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A Combined Approach Using Water Quality Indexes and Statistical Analyses to Assess the Urban Surface Runoff: a Case Study in São Paulo Coastal Zone, Brazil

Uma Abordagem Combinada Usando Índices de Qualidade da Água e Análises Estatísticas para Avaliar o Escoamento Superficial Urbano: um Estudo de Caso na Zona Costeira de São Paulo, Brasil

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Abstract

Although the most conventional methods to determine the quality of an aquatic ecosystem are aimed to evaluate its physicochemical, microbiological and ecotoxicological characteristics, the monitoring of a large number of environmental variables can represent a high cost for developing countries like Brazil. However, a combined approach using water quality indexes and statistical analyses may help us to monitor water quality through a previous selection of a few key environmental variables. In this context, the objective of this study was to highlight the set of environmental variables most useful to assess the urban channels water quality of Guarujá, Brazil, whose diffuse loads flow continuously into four tourist beaches (Tombo, Enseada, Perequê and Iporanga). For this purpose, three different methods were applied: (i) an existent published large data set (30 environmental variables: 28 physicochemical/microbiological, plus 2 ecotoxicological) obtained during a previous monitoring of the urban drainage channels of these beaches; (ii) the potential risks for the aquatic local fauna and flora through established water quality indexes, such as IMPC, TSI and ALPI; and (iii) through statistical methods such as Cohen D test, Standardized Odds Ratio and Logistic Regression, the set of environmental variables with the greatest potential to cause acute and chronic toxicity in urban channels waters. This combined approach using water quality indexes and statistical analyses was effective to successfully reduce the number of environmental variables needed to assess the ecological status of this coastal area. Moreover, this combined approach was useful to gather intuitive and user-friendly environmental information that could help decision makers (i.e., public authorities and environmental agencies) to plan and perform low-cost and effective monitoring plans in different coastal zones worldwide, namely in developing countries such as Brazil.

Keywords: Subtropical ecosystem; Non-point source pollution; Pollution effects

Resumo

Embora os métodos mais convencionais para determinar a qualidade de um ecossistema aquático sejam avaliar suas características físico-químicas, microbiológicas e ecotoxicológicas, o monitoramento de um grande número de variáveis ambientais, pode representar um alto custo para países em desenvolvimento como o Brasil. No entanto, uma abordagem combinada usando índices de qualidade da água e análises estatísticas pode nos ajudar a monitorar a qualidade da água por meio de uma seleção prévia de algumas variáveis ambientais importantes. Nesse contexto, o objetivo deste estudo foi destacar o conjunto de variáveis ambientais mais úteis para avaliar a qualidade da água dos canais urbanos do Guarujá, Brasil, cujas cargas difusas fluem continuamente para quatro praias turísticas (Tombo, Enseada, Perequê e Iporanga). Para tanto, foram aplicados diferentes métodos: (i) foi analisado um grande conjunto de dados já publicado (30 variáveis ambientais: 28 físico-químicas/microbiológicas, mais 2 ecotoxicológicas) obtido durante um monitoramento prévio dos canais de drenagem urbana dessas praias; (ii) os riscos potenciais para a fauna e flora aquática local foram avaliados por meio de índices de qualidade da água já estabelecidos, como IPMCA, IET e IVA; e (iii) por meio de métodos estatísticos como o Teste D de Cohen, a Razão de Chance padronizada e a Regressão Logística, foram avaliados o conjunto de variáveis ambientais com

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maior potencial de causar toxicidade aguda e crônica nas águas dos canais urbanos. Esta abordagem combinada usando índices de qualidade da água e análises estatísticas foi eficaz para reduzir com sucesso o número de variáveis ambientais necessárias para avaliar o estado ecológico desta área costeira. Além disso, esta abordagem combinada foi útil para reunir informações ambientais intuitivas e de fácil utilização que podem ajudar os decisores (ou seja, autoridades públicas e agências ambientais) a planejar e executar planos de monitoramento de baixo custo e eficazes em diferentes zonas costeiras do mundo, nomeadamente nos países em desenvolvimento.

