself.

The justification for central placement was based on oceanographic information of a semi- permanent surface current at a depth between 0 to 2 m formed by the convergence of fresh water coming from Santos and São Vicente estuaries (Marcelino & Macedo, 2006). More recent studies, using data from physical and numerical models have shown that current behavior is not guarantee of plume-flow seawards. Nevertheless it is worthy of note that the Henry Borden Hydroelectric Power Plant, in operation until 1992, was contributing with a volumetric discharge of between 74 to 131 m^3/s, whereas, nowadays the maximum contribution is only 6 m^3/s, thus certainly contributing to the variation in behavior of currents in the Santos bay.

A distorted hydraulic model was adapted in the Hydraulic Laboratory of the Polytechnic School using Froude similitude and occupying an area of 750 m^2, with a horizontal scale of 1:1,200 and a vertical scale of 1:200. In this model, the sea outfalls of Santos, Guarujá and Praia Grande (subsystems 1 and 2) were reproduced, as well as the Santos estuary and the harbor channel, according with figure 3 (Ortiz et al, 2007 and FEHIDRO, 2008).

Figure 3: General view of Hydraulic Laboratory physical model (Ortiz et al., 2007)

The results of the physical model show, for some scenarios, the tendency of recirculation inside the bay and at the exit of Santos harbor channel. For a sea outfall extension of 1 km (outfall length of 5 km) the results show a tendency for plume to flow towards the open sea, as is showed in figure 4 after nearly 6 tide cycles reproduced in the model (Ortiz et al, 2007 and FEHIDRO, 2008).

Computer simulations were applied considering 4 km outfall and the diffuser design presented in Table 2, for design discharge Q = 5,3 m^3/s, without considering stratification layer.

Figure 4: Plume effluent discharge after 6 tide cycle for Santos outfall with 5 km (Ortiz et al., 2007)

In this case, CORMIX 2 for multiport diffusers was employed (Doneker & Jirka, 2000; Jirka & Akar, 1991) with phosphorus concentration reaching 0,0837 mg/L at the end of the near field (112 m far from the multiport diffuser point discharge), which resulted in a dilution of S=62 in the region. Additional information on the resultant jet/plume can be seen in FEHIDRO, 2008. The CFD computer code, Fluent 6.1.22 (academic license FLUENT INC., 2003), based on the finite volume technique, was used for transition and far-field computer simulation. The values obtained using CORMIX were inserted into the CFD code as boundary conditions. In this case, a mixture model was used to simulate the multiphase mixture and to solve plume dispersion (see Fluent INC., 2003). Figure 5 presents the data of the transient discharge considering data on tidal variation in the two entrances of the bay, viz. the access channel to Santos Harbor and that of the Mar Pequeno.

These data were inserted in the FLUENT simulations for scenario of 2 m/s wind action at 50° towards the estuary of the bay. The results simulations are reproduced in figure 6 showing that plume circulate and disperse throughout almost all Santos' bay, with dilution values reaching 67, when considering conservative parameter.

This figure shows phosphorus concentration values in the bay for the following tidal instant times (hours): ¼; ½; 1; 3; 6; 12.

New Diffuser and Preliminary Treatment System

A new diffuser was designed as a step in reformulating the old diffuser of Santos outfall. According with (Subtil et al., 2011), this new diffuser was installed onto the end of the old diffuser, with 425 m of length, 79 vertical flexible rubber risers with two nozzles of 11 cm in the exit of each riser, increasing the outfall length in 425 m.

Although the new diffuser will represent an improvement on the dispersion process as a whole in the near-field, dilutions values, for some flow conditions, do not exceed 100.

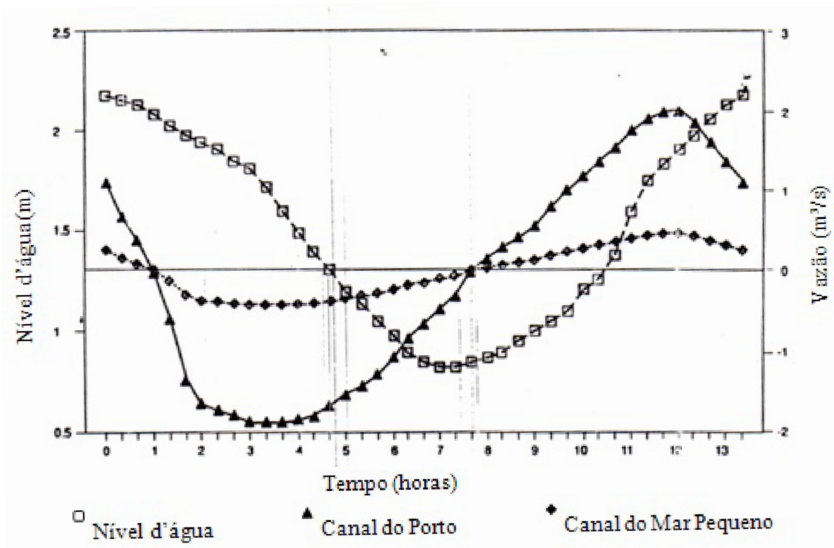


Figure 5: Transient flow and water level in channel harbor and Mar Pequeno exit (Ortiz et al., 2008)

Computer simulations using MIKE 21 were done for the new diffuser design assuming the new design maximum discharge of 5.3 m^3/s for outfalls of 4 km and 5 km, respectively. However, instead of use the transient discharge data in Santos Harbor and Mar Pequeno channels, as mentioned above, it was prescribed freshwater flow from the estuary main rivers, assuming mean volumetric flow based in the data measure in July 2005 (SABESP, 2006). Table 4 presents the rivers contributions simulated for the Santos estuary.

Table 4: Mean Flow Rivers discharge in Santos estuary

Rivers	Mean flow discharge (m3/s)
(a) Santana	1.5
(b) Cubatão	20
(c) Mogi	10
(d) Onça	10
(e) Itapanhau	30
Total	71.5

At the open boundary (north) it was prescribed two conditions for simulation of freshwater

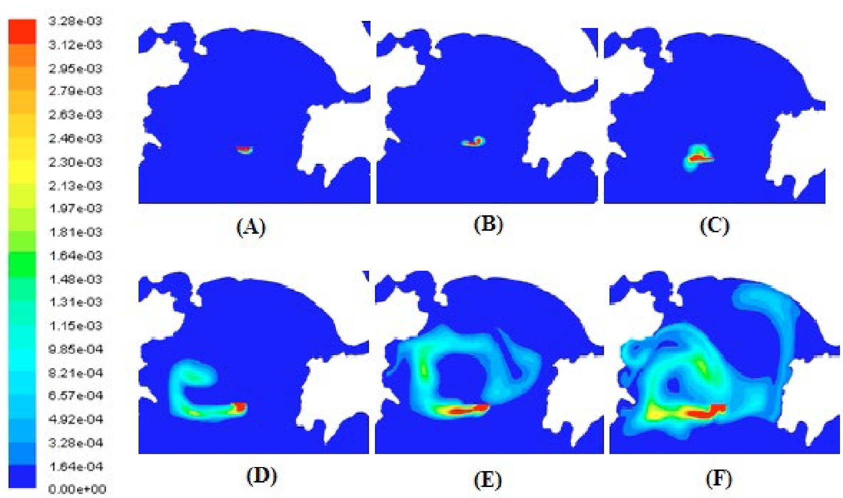


Figure 6: Plume concentration contours of phosphorous (mg/L) for the following tidal instant time, with the wind action: (A) ¼; (B) ½; (C) 1; (D) 3; (E) 6 e (F) 12 (Ortiz et al., 2008)

flow from the main rivers: a critical condition of drought, with almost zero contribution (0.5 m^3/s) and a second condition of 71.5 m^3/s. At the open sea boundary (west) it was prescribed tidal variation. At the open sea boundary (south) it was not prescribed any flow. At the open sea (east) it was prescribed a mean elevation constant value. Wind velocity was assumed constant and equal 2 m/s blowing in the north direction toward to the coast. The simulations were done for 4 and 5 km of outfall extension, respectively, and it was assumed a single point effluent discharge at the exit of the outfall (end of the near field). More details could be seen in Ortiz et al. 2011.

Figure 7 shows the general view of the geometry simulated using MIKE 21.

The hydrodynamic results are presented in Figure 8. Figures 8A and 8B present the simulations with 4 and 5 km outfall length, for condition of almost zero flow from the main rivers. Figures 8C and 8D present the simulation with 4 and 5 km outfall length respectively, for condition of 71.5 m^3/s from major rivers.

The results of the physical model presented in figure 4 shows that 1 km of outfall length extension diminished the bay recirculation, for the critical condition of low flow from the rivers estuary and wind blowing towards the sea, because there is a tendency of plume to leave the bay toward the open sea (figures 8A and 8B).

These results confirm previous results obtained in the distorted physical model (Ortiz et al., 2007 and FEHIDRO, 2008) and in the numerical model using FLUENT.

The increase in the rivers flow to 71.5 m^3/s contributes to minimize the recirculation inside the bay and to drive the plume outside the bay, for condition of smaller length (4 km) outfall.

Praia Grande Outfalls (Subsystems 1, 2, 3)

Marine outfalls of Praia Grande are more suitable when compared with Santos because they discharge in open sea. Three submarine outfalls are in operation in Praia Grande. Subsystem 1 - Praia do Forte and Subsystem 2 - V. Tupi are in operation since 1996, with lengths of 3,300 m. In the design of the subsystem 1, although the standard pre-

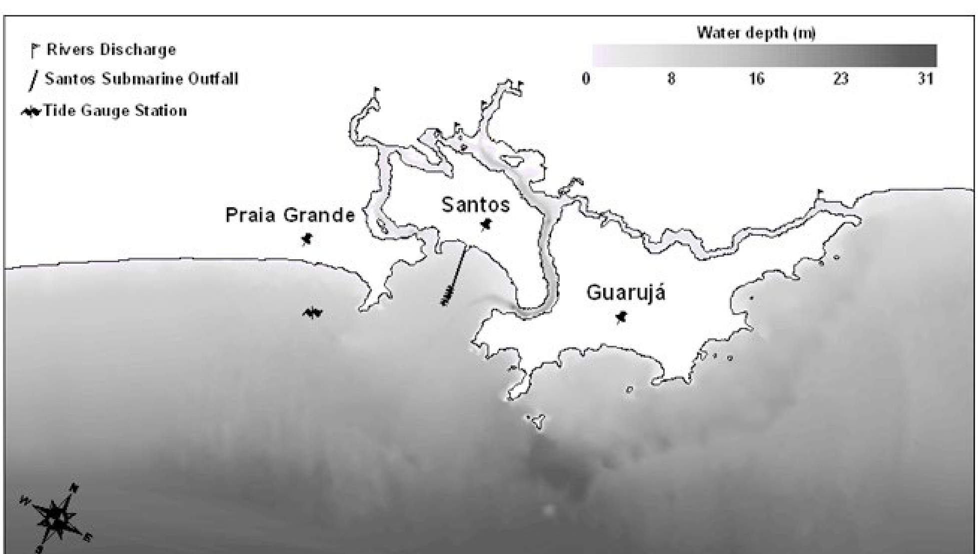


Figure 7: Study area with the bathymetry used in the models (Ortiz et al., 2011).

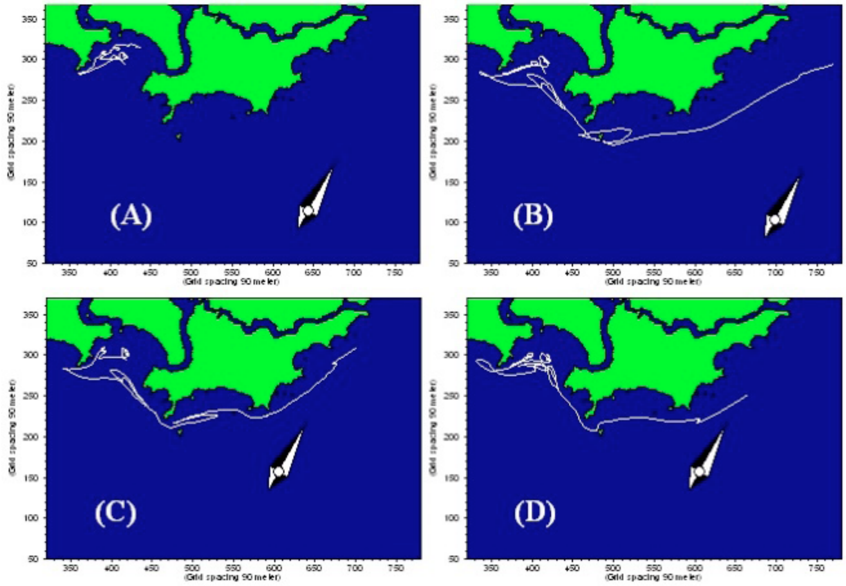


Figure 8: Particle tracking from the outfall effluent discharge exit using MIKE 21. (A) outfall with 4 km and rivers contribution of 0.5m³/s; (B) outfall with 5 km and rivers contribution of 0.5m³/s; (C) outfall with 4 km and rivers contribution of 61.5 m³/s; (D) outfall with 5 km and rivers contribution of 61.5 m³/s. (Ortiz et al., 2011)

liminary plant was forecast this was not built, thus land treatment was basically composed of screening and disinfection by hypocloride. Furthermore, the design multiport diffuser of 435 meters-long with 174 exit ports, was not installed, this being substituted by a much shorter (25 meters-long) diffuser, with 5 exit ports. The same occurred in the subsystem 2 - V. Tupi (see table 2). Subsystem 3 - V. Caiçara is more modern and longer (4,095 m) and began the operation in 2010 with 420 length diffuser and 105 orifices.

The results of initial dilution of Praia Grande Subsystems are much more successful than the Santos/São Vicente, as the outfalls with 3,300 m can conduct the wastewater towards the open sea, which does not occur in Santos, where the wastewater circulate inside the bay. However it is necessary to improve Subsystems 1 and 2 land treatment, as well as the operating diffusers systems, to better explore the suitable conditions arising from the dispersion process. Computer simulations using CORMIX 2 for the subsystem 3 outfall, designed by ENCIBRA S.A. (ENCIBRA 2002), with length of 4 km, considering the diffuser alternative of 420 m or 298 m long, with 75 risers, 3 or 2 nozzles each, show, for the worst scenario, initial dilution of order of S=460 (FCTH, 2005), which is much higher than the minimum required of 100.

Guarujá Outfall

Guarujá outfall with 4500 length, which is in operation since 1998, has a 300 diffuser length and 150 risers, two ports each, according table 2. The Guarujá outfall has been in satisfactory operation since reconstruction in 1998. Subsequently SABESP began connecting channels to the interceptor, solution that was already used in the Santos outfall, which, associated with the complete collection of the shoreline sewage, resulted in a great improvement of coastal water quality in Guarujá.

In accordance to bathing zone monitoring data compounded weekly by CETESB during 2009, the low bacterial concentration is in compliance with the legal limits.

NORTH COAST MARINE OUTFALLS

Some of the most beautiful beaches of the country are to be found along the north coast, linking the states of São Paulo and Rio de Janeiro. Nevertheless, easy access has improved tourism, although the construction of the necessary infrastructure, especially the waste collection and treatment plants for the communities has been neglected. Clean Wave Program investments is improving this situation, according presented in Table 1, however it is important to discuss the better solution of waste collection and treatment to be applied in the region.

There are four sanitary submarine outfalls in operation in the region: two at **São Sebastião c**ity (Araç**ã** and Cigarras), one at Ilhabela (Itaquanduba) and one at Ubatuba (Enseada), which characteristics are presented in Table 2. One other, Saco da Capela at Ilhabela is not in operation. However, the population served in North coast is much smaller (smaller than 50,000 inhabitants), when compared with that of the south coast (greater than 250,000 inhabitants).

The São Paulo's experience in the ocean disposal systems through submarine outfalls is mainly concentrated in large cities. It will be presented in the sequence that this alternative is also a competitive solution for the smaller communities in the northern coast of São Paulo, where are concentrated municipalities with populations of order 50,000 inhabitants or less.

Itaquanduba Outfall

The old marine outfall of Ilhabela, Saco da Capela, although discharging at a depth of 24 m, is very short, i.e. only 220 meters-long, thereby implying that waste disposal occurs within 300 m from the coast, in a zone considered as 'bathing protection'. In order to improve this situation, the new Itaquanduba Marine Disposal System was constructed and is in operation with 800 m length, 32 m of extension diffuser and launching the wastewater at 36 m deep. The population served is 30,536 inhabitants.

According to SABESP, as part of the licensing process for the construction of Itaquanduba outfall, in February 2006 it was carried out a characterization of the São Sebastião channel, in the future area of influence of the outfall, considering normal parameters of seawater quality. Years later, in December 2009, during the emissary's settlement phase, it was carried out another environmental monitoring in the same area, not finding evidence of changes in the parameters analyzed as a result of emissary's construction.

Finally, between July 2012 and July 2013 it was done the first environmental monitoring of this area with the emissary in operation. The results showed that the fecal coliform values and esterococci remain below the legal limit of 1000 MPN/100mL and 100MPN/ 100mL, respectively, across the area of influence of the outfall in the mixing zone (SABESP, 2013).

The results were compared with those obtained during the two previous monitoring campaigns, showing that the discharge of wastewater through the outfall of Itaquanduba is not changing, in a negative way, the receiving environment (SABESP, 2013).

The efficiency of the Itaquanduba outfall was checked through the simulation of the initial dilution of the effluent plume with the aid of Visual Plume software.

The simulations showed initial dilution values well above 100, even in the diffuser outlet. Although Itaquanduba was designed for a maximum flow of 0.154 m^3/s, currently, operates with a minor flow of 0.05 m^3/s, so the simulations were performed for both cases.

The sanitary effluent receives a preliminary treatment prior to the discharge that comprises sieves of 1.0 mm to sand removal and disinfection by sodium hypochlorite. In both cases, the emissary quickly reaches the legal limits for fecal coliform (1000 MPN/100mL) and enterococci (100 MPN/100mL) established in the current legislation. The results of simulations can be seen in Table 5.

The results of simulations are consistent with the results of monitoring carried out between 2012 and 2013 and which were discussed above.

Guaratuba - Boracéia Case Study

The area under study includes five neighborhoods located in the municipalities of Bertioga and São Sebastião: Jardim São Lourenço; Costa do Sol, Morada da Praia, Balneário Mogiano, and Boracéia, as shown in Figure 9. In this figure it is possible to see the Itaguaré, the Guaratuba and the Una rivers.

According to SEADE, the Data Analysis System of São Paulo State (http://www.seade.gov.br), the fixed population of region (winter) is of 9,000 inhabitants. However, in the summer the population could double and could reach the 19,000 inhabitants. Also, in accordance to the study, the population would grow near to 35% over the next 15 years reaching 25,000 inhabitants in the 2030.

With the aim of obtaining arguments for selecting the most adequate domestic effluent treatment and management system for this area, na academic reasearch has been developed by EPUSP group. In this research it was compared the alternative of a submarine outfall (ES) designed coupled to a preliminary treatment with a conventional activated sludge primary treatment plant (ETE-LAB) in terms of costs.

Based on Gonçalves & Souza (1997), Gouvéia et al. (2002) and Garcia (2013) references, two different submarine outfall systems were designed. The first one with 1,500 meters and the second with 2,000 meters of length. Both of systems were evaluated for two different effluent flows, 47 l/s considering the current population (2016) and 64 l/s considering the expected population in 2030. In the Table 6 are showed the main characteristics of the two systems.

Cost Comparison.

Capital Expenditure (CAPEX)

Ortiz et al. (2006), Arasaki & Ortiz (2006), Souza et al. (2007) and Freitas et al. (2011) show that the option to submarine outfalls, in many cases, is a more economic and competitive solution for Brazil and São Paulo coast. The case study corre-

Table 5: Simulations results. Initial dilution and final fecal coliform concentration.

Nutrient Initial Concentration		Effluent Flow (m3/s)	Initial Dilution	Distance from outlet to place plume reaches the surface		Coliform Surface Concentration
				x (m)	y (m)	
Fecal Coliform	1,700,000 MPN/100ml	0.050	561	23.8	3.11	3,030.3 MPN/100ml
		0.154	276	24.39	3.18	6,159.4 MPN/100ml

Figure 9: Study area

sponds to a wastewater maximum flow of 64 L/s for a summer population estimated of 25,000 inhabitants in 2030.

In order to obtain, for the case study, the estimative cost of construction and installation of the submarine outfall designed, it was calculated cost of the prime material of the outfall (pipe PEAD), outfall installation at sea (boats, dredging and diving team), land preliminary treatment station, pump system, among others, based on updated data from SABESP database. For CAPEX cost of preliminary treatment (PREL) was adopted 20% of ETE-LAB cost.

The final budget calculated was US$ 4.4 million for preliminary treatment and design 1 (PREL+ES(1)), US$ 5.5 million for preliminary treatment and design 2 (PREL+ES(2)) and US$ 4.4 million for ETE-LAB. The installation costs for alternatives PREL+ES(1) and ETE-LAB are equivalent, unlike the option PREL+ES(2) which it has an increase of 25% in this cost. This increment is consequence of the 500 m of PEAD pipeline added.

Operating Cost (OPEX)

Another important parameter to consider in the cost analysis is the Operating Cost. This analysis was performed considering a current winter population of 19,000 inhabitants and an annual mean flow effluent treatment of 49 l/s for all alternative systems. The main data for the evaluation of OPEX for ETE-LAB, such as consumption of chemicals, consumption of electricity, sludge disposal, workmanship etc, were also obtained from the

Table 6: Submarine outfalls. Main characteristics.

Design	Outfall length (m)	Outfall diameter (m)	Discharge depth (m)	Difusser length (m)	Ports number	Port spacing (m)	Port diameter (m)
1	1,500	0.315	6.7	14	11	1.3	0.075
2	2,000	0.315	10.8	22	11	2.2	0.075

database of SABESP. These values are presented in Table 7, resulting in a total value of nearly US$ 26,200/month. In the case of the submarine outfall system were analyzed the same main costs that for ETE-LAB and, in addition, it was considered a cost for effluent plume monitoring. The consumption of chemicals was considered null and the sludge disposal for submarine outfall was considered only 10% of the cost in ETE-LAB. These values are presented in Table 7, resulting in a total value of nearly US$ 14,500/month. The analysis of Table 7 shows that the month OPEX is 80% greater when the ETE-LAB is adopted. One of the main advantages of alternative of submarine outfall is the reduction in the cost for sludge disposal, when compared with ETE-LAB.

Table 7: Opex Cost summary.

System	ETE-LAB	ES
Water Flow (m3/month)	128,900	128,900
Chemicals Consumption Cost (US$/m3)	0.04	-
Electricity Consumed Cost (US$/m3)	0.04	0.01
Sludge Disposal Cost (US$/m3)	0.05	0.01
Workmanship Cost (US$/m3)	0.07	0.05
Monitoring Plume Cost (US$/m3)	-	0.05
OPEX Cost (US$/month)	26,200	14,500

Total Cost

Table 8 shows the results of economic feasibility of the alternatives, the total cost is the present value of *CAPEX* and *OPEX* costs over 15 years at a 0.5% monthly rate. In general, for the studied submarine outfall pipeline length range (submerged part between 1,500m and 2,000m), the difference in cost during operation with secondary treatment exceeds the increase in the outfall installation costs, resulting in an long-term economic advantage.

Table 8: Sewage Systems Total Cost

	Sewage Systems Cost (million US$)		
	PREL+ES (1)	PREL+ES (2)	ETE-LAB
CAPEX	4.4	5.5	4.4
OPEX	1.7	1.7	3.1
TOTAL	**6.1**	**7.2**	**7.5**

Environmental Cost

Another important factor to consideration is the environmental cost. The ETE/LAB alternative that, hypotheticaly, is proposed to be construct in the border of Guaratuba River, as shown in Figure 10, with the effluent discharge in the river, exclude, permanently, the classification of Guaratuba River, as Class 1, limiting the multiple uses of river's water, as well as, it will cause problems for bathing in Guaratuba beach. Na alternative of short marine outfall coupled to ETE-LAB, not considered in this research, will increase substantially the cost presented in Table 8. However, the marine outfall installation would enable the classification of Guaratuba River as Class 1 in its entire course, allowing the use of its waters for human consumption and ecological recreation. Also, it is important to emphasize, that the water crisis in São Paulo city has forced to get a volumetric discharge flow of 0.5 m3/s river upstream (Revista Engenharia, 2015). This kind of decision during sever dry season in São Paulo metropolitan area, could affect the river dilution capacity of the effluent discharge, in this period.

When considering marine outfall alternative as a solution it is necessary an environmental analysis of the outfall discharge for the evaluation of the possible impacts of the effluent discharge in the mixing zone.

The computational simulation of the plume dispersion process of a sewage effluent in the mixing zone downstream of the effluent discharge in

Figure 10: View of Guaratuba river in its last stretch (Ortiz et al., 2015)

the sea is nowadays an indispensable tool in the decision making process for both environmental agencies and operating companies of marine outfalls systems (Ortiz & Bessa, 2004).

Mathematical models, which are developed to simulate the phenomena, estimate the effluent dilution as function of different parameters including, but not limited to, the discharge depth, dimension and kind of diffuser, effluent outlet velocity, density ratio between the effluent and the receiving body and the sea currents with or without stratification, allowing the simulation of different systems and the evaluation of its future performance.

In the case here presented simulations were performed using Visual Plume in order to evaluate the behavior of the initial dilution of the effluent, the concentration of fecal coliforms and phosphorus when the effluent plume reaches the surface and the distance that these occur. It was considered an effluent discharge with an initial fecal coliforms concentration of 1.7 x 106 MPN/100 mL and phosphorus concentration of 8 mg/L. The results of simulations can be seen in Table 9.