Palavras-chave: Ecossistema subtropical; Poluição de fonte não pontual; Efeitos da poluição

1 Introduction

The high population concentration living in the Brazilian's coastal cities raises several environmental and socio-economic concerns (Barragán & de Andrés 2015; UNDESA 2017; Blackburn et al. 2019). In 2020 Brazil had around 210 million inhabitants, 26.6% of which inhabit the coastal zone (SMA/CPLA 2012; IBGE 2018; Roveri 2019). Consequently, countless economic activities that occur in this coastal area, such as civil construction, port operations, industrial activities and seasonal tourism, cause several impacts to coastal marine ecosystems (SMA/CPLA 2012; Roveri 2019; Roveri, Guimarães & Correia 2020). According to United Nations (UN), the nonpoint-source pollution flowing into the coastal areas has been viewed with concern in the last decades, due to the complexity in the identification, delimitation, control and monitoring (UN 2018). This is the current scenario of São Paulo coastal zone, a region that includes 16 municipalities (including Guarujá, focus city of this study) and represents 10% of the Brazilian coast, where over 600 urban drainage channels, discharge daily a complex mixture of urban runoff and untreated domestic sewage into 290 touristic beaches (Roveri, Guimarães & Correia 2020, 2021).

Recent studies carried out in Guarujá, considered one of the main Brazilian tourist destinations, showed that as urbanization progresses and tourism intensifies, the diffuse pollution increases and introduces a complex mixture of pollutants into the South Atlantic Ocean (Roveri, Guimarães & Correia 2020, 2021). The last two mentioned studies used a large set of environmental variables for this diagnosis, namely, 30 physical-chemical, microbiological and ecotoxicological variables (Roveri, Guimarães & Correia 2020, 2021). However, a water quality monitoring program through of that numerous critical environmental variables can represent a high cost for cities in developing countries, such as Guarujá, which has limited human, technical and financial resources for this program (Shil et al. 2019; Banda and Kumarasamy 2020a; Ewaid et al. 2020). Moreover, a combined approach using water quality indexes and statistical analyses could improve water quality monitoring of Guarujá through a selection of representative environmental variables (Deepa & Venkateswaran 2018; Ustaoğlu & Tepe 2018; Shil et al. 2019).

The use of water quality indexes is a valuable way to use and transform large quantities of environmental data into a single and ranked term, which represents the water quality level at a particular time and location (Misaghi et al. 2017; Şener et al. 2017; Nong et al. 2020). Moreover, the application of statistical methods, as a complimentary technique, helps us to interpret complex data matrices and to understand the water quality and ecological status of the studied ecosystem (Ustaoğlu & Tepe 2018; Shil et al. 2019; Ustaoğlu et al. 2020). This combined approach has been successfully applied worldwide in water quality studies carried out in Vellar River, India (Deepa & Venkateswaran 2018), in Pazarsuyu Stream and Turnasuyu Stream, Turkey (Ustaoğlu & Tepe 2018; Ustaoğlu et al. 2020) and in Mahananda River, India (Shil et al. 2019). Moreover, in the case of Guarujá, the use of water quality indexes and statistical analyses is welcome because studies about the surface runoff quality are scarce (Roveri, Guimarães & Correia 2020, 2021).

The aim of the current study was to apply a combination of different water quality indexes and statistical methods, to highlight among a set of 30 environmental variables already published (Roveri, Guimarães & Correia 2020, 2021), which ones have the greatest potential to cause toxicity in the waters of the Guarujá urban drainage channels, whose diffuse loads flow into four different tourist beaches (Tombo, Enseada, Perequê and Iporanga). The expected outcomes can serve as a guideline for the Brazilian public authorities and environmental agencies, in the selection of the best environmental variables for the monitoring of the urban surface runoff flowing into the coastal zones. Acquired knowledge, it may help decision makers to plan and perform effective and low-cost monitoring programs in different coastal zones worldwide.

2 Materials and Methods

2.1 Study Area

The study area comprised the coastal communities of the city of Guarujá, São Paulo, Brazil (23°59'34" S, 46°15'21" W), which is considered the third largest coastal island in the state (143 km^2) (Ribeiro & Oliveira 2015;

Roveri 2019). Guarujá has a tropical climate, characterized by a mean annual precipitation and temperature of 3000 mm and 22 °C, respectively. Two main seasons are observed in the region: a rainy (November to March) and a dry (April to October) period (SMA/SPLA 2012; Roveri 2019).