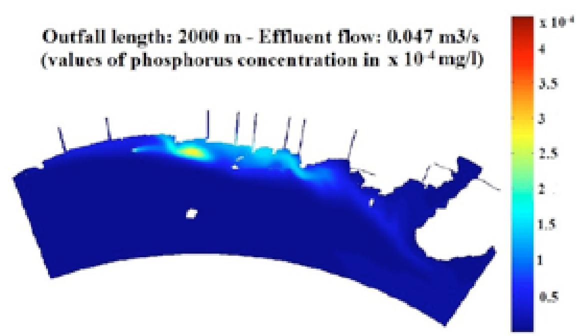
The legal limits for fecal coliforms and total phosphorus, defined in the current legislation are 1000 MPN/100mL and 0,062 mg/L, respectively. As it is possible to see in Table 9 for both marine outfalls systems simulated it was reached values of initial dilution, greater to 100.

With respect to the concentration of phosphorus it is possible to see that the legal limit is quickly reached, for both systems. In the case of fecal coliforms, although the concentration in plume, when it reaches the surface, is greater than the legal limit for the smaller outfall length, it is important to note, that this fact occurs over than 1 km from the protected area. Certainly, the dispersion process and bacterial decay will take care and will get pollutants values in the protected area of 300 meters much smaller than the limits.

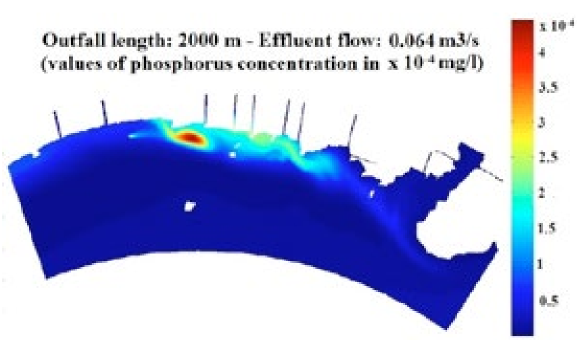
In Figure 11 it is possible to see the evolution of the effluent plume of this system after 20 days of simulation. The phosphorus concentration was used to follow the trajectory of the plume. It is important to emphasize that limit legislation of 0.062 mg/L of phosphorus is much higher than the end of scale value represented in Figure 11.

Table 9: Results of simulations. Initial dilution for fecal coliforms and phosphorus concentrations

System	Nutrient parameter	Initial Concentration	Effluent Flow (m3/s)	Initial Dilution	Distance from outlet to place plume reaches the surface x (m)	y (m)	Nutrient Surface Concentration
PREL+ES(1) 1,500 m	Fecal Coliform	1,700,000 MPN/100mL	0.047	157.4	-0.628	0.807	10,523.4 MPN/100mL
	Phophorus	8 mg/L					0.031 mg/L
	Fecal Coliform	1,700,000 MPN/100mL	0.064	117.1	0.666	1.033	14,145.9 MPN/100mL
	Phophorus	8 mg/L					0.0416 mg/L
PREL+ES(2) 2,200 m	Fecal Coliform	1,700,000 MPN/100mL	0.047	484.6	-2.062	0.807	3,420.9 MPN/100mL
	Phophorus	8 mg/L					0.0101 mg/L
	Fecal Coliform	1,700,000 MPN/100mL	0.064	333.3	-5.204	1.033	4,968.1 MPN/100mL
	Phophorus	8 mg/L					0.0146 mg/L



(A)



(B)

Figure 11 (A-B): Phosphorus concentration distribution after 21 days of simulation.

As a result of the study conducted here the alternative of inland preliminary treatment coupled with a 2,000 meters marine outfall is more competitive and cheaper solution when compared to the alternative of conventional treatment ETE-LAB, particularly if a short submarine outfall is considered coupled to *ETE-LAB*.

From the environmental point of view, the stronger point of the marine outfall alternative would be the possibility of recovery and preserved Guaratuba water quality river, preserving its classification as a river of Class 01 according to CONAMA resolution. Figure 12 and Figure 13 showed the natural beauty of Guaratuba River.

Figure 12: View of the river discharging in Guaratuba beach (Pereira et al., 2014)

Figure 13: View of Guaratuba river in its last stretch (Pereira et al., 2014)

PUBLIC CONCERN, LAWS, REGULATIONS

The discussion presented here shows that the occupation of coastal area of São Paulo state is stressing the environment thereby implying the urgent need for applying coastal zoning legislation, planning coastal communities and improving the CONAMA (Environmental National Council) resolution for achieving sustainable development in this area. Sanitary wastewater marine outfalls must be regarded as a solution, not as a problem, although it is recognized that the planning, design, construction and operation of these systems need to be improved.

New projects must follow the best relationship for the level of treatment - outfall length/ diffusers.

A marine disposal system must consider three main actions: an executive project that adopts exhaustingly studied criteria and minimizes negative action in the aquatic environment; emergencies' actions (a contingency plan) for chemical products, solid residues and pipeline disruption; a permanent program for sea and treatment plants, as well as submarine monitoring and equipment.

In Brazil, the quality of water and the effluent discharge patterns is regulated by environmental resolutions established by the National Environment Council: CONAMA 274/2000, 357/2005 and 430/2011. The 274/2000 defines the proper bathing criteria of the beaches, the 357/2005 introduce new parameters limits to be considered together with four classes of water for the water resources management and the 430/2011 incorporates the concept of mixing zone for marine disposal defined as "the region of the water body where the effluent initial dilution occurs", and provides the regulation of the wastewater disposal defining the conditions and standards of parameters concentrations in the point of effluent discharge. CONAMA 430/2011 resolution improves the previous resolutions and incorporates the concept of ocean disposal through marine outfalls.

In São Paulo state there is also the *Decreto Estadual No. 84468/76* which establishes in the Art. 18 the standard parameters for effluent discharge in interior and coastal waters.

Some coastal cities in Brazil have been approved a more restrictive municipal environmental resolution compared with CONAMA 430, concerning the use of marine outfall.

There is no room in this paper to discuss the Brazilian Environmental Legislation presented above, but one of the main conflict related with wastewater marine disposal is the type of inland treatment system do be adopted (preliminary, primary or secondary), before effluent launched in the marine outfall. Although, with the increase of the inland treatment (primary or secondary) it is possible to increase SST and DOB removal, before river or marine effluent discharge, this is not a guarantee of best effluent dilution. Primary or secondary treatment will also increase the sludge generation that must be treated and disposed properly, causing a cost increment, with an additional economic and environmental impact (Ortiz & Sobrinho, 2013).

Although it is recognizes the evolution and the importance of the existing Brazilian environmental legislation presented above, its simple application does not necessarily guarantee the best solution for environmental preservation of the coastal water. It is necessary to improve this discussion so that decision makers could take in consideration technical solutions, cost benefit analysis and environmental impact, looking maximizing sustainable development in the region.

CONCLUSIONS

The main conclusions of this overview are summarized below:

- In Santos city, SABESP must continue systematic monitoring campaign of the marine outfall in the mixing zone. These monitoring data together with the channels operation data (rainwater contribution, gates operation, volumetric discharges, and channel water quality) could be the foundation for a real time database to be included in the CETESB data base water's fitness for bathing/swimming. Other cities of São Paulo coast like Guarujá and Praia Grande could adopt the same ideas.
- The option for marine outfalls in smaller communities in São Paulo coast must be considered compared with others solutions in terms of capital expenditure, operation cost and environmental impact.
- Environmental legislation could be improved through development of database like mentioned above and generating technology information possible to be applied in the coastal zone management.
- Finally, according with table 1, Clean Wave Program investments are improving a lot the standard wastewater collection and treatment, but it is necessary that these investment must be followed by coastal cities struggle to improve solutions for urban planning and irregular occupation of these regions, so that the data presented in table 1 could reflected the reality in the next years.

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Seawater Monitoring under the Influence of SABESP Sea Outfalls in Baixada Santista (South Coast) and North Coast - São Paulo State - Brazil

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ABSTRACT

In order to assess the environmental conditions of the receiving water body, as well as to measure the dispersion of the outfall plume before the construction and during its operation, environment monitoring has been an essential tool. SABESP has been using monitoring programs for decision making and to give reliability in diagnoses and prognoses for sea outfall management. This paper presents a compilation of the main monitoring programs that SABESP has been working on over the last 10 (ten) years (since 2005) in São Paulo coastal regions under influence of several sea outfalls. Through the major monitoring results, the aim of this paper is to discuss the impacts that outfalls have been causing in the coastal area of São Paulo State. In summary, the influence of ocean outfalls in changing the quality of water in Baixada Santista and North Coast is limited mainly at the mixing zone close to the diffuser.

Keywords: *environment monitoring programs; environmental impacts; sea outfall*

RESUMO

Os monitoramentos ambientais têm sido essenciais para avaliar as condições ambientais dos corpos d'água receptores e para mensurar a pluma de dispersão antes e durante a operação dos emissários submarinos. A SABESP tem utilizado os resultados dos programas de monitoramento, seja para a tomada de decisão, seja para dar confiabilidade nos diagnósticos e prognósticos dos impactos ambientais. Este artigo apresenta a compilação dos principais programas de monitoramento que a SABESP tem trabalhado nestes últimos 10 anos (desde 2005), na região costeira do Estado de São Paulo sob influência dos vários emissários submarinos. Através da apresentação dos principais resultados desses monitoramentos, o principal objetivo deste artigo é discutir os impactos ambientais que os emissários submarinos têm causado na região costeira de São Paulo. Em resumo, a influência das descargas dos emissários submarinos na costa de São Paulo está limitada à zona de mistura, próxima ao trecho difusor destes emissários.

Palavras-chave: programas de monitoramento ambiental; impactos ambientais, emissários submarinos

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INTRODUCTION

In order to assess the environmental conditions of the receiving water body, as well as to measure the dispersion of the outfall plume before the construction and during its operation, environment monitoring has been an essential tool. SABESP has been using monitoring programs and mathematical models for decision making and to give reliability in diagnoses and prognoses for environment and sea outfall management. This paper presents a compilation of the main monitoring programs that SABESP has been working on over the last 10 (ten) years (since 2005) in Baixada Santista (South Coast) and North Coast of São Paulo State. These monitoring programs comprise areas under influence of 5 (five) existing outfalls in Baixada Santista and 2 (two) in North Coast. This paper shows an abstract of seawater parameters.

Metropolitan Region of Baixada Santista is located along São Paulo State shoreline in 160 km length, and comprises Santos (major city), São Vicente, Cubatão, Guarujá, Bertioga, Praia Grande, Mongaguá, Itanhaém and Peruíbe municipalities.

Baixada Santista is characterized as the most dynamic economy of São Paulo coast, supported by harbour activities and industrial complex in Cubatão city. The region has two inter-regional key importances: urban-harbour-industry in Santos, São Vicente, Cubatão and Vicente de Carvalho district (Guarujá); and leisure and tourism in the other cities. The region has an ecosystem of paramount importance for economic-environmental approach, like São Vicente, Bertioga and Santos channels.

According to the IBGE statistic institute, the resident population in Baixada Santista is 1,797,500 inhabitants (estimation of July/2015), living along 2,887 km^2 (http://downloads.ibge.gov.br/downloads_estatisticas.htm). This region has the population increased up to the double during vacations period. The sewage system coverage rate is 72% and the treatment of collected sewage is 100% in Baixada Santista.

The North Coast of São Paulo State comprises São Sebastião, Ilhabela, Ubatuba and Caraguatatuba municipalities. According to the IBGE statistic institute, the resident population in North Coast is 314,926 inhabitants (estimation of July/2015), living along 1,947 km^2 (http://downloads.ibge.gov.br/downloads_estatisticas.htm). The sewage system coverage rate is 56% and the treatment of collected sewage is 100%. Both sea outfalls are placed in São Sebastião channel which is 24 km length and 6.0 km average width (see Figure 5). Table 1 lists the main characteristics of the existing sea outfalls in São Paulo coast.

Table 1: Characteristics of the major existing sea outfalls in Baixada Santista and North Coast
Obs: pre-treatment using grit chambers, miliscreens and disinfection.

City	System	Maximum population served (inhabitants)	Maximum flow (m3/s)	Outfall length (m)	Diameter (m)	Depth (m)	Pipe Material
Praia Grande	Praia do Forte	253,755	1.041	3,300	1.00	12.5	PEAD
Praia Grande	Vila Tupi	348,635	1.047	3,300	1.00	13	PEAD
Praia Grande	Vila Caiçara	559,103	1.400	4,095	1.00	13	PEAD
Santos	José Menino	1,322,100	7.267	4,425	1.75	10	coated steel concrete
Guarujá	Praia da Enseada	445,858	1.447	4,500	0.90	14	PEAD
São Sebastião	Araçá	21,396	0.140	1,215	0.40	17	PEAD
Ilhabela	Itaquanduba	30,536	0.154	941	0.45	36	PEAD

GOALS

The main goals of this paper are to present the last seven monitoring programs run by SABESP along São Paulo state shoreline, specifically Baixada Santista and North Coast regions, and discuss about sea water quality under influence of the outfalls.

METHODOLOGY

The primary data collected in shoreline under sea outfalls influence in São Paulo state are shown in a systematized form in this paper. Firstly, monitoring programs are presented showing the location of sampling points, evaluated parameters, and sample quantity/frequency. In the following, major results of monitoring programs are presented. The results are discussed under environmental law and technical aspects of the existing outfalls.

ENVIRONMENTAL MONITORING PROGRAMS AND RESULTS

In this article 3 (three) works of Baixada Santista and 4 (four) works of the North Coast were selected for presentation. The samples were collected according to recommendations of the Standard Methods for the Examination of Water and Wastewater for each type of analysis. Those programs generated a very large amount of data used for related assessments to individual objectives of each program. This paper presents the compilation of results of some representative parameters of water quality in order to assess the temporal evolution and spatial distribution of the environmental characteristics of the region. The results of four water quality parameters were compared with the limits established by CONAMA Resolution No. 357/05 (BRASIL, 2005), for Class 1 of saline water.

1. Environmental Monitoring Program of the areas under the influence of the outfalls of sewage Santos and São Vicente and Praia Grande, Subsystems 1, 2 and 3 (2005-2006) - ENCIBRA / TECAM / FALCÃO BAUER. (SABESP, 2006b)

The main purpose of the monitoring was to verify the conditions of the area under the influence of the Marine Outfall of Santos/São Vicente and Praia Grande, assessing the impairment of quality of sea water, associated to discharge of effluent through these outfalls. Samples were collected in six campaigns in the sea water at three depths (surface, average depth and bottom) to perform the following analyzes: temperature, salinity, DO, TOC, oils and greases, nitrate, nitrite, ammonia nitrogen, Turbidity, soluble phosphate, Total phosphorus and fecal coliforms and chlorophyll-a.

Figure 1 shows the location of the sampling points of the sea.

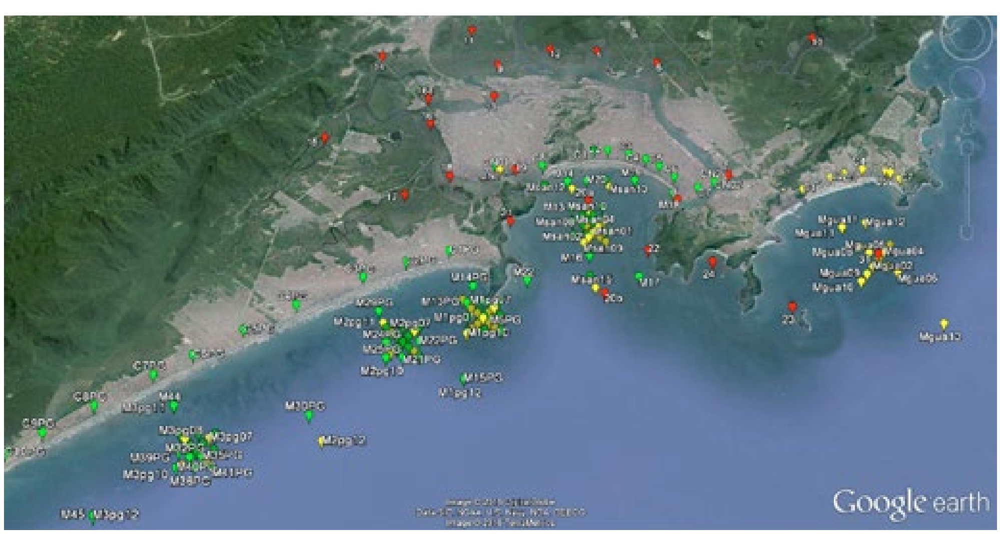


Figure 1: Location of sampling points in Baixada Santista - SABESP, 2006 (green); SABESP, 2013a (red); – SABESP, 2013b (yellow)

According to SABESP (2006), in Santos, for 5 (five) sampling campaigns values were identified over the limit the use of class: TOC (25% of samples), nitrate (2%), nitrite (1%), and ammonia (2%) Total phosphorus (42%) and fecal coliforms (6%). Considering all data, TOC and Total phosphorus were the parameters that were most in disagreement with the limits of CONAMA 357/05, and occurred over the limit values spread over all monitored points, including the control point. Moreover, nitrogenous compounds and fecal coliforms were rarely above limits, and into the mixing zone.

Considering the five campaigns between 2005 and 2006 to the emissaries of Praia Grande, were identified values above the limit for the analysis of TOC (38% of the samples in PG1, 17% PG 2 and 1% PG3); Nitrate (1% in PG2 and PG3); Nitrite (2% and 1% PG1 PG2); Total Phosphorous (47% and 34% PG1 and PG2) and fecal coliforms (0.4% PG1). Considering all data, TOC and Total phosphorus were the parameters that were most in disagreement with the limits of CONAMA 357/05, and occurred over the limit values spread over all monitored points, including the control point. Moreover, nitrogenous compounds and fecal coliforms were very few times above the threshold, and within the mixing zone.

2. Quality Monitoring Marine Water, Sediment and Organisms in the estuary of Santos and São Vicente and coastline and Adjacent areas in the cities of Bertioga, Guarujá, Cubatão, Santos, São Vicente and Praia Grande (2010 – 2013) – ENCIBRA / TETRATECH / TECAM / JICA (SABESP, 2013a)

This monitoring program is included in the scope of the Environmental Recovery Program for the Baixada Santista (RMBS) - Clean Wave Program, the Government Japanese Cooperation Agency - JICA and aimed to assess the marine water quality in Baixada Santista with the improvements implemented by the works of Onda Limpa program. Figure 1 shows the location of the sampling points.

Ten sampling campaigns were carried out and the evaluation of results of Santos Estuarine region was divided into three compartments: (a) Estuary of Santos and Bertioga Channel; (b) Estuary of São Vicente and (c) Santos Bay. In the Estuary of São Vicente there was a very large percentage of non-compliance. Figures 2 show the spatial distribution of mean values of total phosphorus in the water sampling points in the estuary of São Vicente.

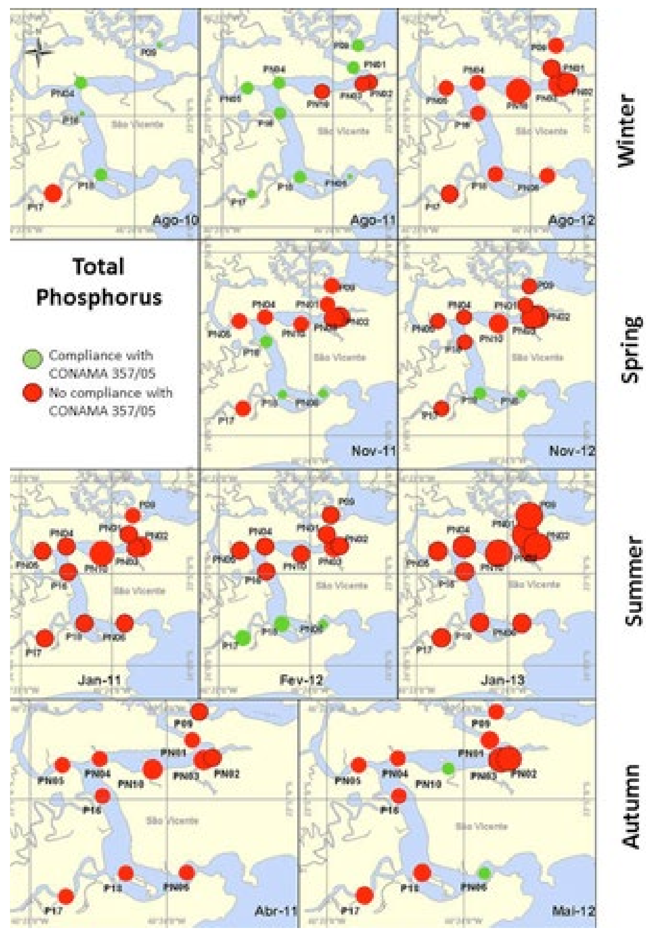


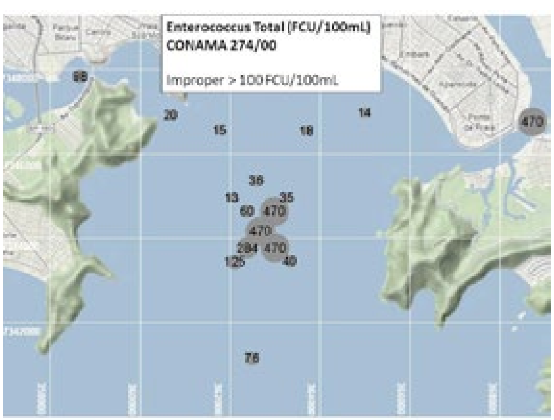
Figure 2: Average values of total phosphorus in the water sampling points in the estuary of São Vicente, all sampling campaigns.

The evaluation of the waters of the Bay of Santos was conducted in five sampling points. The largest number of parameters and the highest percentages of non-conformities in the Bay of Santos were verified in the summer campaigns. Concentration of coliforms above the limit of CONAMA 357/05 were verified only at the point located at the exit of Santos outfall, and therefore into the mixing area, the place where the default class is not reached.

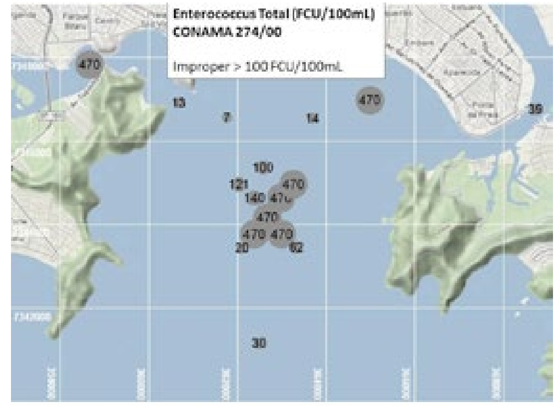
3. Monitoring of water quality under the influence of ocean outfalls of sewage systems Sanitary Guarujá, Santos and São Vicente and Praia Grande. (2011 – 2012) – DTA. (SABESP, 2013b)

Monitoring had quarterly campaigns for the sea. The same parameters of previous campaigns were analyzed. In this program were carried four sampling campaigns, with samples at 3 depths. In the Santos bay were sampled 15 points; in Praia Grande were 36 points and Guarujá 13 points.

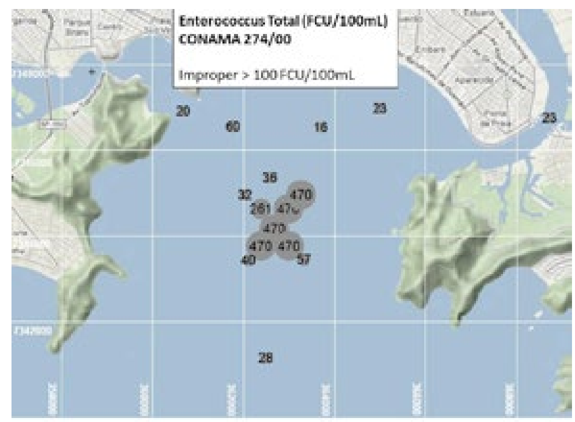
Figure 3 presents the spatial distribution of Enterococcus concentrations and it shows that close to the emissary exit the concentrations were higher than in the more distant points. It is also shown that in the points near the coast, especially near São Vicente, higher concentrations are found. There is a significant contribution of contaminants of Santos and São Vicente channels that contribute to the deterioration in water quality near the coast.



(a)



(b)



(c)

Figure 3: Distribution of Enterococcus Total - Surface (a) Half height (b) Bottom(c). (SABESP, 2013b

Figure 4 shows the compliance rate between the monitoring results and the water quality standard of CONAMA 357/05 legislation of the four major water quality parameters. The results of Santos and Praia Grande comprehend the period 2005-2013 and Guarujá cover the period 2011-2012.

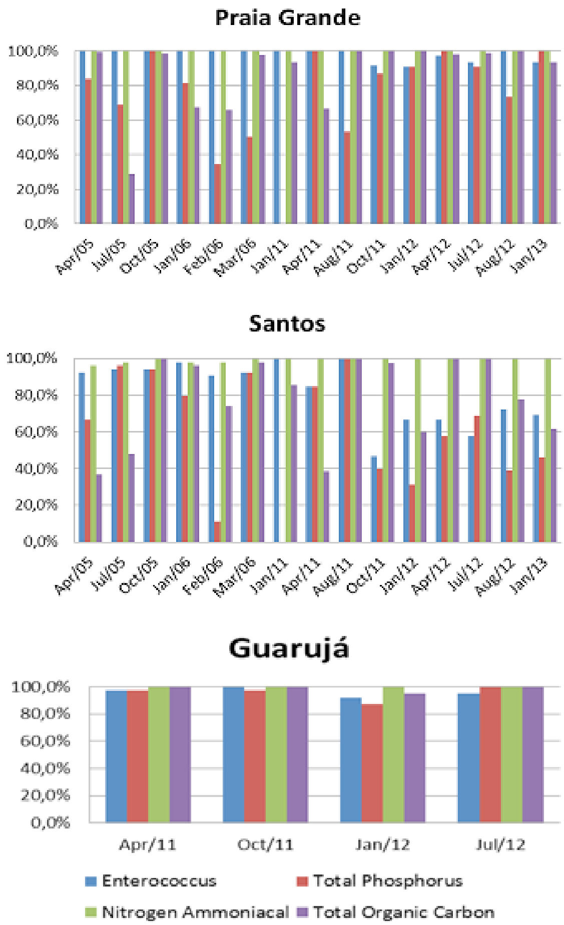


Figure 4: Results of seawater quality compliance with CONAMA 357/05 for Praia Grande, Santos and Guarujá outfalls.

The results show 100% compliance in the campaigns of 15 ammoniacal nitrogen monitoring to Praia Grande and Guarujá, and 99.4% for Santos. The results show for Total Phosphorus 60.5% compliance for Santos and 74.2% for Praia Grande and COT 78.3% compliance for Santos and 87.2% for Praia Grande. For fecal coliforms and Enterococcus results show 81.8% compliance for Santos, 97.8% to Praia Grande and 96.2% for Guarujá. The results indicate that the quality of the sea water is not being adversely affected by the outfall discharge, except within the mixing zone.

4. Environmental characterization of São Sebastião channel under Itaquanduba sea outfall influence area. Ilhabela municipality – Sep. and Dec./2005 – ASA (SABESP, 2006a)

The main target of this monitoring program was the environmental characterization of the influence area before the construction of Itaquanduba sea outfall, which started to run in 2010. Monitoring involved 2 (two) sea monitoring including physical, chemical and microbiological parameters, phyto and zooplankton, benthos, water toxicity and sediments as well as fish community. Sample collect were done in 19 (nineteen) sea sampling points. Figure 5 shows the sampling points in sea water, beach and creek around the area under influence of Araçá and Itaquanduba sea outfalls. Environmental monitoring of São Sebastião channel during operations of Itaquanduba Ocean Disposal System – Ilhabela municipality – 2012/2013 - FALCÃO BAUER (SABESP, 2013c) were carried out after Itaquanduba outfall started the operation in order to evaluate the efficiency of the system by comparing the sea water quality before and after the inauguration.

The monitoring involved 4 (four) sea campaigns carried out in October 2012, January, April and July 2013, including physical, chemical and microbiological (coliform and enterococcus) parameters, phyto and zooplankton, benthos, water toxicity and sediments. Sampling were done in 10 (ten) sea sampling points, 2 (two) in the beach, 2 (two) in the creeks and monthly samples from affluent and effluent of pre-conditioning plant.

The seawater evaluation of September and December 2005 (SABESP, 2006a), before the sea outfall operation, shows that results of seawater quality were in normal conditions, except regarding the following parameters that exceeded the standard limits: phosphorus, turbidity, oil & grease and dissolved oxygen (DO). In terms of fish evaluation, no deformity or physical morphologic/morphometric modification and atypical odor were observed.

Environmental monitoring carried out from August 2012 to July 2013 (SABESP, 2013c), after the outfall installing and operation, assign that results of seawater quality were in normal conditions, particularly for microbiological aspects, except regarding the following parameters: turbidity, DO and total organic carbon (TOC). Creeks water quality revealed high concentration of coliform and enterococcus.

Figure 6 shows the compliance rate between the monitoring results and the water quality standard of CONAMA 357/05 law before and after 2010, when Itaquanduba sea outfall started the operation. The results of the four major water quality parameters show 100% compliance in the last two monitoring campaigns, which indicates that seawater quality is not being negatively affected by the outfall discharge.

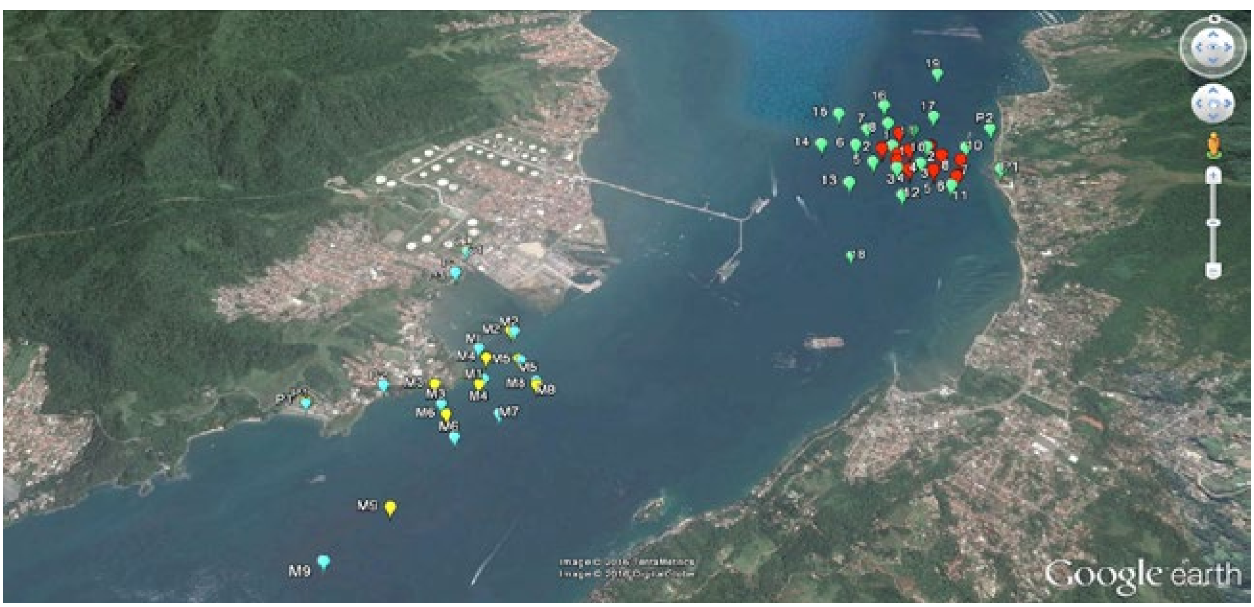


Figure 5: Location of the sampling points in São Sebastião channel. Itaquanduba outfall – SABESP, 2006 (green) and SABESP, 2013c (red); Araça outfall – SABESP, 2012 (blue) and SABESP, 2015 (yellow)

5. Environmental Monitoring under Araçá sea outfall influence area - São Sebastião municipality - Jan/Jul/2012 (SABESP, 2012)

Monitoring program carried out during this period evaluated the environmental conditions in the area under influence of sea outfall before its 150 meters extension increase in 2014.

The monitoring involved 2 (two) sea campaigns including physical and chemical quality in water column and benthos. Sample collect were done in 9 (nine) sea sampling points in 2 (two) depths in January and July/2012, 3 (three) beach stations as well as 1 (one) creek and samples from affluent end effluent of pre-conditioning plant along six months.

6. Environmental monitoring under Araçá sea outfall influence area - São Sebastião municipality - Jan/Fev/Abr/2014 (SABESP, 2015)

Monitoring carried out during this period evaluated environmental conditions in the influence area of the sea outfall before, during and after the installation of 150 meter pipe extension at the end of the existing sea outfall in 2014. The monitoring involved 6 (six) sea campaigns including physical, chemical and microbiological quality in water column and benthos. Sample collect were done in 9 (nine) sea sampling points in 2 (two) depths in January and July/2013/2014/2015, 3 (three) beach sampling points as well as 1 (one) creek and samples from affluent end effluent of pre-conditioning plant along six months.

Environmental monitoring carried out in January and July 2012 (SABESP, 2012), before the 150 meters outfall extension, show that results of seawater quality were in normal conditions, except regarding DO and chlorophyll-a parameters. On the other hand, creeks water quality revealed high concentration of coliform and enterococcus, which affected the bathing water quality of the beach nearby.

The environmental monitoring of January and July 2013, 2014 and 2015 (SABESP, 2015), some of them after the pipe extension in Apr/2014, indicates that results of seawater quality were in normal conditions, except for DO, phosphorus and total organic carbon (TOC). Bacterial parameters exceeded legal standard in January/2015 marine campaign and in all creek and beaches water campaigns.

Figure 6 shows the compliance rate between the monitoring results and the water quality standard of CONAMA 357/05 law before and after 2014, when Araçá sea outfall was extended in 150 meters and the discharge depth turned from 7 meters to 17 meters. The results of the four major water quality parameters show more than 80% compliance in every monitoring campaign. However, the improvement with a deeper discharge after the pipe extension in 2014 had no expected results and indicates that seawater quality is supposed to be negatively affected by other pollution sources such as the creeks, non-point loads and harbor activities.

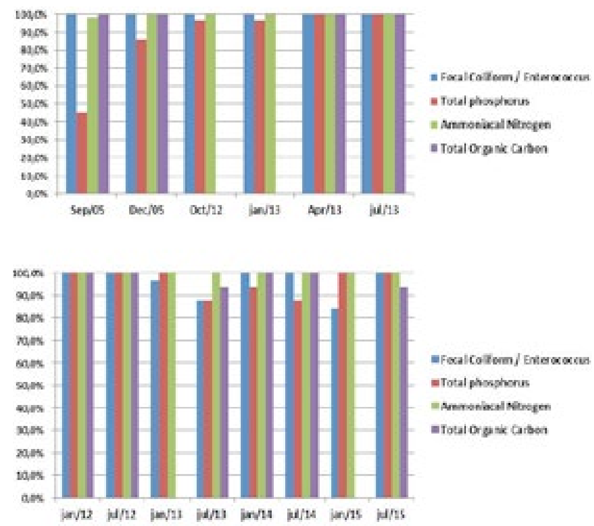


Figure 6: Results of seawater quality compliance with CONAMA 357/05 law for Itaquanduba outfall (upper chart) and Araçá outfall (lower chart)

DISCUSSION

In this section the main results of the monitoring are discussed by ocean outfalls and its respective area of influence:

1. Santos Sea Outfall:

From the results of the presented monitoring the water quality in estuary of São Vicente and Santos Bay is heavily influenced by the input of nutrients and organic compounds into the system, especially in times associated with intense rainfall and increasing floating population in Baixada Santista. The presence of fecal coliforms and enterococci in estuary waters demonstrates the inadequate discarding of domestic sewage in the estuarine environment. Natural and artificial channels receive clandestine wastewater as well as the rainwater and urban drainage, which also contribute to contamination. The outfall is not the only and does not the biggest source of contribution for total phosphorus in the bay of Santos. Regarding Enterococci, the results in the bay of Santos indicate 100% compliance with the limit, in points outside the mixing zone. Inside the mixing zone the results demonstrate good dispersive capacity of the plume even within the bay.

2. Praia Grande Sea Outfalls:

Compared to the Bay of Santos, Praia Grande has a lower trophic level. Due to the high hydrodynamic, this region has faster recover capability from ocean outfalls discharges. According to the monitoring carried out, it can be said that Praia Grande Outfalls are affecting very little the water quality of the area outside the mixing zone of the emissaries.

3. Guarujá Sea Outfall:

Only 5 out of the 39 water samples analyzed in seawater surrounding the Guaruja outfall showed higher concentration to the limit of CONAMA 357/05 for total phosphorus, and in 2 points the concentration of total organic carbon exceeded the limit. It may not say that Guaruja outfall is impacting on water quality in its surroundings considering the quality standards of CONAMA resolution 357/05.

4. Araça Sea Outfall – São Sebastião:

An overall approach on water quality under influence of Araçá sea outfall indicates that although bacterial concentration around outfall discharge comply with the legal standard (over 90% of the samples), raw sewage from communities not served by the sewage system strongly impacts Mãe Izabel creek and cause fecal pollution on surrounding beaches in front of the sea outfall. Regarding seawater quality, despite the additional extension in 150 meters of the sea outfall in 2014, making the discharge 10 meters deeper, no reduction in parameters concentrations has been observed so far, which indicates that only diffuser dilution increase is not enough and seawater quality depends on other organic sources.

5. Itaquanduba Sea Outfall – Ilhabela:

In general seawater quality under influence of Itaquanduba sea outfall indicates that bacterial concentration around outfall discharge comply with the legal standard (100% of the samples in the last two campaigns), and as a rule, an improvement in water quality was observed after the collecting, treatment and disposal of sewage was completed in the nearby watershed. However reminiscences of raw sewage from illegal connections and communities not yet served by sewage system strongly impacts creeks and cause fecal pollution on surrounding beaches in front of the sea outfall, especially during the rains, which were supposed to eventually affect seawater quality in terms of carbon and suspended solids. Nutrient parameters complied 100% in the last two campaigns.

CONCLUSION

Environmental monitoring of the areas under the influence of SABESP outfalls, which were conducted between 2005 and 2013 were quite comprehensive and complex. Based on these results, some of the conclusions are as follows: (i) regarding the results of Enterococci in seawater, it can be concluded that there has been no return to the beaches of the effluent released by the outfalls. However, the collection results in streams that reach beaches showed high values of coliforms, indicating that pollution control measures should be made on these streams, increasing the collection rate in the city, diffuse pollution control as well as illegal connections control; (ii) For total phosphorus parameters, the results indicate that the outfalls have not been the only contribution source in the region of Baixada Santista; (iii) The results show almost 100% compliance in all monitoring campaigns for Ammonia Nitrogen. In summary, the influence of ocean outfalls in changing the quality of seawater in Baixada Santista and North Coast is limited at the mixing zone near the diffuser, and that far away from this area the effects are not noticeable.

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Submarine Outfalls are an Effective Solution for the Disposal of Properly Treated Sewage of Coastal Cities

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DOI 10.4322/dae.2016.016

ABSTRACT

Many coastal cities in the world have adopted submarine outfall as the solution for their sewage disposal. Brazil, a country with a coastline of 7,500 km, or quite more if one includes the perimeters of bays, has had a good experience with submarine outfalls for sewage disposal. It has proved to be a safe and economical solution to keep coastal waters to meet quality standards. The paper covers aspects such as bathing standards, legislation, refers to the main outfalls in Brazil, suggested pretreatment, and trends in the outfall design.

Keywords: *Submarine outfall, sewage disposal, seawater quality, pretreatment, bacterial decay model.*

RESUMO

Muitas cidades litorâneas no mundo têm adotado emissários submarinos como solução para a destinação final de seus esgotos sanitários. No Brasil, um país com uma linha de costa com mais de 7500 km,ou bem mais incluindo perímetros de baías, esta solução tem-se mostrado segura e econômica para manter a qualidade das águas costeiras de acordo com os padrões de qualidade.

O artigo cobre aspectos como padrões de balneabilidade, legislação, comenta sobre os principais emissários no Brasil, pré-tratamentos recomendados, e tendências em projeto de emissários.

Palavras-chave: Emissário submarino, disposição final de esgotos, qualidade da água do mar, pré-tratamento, modelo de decaimento bacteriológico.

INTRODUCTION

Brazil is the largest country in South America, with a coastline of 7,500 km, or quite more if one includes the perimeters of bays. It's beautiful beaches are famous, such as Copacabana and Ipanema in Rio de Janeiro, as seen in Figure 1.

Figure 1: Ipanema Beach, in Rio

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Having such a long coast, sewage disposal through submarine outfalls comes to be an economical and safe solution. Yet, proper legislation must control projects that adopt such a type of solution.

LEGISLATION

Brazil´s Federal Resolution 357/2005 presents different "classes of water", including saline water, and the Resolution 430/2011 establishes specific conditions for sewage discharge into the ocean. CONAMA, the Brazilian Council for the Environment, issued both. Back in the year 2000, the same federal agency had issued bathing standards for seawater.

Table 1 shows standards for saline water, and Table 2 shows quality criteria required for any discharge from a treatment plant (WWTP). The beneficial uses intended for the water define required quality standards.

States in Brazil may have legislation that is more stringent. For instance, Rio de Janeiro State requires at least a standard primary treatment prior to any sewage outfall, even into the ocean.

Table 1: Bathing standards for saline waters (*).

Water Class	TOC (mg/L)	DO (mg/L)	FC (mpn/100mL)
1	3	6	1000
2	5	5	2500
3	10	4	4000

(*)CONAMA 357/2005. TOC = Total Organic Carbon; DO = Dissolved Oxygen; FC = Fecal Coliform.

Table 2: Minimum quality for effluent from WWTP (*)

Parameter	Concentration (≤)
pH	5 – 9
Temperature	40 °C
Settable Solids	1 mL/L
O&G sol. in hexane	100 mg/L
Floatable material	Absent
BOD	120 mg/L

(*)CONAMA 430/2011

BRAZILIAN OUTFALLS

Table 3 shows the main outfalls and their characteristics along the Brazilian coastline.

Table 3: Main outfalls along the Brazilian coast.

City	Flow (m^3/s)	Æ (m)	Length (m)	Depth (m)	Material
Belém	*0.6*	*0.80*	*3,200*	*12*	*C*
Fortaleza	*2.5*	*1.50*	*2,300*	*15*	*PEAD*
Bahia 1	*8.3*	*1.75*	*2,350*	*27*	*C*
Bahia 2	*5.9*	*1.60*	*3,670*	*45*	*C*
Vitoria	*2.1*	*1.50*	*4,035*	*29*	*- -*
Niterói	*2.2*	*1.40*	*3,505*	*20*	*PEAD*
Rio (*)	*15.0*	*2.40*	*4,325*	*26*	*CP*
Rio (**)	*5.3*	*1.50*	*5,000*	*---*	*PEAD*
Santos O	*1.0*	*0.86*	*200*	*10*	*S/C*
Santos N	*4.1*	*1.50*	*4,500*	*- -*	*- -*
P. Alegre	*2.7*	*1.26*	*733*	*12*	*S*
Manaus	*1.0*	*1.00*	*3,600*	*58*	*PEAD*
Maceió	*0.4*	*0.50*	*4,250*	*17*	*PFV*
Aracruz	*3.0*	*1.20*	*2,500*	*17*	*PP*

Ipanema. (**) Barra da Tijuca. Santos O = old. Santos (*) N = new. Bahia 1 = Rio Vermelho (Salvador). Bahia 2 = Jaguaribe (Salvador).
C = concrete; CP = prestressed concrete; S = steel; S/C = concrete (steel covered); PEAD = high density polyetilene; PFV = polyester; PP = polypropylene

Allegedly, these outfalls operate according to the expected studies and design, providing safe conditions for bathing and recreational activities along the beaches.

However, although the costal currents disperse adequately the plume of the Ipanema outfall, granting that its effluents do not affect the bathing zone along the beaches, its pretreatment facilities are limited to screens.

PRETREATMENT

Any submarine outfall must be preceded by some minimal pretreatment system, capable to retaining solids above a very small particle size (such as 1.0 mm), that otherwise would float in the receiving waters. Usually there are local legislations and norms concerning the minimum level of treatment.

In the ocean, the sewage plume ejected from the outfall might disperse rapidly. Usually, the near field dilution is in the order of 1:100 to 1:200. Under such dilution rates, the concentrations of BOD and nutrients will meet quality standards at the end of the near field zone. The issue remains in meeting proper bacteriological indices, according toTable 4.

Table 4: Bathing Waters Classification according to Bacteriological Indices (*).

Condition	FC(≤)	EC(≤)	ENCC (≤)
Excellent	*250*	*200*	*25*
Very Good	*500*	*400*	*50*
Satisfactory	*1000*	*800*	*100*
Inadequate	*>2500*	*>2000*	*>400*

(*)CONAMA-357/2005; Numbers apply to 80% of the time in samples collected in the previous 5 weeks. FC = Fecal Coliform; EC = Escherichia Coli, ENCC = Enterococcus

In the far field, due to further mixing and decay processes, within a few hours concentrations can decrease more than 10,000 times. Thus, for marine disposal of domestic wastewater, it might be irrelevant to adopt secondary or biological treatments prior to the outfall. Moreover, the BOD removal in any pretreatment process will not affect significantly the oxygen content of the seawater.

On the other end, nutrient disposal to the ocean does not create any harmful pollution problem. Ocean currents properly disperse any nutrient load from the wastewater, even if the diffuser line of the outfall has a good design.

Considering these comments, the system should remove two kinds of pollutants, besides coarse debris through screening, and grit at grit chambers:

- Floatable material, which may cause a deleterious appearance; and
- Possible pathogenic bacteria and viruses.

Nowadays the best equipment to remove floatable and small solids particles is a micro-screen, with sifter holes of 0.25 mm, v.Figure 2. Usually sifter holes are from 0.5 to 1.5 mm. See METCALF & EDDY (2014) and JORDÃO & PESSÔA (2014).

Figure 2: Micro-screens for floatables and small solid particles removal.

PUBLIC HEALTH

Chlorination, and/or inactivation at the seawater, can greatly reduce bacteria and viruses concentrations. Salinity, but mostly the ultraviolet radiation of sunlight, is effective inactivation agents.

In Brazil, the CONAMA-357/2005 resolution classifies bathing waters according to Table 4.Usually proper dilution and ambient inactivation suffices to meet the standards, without the need of chlorination. However, if a shorten length of the outfall is desired, disinfection may be required.

Any outfall disposal study should take into account the costs and risks associated with chlorine disinfection. Besides the usually high costs, there are hazards in transporting large quantities of chlorine to the outfall site. Chlorine may pose risks to the plant personnel, and cause toxicity in the aquatic environment.

MODERN TRENDS

There are public opinion issues concerning the use of submarine sewage outfalls, but most are misconceptions. The common idea that sewage outfall plumes pollute bathing zones along nearby beaches, and cause eutrophication in coastal waters, is often a fallacy that does not stand quantified analyses.

Computer models can simulate quite accurately the complex behavior of outfall plumes in the marine environment, including realistic variable bacterial decay processes, FEITOSA R.C. & ROSMAN P.C.C. (2007). From the near field, where initial dilution and active mixing of the ejected plume from the diffuser line occur, to the vanishing passive plume in the fringes of the far field stretch.

In confronting field data with model results, following proper calibration and validation procedures, one can be confident in such quantified analyses. See, e.g., section 9 in ROSMAN P.C.C. (Ed.) (2016). Therefore, one must confront misconceptions with real values, and assess the actual impact of the outfall plume in the environment.

Modern computer models are capable to simulate, with adequate accuracy, at least the following coupled phenomena: near field active mixing, that forms the waste field to be passively transported in the far field, by advective-diffusive processes, and variable bacterial decay kinetics, as a function of water salinity and temperature, and incidence of solar radiation.

COUPLED NEAR AND FAR FIELDS

Within the near field of the diffuser line, the main process is the active mixing due to momentum gradients between the ejected effluent and the receiving waters. Referring to Figure 3, momentum gradients derive from differences in densities and velocities of the effluent ($\rho_o U_o$) and the receiving waters ($\rho_z U_z$). At the end of the near field length, among other variables, models must compute the minimum dilution rate (C_{max}/C_o), the thickness of the formed passive waste field (H), and the distance from the bottom to the top of the passive plume (Z_{top}). C_{max} and C_o are concentrations.

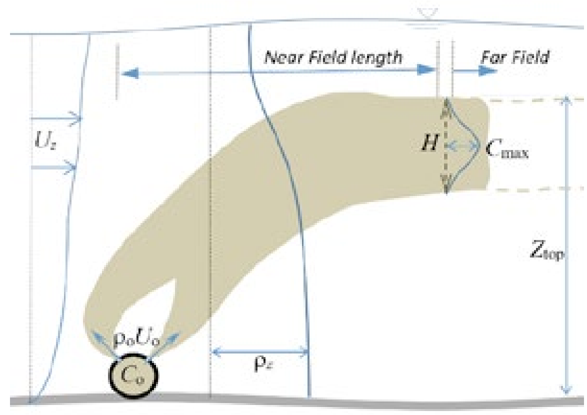

Figure 3: Main variables pertinent to the near field of the plume ejected from the diffusers of the outfall.

Considering momentum conservation principle, as the effluent buoyant jet rises from the diffusers, entrainment with the receiving waters increases the jet mass and density, and decreases its velocity in similar proportion. This occurs along the near field length, up to a distance where momentum inside and outside of the developing plume nearly equalize. Thereon, the plume is passively transported by ambient currents, and the far field processes begin. There are many seminal papers in this respect published by Philip J. W. Roberts and coauthors, starting in ROBERTS, P.J.W. (1979). FEITOSA R.C. (2007) refers to an extensive list of such papers.

In twenty minutes or so, the ejected effluent reaches the end of the near field. For that, it is irrelevant to consider decay processes in this active mixing zone. But those are very important in the passive mixing zone of the far field.

In the far field, there are no momentum differences between the receiving waters and the plume. Therefore, its hydrodynamic influence in the ambient flow is practically nil, the plume is transported passively, affecting only the water quality within its bounds. Any model must account for three main processes in the far field: advection, turbulent diffusion and kinetic reactions.

Advection comprises the advective transport caused by the prevailing currents. The ambient turbulence passively mixes the plume within itself and with surrounding waters. This turbulent diffusion processes continue to dilute the plume, but in a much lower rate than the one in the active mixing zone within the near field.

Advection and turbulent diffusion are intertwined processes that depend heavily on the refinement of the computer model spatial discretization. Turbulent diffusion is the way to account for the flow minutia that cannot be directly resolved with the adopted spatial discretization. For instance, consider modeling the same flow field with two spatial grids. The first quite fine and the second coarser. In the first case, the model can resolve more varied nuances and details of the flow field, and a richer advection results. In this case, there is less unresolved flow field details to be modeled as turbulent diffusion. In the second case, the opposite occurs. In the unreachable theoretical limit, a model in minute direct simulation scales would compute all microscopic details of the flow field, turbulence would vanish, remaining only advection and molecular diffusion.