Favoured by these climate conditions, and endowed by an ecosystem diversity, it is possible to find along its coastal area mangroves, rocky shorelines, sandbanks and estuaries, besides 26 beaches providing good conditions for tourism through-out the year (SMA/CPLA 2012; Ribeiro & Oliveira 2015; Roveri 2019). These beaches receive daily contributions of urban runoff from 43 rainwater drainage channels (Roveri, Guimarães & Correia 2020, 2021). These channels are made of concrete, and none of them has a grating system, thus their content (composed of a mixture of urban diffuse load and untreated domestic sewage) is directly discharged onto these beaches without any treatment (Roveri, Guimarães & Correia 2020, 2021).

In the present study, four of the twenty-six beaches of Guarujá were selected due to the different characteristics of land use and occupation; (i) Tombo: beach with Blue Flag certification, which is awarded to beaches that have met strict international standards in four different categories: water quality, environmental education, environmental management and safety and services (Ribeiro & Oliveira 2015); (ii) Enseada: a very touristic beach; in spite of presenting medium and high standard hotels and residences, this beach contrasts with the presence of illegally occupations on the slope of Santo Amaro's hill (Ribeiro & Oliveira 2015); (iii) Perequê: the largest fishing community in Guarujá (about 10,000 residents), which settled illegally along the edge of the beach in an environmentally protected area (Ribeiro & Oliveira 2015); and (iv) Iporanga: beach with restricted tourist access as it is located in the Environmental Protection Area (EPA) of Serra do Guararu (Figure 1) (Ribeiro & Oliveira 2015).