Direct simulation scales are unviable for modeling geophysical flows, considering costs and consistent data to feed the model. In response, a usual viable approach is to model the flow field in a conventional eulerian coarse mesh, and adopt a lagrangian approach to model the transport of the plume. With this method, concentrations are computed in cells of an adaptive refined computational mesh that dynamically surrounds the transported plume. Thence, advection and turbulent diffusion processes are properly represented cf. Figure 4.

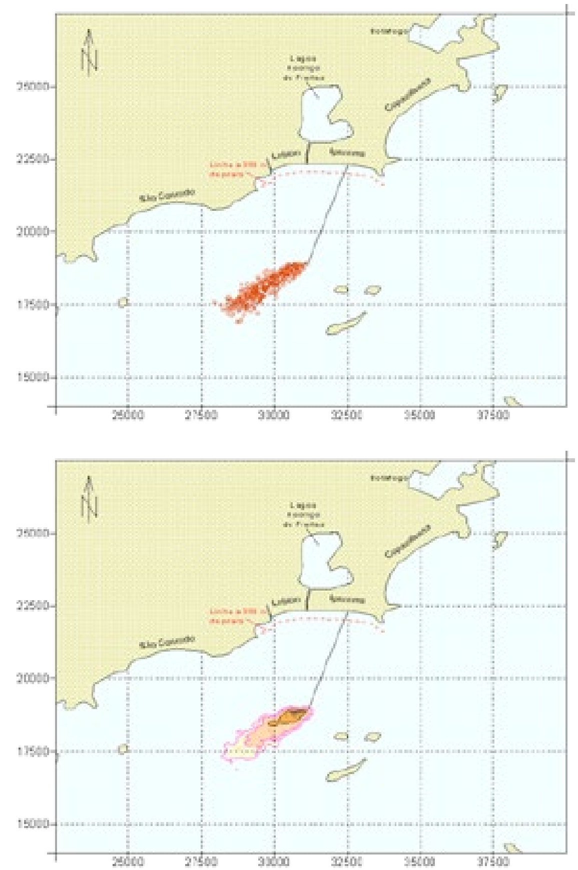

Figure 4: Top map shows the advective and dispersive turbulent transport of particles in a lagrangian model of the Ipanema outfall plume in the far field. The bottom map depicts concentration isolines computed via an adaptive mesh that surrounds the moving plume of particles, ROSMAN P.C.C. (Ed.) (2016).

Academic research on the methodology of integrating near and far field phenomena to model outfall plumes is going on for more than twenty years. Some early examples are in the works of SANTOS (1995), HORITA (1997), AND ZHANG & ADAMS (1999). EXAMPLES OF MORE RECENT, AND REALISTIC APPROACHES ARE IN THE WORKS OF BLENINGER (2006) AND FEITOSA (2007).

COUPLED VARIABLE BACTERIAL DECAY MODEL

Bathing conditions, cf. Table 4, is perhaps the main issues regarding public opinion misconceptions towards sewage outfalls. Quite often, media articles blame outfalls for improper bathing waters along beaches in the vicinity.

Considering that the near and far field advective diffusive transport of plumes are well represented by modern computer models, the coupling of a realistic bacterial decay kinematics in the processes is of utmost importance.

Unfortunately, some studies continue to apply simplistic first order reactions to compute bacterial decay. Such models usually adopt a constant T90, i.e., the characteristic time required for a decay of one order of magnitude, or 90%, in the bacterial concentration, irrespective of dilution processes.

In fact, no matter how sophisticated are the coupling of near and far field hydrodynamic and turbulent transport models, if the decay kinetic is not realistically simulated, calculations of bacterial concentrations will be, at least, very questionable, CARVALHO, J.L. et al. (2006).

FEITOSA et al. (2013) present an extensive analysis comparing eight bacterial decay models for computing the fate of plumes of submarine sewage outfalls.

Starting with the work of FEITOSA R.C. (2007), the modeling system SisBaHiA®, can realistically simulate coupled processes in the near and far fields with bacterial decay kinetics varying with water salinity and temperature, and incidence of solar radiation. Details in section 7.5 in ROSMAN P.C.C. (Ed.), (2016).

With the aid of such modeling tools one can perform confident analysis concerning the risk of polluting bathing waters in beaches in the vicinity of outfalls. For design purposes, it is possible to optimize the length of an outfall, for a given a risk factor that the plume might reach the bathing water zone, with improper bacterial concentration.

Considering that one kilometer of outfall has a multimillion dollars cost, such optimization analyses have a very interesting benefit / cost ratio, minimizing uncertainties. Figure 5 illustrates the concept for the case of the ESPN outfall in the coast of Natal, State of Rio Grande do Norte, Brazil.

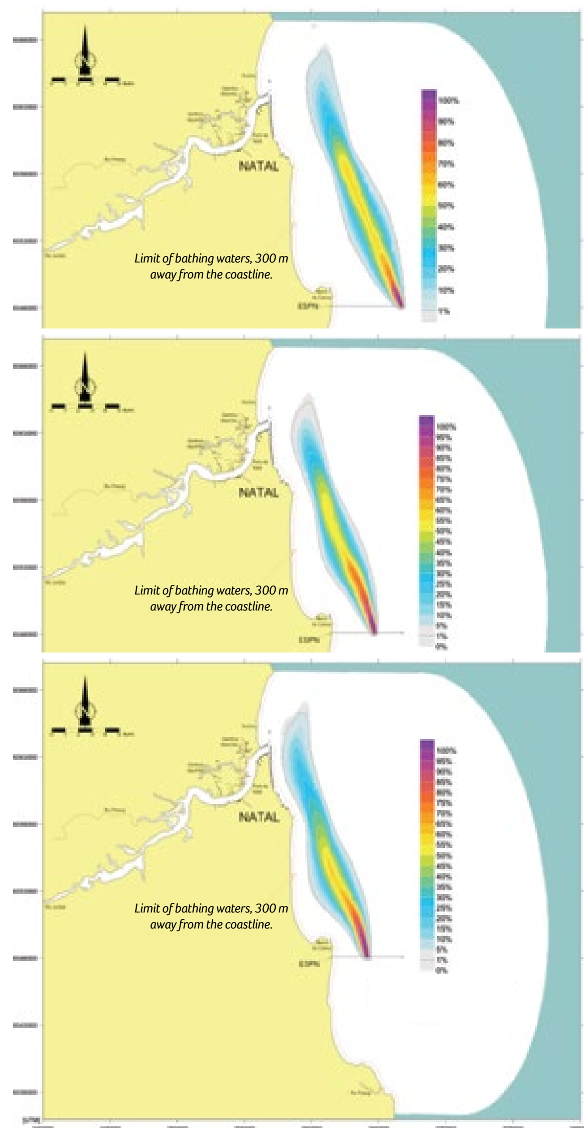

Figure 5: Optimizing outfall length: Isolines of probability of passage of the plume with FC > 1000 mpn/100mL, v. Table 4, for three different lengths of the outfall. ROSMAN P.C.C., SCUDELARI, A.C. (2009).

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Sanitation and microbiological water quality in the watershed of Santos - São Vicente Estuary

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ABSTRACT

This study assessed the evolution in sanitary services and water quality in the watershed of Santos and São Vicente Estuary from 2004 onwards. Results show evolution in services offered to the population after conclusion of the first phase of Onda Limpa Program, when sewage treated at the secondary level evolved from 11% to 14% of population, the pre-conditioning followed by submarine outfall 49% to 53% and population without a sewerage system fell 40% to 33%, being that for the latter 41% are in irregular areas not subjected to coverage. Among the four most populous sub-basins, each has about 90,000 people without a sewerage system, including urbanized and irregular areas. This factor, added to high level of annual rainfall still harms the water quality on the region.

Keywords: *bathing; water quality; Santos Estuary; sanitation*

RESUMO

Este estudo avaliou a evolução do atendimento sanitário e a qualidade da água na bacia hidrográfica do Estuário de Santos e São Vicente a partir de 2004. Resultados mostram evolução no atendimento à população após a conclusão da primeira fase do Programa Onda Limpa, quando o esgoto tratado a nível secundário evoluiu de 11% para 14% da população, os pré-condicionamentos seguidos de emissários submarinos de 49% para 53% e a população sem rede de esgoto caiu de 40% para 33%, sendo que deste último, 41% estão em áreas irregulares não passíveis de cobertura. Dentre as quatro subbacias mais populosas, cada uma possui ainda cerca de 90 mil pessoas sem rede de esgoto, incluindo áreas urbanizadas e irregulares. Este fator, aliado a elevada pluviosidade anual ainda prejudica a qualidade das águas na região.

Palavras-chave: balneabilidade; qualidade da água; Estuário de Santos; saneamento

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INTRODUCTION

Santos and São Vicente Estuarine System (SSVES) is a transition zone between the salt waters of the Atlantic Ocean and the fresh waters found in the watershed of five cities, Cubatão, Santos, São Vicente, Guarujá and Praia Grande (Figure 1). Located in the coastal slope of the state of São Paulo, it is part of Baixada Santista Metropolitan Region (BSMR), made up of nine municipalities covering a 2,402 km^2 area. Despite BSMR having a large area, more than 75% of its fixed population lives in the watershed of SSVES, outnumbering a million inhabitants in 835 km^2.

In the SSVES, the sources of water pollution are industrial and portuary as well as domestic, being the sources of domestic origin and their relation with the water quality in the sub-basins our focus.

Since the Johannesburg Conference in 2002, according to Gianesella & Saldanha-Corrêa (2010), it became evident that the health of coastal environments is directly related to the health of the watersheds, since about 80% of terrestrial pollution reaches the coastal regions through watersheds. In world proportion, these receive almost 90% of *in natura* effluents.

In this sense, an integrated approach between the SSVES watersheds (Figure 1) and the neighboring coastal region turns out to be essential.

According to CETESB (2016), the growth of the towns has caused the urban drainage canals to be the main source of fecal pollution into the beaches, because of numerous sewer connections as well as diffuse pollution. Additionally, areas without a sewerage system and precarious irregular dwellings found in SSVES's watershed, made up of 10 sub-basins, also contribute to the contamination of the region's water bodies.

Precarious dwellings in irregular areas are found in the five cities that make up the SSVES. As reported by Young e Fusco (2006), there are settlements in the region that have been waiting for land regularization for decades, because they require complex solution for being too densified. However, while waiting for solutions, domestic effluents are being dumped in ditches, sewerage systems or directly on the estuarine canals, such as current dwellings as palafittes (SAMPAIO *et al.*, 2008a). Moreover, it is found that the waters of the estuary's interior, too close to places with greater concentration of these dwellings, are used by adults for subsistence fishing and by children and teenagers that live nearby for primary contact leisure, instead of the beaches, more distant from their homes.

In Santos city, issues related to point and diffuse pollution are found to be evident and a couple of measures have been taken, since their beaches and rivers have had frequent oscillations in water quality, harming their use for recreation, despite the city counting on the most widespread coverage of sewerage system, above 93%.

In recent study (RUIZ *et al.*, 2015), the influence of rains in bathing water quality was strongly demonstrated in significant increases in the number of beaches with poor bathing water quality recorded in Santos.

Since 2007, the BSMR has been receiving investments from SABESP through their Onda Limpa Program to achieve the universalization of sewerage system until the year 2025 and improve the indicators of health and water quality.

However, results from coastal water quality monitoring point out that, despite investments, great variation in statistics of bathing water quality has been found in recent years, showing how complex is the ecosystem (CETESB 2016).

GOALS

This work aims to assessing the evolution of SSVES sewerage system coverage between 2004-2014, assessing its influence as well as pollution we will simply call "diffuse" on the microbiological water quality in the sub-basins regions, thus contributing with information to its improvement.

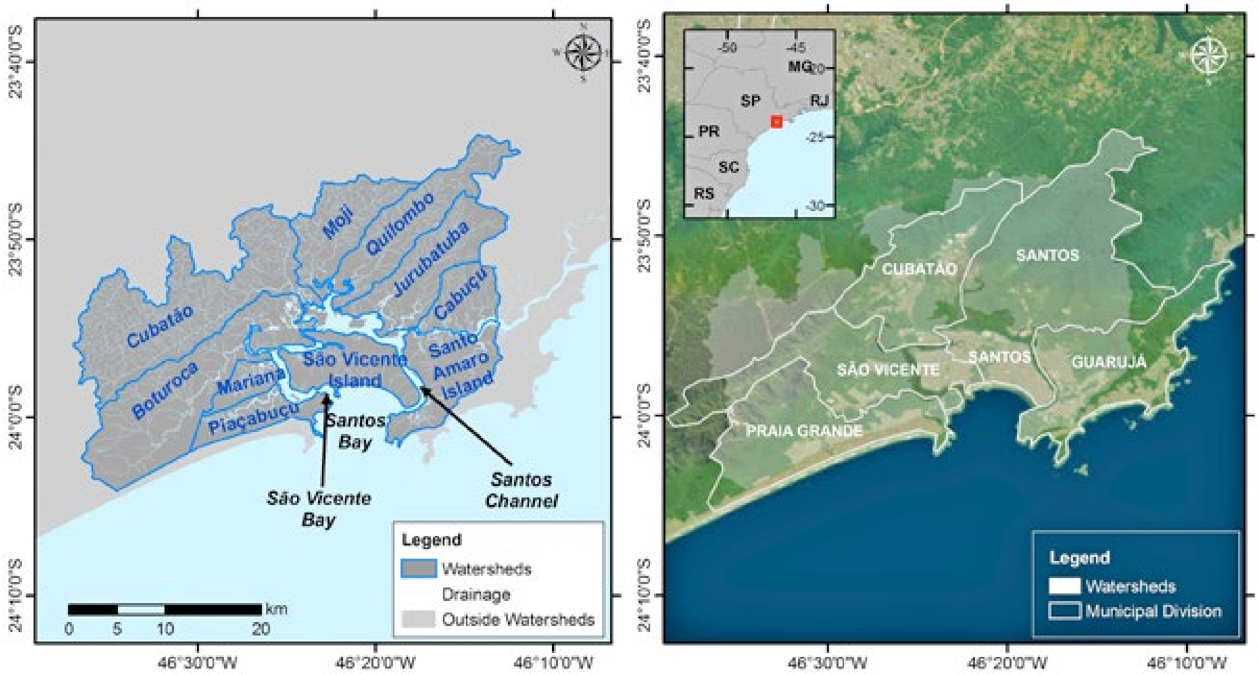

Figure 1: Location of SSVES. On the left watershed (dark grey) and sub-basins division, and right municipal division.

METHODS

To assess the evolution of sewerage system coverage and the population attended at SSVES sub-basins, the sewerage system coverage plants provided by SABESP for the five cities in the region were all georeferenced. These plants have had two distinct years of reference: a) the first, obtained during the ECOMANAGE Project (NEVES *et al.*, 2008), related to the amplitude of the sewerage system coverage for the year 2004, before the works for Onda Limpa Program were started (MACEDO *et al.*, 2007); b) and the second, related to the year 2014, with the first phase for the works of Onda Limpa Program concluded, with its complementary works remaining before its second phase can start.

To assess the number of people attended by the sewerage system, the information of the coverage área of the system in 2004 and in 2014 were merged with the populational data of census sectors of demographic censuses carried out in 2000 and 2010 (IBGE, 2000; 2010) using a GIS tool. In the scale of census sectors, greater detail in the population attended was obtained, different from that found in previous studies at the scale of neighborhoods (SAMPAIO *et al.*, 2008b) or in conventional approaches at municipal scale (BRASIL, 2016).

Under this method, the quantitative data of the population attended or not by the sewerage system could be re-grouped in the division into sub-basins. The spatial outline of the sub-basins and the municipal information related to the macrodrainage system were obtained through the cartographic base of the Baixada Santista Committee for Watersheds (CBH-BS, 2013).

To assess the effect of the diffuse pollution with the contribution of drainage from the sub-basins, a monitoring campaign for quantifying the concentration of *Escherichia coli* and *Enterococcus* was carried out in nine points distributed at the mouth of the sub-basins, as well as two points at São Vicente Bay that counts on no floodgate system for its drainage, as well as most of tributary drainage system of the Santos Bay, totalling 11 microbiological data collection stations (Figure 2). This campaign took place during a quadrature tide in the summer of 2016 for four days in a row, being the first day with a dry weather collection, no rainfall at all, and the three following days happened during and after rainfall. For comparison, in seven out of the 11 points monitored, concentration of *E. coli* monitoring station carried out in quadrature tide in the summer of 2007 were brought together during the ECOMANAGE Project, prior to the works of Onda Limpa Program.

Samples of water from 2007 and 2016 were collected on the surface, kept in ice, taken to the Baixada Santista Environmental and Sanitary Laboratory from SABESP where microbiological analyses of E. coli were carried out by means of the method *Colilert®*. In addition, in the 2016 campaign, samples were analyzed by the method *Enterolert®*.

Data from the meteorological stations of DAEE and CEMADEN were obtainded to assess the rainfall volume in the sampling periods (Figure 2).

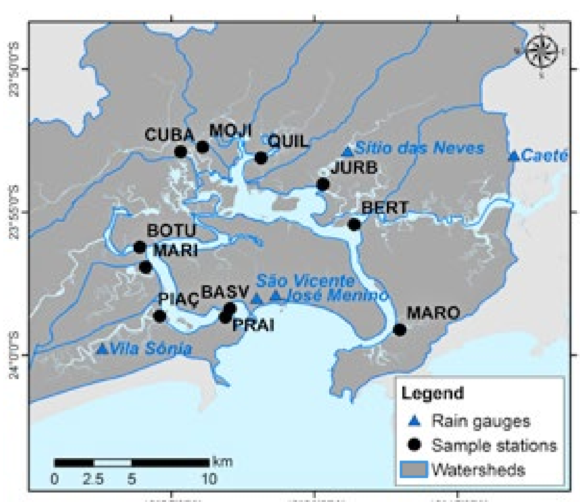

Figure 2: Location of the water sampling stations (black circles) and the rain gauges (blue triangles).

RESULTS AND DISCUSSION

Considering the total population distributed in sub-basins (1,240,249 inhab.), the most populous one, housing more than half of the total resident population of SSVES is that of the São Vicente Island (52%), followed by Santo Amaro Island (17%), Boturoca (12%), Piaçabuçu (10%), Mariana (6%) and Cubatão (2%) whereas Cabuçu, Jurubatuba, Moji and Quilombo hold together less than 0,1% of the total population.

According to the results obtained (Table 1), there was an increase in about 100.000 inhabitants (8%) between 2000 and 2010 and it happened in a heterogenous way in the basin. The sub-basins that showed populational growth among the highest in this period were Piaçabuçu (32,754 inhab.; 35%), Boturoca (24,740 inhab.; 20%) and Mariana (14.695 inhab.; 26%), followed by Santo Amaro Island (13,321 inhab.; 7%) and São Vicente Island (8,377 inhab.; 1.3%), whereas in Cubatão and Moji, population decreased 1,014 inhabitants (-3%) and 920 inhabitants (-67%) respectively; in Cabuçu and Jurubatuba a small populational nucleus was recorded only in 2010.

Predominantly located in the sub-basin of São Vicente Island, Santos is still the most populous city (419,400 inhab.) and the one that shows a near zero growth rate within the sub-basin in the period. On the other hand, Praia Grande, despite having only a small portion of its territory placed in SSVES's watershed (sub-basins Piaçabuçu and Boturoca), concentrated 59% (155,207 inhab.) of total population of the town (262,051 inhab.) in this area and had the highest rate of populational growth in the period assessed (33%). São Vicente, the second largest city in population (332,445 inhab.), with its territory divided into two portions, one of them being in conurbation with Santos on São Vicente Island and the other distributed in four sub-basins in the continent (Piaçabuçu, Boturoca, Mariana and Cubatão) showed a populational growth of 9%. However, previous studies carried out by Sampaio *et al.* (2008b), point out that the populational growth vector of the town has been occuring in the continental part of the city (sub-basins Piaçabuçu and Mariana). This trend may be confirmed when observing the populational increase in 26% between 2000 and 2010 in Mariana's sub-basin.

About sanitary infrastructure, the SSVES's watershed is provided with five wastewater treatment plants (WWTP) distributed in the Cubatão, Boturoca, Mariana and Santo Amaro Island sub-basins, two of them deployed in the period assessed. Besides, the region is provided with a marine outfall (Santos) that serves the sub-basin of São Vicente Island and other four marine outfalls (three at Praia Grande city and one in Guarujá city) located out of the SSVES's watershed, that serve a small part of the population in Boturoca, Piaçabuçu and Santo Amaro Island (Figure 3).

Table 1: Inhabitants per sub-basins. In parentheses the names of the sampling stations related to sub-basins are given.

SUB-BASINS	Population (2000)	Population (2010)	Growth%
Ilha São Vicente (BASV / PRAI) *	636,250	644,627	1%
Sto Amaro (MARO)	203,164	216,485	7%
Boturoca (BOTU)	125,235	149,975	20%
Piaçabuçu (PIAÇ)	93,247	126,001	35%
Mariana (MARI)	56,326	71,021	26%
Cubatão (CUBA)	31,538	30,524	-3%
Cabuçu (BERT)	-	654	-
Moji (MOJI)	1,377	457	-67%
Jurubatuba (JURB)	-	262	-
Quilombo (QUIL)	-	243	-
TOTAL	1,147,047	1,240,249	8%

*Stations in São Vicente bay

It is possible to see that the sanitary conditions are very different in the sub-basins of the region (Figure 4). This comes as evident by analyzing the four most populous sub-basins (São Vicente and Santo Amaro Islands, Boturoca and Piaçabuçu), that hold over 92% (1,137,088 inhab.) of the resident population of SSVES.

Analyzing the coverage of sewerage system implemented in these most populous sub-basins until 2014 (Table 2), 68% (771,296 inhab.) of the resident population are being served by a sewerage system, an evolution of 21% as related to 2004. In the most populous, São Vicente Island, 86% (551,395 inhab.) of the population had a sewerage system linked to the preconditioning plant and to the Santos submarine outfall, whereas 6% of the population (39,472 inhab.) remains in irregular areas, despite the decrease in 28% in the period (Table 3). In the sub-basin of Santo Amaro Island, there was an increase of 52% in servicing, evolving to 62% (133,395 inhab.) of population served by sewerage systems (36,4% connected to a new WWTP and 25,2% connected to the preconditioning plant and to the Guarujá submarine outfall), while 19% (40,926 inhab.) of the population is in irregular areas and 19% (42,164 inhab.) in an urbanized area without a sewerage system. In Boturoca, there was also an evolution of wastewater services in 63%, the second largest in the region in percentage; however, 60% (90,537 inhab.) of population has no sewerage system (36% in urbanized area, 20% in irregular areas and 4% in non-urbanized areas); in this sub-basin the number of people in irregular dwellings increased to 84% in ten years. Although the population served by the sewerage system has increased in 1,213%, in the sub-basin of Piaçabuçu, the high rate of populational growth in the period kept unchanged in 79% (98,933 inhab.) the percentage of population without a sewerage system (63% in urbanized area and 16% in irregular areas) and the number of inhabitants in irregular areas increased in 62%.

It is worthy noting that the number of people living in irregular areas in the region need more comprehensive and detailed investigation. Surveys provided by municipal administrations published by Sampaio e Harari (2012) in periods that were very close to the census carried out in 2000 showed a populational difference of up to 69% higher as related to the IBGE Census for 2000, showing that the numbers of the census in the region are underestimated. According to Maricato (2000), there are no general trustworthy statistics about the occurence of slums or irregular lotting throughout Brazil. On account of methodology failures or even of an obvious difficulty in learning about land possession documents of the land slums are currently settled on, IBGE shows data that is rather undersized. The search for more accurate statistics leads us to some diagnostics elaborated by municipal administrations, academic theses or state organisms that, however, provide restrict and local-limited data. Thus, the total number of people living in irregular areas, as presented in this work, 130,682 inhabitants, may be even greater.

Analyzing results of *Enterococcus* concentration, a marked influence of contribution of drainages from the sub-basins and consequently of diffuse pollution was clear to observe. At the first day of sampling (without rainfall in the last 24 hours - Table 4), the quartile of 75% was 65 MPN/100ml. On the two following days, with rainfall (ranging from 8.1 to 78.6 mm/day), the quartile of 75% was 1,202 and 905 MPN/100ml, respectively, thus representing an increase in up to about two orders of magnitude. On the last day, with the cumulate of rainfall ranging from 0.0 to 7.5 mm/day, the *Enterococcus* concentrations decreased, the quartile of 75% coming to 79 MPN/100ml (Figure 5).

This pattern, influenced by rainfall was also observed in *E. coli* concentrations (Figure 6). Overall, the concentrations were higher on the second and third sampling days, decreasing on the fourth. At the sampling points located at the São Vicente Bay region (BASV and PRAI), the concentration of *E.coli* was similar, when were compared the second and third sampling days. However, it's worth noting that the sampling stations located in sub-basin more to the west (PIAC to MOJI) showed greater contamination on February the 17th, whereas at the stations at sub-basins more to the east (QUIL, JURB, BERT and MARO) the greatest concentrations were on February the 16th. Rainfall along the sub-basins also showed similar variation: on the pluviometer located more to the west the cumulation of rain in 24 hours was higher on February the 17th, while the opposite was recorded in the pluviometers located to the east.

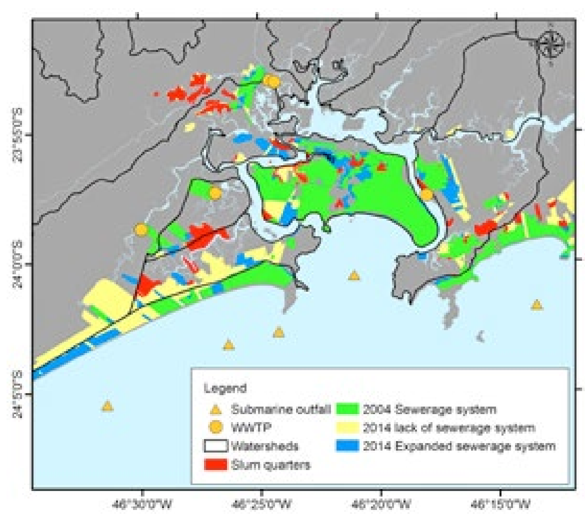

Figure 3: Sewerage system coverage. Areas with sewerage system (green), without one (yellow), area with irregular dwellings (red) and expanded sewerage system area between 2004 and 2014 (blue). Based on SABESP (2014) and IBGE (2010).

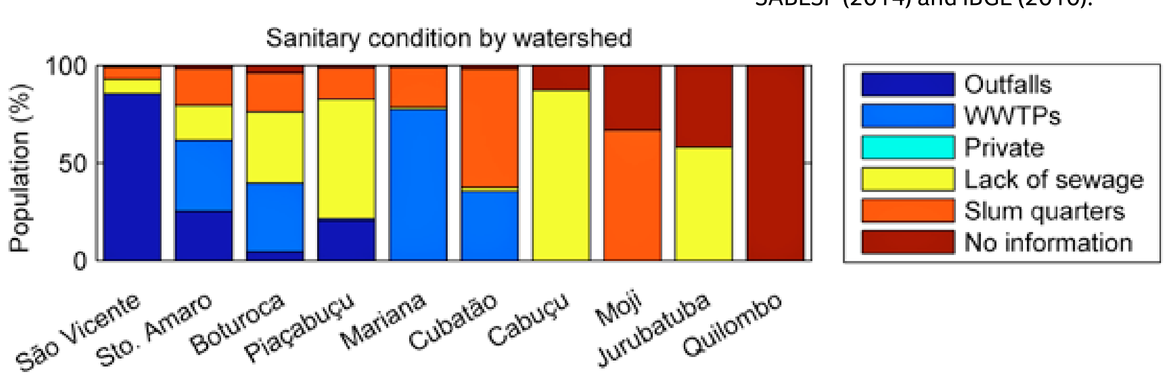

Figure 4: Sanitary conditions in 10 sub-basins of SSVES (in descending order of population from left to right). Based on 2014 sewerage system coverage and total inhabitants from IBGE 2010 census.

Table 2: Inhabitants in the four most populous sub-basins with (wSS) and without (nSS) sewerage system from 2004 and 2014, and its evolution. Data and percentage are based on total inhabitants from IBGE 2000 and 2010 census.

SUB-BASIN	2000/2004		2010/2014		Evolution	
	wSS	nSS	wSS	nSS	wSS	nSS
SÃO VICE	510,357 (80%)	125,893 (20%)	551,395 (86%)	93,232 (14%)	8%	-26%
MARO	87,986 (43%)	115,178 (57%)	133,395 (62%)	83,090 (38%)	52%	-28%
BOTU	36,574 (29%)	88,661 (71%)	59,438 (40%)	90,537 (60%)	63%	2%
PIAÇ	2,061 (2%)	91,186 (98%)	27,068 (21%)	98,933 (79%)	1,213%	8%
TOTAL	636,978 (60%)	420,918 (40%)	771,296 (68%)	366,152 (32%)	21%	-13%

Table 3: Inhabitants in irregular dwellings in the four most populous sub-basins and its evolution. Data and percentage are based on total inhabitants from IBGE 2000 and 2010 census.

SUB-BASIN	2000	2010	Evol.
SÃO VICE	55,075 (9%)	39,472 (6%)	-28%
MARO	62,702 (31%)	40,926 (19%)	-35%
BOTU	16,425 (13%)	30,269 (20%)	84%
PIAÇ	12,349 (13%)	20,015 (16%)	62%
TOTAL	146,551 (14%)	130,682 (11%)	-11%

Regarding the variation of *Enterococcus* concentration along the sampling stations, the station found in the sub-basin of Cubatão River (CUBA) showed a smaller median concentration (25 MPN/100ml), followed by BERT (25,5 MPN/100ml). On the other extreme, the stations MARO and PIAÇ showed the greatest medians (1,817 e 984 MPN/100ml), being that in the sub-basins of both stations there is a significant number of people not served by sewerage system (Piaçabuçu about 100,000 inhab., Santo Amaro Island about 83,000 inhab.). However, is worth mentioning that the monitoring station MARO despite located in this sub-basin, receives only part of the drainage of this number of dwellings without a sewerage system. On the other hand, even in the two sampling stations of São Vicente Bay that receive effluents from the urban drainage from areas already served by a sewerage system showed median concentrations of 200 MPN/100ml.

Moreover, the samples located in not very populated sub-basins (QUIL: 243 inhab. and JURB: 262 inhab.) also showed elevated concentrations for both fecal contamination indicators in samplings collected after the periods of intense rainfall. This can be related to both the natural contribution of the sub-basin from hot-blooded animals; it might be not necessarily related to the presence of pathogenic organisms (SOLLER *et al.*, 2010), but it might also be related to sources unidentified in this work, for instance, the presence of industries and a landfill, thus pointing out to the need of more investigation.

Concerning the evolution of the water quality on the horizon of time between the samplings carried out by ECOMANAGE Project and those of the current work, there is a high variability in the concentration of these indicators, chiefly related to diffuse pollution, rainfall, among other factors (BOEHM *et al.*, 2002). In 2007, on the days prior to the sampling, significant rainfalls occured; this way conditions were similar to the samplings carried out on the 16th and 17th of February 2016, and by means of comparison of *E.coli* concentration results, it is noted that the values are in the same order of magnitude. Therefore, despite de significant difference found between the samples collected in 2007 and the first sampling of 2016 carried out in this study, one cannot affirm there was a positive evolution in the bathing water quality in the inner region of SSVES.

In this sense, the results of fecal indicator bacteria at the mouth of SSVES and São Vicente Bay sub-basins, using *Enterococcus* and *E.coli* show that there is still compromising of the bathing water quality and it is worsening through diffuse pollution after heavy rainfall events.

However, overall, there was an evolution of the services to the population between 2004 and 2014 in both, drainage and treatment of wastewater. In this period, the treatment by secondary-level WWTPs increased from 11 to 14% of total SSVES population, the outfalls increased from 49% to 53% and unserved population fell from 40 to 33%. From these 33%, at least 164,026 people (41%) are in irregular areas that demand complex solutions to ensure for them access to these services in the future. Among the four most populous basins, each one holds about 90,000 people without a sewerage system among urbanized areas without a sewerage system and irregular areas, being that two of them showed the greatest populational growth in one decade.

Table 4: Accumulated rainfall (mm) in the 24 and 48 hours prior to the sampling dates in different rain gauges located in the study area.

DATE	RAIN GAUGE	CUM.	
		mm/24h	mm/48h
10/04/2007	Caete	34.7	41.6
	São Vicente	10.9	10.9
15/02/2016	S. das Neves	0.0	0.0
	José Menino	0.0	0.0
	Vila Sônia	0.0	0.0
16/02/2016	S. das Neves	78.6	78.6
	José Menino	21.1	21.1
	Vila Sônia	26.6	26.6
17/02/2016	S. das Neves	22.0	100.6
	José Menino	8.1	29.2
	Vila Sônia	36.8	63.4
18/02/2016	S. das Neves	7.5	29.5
	José Menino	0.0	8.1
	Vila Sônia	0.6	37.4

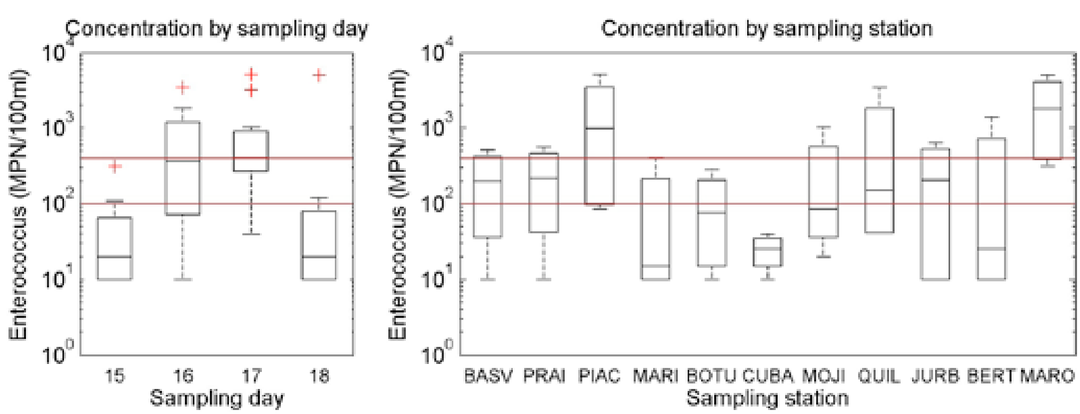

Figure 5: Box plot for Enterococcus concentration (MPN/100ml) considering all of the stations in each sampling day (to the left), and considering all the days sampled in each sampling station (to the right). Red lines represent the thresohlds of 100 and 400 MPN/100ml (Box-plot presenting the values of maximum, minimum, 25% and 75% quartiles with their respective median. The symbols + on the figure to the left stand for extreme values that were removed from the box plot).

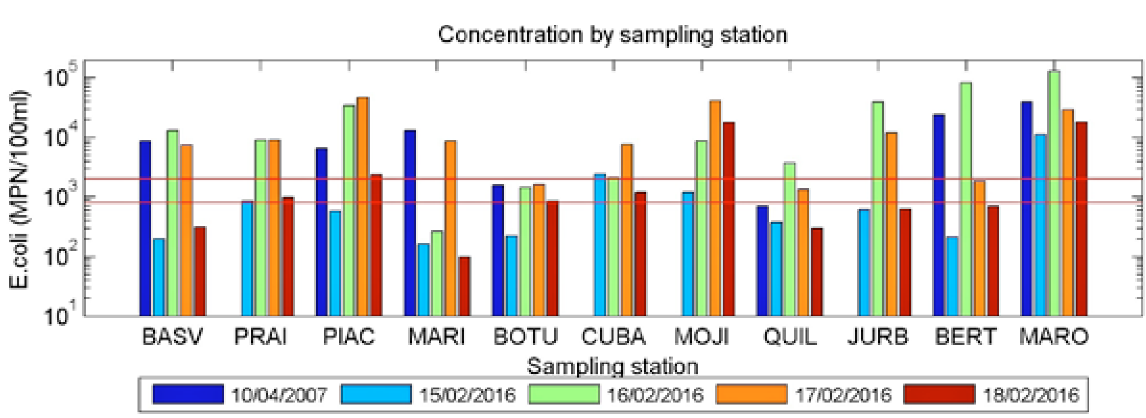

Figure 6: *E. coli* concentration at stations sampled between 15 and 18 feb 2016, and also sampled 10apr2007 (dark blue). Red lines represent the thresohlds of 800 and 2,000 MPN/100ml.

CONCLUSIONS

Data analyzed showed a positive evolution of the sewerage system to the population between 2004 and 2014. However, its universalization is yet to occur, foreseen for 2025, with the conclusion of the second phase of the Onda Limpa Program. Among the four most populous sub-basins, each one holds about 90,000 people without a sewerage system, considering urbanized and irregular areas. This factor, added to a high level of rainfall in the region still incurs the poor water quality in the studied sub-basins. Thus, besides the universalization of sewerage system and land regularization, needing further assessments of the impact of diffuse pollution on the SSVES and mitigating actions of this impact.

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Modeling Extreme Conditions of Sewage Plumes in Central – South Coastal Region of São Paulo State – Brazil

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ABSTRACT

The study region is located in the central-south coast of Sao Paulo State (Brazil), centered at 24.5°S - 46.5°W, and is influenced by three outfalls of the city of Praia Grande and sewage releases by Itanhaem River. The objective of this study is analyzed the dispersion of effluent plumes emitted by the submarine outfalls and the Itanhaem River, concerning the concentration of contaminants in extreme conditions (summer month). For that, Delft3D model's hydrodynamic and water quality modules were used, as well as the Visual Plumes model. Results of hydrodynamic simulations were consistent with the hydrodynamics features established in the literature. The near-field modeling showed the influence of currents in the transport and initial dilution of effluent plumes. The far-field modeling's results of the plumes from the submarine outfalls and Itanhaem River showed that those plumes do not exceed the maximum levels established by the National Environmental Council when reaching the shore. Once observations indicate that the local beaches are often classified as inappropriate for bathing and with bad water quality, streams that dump raw and untreated sewage directly on the beaches can be identified as the responsible for the environmental contamination of the study area shore.

***Keywords**: Marine pollution, submarine outfall, sewage, numerical modeling, water quality, VP, UM3, Delft3D.*

RESUMO

A região de estudo está localizada no litoral centro-sul do Estado de São Paulo (Brasil), centrado em 24,5 °S – 46,5 °W, e é influenciada por três emissários da cidade de Praia Grande e lançamentos de esgoto pelo rio Itanhaém. O objetivo deste estudo foi analisar a dispersão das plumas dos efluentes emitidos pelos emissários submarinos e do Rio Itanhaém, sobre a concentração de contaminantes em condições extremas (mês de verão). Para isso, foram utilizados módulos de qualidade de água e hidrodinâmicas do modelo Delft3D, bem como o modelo Visual Plumes. Os resultados das simulações hidrodinâmicas foram consistentes com as características hidrodinâmicas estabelecidas na literatura. A modelagem de campo próximo mostrou a influência das correntes no transporte e diluição inicial de plumas de efluentes. Os resultados das simula-

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ções de campo-distante da modelagem das plumas dos emissários submarinos e Rio Itanhaém mostraram que as plumas não excedam os níveis máximos estabelecidos pelo Conselho Nacional do Meio Ambiente ao atingir a costa. Uma vez que as observações indicam que as praias locais são geralmente classificadas como impróprias para o banho e com má qualidade da água, o esgoto bruto despejado através dos córregos ou diretamente nas praias pode ser identificado como o responsável pela contaminação ambiental da costa na área de estudo.

Palavras-chave: poluição marinha, emissário submarino, esgoto, modelagem numérica, qualidade da água, VP, UM3, Delft3D.

INTRODUCTION

In outfalls, usually the sewage passes through only preliminary treatment, with subsequent disinfection with chlorine. However, when dumping untreated sewage, the sea allows dilution. After the sewage is dumped into the marine environment, either by a submarine outfall or through streams that flow into the sea, the mixture of effluents then occurs. In the case of emissaries, the mixture takes place in three zones, with different spatial-temporal scales: near field, intermediate field and far field (Lamparelli, 2007; Harari et al., 2013; Gregorio, 2009; Delfim, 2011; Subtil, 2012).

The region of near-field has interactions with the surface, the pycnocline region and the bottom, with great influence of physical processes and pipe diffusing features, which can significantly affect the initial mixture. In the near field, the spatial scale is of the order of 10 to 100 m, while the timescale is in the range of seconds to minutes.

The region of intermediate-field is the zone of stability between the regions of near and far fields, and has a dynamic dependence on the momentum and buoyancy forces of sewage discharge and the local current intensities. Its spatial and time scales are typically from 100 to 1000 m and from minutes to hours, respectively. From that point, with the hydrostatic equilibrium achieved, is characterized the presence of the far-field region, where the effluent begins to behave like a plume, whose dispersion is controlled by advection and diffusion processes. In the far-field, the spatial scale is approximately 10^3-10^5 meters while the time scale ranges in order of hours to days.

The near-field models are used to simulate the mixing processes in the initial release region, being dependent on both environmental factors (such as intensity of currents, stratification of the water column and the sea turbulence), as well as releasing features (number of emitting orifices, their dimensions, etc.). Moreover, far-field models are used to simulate the dispersion of sewage without the need to take into account how is performed their release into the marine environment, being used for simulations of effluent dispersion in coastal regions and estuaries, starting from previously obtained results of near field models (Delfim, 2011).

In the study region, centered on 24.5 ° S 46.5 ° W, are installed three outfalls, all in the municipality of Praia Grande, called Praia Grande I (PG 1, 24.01°S 46.40°W), Praia Grande II (PG 2, 24.05°S 46.44°W) and Praia Grande III (PG 3, 24.09°S 46.53°W) (SABESP, 2010).

However, the cities of Peruibe, Itanhaem and Mongaguado not have outfalls, and discharge part of their wastewater without any proper treatment, directly into streams, estuaries and the sea (Jakob, 2002). One of the main destinations of these effluents is the Itanhaem River (24.20°S 46.80°W), whose estuary has typical vegetation of mangroves and is greatly influenced by the sea (Souza Pereira & Camargo, 2004).

OBJECTIVES

The main objective of this study was to analyze the dispersion of the effluent plumes emitted by outfalls of Praia Grande and the Rio Itanhaem, through numerical modeling.

METHODOLOGY

Delft3D is a model used to perform numerical simulations, determining spatial and temporal variations and interactions between hydrodynamic phenomena, sediment, ecology and water quality, especially in natural environments such as coastal regions, rivers and estuaries, but also in artificial coastal environments, as ports and docks (Deltares, 2013).

It was established in Delft3D (D3D) a grid model to cover the region of interest for the hydrodynamic modeling, in spherical coordinates, type C of Arakawa (Mesinger & Arakawa, 1976). This computational grid contains 227 by 227 horizontal cells, being inclined at 45° counterclockwise with horizontal spacing of 350 m, and vertical spacing comprising five equidistant sigma layers (Harari et al., 2006).

The water quality module Delft3D D3D-WAQ allows physical and chemical processes specific to each pollutant to be activated independently, aiming the creation of scenarios to represent real dispersion and decay of pollutants into the environment (Deltares, 2013a).

Visual Plumes software (VP), Version 1.0, was used (Frick et al., 2001; Frick, 2004), for modeling the near and intermediate field due to sewage discharge from the three emissaries, more specifically, its module Three Dimensional Updated Merge (UM3). Mixing processes in the initial region were simulated from: technical information of the outfalls; concentration values and decay of the concerned pollutants; and results of D3D-FLOW in hydrodynamics characterization of environment where sewage plumes were released.

The UM3 is a Lagrangian 3D model of initial dilution of the plume, through the equations of conservation of mass, horizontal momentum and energy; UM3 performs near-field and intermediate- field simulations of plumes derived from ocean outfalls (Baumgartner, Frick & Roberts, 1994).

The fecal coliform pollutant Escherichia coli (E.coli) were selected for this study. The upper limit for a coastal water to be considered as appropriate for bathing, as function of E.coli concentration, is 800 MPN / 100ml, in at least 80% of the samples (BRASIL, 2001).

Information of concentrations of the pollutants discharged by outfalls were obtained from SABESP (2010), IBGE (2015), Marcellino (2004) and Macedo et al. (2009); details can be found in Yang (2016).

Values of concentrations of pollutants released by Rio Itanhaem were obtained in Quiñones (2000), for the periods of summer (January and February) of 1998. The release of pollutants was continuous and constant along time. Temperature and salinity values were obtained at the river mouth following Souza Pereira & Campbell (2004). On the other hand, values of the average monthly discharges of Rio Itanhaem were obtained in DAEE (2015).

The hydrodynamics and the near, intermediate and distant field modeling was performed to

February 2012, considered an extreme case because it is a summer month, with a large number of tourists. As the research aimed to monitor the pollution plumes only due to the outfalls of Praia Grande and Rio Itanhaem discharge, it was used, as an initial condition, zero concentration values across the entire grid.

RESULTS

In this section will initially be presented a selection of modeling results of plumes, referring to the near and intermediate fields (VP model results), for February 2012, with angular histograms of dilution, travelled distance and concentration of E. coli (Figure 1).

Next, time series of *E.coli* concentrations, at the surface and the bottom, are presented in Figures 2 and 3, as given by the far-field modeling results for February 2012. Finally, Figures 4 and 5 show distributions of E. coli at the surface and bottom, in the periods of maximum values in Praia Grande and Rio Itanhaem, in February 2012.

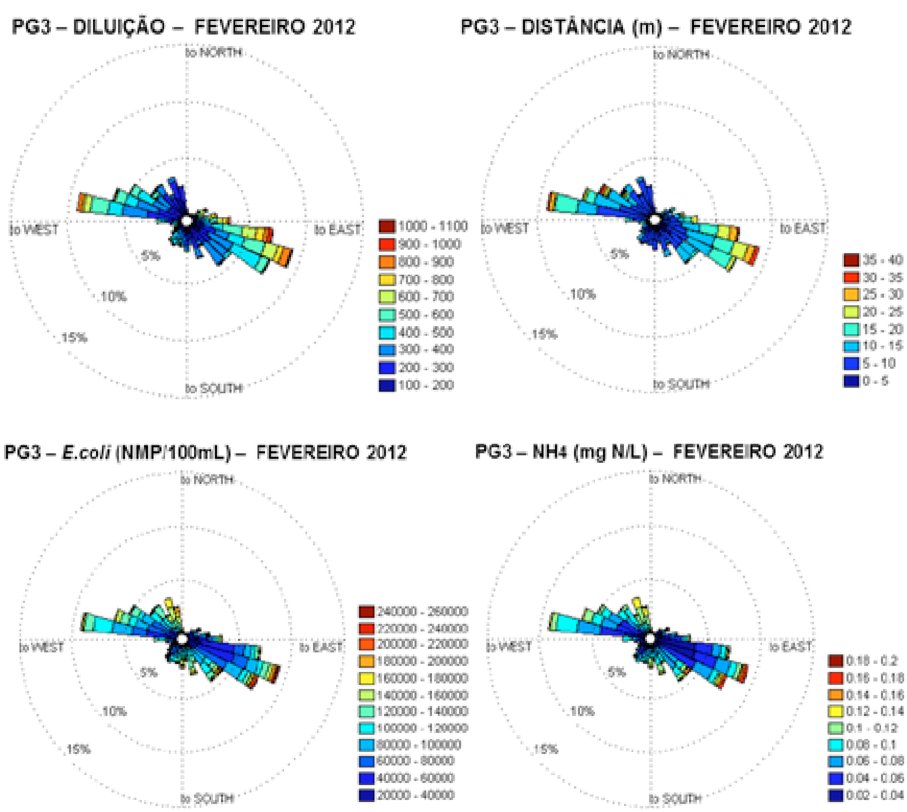

Figure 1: Angular histograms of dilution, travelled distance and concentration of E. coli plumes of PG3 emissary to each of its diffusers, in February 2012.

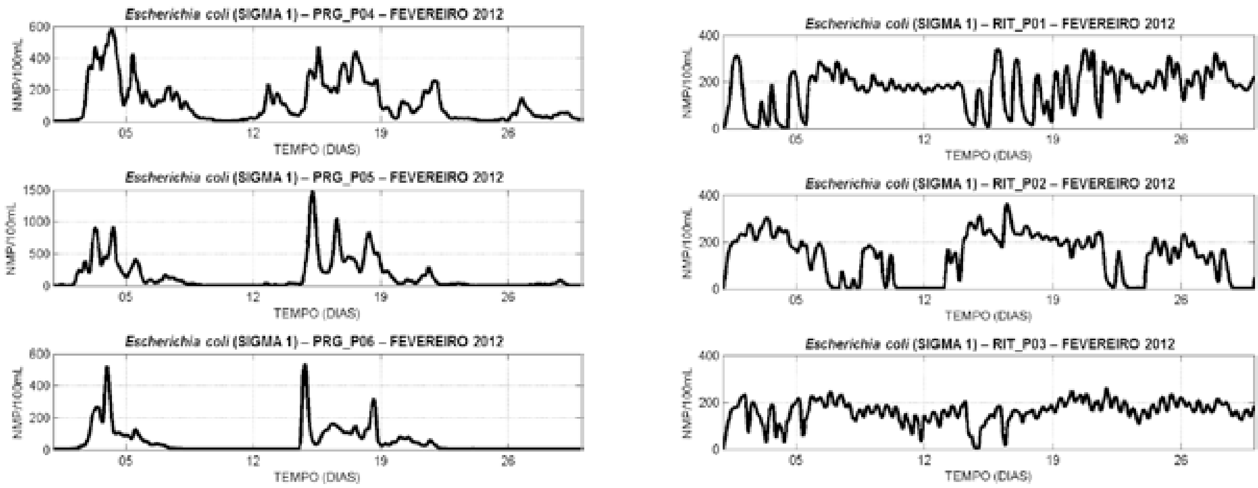

Figure 2: Time series of E. coli at the surface, in points PRG_P05 (24.40°S 46.45°W) and RIT_03 (24.20°S 46.78W), for the month of February 2012

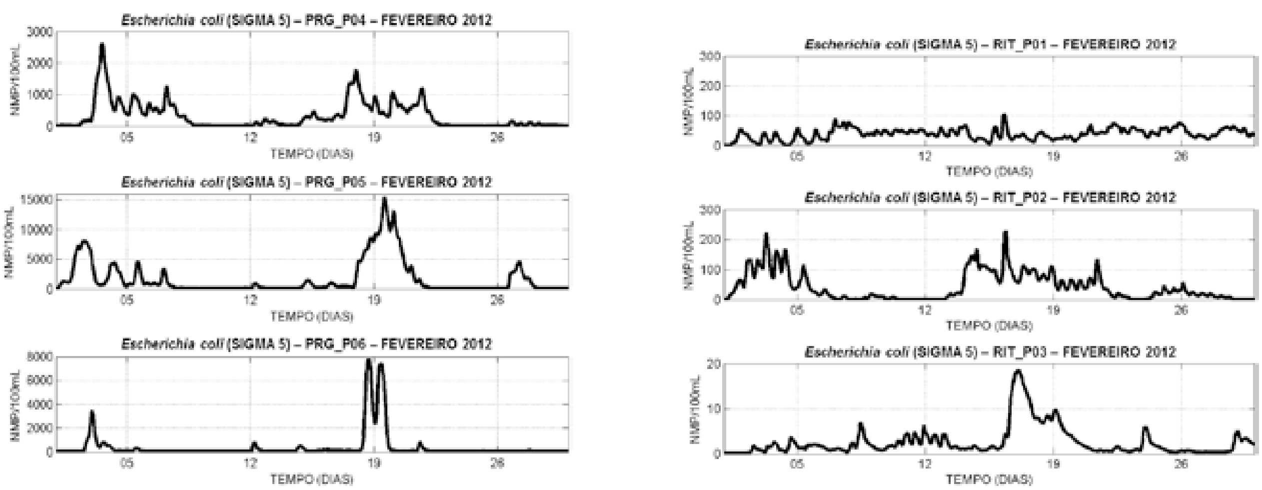

Figure 3: Time series of E. coli on the bottom, in points PRG_P05 (24.40°S 46.45°W) and RIT_03 (24.20°S 46.78W), for the month of February 2012

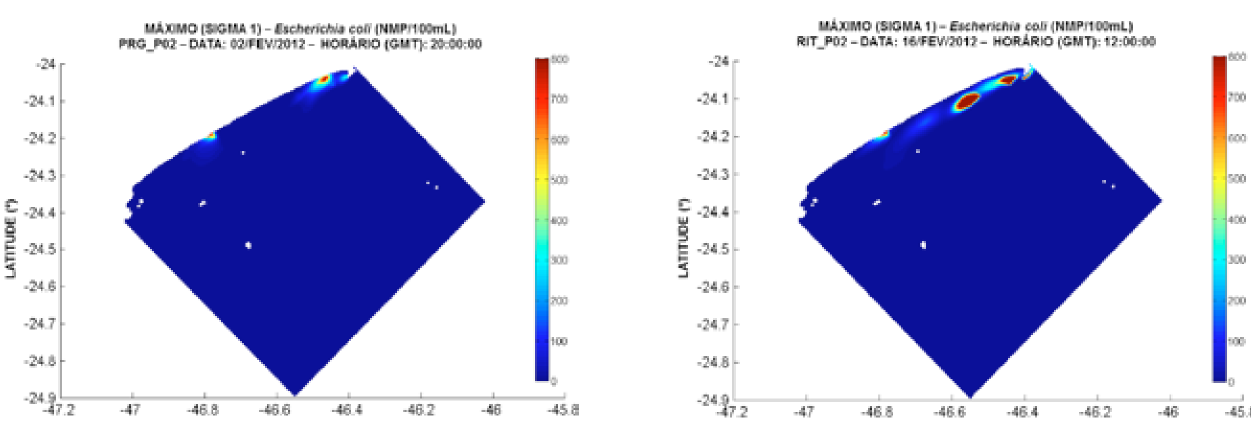

Figure 4: Distributions of E. coli at the surface, at the period of maximum values in Praia Grande (above) and Rio Itanhaem (below), in February 2012.

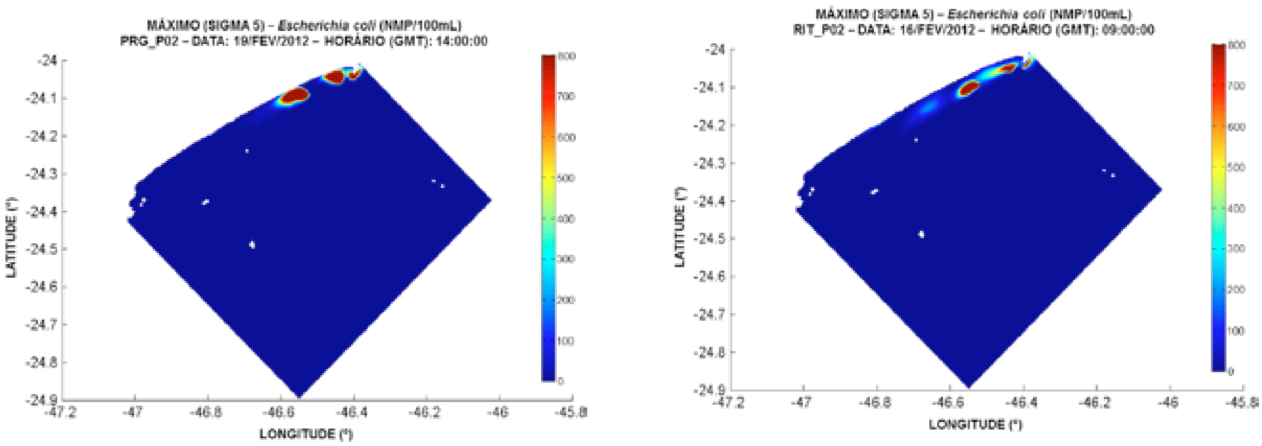

Figure 5 - Distributions of E. coli on the bottom, at the period of maximum values in Praia Grande (above) and Rio Itanhaem (below), in February 2012.

DISCUSSION

The maps of pollutant plumes distribution show that the entire coastal strip, until approximately the depths of 25 to 30 m, is subject to the impacts of effluent plumes coming from Praia Grande emissaries and the mouth of the Rio Itanhaem, both in surface layer and the bottom layer.

As for time series and statistical calculations, concentrations were reported for Escherichia coli above 800 MPN / 100ml limit in most cases, much of simulated time, in points located between the outfalls as well as at points located in their vicinity.

In points located on the beaches of the municipalities of Praia Grande and Itanhaem, no model result exceeded the *E.coli* limit of saline water Class 1 considered as appropriate for bathing. This is because the concentration of a pollutant decrease due to the dispersion of the plumes, so the tendency is to occur a gradual reduction of the concentration of coliforms according to the distance covered by the plumes; in fact, there is a high dynamism of the sewage purification process (Ferreira, 2015), which in the case of fecal coliforms is a function of incident solar radiation, chlorinity and temperature of seawater. As for the area near the mouth of the Rio Itanhaem, besides the resulting plumes of Praia Grande emissaries are already with significantly reduced coliform concentrations to reach this area, the river plume has less potential pollution plumes than of the three submarine emissaries, due to the initial values of *E.coli* considered.

Monitoring of beaches of the municipality of Itanhaem, carried out by CETESB (2013), showed the same percentage of time with adequate water quality as given by D3D-WAQ results. However, the model results and in situ sampling on the beaches of Praia Grande did not agree, and one possible explanation for this discrepancy is that the simulations in D3D-WAQ model considered as polluting sources only the three outfalls of Praia Grande and the Rio Itanhaem discharges, while the in situ samples had the influence of other sources of pollution in the coastal region, such as streams that dump raw sewage directly into the Praia Grande coast (SABESP, 2010). When pollution of these streams joins with the plumes of the emissaries, results an increased concentration of coliforms, which can exceed the bathing limits, making the beaches improper for use by bathers.

CONCLUSIONS

According to the annual reports of beaches quality of Sao Paulo State, published by CETESB (2013), the Praia Grande, Mongagua, Itanhaem and Peruibe beaches have registered improper conditions of bathing, especially during the summer months. The use of D3D-WAQ model, together with the hydrodynamic results of D3D-FLOW, for monitoring the dispersion of plumes of emissaries PG1, PG2 and PG3 and Rio Itanhaem, showed that their plumes hit the coast until the depths of about 25 to 30 m. However, pollution from such sources at local beaches does not exceed the limits of bathing, being above the limit values only near the outfalls. Therefore, one can say that the Praia Grande outfalls are well sized and operate correctly, and, along with the Rio Itanhaem, cannot be considered as responsible for improper bathing beaches in the region.

In the case of Praia Grande, where bathing in general remained improper in most of the beaches in the summer of 2012 (CETESB, 2013), the 10 streams that flow directly in the coastal area of the city can be considered as the major responsible for pollution and poor water quality in its coastline, as they bring raw and untreated sewage directly to the beaches (SABESP, 2010).

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Combining measurements, models and decision support systems to optimize outfall sitting

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ABSTRACT

Santa Catarina Island is located in Southern Brazil and is a touristic spot of the country due to its beautiful beaches. Population growth and seasonal variability demand an improved sanitation system, to be provided by the local government. This paper presents the methodology used to define the optimal design for the wastewater management system for the northern part of the Island. TOPSIS methodology was used to rank the 42 possible alternatives. Subsequently, a 3D hydrodynamic model was implemented which was calibrated and validated for one year using measured oceanographic data. Afterwards, a near-field model was used to evaluate the dilution of each location and to set up the input concentration data for the far field water quality model to analyze the dispersion of nutrients, BOD and bacteria in order to assess each alternative regarding the environmental legal requirements. Results show that the method was able to find optimal solutions out of dozens of alternatives, and thus provides guidance to decision makers, sanitation and environmental agencies, and stakeholders.

Keywords: field measurements, hydrodynamic models, near-field, far-field, TOPSIS, outfall, discharge, water quality

RESUMO

Localizada ao sul do Brasil, a Ilha de Santa Catarina é uma atração turísticas do país devido suas belas praias. O crescimento populacional e a variação sazonal exigem o aperfeiçoamento do sistema de saneamento, proporcionado pelo governo estadual. O artigo apresenta a metodologia para definir a melhor configuração para o gerenciamento do sistema de águas residuárias da parte norte da Ilha. A metodologia TOPSIS classificou as 42 alternativas possíveis. Na sequência, o modelo hidrodinâmico 3D foi implementado, calibrado e validado para um ano a partir de dados oceanográficos medidos. Posteriormente, um modelo de campo próximo foi utilizado para a avaliação da diluição de cada local, e para definir a concentração dos dados de entrada do modelo de qualidade de água no campo afastado, a fim de analisar a dispersão de nutrientes, DBO e bactérias para determinar a performance de cada alternativa de acordo com as condições legais do meio ambiente. Os resultados mostrem que a metodologia apresentada foi capaz de identificar soluções otimizadas e assim servir para tomadas de decisão.

Palavras-chave: medições em campo, modelos hidrodinâmicos, campo próximo, campo afastado, emissário, descarga, qualidade de água

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INTRODUCTION

Despite of coastal water quality problems being studied since decades and solutions exist for their mitigation, major large water projects in coastal regions, such as marine outfall systems and wastewater treatment schemes are experiencing considerable delays in commissioning (Bleninger, 2012). For example, objections in Australia and the USA regarding environmental impacts have already become key issues for project permits, often considerably influencing plant commissioning and design (e.g. Huntington Beach, or Carlsbad, www.carlsbaddesal.com), and thus overall project costs. Henry Salas, formerly of the Pan American Health Organization (PAHO) showed in his keynote at the International Symposium on Outfall Systems in Mar del Plata, Argentina (see IAHR/IWA Joint Committee on Marine Outfall Systems, and Bleninger and Roberts, 2012) that many coastal wastewater projects in Latin America did not yet conclude their outfall system. More than 10 large-scale projects (each more than 1 million population served) were mentioned where almost completely raw sewage has been continuously discharged at the shoreline for more than 10 years due to these delays. Such problems of water projects seem to be mainly related to political and administrative problems, but often also to poor understanding of those systems.

There is often a misconception that treatment results in a 'pure' and 'clean' effluent which can be discharged directly on the shorelines or beaches. However, bacteria concentrations even of tertiary treated effluents are still order of magnitudes above bathing water limits (see Table 1).

Table 1: Discharge concentrations and ambient standards in comparison with required dilutions according to typical concentration reductions of treatment levels. Source: Bleninger (2006) - Adapted

	Raw sewage concentration (Sperling, 2014)	Ambient Standard (AS) (World bank, 2007)	Required Dilution	Required Dilution After Primary Treatment	Required Dilution After Secondary Treatment	Required Dilution After Tertiary Treatment
BOD [mg.L^{-1}]	300	30	10	8	2	1
Total Nitrogen [mg.L^{-1}]	45	10	5	4	4	0
Total Phosphorus [mg.L^{-1}]	7	2	4	3	3	0
Total suspended solids [mg.L^{-1}]	1100	50	22	9	3	1
Total Coliform [MPN.(100 mL)$^{-1}$]	10^6 - 10^{10}	400	25000 - $2.5x10^8$	1250 - $1.25x10^7$	10^3 - 10^7	500 - $5x10^6$

Dilution is herein defined by the concentration decay of a solution by the increase of its solvent. It happens when a wastewater treatment effluent is discharged by an outfall. The dilution of a conservative effluent (no decay processes) in an environment with a background concentration is defined by:

$$S = \frac{c_0 - c_a}{c - c_a} \quad (1)$$

Where the dilution *S* is dimensionless, c_0 is the concentration of the solution that will be diluted (in this case the effluent concentration), c_a is the ambient background concentration and c is the observed or required concentration (after the dilution, or ambient standard).

Consequences of the misconception are thus often overly expensive wastewater systems, which themselves not necessarily solve the water quality problems. This happens when either the technology blend of the system (treatment and outfall) is not properly designed or further pollutant sources (such as drainage systems with illegal sewer connections or diffuse sources) were not considered in the whole scheme. Thus, purely treatment based solutions oversee the potential and necessity for a more holistic approach. The trend is clear, however, and should not be about competing systems but blended system with optimized combination of collection, treatment, and disposal.

The objective of this article is to illustrate how decision-making processes can be based on hard facts and objective analysis for choosing the best technology blend for wastewater management systems in coastal cities.

METHODOLOGY

The methodology used is a tiered approach starting with i) a screening phase to define feasible alternatives (see below), followed by ii) a measurement phase characterizing the current situation and boundary conditions (next chapter). The phase of field studies is complemented in parallel with the development and calibration of numerical models representing the current situation (basecase). In a third phase iii) all scenarios are simulated (third chapter) and analyzed in a fourth phase regarding their iv) compliance with environmental and cost-benefit criteria.

The environmental guidelines used in this study are based on Brazilian legislation, namely Conama 357/2005, supported by Conama 274/2000 and amended by Conama 430/2011.

SANTA CATARINA ISLAND

Santa Catarina Island is located in the Florianópolis municipality, capital of the State of Santa Catarina in south Brazil. It has an area of approximately 425 km^2, 54 km length from north to south and 18 km width (Figure 1A). The island has a population of 589,720 inhabitants, which can reach almost 1 million during the summer (IPUF, 2007); Florianópolis is well known as one of the major touristic attractions of the south of Brazil, mainly due to its beautiful beaches and landscapes. Besides tourism, fisheries and aquiculture represent important economic activities, since Santa Catarina is the national leader on oysters and mussels' production. Therefore, Florianópolis bays are important contributors (Santos & Costa, 2014). The city is surrounded by several important environmental preservation areas such as mangroves, dunes and islands, especially the Arvoredo marine biological reserve located 10 km north.

In 2010, only 39% of the population was attended by wastewater service, which could drop to 26% in the summer season (PMF, 2011). CASAN targets to designate significant investments in order to have 100% wastewater service until 2030.

This paper focuses on solutions for the northern part of the island (Figure 1B), where the hot spots for touristic and aquaculture activities are located, and where coastal pollution problems a more severe.

SCREENING OF ALTERNATIVES

In order to support the decision making process to define the optimal design for the outfall system (collection, treatment, disposal), there were considered several relevant factors such as the current sanitation infra-structure, population growth estimation, social aspects, cost analysis and potential environmental impacts. There were considered three different wastewater treatment systems: primary, chemically enhanced primary and secondary treatment, followed by either a short or long outfall at three potential locations (Canasvieiras, Ingleses and Rio Vermelho, Figure 1D), resulting in 42 possible alternatives. In order to evaluate the alternatives, the TOPSIS methodology (Aruldos et al., 2013) was applied, which represents a multi-criteria decision making approach based on similarity to an ideal solution (Falkenberg et al., 2016). The results showed (in detail in Falkenberg et al., 2016) that the TOPSIS criteria ranked three best alternatives overall and the best alternatives for each location to be evaluated in more detail with field-studies and near field and far field numerical modeling.

Regarding engineering, social, environmental and economic aspects, the following criteria were considered:

- Construction site access (engineering) → evaluate the difficulty of pumping wastewater effluent from treatment plant to ocean disposal site;
- Influence on aquaculture (social and environmental) → linear distance between diffuser to aquaculture area;
- Initial dilution potential (engineering and social);
- Proximity to Arvoredo Marine Biologic Reserve (environmental);
- Wastewater Treatment solution (environmental)
- Coastline plume proximity (social);
- Construction complexity due to depth (engineering);
- Global Outfall cost (economical);
- Global cost regarding wastewater conveyance from main wastewater treatment plant(s) to outfall (economical).

In order to attribute scores to each criterion referred to each alternative, the state sanitation company CASAN (Companhia Catarinense de Águas e Saneamento) invited 43 employees from different company areas, including environmental, technical, management, economical and operation sectors, which results indicated that several individual outfall systems were not cost attractive, corroborating Roberts et al. (2010), and the best ranked solutions over all were:

- Rio Vermelho: long, secondary treatment;
- Rio Vermelho: long, chemically enhanced primary treatment;
- Rio Vermelho: short, secondary treatment.
- The best alternatives for each location were:
- Canasvieiras: long, secondary treatment;
- Ingleses: long, secondary treatment;
- Rio Vermelho: long, secondary treatment.

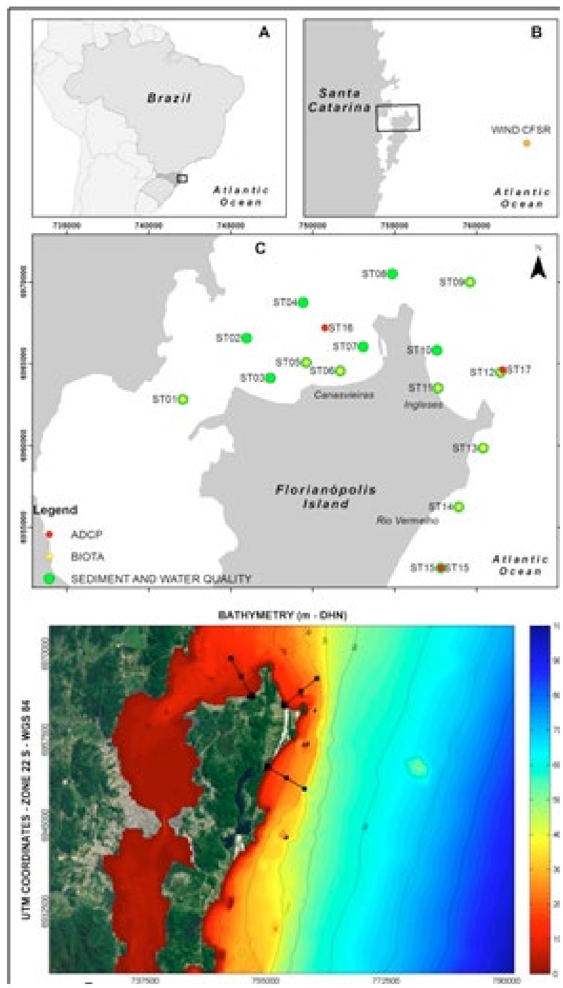


Figure 1: A - Location of Santa Catarina Island. B -North of Santa Catarina Island. Figure also shows wind data location. C - Locations of data sampling. Red dots for ADCP stations (current profile, temperature at depth, wave and sea level). Green dots for Sediment and water sampling stations. Yellow dots for biological samples. . D- Possible locations of the submarine outfall system (black lines and dots) and bathymetry (UTM Projection, Zone 22s, WGS 84).

FIELD MEASUREMENTS

Large and intensive field studies have been performed by CB&I under contract of CASAN (Barletta et al., 2016). Biological, chemical and physical parameters were analyzed at over 15 stations (see Figure 1C), comprising two campaigns per season. Aiming to characterize physical oceanographic conditions measurements during more than one year were performed to understand the behavior of waves, tides, currents and water properties. Therefore, three ADCPs (Acoustic Doppler Current Profiler), one for each proposed location (ST15 - Rio Vermelho, ST17 Ingleses ST16 Canasvieiras, see Figure 1C) were deployed. Deployment depths were approximately 28, 13 and 16 m respectively. These devices were installed on the seabed inside a structure with the transducer facing up (upward-looking) in order to perform measurements of the vertical velocity profile (1m per cell) and measuring the waves with an AST sensor, sea level with a pressure sensor, as well as temperature. The ADCPs were configured to acquire information at 30 minute sampling interval. For measuring wave, data was acquired for 20 minutes at every hour in an acquisition rate of 2 Hz (0.5 s).

The analysis of currents (see Figure 2B) for ST15, the most exposed station located at Moçambique's beach inner shelf, shows that the average directional axis of the water column flow measured was 15° from the north, aligned to local isobaths. The maximum speed of the integrated current reached 0.77 m/s, however 75% of the analyzed data were equal to or below 0.21 m/s with the average velocity of currents of 0.15 m/s. Over 57% of current measured occurred from northern to the southern quadrant (average of 184° N). Forty three percent (43%) of current occurred in reverse direction (average of 27° N). The mean axis of movement of the current happened between 8° and 22°, where the direction of the prevailing flow varied between measurement periods. In general the currents from south to north measured were associated with cold front events, while the flow in the opposite direction was observed for intervals between these fronts. The greater intensity currents were observed in winter with the average speed of 0.21 m/s, while the less intense were measured in summer, with an average speed of 0.09 m/s.

At ST16 there was flow predominance from northeast to southwest, recorded in 55% of the measured currents, to an average direction of 226°. Conversely it was found 45% of the measured data, flowing towards a direction of 56°, resulting in a mean axis of the current of 51°. The maximum speed of the mean currents along the water column reached 0.49 m/s, however 75% of the data were below 0.15 m/s with an average rate of 0.11 m/s. The pattern of currents was similar in all layers of the water column and differences between bottom stream velocity and surface are higher for currents from southwest to northeast (ebb tide) than for northeast to southwest (flood tide). The greater intensity was observed in summer and the slowest in spring. The mean axis of movement of currents varied between 48° and 53°.

The annual pattern of currents for ST17 (Ingleses) showed dominant axis from northwest to southeast at an approximate average of 112°, present in about 60% of the data. Forty percent (40%) of the remaining data showed the reverse direction, with a flow towards 316°, resulting in an average axis of 124°. This station showed the most intense currents, reaching maximum speed of 0.81 m/s. However, 75% of the data presented magnitudes equal to or less than 0.25 m/s, with an average speed of 0.18 m/s. The middle axis of movement of the currents ranged between 121° and 125°, aligned with the morphology of the seabed. The direction from the main stream was from northwest to southeast, except for the autumn.

For the meteorological characterization, the directional distribution of the winds offshore Florianópolis was obtained through CFSR reanalysis data (Saha et. al, 2010) for the period between 2001 and 2014. Seasonality of fourteen year of data was then compared with the seasonality of the year for what measurements were performed (2013 to 2014). Figure 1B shows CFSR coordinate used to extract wind information.

The wind analysis results show the predominance of the northeast winds with a larger number of occurrences from this quadrant, although winds from south and SW show the higher intensities. The accumulated directional distribution for the monitored year for the present work are shown in Figure 2A and showed to be very similar to the data set of 14 years. Extreme events occurred almost exclusively with southern and southwestern winds. The results agree with previous climate descriptions for the area. Figure 2B illustrates 2014 currents integrated at the water column for each sample station.

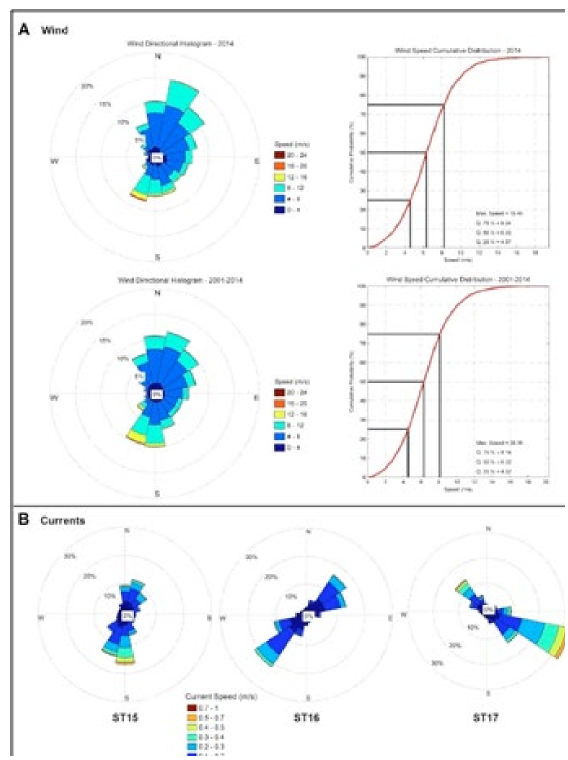


Figure 2: A- Analysis of wind measurements. B-Measured coastal currents at the three potential outfall locations.

Figure 3 shows an example of the processed tidal data of all seasons for sampling station ST15 (Moçambique). Meteorological tide is represented by the red lines. In general terms, the tide is mixed with predominance of semi-diurnal tides with inequalities of height and also diurnal variations (0,25<Courtier<1,5), micro tide system of the order of 1 m. The data is in agreement with literature about the "Meteorological tide", that plays an important role to sea-level variations at southern

Brazil (and also as upwelling mechanism), which causes sea level oscillations from -60 cm to 60 cm around mean sea level. To separate the meteorological tide from the sea level data and to calculate the Courtier number a harmonic analysis was carried out (Barletta et al., 2016).

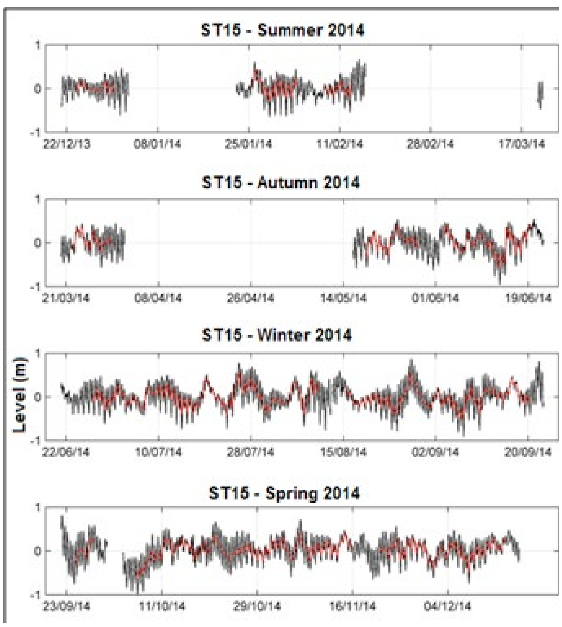


Figure 3: Example of tidal signal for ST15 (in red meteorological tide).

To obtain vertical profiles of salinity and temperature, CTDs were used at the campaigns. Measurements of salinity and temperature profiles were performed at 15 locations (see Figure 1C) over one year with two campaigns per season, from spring of 2013 through spring of 2014. From the total of salinity and temperature data obtained by profiles during the campaigns, a TS diagram was generated for the characterization of water masses in the region, using as a benchmark the work of Castro et al. (2006).

The presence of four masses of water was found by the thermohaline characteristics measured at the study area. The conditions during the spring and summer period were characterized by the interaction of at least three water masses, with ACAS (Portuguese acronym for Central Water of South Atlantic) occurring in the lower vertical extracts and AT (Tropical Water) occurring at the upper extracts especially at sample points 8, 9, 12 13, 14 and 15 (see Figure 1C). The same occurs at ST10 and ST11, but only in one sampling campaign. Such a thermocline has not been verified at stations 3, 4, 5, 6 and 7, thus showing no intrusion of denser water masses from deeper layers. It was found that the AC (Coastal Water) occurred in the surface layers of these and other points, being sometimes influenced by fluvial discharge that was able of reducing 5 PSU from the salinity of surface, mixing with the AP water mass (Platform Water), which was present especially in autumn and winter.

NUMERICAL MODELING

The processes of substance mixing, transport and degradation resulting from wastewater systems in coastal regions can be divided in two regions: near and far field. The first one is the zone of initial dilution, where the effects of the discharge prevail. The second is the region where the dynamics of the water body, as tidal currents, as well as bio-chemical reactions and substance degradation, govern the plume water quality behavior. The different dynamics of near and far field implies the necessity of distinguished models.

LARGE SCALE COASTAL WATER QUALITY MODELING (FAR-FIELD)

For the far field numerical modeling the Delft3D-FLOW model (Deltares, 2011a) was used. The hydrodynamic model was set up with 5 vertical sigma layers, including the processes of winds, salinity and temperature. The model was forced with predicted astronomical tide, measured winds, precipitation, fluvial discharges and meteorological tide, and salinity and temperature data provided by the global ocean model Hycom (Hybrid Coordinate Ocean Model). The model was run for one entire year. Water level and currents were calibrated and validated with measured data of the three ADCP stations, and salinity and temperature profiles were validated using the 15 measurementt stations. Figure 4 illustrates the hydrodynamic validation results for station 17 (Ingleses), for the surface layer during fall season.

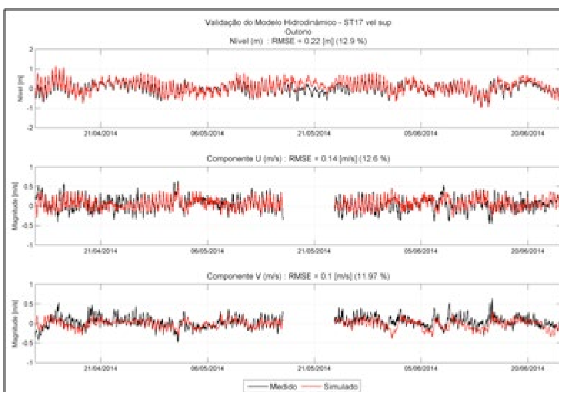


Figure 4. Hydrodynamic validation results for station 17 (Ingleses), Surface layer, fall season. Water level [m] (superior), U velocities [m/s] (middle) and V velocities [m/s] (inferior). Black – measured; Red – simulated.

DISCHARGE DISPERSION MODELING (NEAR -FIELD)

The outfall is a pipeline or tunnel from the wastewater treatment plant to the receiving water, which terminates in a diffuser that efficiently mixes the effluent in the receiving water. It thus follows two main principles: (1) locate the disposal area into environmentally less sensitive, and antropogenically less used, offshore regions, which in addition have higher mixing and assimilative characteristics, and (2) enhance the initial mixing by multiport diffuser systems, providing efficient and fast initial mixing in a limited zone that reduces pollutant levels to ambient standard requirements, and facilitates the natural assimilative processes.

The mixing zone expert system CORMIX (DONEKER, R.L. & JIRKA, 2007) has been used in this study. Based on an integral method for near field, it contemplates situations of single port, multiport diffusers and surface discharges. It was developed in cooperation of several institutions, among them the U.S.EPA (Environmental Protection Agency), Cornell University, Oregon Graduate Institute and MixZon. It makes qualitative analysis with length scales (empirical method, where the boundaries are considered) selecting a - flow class that can identify a key aspect. The quantitative analysis is made by the submodule CorJet (Buoyant Jet Integral Model). Besides the plume geometry, CORMIX simulates the initial dilution (DONEKER & JIRKA, 2007).

Due to the process complexities in the near-field the model however considers only steady state conditions, although the environment is unsteady. To overcome that limitation, a time series approach has been employed running the near-field model for hundreds of times. CorTime is the herefore developed post-processing tool of CORMIX.

The far field hydrodynamic numerical model results for one year simulation were used to provide input data to the near field model Cormix. Those were ambient velocity and density distributions.

The main output of CorTime is the Status Report, where the characteristics of the modeled plumes are summarized for each time step. They are the plume central line coordinates at the end of the near field and at the end of the regulatory mixing zone, its dimensions, dilutions, concentrations and the travel time until this point. Those results were post-processed for near-field dilution mapping as shown in Figure 5 for further analysis (Ishikawa et al., 2016).

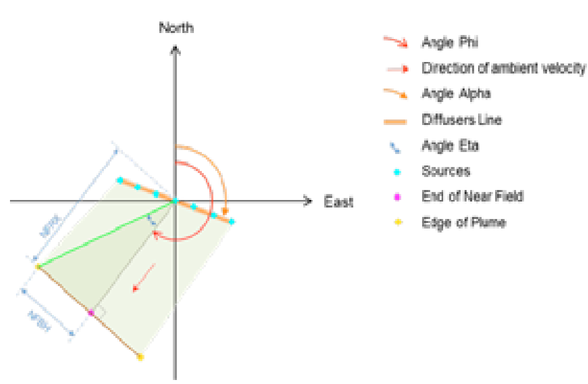


Figure 5: Scheme adopted to interpolate the dilution of plumes at the near field region

The NFRX is the distance from the source to the end of the near field region towards to the ambient velocity (indicated by the angle phi, counted clockwise from the geographic north), and the NFRBH is the half-width of the plume. With these two lengths a right triangle is defined, and the coordinates of the corners are defind. The sources are matched as zero dilution, the corners and the NFRX point are matched with the final solution simulated by CORMIX. After that the dilution of the whole plume is set by a simple interpolation.

RESULTS AND DISCUSSION: ASSESMENT OF ALTERNATIVES

Effective wastewater management systems are combined systems using the optimal technology blend between wastewater treatment and discharge technologies, latter being related directly to the assimilative capacities of the receiving waters.

Depending on the substance of concern, required wastewater treatment levels and discharge dilution rates can vary considerably. Some (such as BOD) can be achieved by treatment or dilution on its own, others, such as bacteria, require a blend of both technologies (see table 1).

NEAR-FIELD MIXING RESULTS FOR ALTERNATIVE WITH PRE-TREATED EFFLUENT

The harmonic mean dilution around the source, resulted from the near field model is visualized in Figure 6. For a long outfall at Rio Vermelho, the mean dilution is 380:1. The last contour line in Figure 6 represents this value. Within an arbitrarily defined regulatory mixing zone of 200m there is at least a dilution of 350:1. The size of this zone is usually defined by regulators, however, often being proportional to several times the local water depth (Bleninger and Jirka, 2011). The dilution requirements (compare with table 1) for all but bacteria were much lower than the computed dilutions showing the effectiveness of the outfall in combination with a large receiving water body.

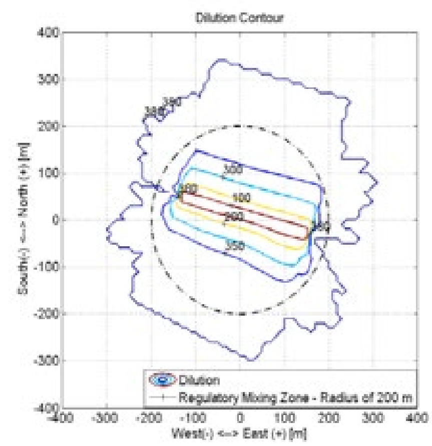
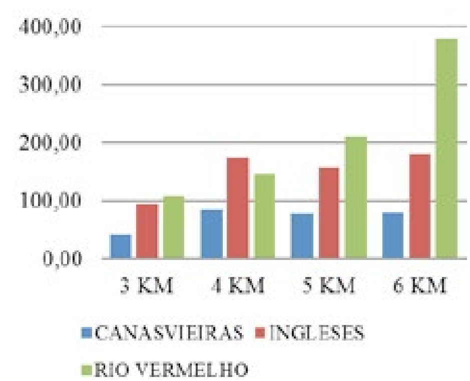


Figure 6: Harmonic mean dilution around the source for Rio Vermelho with a long outfall

This calculation has been applied to all potential alternatives, and results are shown in Graph 1 by comparing only mean dilutions of each alternative.



Graph 1: Harmonic mean dilution for the possible locations of the submarine outfall

To provide further guidance and support for decision making, the exceedance frequency is shown in Figure 7 for a long outfall solution at Rio Vermelho, for BOD. It was idealized that a dilution of 10:1, as shown in Table 1, was necessary to be in compliance with the ambient standards.

The variation of outfall locations using the post-processing method shown here allows to visualize exceedance frequencies of water quality standards for different discharge sites (see Figure 8). Both locations shown were in compliance with the imposed requirements, and the longer outfall showed higher efficiency than the shorter outfall.

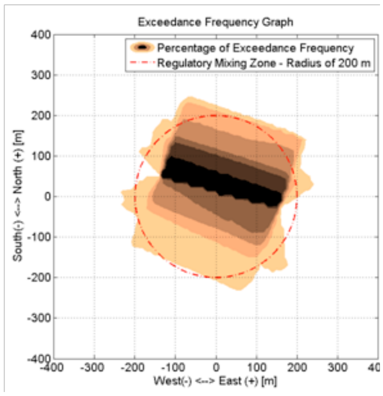


Figure 7: Exceedance frequency for BOD for a long outfall at Rio Vermelho.

Figure 8 : Exceedance frequencies of BOD concentrations for two scenarios with different outfall lengths for pre-treated wastewater discharging at Canasvieras.

However, the results clearly show that the dilution rates are still too low to be in compliance with required dilutions for bacteria. Thus, near-field mixing alone is not sufficient to achieve bathing water criteria. Therefore, an additional analysis is required for the far-field region (i.e. beaches and environmentally protected areas), and including bacterial decay and water quality processes as described as follows.

FAR-FIELD WATER QUALITY MODELING FOR DIFFERENT ALTERNATIVES

Currently there are four wastewater treatment plants in the north of the Island that will be integrated to the outfall disposal system. The E.Coli concentration according to CASAN, for each season (spring, summer, fall, winter) are of the order of 107 and 108 MPN/100 ml E.Coli concentration.

The results from the near-field model were used for the studied cases as source for the water quality model Delft3D-WAQ (Deltares, 2011b), which was applied for the three locations (and a short and long outfall solution) for a one year period to simulate dissolved oxygen, Chemical oxygen demand (COD), biochemical oxygen demand (BOD), nutrients and bacteria (E.Coli), considering primary and secondary treatment based on typical wastewater parameters according to Von Sperling (2005). The processes considered were mineralization of organic matter, reaeration, nitrification and ammonification. Temperature and salinity data inputs were obtained from the hydrodynamic model.

Results for nutrients and oxygen demand indicated a low oxygen demand and compliance with legislation regarding COD and BOD. However, even though the near-field results indicated sufficient nutrient dilution also at Canasvieiras, the nutrient build-up, due to limited flushing capabilities at that location, can be shown in the far-field model indicating the possibility of nitrate and phosphate accumulation inside the northern and southern bay (Figure 9top). Phosphate concentrations consequently are also being higher than required by environmental legislation. Thus, Canasvieras site has been discarded as alternative.

Figure 9 shows the results for phosphate concentration after 10 months of simulation for Canasvieras and Rio Vermelho for primary treatment and maximum effluent discharge (3,07 m^3/s).

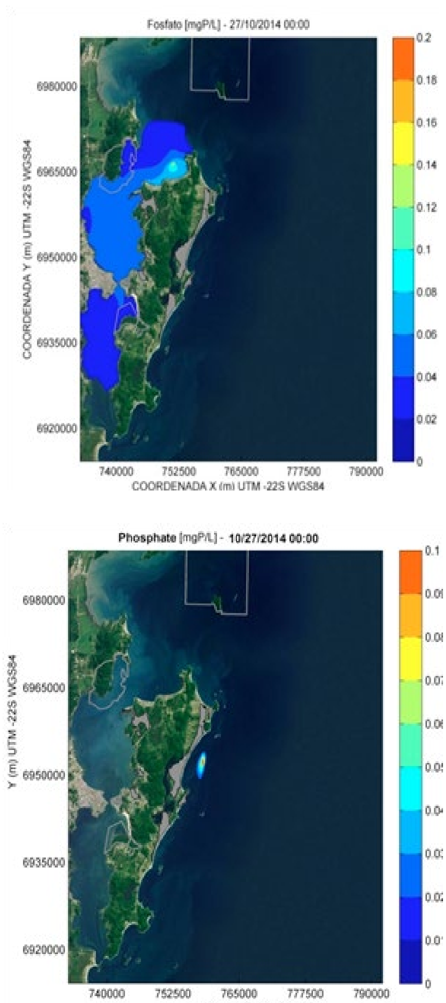


Figure 9. Phosphate concentration after 10 months of simulation for primary treatment and maximum effluent discharge (3.07 m^3/s). Top: Canasvieras. Down: Rio Vermelho.

The bacteria decay simulation using Delft3D-WAQ is done according to the Mancini (1978) formulation. After a sensitivity analysis, it was used a default UV extinction coefficient of 3m-1 and a variable solar radiation based on representative one year measured values.

Brazilian environmental legislation stipulates that at general purpose saline waters E.Coli can be used as a representative parameter, and satisfactory water quality is represented if 80% of the time E.Coli concentrations are lower than 800 MPN/100 ml. In addition, there should be no occurrence of concentrations higher than 2000 MPN/100 ml.

Figure 10 presents probability maps (%) of E.Coli concentrations higher than 800 MPN/100 ml for Ingleses for a discharge of 3.07 m^3/s and an initial E.Coli concentration of 107 MPN/100 ml (primary treatment), with a short outfall. The yellow line indicates an offset distance of 200 meters from the coastline. The red line indicates the furthermost occurrence of 2000 MPN/100 ml E.Coli concentration. Values lower than 1 % were not visualized.

Further simulations were performed extending the outfall length in order to look for a feasible alternative for other treatment levels. However, the results showed that a longer outfall increases the risk of the plume reaching Arvoredo Marine Biologic Reserve, and even higher treatment levels were not able to keep the plume off the coast continuously, as it was possible for a simpler configuration for Rio Vermelho.

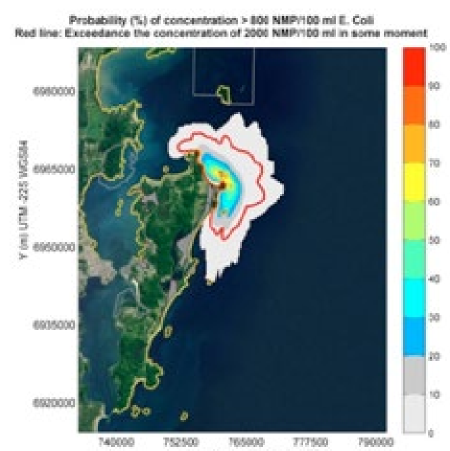


Figure 10. Probability maps results (%) of E.Coli concentration higher than 800 MPN/100 ml for Ingleses, discharge: 3.07 m^3/s; E.Coli effluent concentration: 107 MPN/100 ml (primary treatment); short outfall. Yellow line: 200 meters offset from coastline. Red line: furthermost occurrence 2000 MPN/100 ml E.Coli concentration. Gray color: permitted by environmental legislation.

Figure 11 presents probability maps (%) of E.Coli concentrations higher than 800 MPN/100 ml and a exceedance time map (days) where E.Coli concentrations are higher than 800 MPN/100 ml for discharge of 3.07 m^3/s and E.Coli concentration of

107 MPN/100 ml (primary treatment), with a long outfall at Rio Vermelho. Same in Figure 12 for secondary treatment.

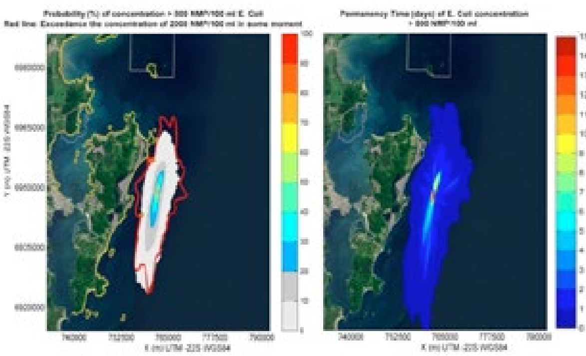


Figure 11. Rio Vermelho probability maps results (%) of E.Coli concentration higher than 800 MPN/100 ml (left) and exceedance time (days) when E.Coli concentration is higher than 800 MPN/100 ml (right). Discharge: 3.07 m^3/s; E.Coli effluent concentration: 107 MPN/100 ml (primary treatment); long outfall. Yellow line: 200 meters offset from coastline. Red line: furthermost occurrence 2000 MPN/100 ml E.Coli concentration. Gray color: permitted by environmental legislation.

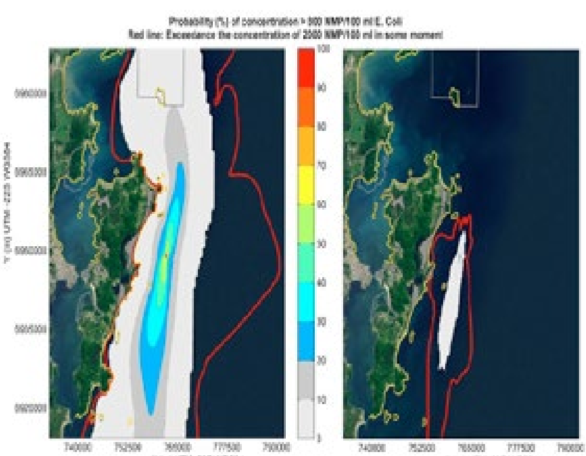


Figure 12. Probability maps results (%) for discharge of 3.07 m^3/s: secondary treatment, and long outfall. Gray color: permitted by environmental legislation.

CONCLUSIONS

The combined utilization of screening methods, field measurements, and numerical modeling techniques showed that there is no unique modeling or design approach, and no unique solution, satisfying all boundary conditions and constraints. However, the combined approach clearly showed strengths and weaknesses of the applied techniques and their advantage when using them together in the decision-making process.

Regarding the studied case of Santa Catarina Island, 42 alternatives have been defined in the screening analysis. The field measurements, complemented with the basecase numerical modeling allowed to understand and quantify ambient water characteristics at the surroundings of the potential treatment and discharge sites. The TOPSIS methodology was efficient in funneling possibilities and showed consistent results compared with the best alternatives obtained after field studies and numerical modeling.

Combined with near field and far field numerical modeling, TOPSIS proved to be an efficient strategy towards a multipurpose best alternative screening. In addition, the participation of several sanitation specialists in the topsis phase provide them to be integrated do the project in a broader perspective and to have a better understanding of each criterias importance in the final decision. Furthermore, the application of multiple analysis (Field measurements, TOPSIS, numerical modeling) and the participation of specialists from different areas, provides more confidence to the decision maker board towards the chosen alternative.

Results indicate are clear tendency to Rio Vermelho being the most effective solution with either a long outfall and primary treatment or a shorter outfall with. secondary treatment. The numerous near-field simulations allowed to optimize the outfall design to achieve fast initial mixing after short regions, achieving dilutions much higher than required for all substances, except bacteria. The far-field water quality simulations used the output from the near-field model to verify flushing and decay characteristics of nutrients, and bacteria for bathing water analysis. The numerical model results provided hereby a deeper evaluation of the exceedance frequency that would not be acquired with standard water quality field measurements.

The results however still require further decision making to find the best blend of minimum required treatment under given and highly variable operational conditions. This final decision depends more on strategical criteria at all levels (sanitation company, state government, environmental agency and stakeholders). It is hereby very important to integrate all in the process towards the final decision in order to combine feasible cost alternatives with minimum environmental impact.

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Prior environmental characterization strategies for outfall systems

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ABSTRACT

Florianópolis is one of the most important touristic cities in the south region of Brazil. Six Wastewater Treatment Plants handles 50% of city sewage treated and disposal into fragile areas such as small rivers, mangroves and near shore locations into sheltered waters. To improve this situation two outfall systems are being planned.
Several aspects must be studied in the planning phase of a sewage project strategy through the construction of new treatment plants and disposal outfall. It always generates controversy with political, technical and social stakeholders. Local oceanographic and environmental knowledge are fundamental for the better understand about the outfall principles and phenomena.
This paper presents the strategies used to prior environmental characterization to support location and outfall technologies of two treated wastewater disposal systems. It summaries how a failure history turned to a wide data collection effort to support decision of design systems.

***Keywords**: environmental characterization, outfall, environmental assessment*

RESUMO

Florianópolis é uma das mais importantes cidades turísticas do Sul do Brasil. Seis estações de tratamento recebem 50% do esgoto da cidade para tratamento e disposição final em áreas consideradas frágeis, tais como pequenos rios, manguezais e locais abrigados próximos à costa. Para melhorar esta situação dois emissários submarinos estão sendo planejados.
Diversos aspectos precisam ser estudados nestes empreendimentos devido às controvérsias entre os atores políticos, técnicos e sociais. Conhecimentos específicos sobre a oceanografia e ambiente local são fundamentais para um melhor entendimento sobre os princípios e fenômenos que cercam os emissários submarinos.
Este artigo apresenta as estratégias utilizadas para a caracterização prévia do ambiente para dar suporte à definição das alternativas técnicas e locacionais destes emissários. Ele resume como uma história de fracasso se tornou em um dos maiores esforços de coleta de dados para dar suporte a tomada de decisão sobre estes sistemas.

Palavras-chave: caracterização ambiental, emissário submarino, avaliação ambiental

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INTRODUCTION

Florianópolis, lies at the central coast of Santa Catarina State (figure 1), lapped by south Atlantic waters. The main island is separated by the continental part through a narrow channel of 500 meters approximately, which extension originates North and South Bay. (Diehl & Horn Filho, 1996 apud CASAN and CB&I, 2015).

The main island is presently served by six WWTP that collect and treat approximately 50% of sanitary wastewater produced in the city. Due to the rapid population growth and its fragile environment, full of small rivers, mangroves an bays, water pollution has been a big concern, important both from an ecological and social-economic point of view. Santa Catarina Water and Sanitation Company (CASAN) is planning two outfall systems in order to protect water quality on the beaches and in the fragile environments, avoiding wastewater disposal into the main bays on the west coast of the island.

Prior to outfall construction and because of the environmental requirements, it´s necessary to undertake an environmental diagnostics of the influence area. At this stage, a good characterization represents a general concern and a great challenge, as it will support necessary steps in the development of these enterprises, from early outfall basic conception, project planning, design, construction, and operational monitoring.

According to Brazilian Environmental Council – CONAMA resolution 001/86 (BRASIL, 1986), environmental diagnostics should create a deep knowledge of the area of influence of each project covering physical, biotic, social and economic aspects. Besides compiling existing information through literature review of available materials in the public domain, it is necessary to create and implementing a data collection plan that should last at least one completed hydrological year.

Data collection in the sea must be well planned due to significant effort and cost involved. Example of challenge to overcome during environmental campaigns such as the weather conditions in each season of the year, and equipment loss and degradation.

Earlier studies developed by CASAN and UNIVALI for environmental licensing process failed because of project problems, especially in the alternative election. This paper aims to present strategies adopted by CASAN to support environmental characterization prior to outfalls implementation in order to achieve goals within predetermined timetable and to retrofit the outfall design.

GOALS

Strategies adopted for prior environmental characterization of Santa Catarina Island shore are showed for the better understand of oceanographic, physical chemical and biological aspects, and their interrelation, for decision support of an outfall project in the study area.

METHODOLOGY

In this article are presented data of two case studies developed in the area, one on the North (CASAN and CB&I, 2015) and other in the Southeast (CASAN and POLAR, 2016) portion of the island, with similar data acquisition approaches between 2013 and 2015 (table 1).

Water quality samples were collected at 3 depths (surface, half-deep and bottom) in 32 stations (figure 1). On the same stations sediment analysis and biological indicators were evaluated in an effort to identify relations between environmental compartments.

For the oceanographic characterization, four Acoustic Doppler Current Profiles (ADCP) were installed (figure 1) on the seabed inside a structure with the transducer facing up (upward looking) in order to perform measurements of the vertical velocity profile with a pressure, temperature and salinity sensors as well. At the same time, in water quality campaigns, density profiles were investigated using a CTD profiler in each station.

Biological indicators like abundance, diversity, richness and equitability were calculated for different groups of the fauna and flora for each aquatic environmental, benthic and plankton, for the consolidated and unconsolidated subtracts (figure 2).

Table 1: Data acquisition period for the Norther (N) and Southeaster (S) outfall studies.

		Currents	Water Quality	Biological Indicators	Sediment Quality
2013	Autumn	-	-	-	-
	Winter	S	S	S	S
	Spring	S	S	S	S
	Summer	S	S	S	S
2014	Autumn	S	S	S	S
	Winter	-	-	-	-
	Spring	N	N	N	N
	Summer	N	N	N	N
2015	Autumn	N/S	N	N	N
	Winter	N	N	N	N
	Spring	N/S	N	N	N
	Summer	S	N	N	N

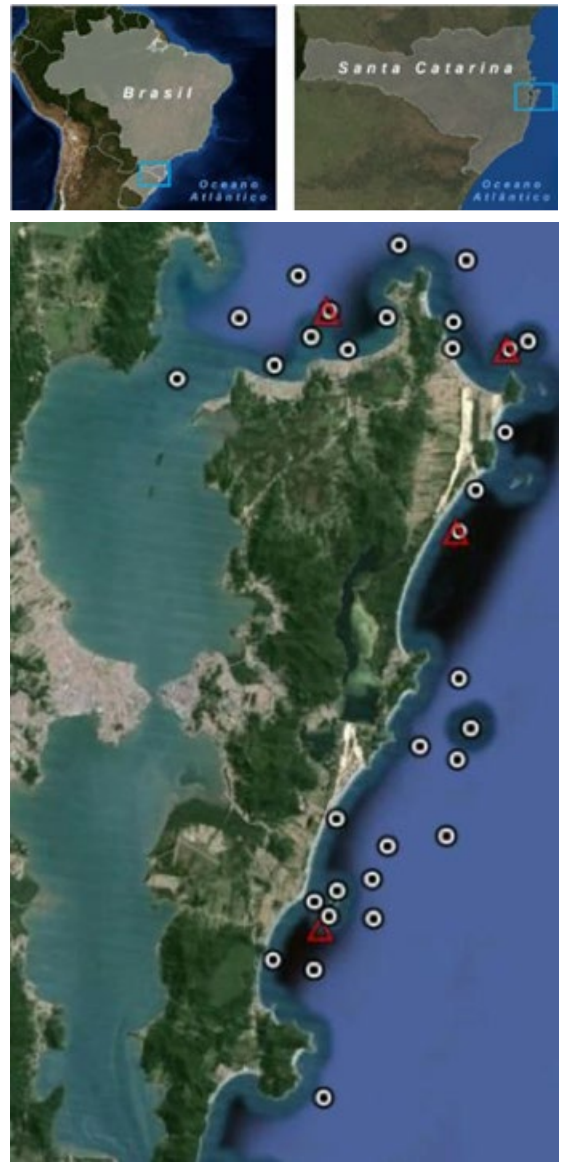

Figure 1: Study area - Santa Catarina Island. ADCP's (red triangle) and water quality (white points) stations locations.

Several water quality and sediments parameters were obtained, as showed in tables 2 and 3, like nutrients, microorganisms, physicochemical, metals, emerging pollutants (poly Aromatic Hydrocarbon – PHAs) and Eco toxicological tests.

Table 2: Analyzed parameters for water quality.

Physicochemical	Temperature,Salinity
	Conductivity, pH
	Turbidity, Transparency
	Oil and greases, Surfactants
Nutrients	Total Organic Carbon
	Chemical Oxygen Demand
	Sulfide, Ammonia
	Nitrite, Nitrate
	Total and Organic phosphorus
	Organic Phosphorous
Solids	Dissolved solids
	Volatile solids
	Settleable solids
	Suspended solids
	Total solids
Organisms	Chlorophyll a
	Thermotolerant coliforms
	E. coli
	Enterococcus
	Total coliforms
Metals	Dissolved Aluminum, Cooper, Iron
	Total Arsenic, Cadmium, Lead, Manganese, Mercury, Nickel, Zinc
Other	Total Phenol
	∑PAHs
	Eco toxicological test

On the sediments, besides the chemical characterization, a granulometric analysis was performed to identify the most adsorption susceptible areas.

Table 3: Analyzed parameters for sediment quality.

Metals	Arsenic, Cadmium,
	Chromium, Copper,
	Lead, Mercury,
	Nickel, Zinc.
Nutrients	Total Organic Carbon
	Phosphorus
	Nitrogen
	Sulfur
Other	Granulometry
	∑PAHs
	Enterococcus

Table 4: Biological groups studied.

Plankton	Ichthyo
	Zoo
	Phyto
Benthic	Macrophyto
	Macrofauna
Other Groups	Demersal fauna
	Marine mammals
	Chelonia

Figure 2: Biological collect for the different substracts and groups (A and B – Benthic macro fauna, C – Phytoplankton and D – Benthic macro fauna and macro phytobenthic in a rocky coast). (CASANand POLAR, 2016)

RESULTS

Both studies bring up about 30,000 water quality data, 2,000 sediment data and 640 biological samples between 2013 and 2015, in one the major data collection campaigns realized in the region.

Furthermore, this amount of information was also converted into thematic maps for the trial and identification of patterns and relation between parameters, compartments and stations. Each campaign and depth was presented in a map, as shown on figures 3 and 4, in order to evaluate seasonal patterns and to look for local phenomena related in the literature, such as upwelling (CAMPOS et al, 1995 and CARVALHO et al, 1998). Special attention was given for temperature, salinity and nutrients, due to the upwelling reports and its implications for the wastewater plume.

On sediments, the same graphical approach was used in order to make data interpretation easier. It was possible to identify that more exposed areas had sand prevalence and clay enrichment, which was observed closed to the protected waters of the northern bay (figure 5).

Oceanographic time series measurements were treated to remove peaks and other deviation occurred during the data collect procedures, such as pitch and roll.

Filtered data was submitted to a frequency of occurrence verification and water level groups summarize data for different layers (surface, half-deep and bottom) and different shore orientation (x – cross-shore and y – long shore) (figure 6). Velocities profiles along campaigns were also generated observing total currents, South-North and North-South orientation. Different approaches were made to analyze data such as polar diagrams, distribution of vertical profiles, magnitudes histograms and accumulated distribution (figures 6 and 7).

The biological samples were submitted to an ecological approach. Descriptors and indicators were combined at different stations and groups, such as phytoplankton, zooplankton and benthonic organisms. The studies performed the Shannon-Weaver and Pielou index in complement to abundance and richness analysis, like the example showed in figure 8.

DISCUSSION

Previous studies involving environmental data collection were developed by CASAN at the same region few years ago to support first outfall projects. According to CARVALHO et al (2013) time series of wind, water levels current and temperature profiles were acquired over a period of 31 consecutive days in order to determine the best location for the diffusers. Due to the short monitoring period, the environmental agency considered not sufficient to afford knowledge of the local oceanographic aspects. The intention to validate biological data collected from one monitoring point to another, in order to avoid other campaign effort failed, even due to their spatial proximity. These justified a new primary data collection for the whole area for a better and complete environmental characterization, into a new licensing process. These studies were developed into this methodology.

To prevent loss of equipment and ensure the data quality, it was provided one campaign every 45 days for ADCP maintenance and data collection. First campaign showed problems with lost or drag of 3 ADCPs. This approach permitted an exchange location to near protected areas and ensure the data acquisition for the next measurements.

Large majority of sediment data was detected above limits of Brazil legislation for dredged material (BRASIL, 2012), with almost all data even below the method detection limits, showing that the area is preserved for anthropic interference. For water quality it was observed the same characteristic with few parameters up to the regulation patterns (BRASIL, 2005). Additional interesting information is that sediment granulometric composition had variability over the seasons and over the different exposure areas, like bays and open sea, and bathymetric profiles (figure 5).

CARVALHO et al. (1998) observed two distinct oceanographic seasonal patterns influenced by the wind in this region. During spring and summer the water columns was stratified and upwelling and doweling events occur according to the northern and southern winds. During autumn and winter the water column was homogeneous because of doweling or advection of modified subantartic water into the area. The upwelling of Central Southern Atlantic Waters (ACAS) was detected in the northern study during spring and summer as showed in figure 9. CTD data (figure 10) showed the same upwelling pattern with additional temperature and salinity stratification on the spring of 2013 (green) and in summer of 2014 (cyan), in according with the author.

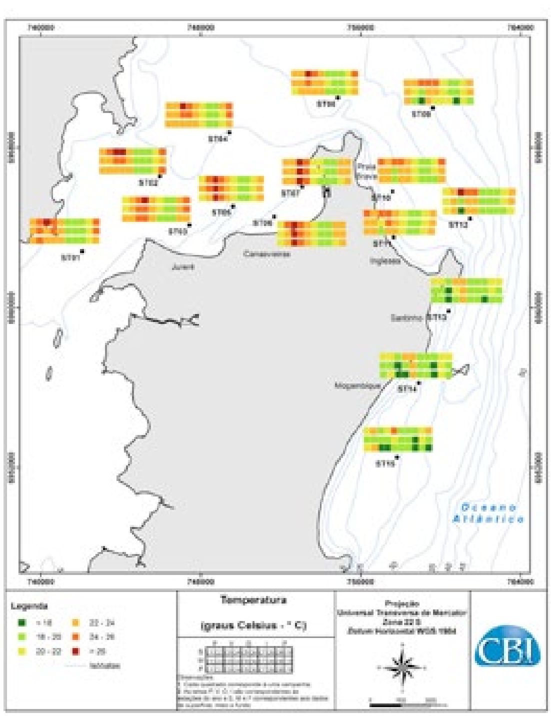

Figure 3: Water quality (Temperature) maps developed in the North Outfall study. (CASAN and CB&I 2015

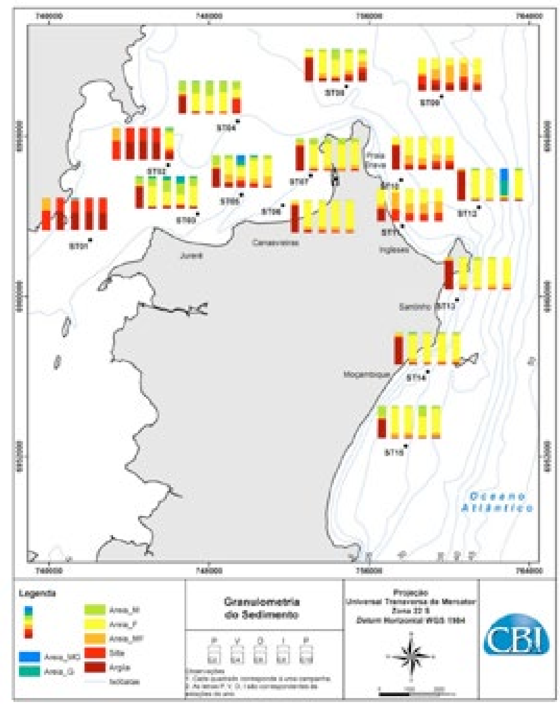

Figure 4: Example of water quality (Temperature) maps developed in the Southeastern Outfall study. (CASAN and POLAR, 2015)

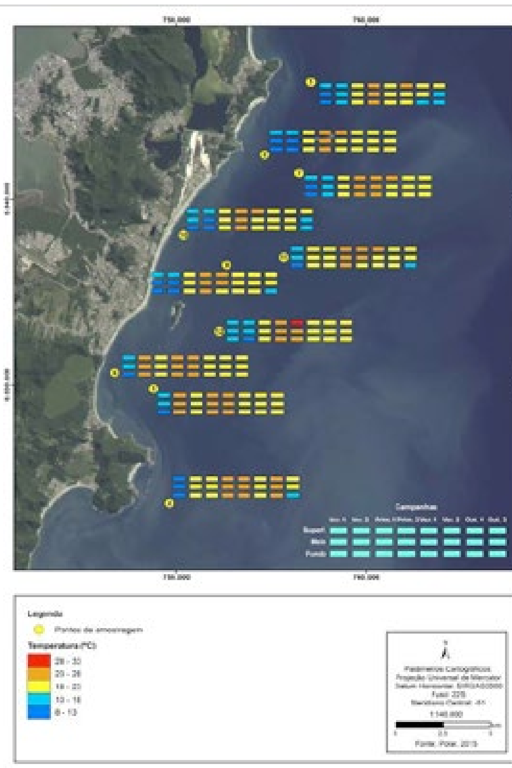

Figure 5: Example of sediment classification distribution on the Northern Outfall study. (CASAN and CB&I, 2015)

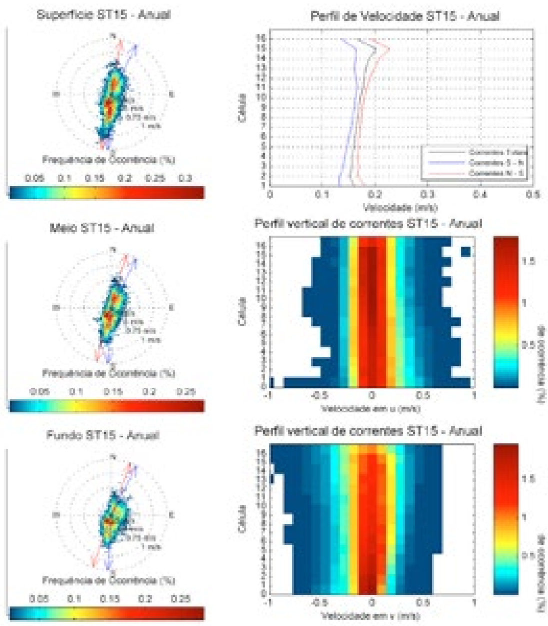

Figure 6: Example of oceanographic data analysis with polar distribution and vertical profiles. (CASAN and CB&I, 2015)

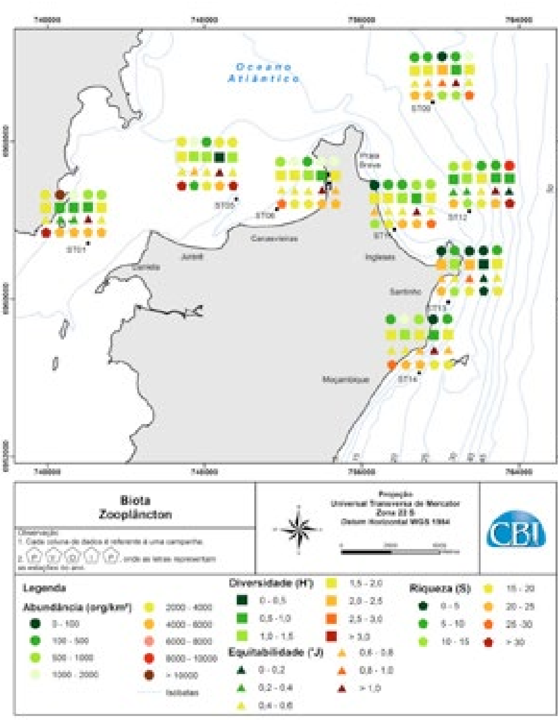

Figure 7: Example of oceanographic data analysis with histogram of magnitude and accumulative distribution. (CASAN and CB&I, 2015)

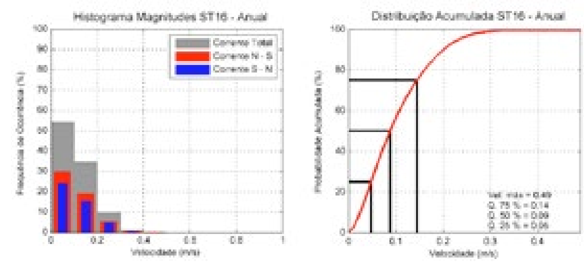

Figure 8: Example of biological indicators distribution for de Northern Outfall study. (CASAN and CB&I, 2015)

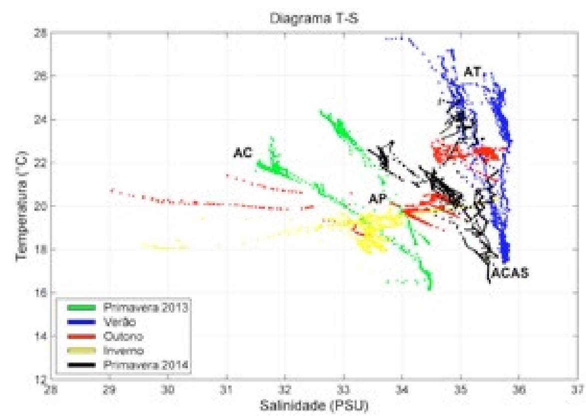

Figure 9: Analysis of water masses occurrence in a Temperature versus Salinity diagram. (CASAN and CB&I, 2015)

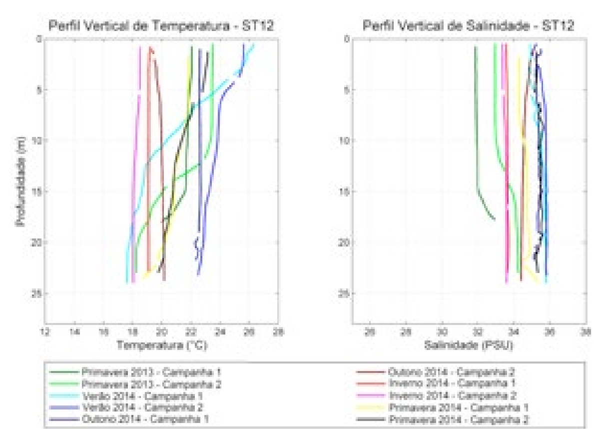

Figure 10: CTD profiles for one station in the northern study.Temperature on the left and salinity on the right. (CASAN and CB&I, 2015)

FALKENBERG et al (2016) and BARLETTA et al (2016) also discussed the oceanographic data of the northern outfall with more details showing that even in a small region the local geomorphology differences plays an important role defining the major forces that act in each site. Tides look the most relevant forcing phenomena on the bay influenced areas. Waves and meteorological aspects, such as cold fronts, performed the most significant influence on the more exposure areas on the east.

Taking into account the regular characteristics of urban sewage and treated wastewater, it is important to evaluate the natural background of nutrients such as total organic carbon, nitrogen and phosphorous forms. The study showed a previous background carbon (figure 11) observed sometimes in the whole region. Probably this phenomenon is related to the different water masses, and oceanographic and meteorological interactions. The same background pattern was observed in the southern region with nitrogen forms.

Shannon´s diversity index (H') scored the highest values during winter and spring when climate conditions, physical environment and also local environmental factors favored richness values (S). In the Northern study, autumn had the highest values of Pielou (J) index of equability where there was a better distribution in the number of organisms between species without significant dominance. However, in the Southeast study, highest Pielou values were obtained in summer period.

Taxonomic richness is strongly correlated with climate and environmental conditions, both for northeast and south part of the island.

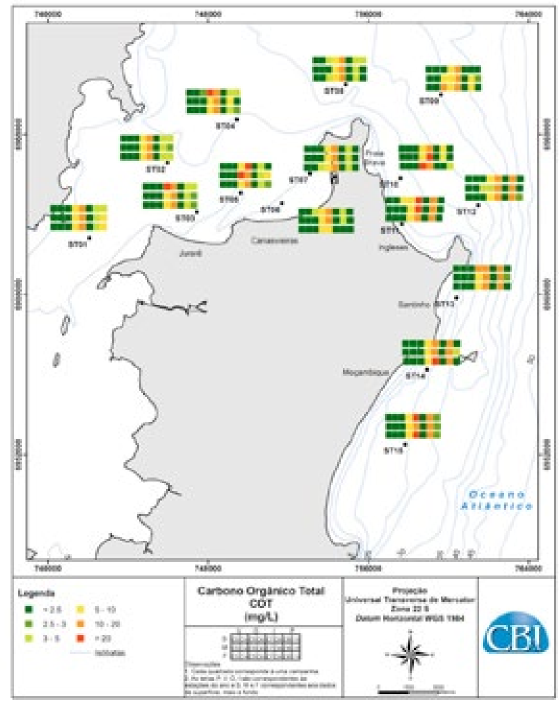

Figure 11: Total Organic Carbon distribution over northern shore. (CASANand CB&I, 2015)

CONCLUSION

Practical experience shows that in public discussion of an environmental assessment, divergences are about few key subjects that attract public interest (SANCHEZ, 2011). Most of these talks are about locational characteristics, following the not in my backyard feeling. In Brazil, public meetings and discussion take part into environmental licensing process. Before these meetings, a complete diagnosis of the biological, physical and social aspects must be presented for a complete evaluation of the environmental authority.

Previous characterizations is a fundamental tool for the decision making process of an outfall system. Several social aspects must be taking into account, but the most important issue is show to the stakeholders and to the scientific and technical community that the best efforts are being made in the planning phase to make sure that the outfall will not damage the environmental, especially the beaches and other social uses.

Nutrients parameters are especially important. Combined with circulation data they helped to detect upwelling events. These background data will help further studies to understand the real impact of the outfall operation.

Taking into account that during outfall operation, water quality, sediment sand biological indicators will be monitored, it is important to pay attention in some aspects like methodology detection limits of water quality and sediment parameters. These limits cannot be closer to regulators standards. At least one order of magnitude lower that Brazilian regulation standards.

Other studies were performed next to these study area by different institutions covering all around the island, but this efforts are not integrated. This increase the need of a public and open database to permit frequent partnership between institutions and support discuss with stakeholders to improve projects and minimize social restrictions and doubts about outfall solutions.

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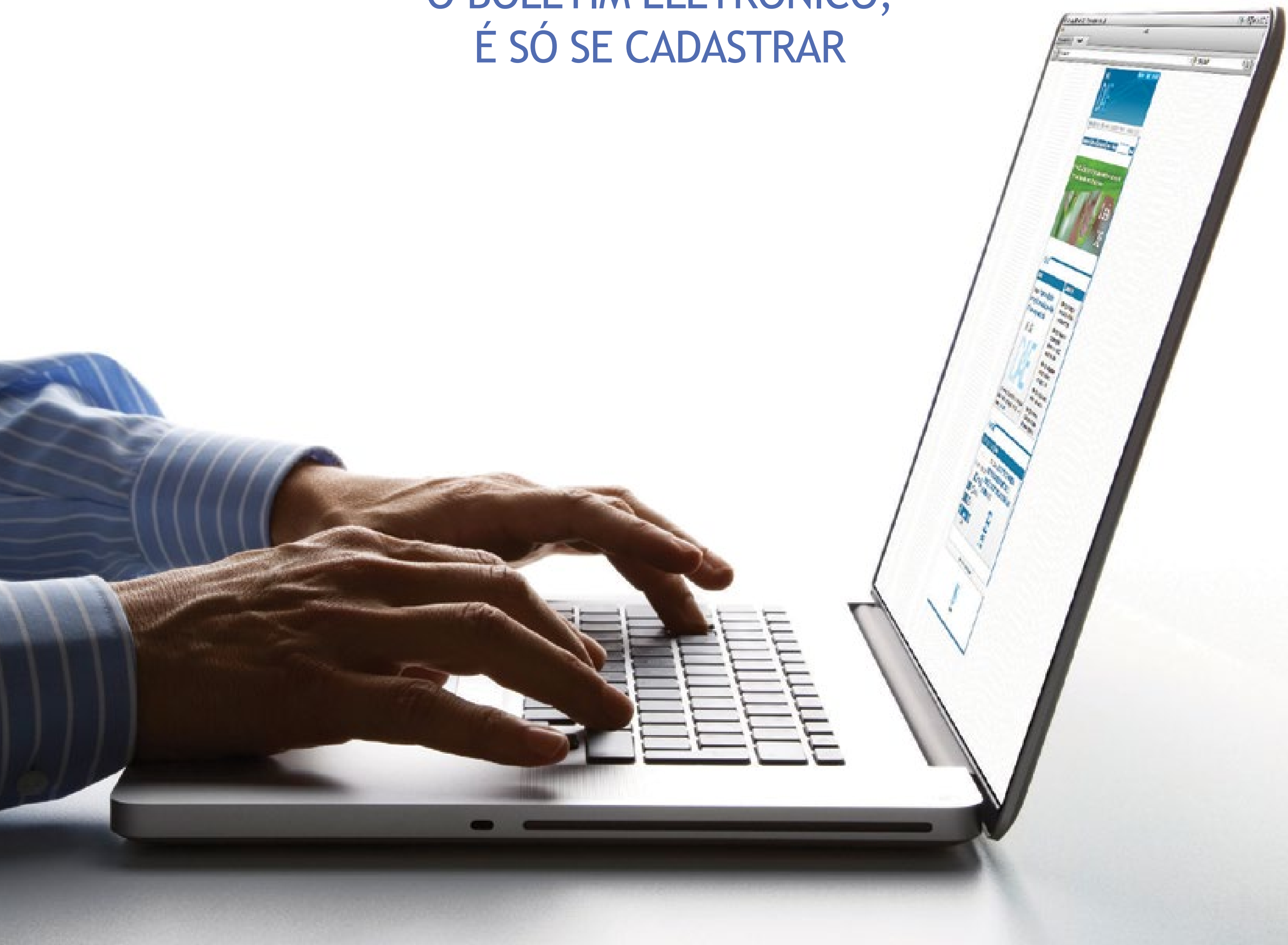

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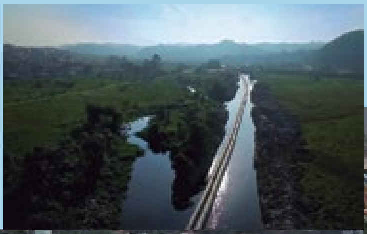

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