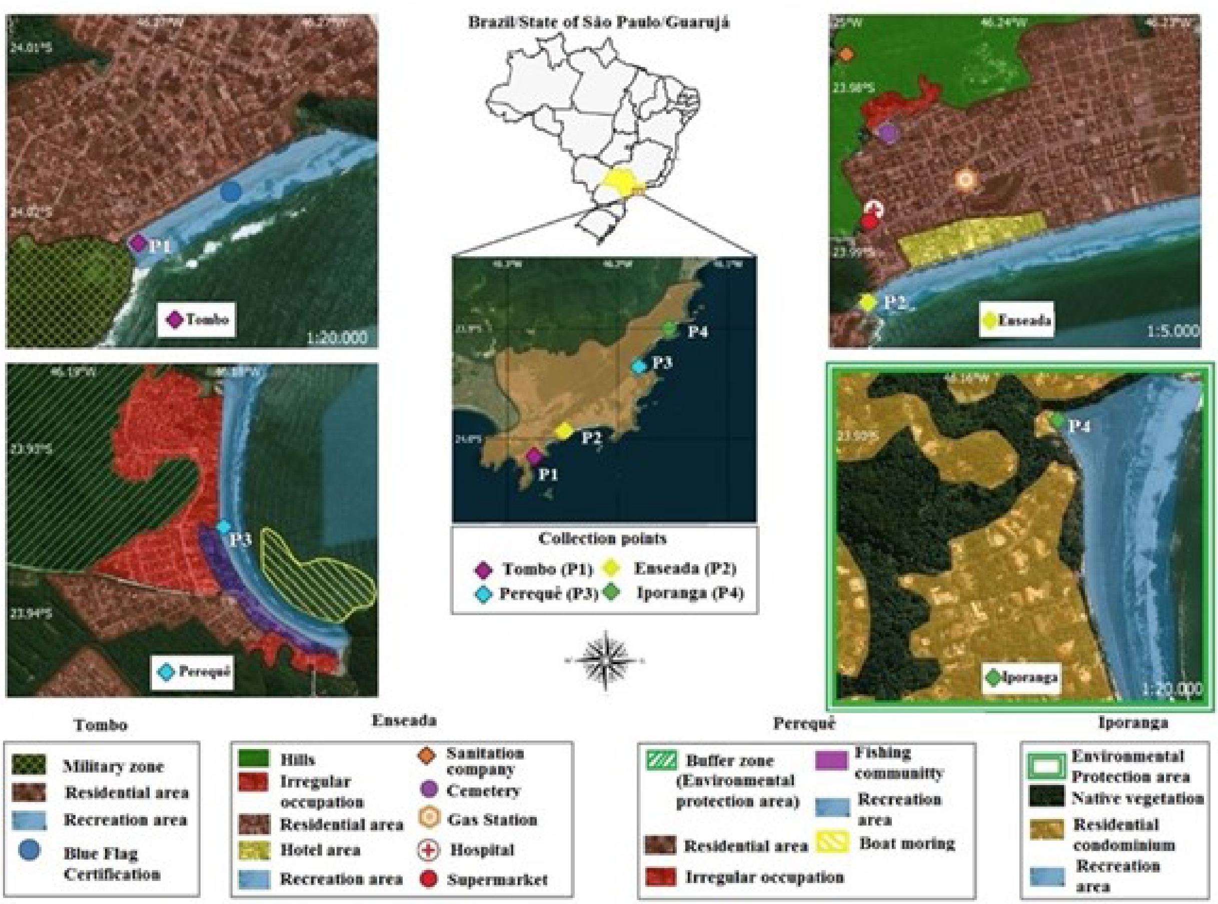

Figure 1 Map of the study area showing the city of Guarujá, São Paulo State, Brazil. Beaches [Tombo (P1), Enseada (P2), Perequê (P3), Iporanga (P4)] here was assessed of stream quality of urban surface runoff flowing to the beaches of Guarujá, through a combined approach, using water quality indexes and statistical analysis. The figure also presents the main characteristics regarding the use and land occupation of the selected beaches.

2.2 Water Quality Indexes

To integrate the different results previously obtained by Roveri, Guimarães and Correia (2020) and Roveri, Guimarães and Correia (2021), the ALPI (aquatic life protection index) was calculated. The ALPI aims evaluating the water quality for fauna and flora protection. This index performs an integrated analysis of water quality through a combination of different environmental variables (Zagatto et al. 1999). First, the IMPC (index of minimum parameters for the protection of aquatic communities) was calculated, by considering two groups of variables: (i) essential variables (e.g., dissolved oxygen, pH and acute and chronic toxicity) and (ii) toxic variables (e.g., surfactants and heavy metals: cadmium, lead, copper, chromium, nickel and zinc). According to IMPC, three levels could be established for the water masses:

(i) Level A (weighting 1): waters with desirable characteristics to maintain the survival and reproduction of aquatic organisms. It meets the quality standards of the CONAMA Resolution nº 357/2005 (class 2) (Brazil 2005).
(ii) Level B (weighting 2): waters with acceptable characteristics for the survival of aquatic organisms, but reproduction may be affected over time.
(iii) Level C (weighting 3): waters with characteristics that may compromise the survival and reproduction of aquatic organisms.

According to Zagatto et al. (1999), the limits of levels B and C are obtained from the French (Code Permanent: Environnement et Nuisances, 1986) and American (USEPA 1991) legislations that establish maximum permissible limits of chemicals in water, aiming to avoid acute and chronic toxicity effects to aquatic biota. The IMPC was calculated using the following Equation 1:

$$\mathrm{IMPC} = \mathrm{VE} \times \mathrm{ST} \quad (1)$$

where:

VE: Value of the highest weighting of the group of essential variables.

ST: Average value of the three highest weightings of the group of toxic variables.

After the calculation, the following classification is obtained: good = 1 (indicated with the green colour); regular = 2 (indicated with the yellow colour); bad = 3 and 4 (indicated with the orange colour); terrible ≥ 5 (indicated with red colour).

In a second step, the TSI (Trophic State Index) was calculated according to Lamparelli (2004) [this index was already calculated in Roveri, Guimarães and Correia (2020)]. After the calculation, the following classifications are obtained: ultraoligotrophic = 0.5 (indicated with the blue colour); oligotrophic = 1 (indicated with the green colour); mesotrophic = 2 (indicated with the yellow colour); eutrophic = 3 (indicated with the orange colour); supertrophic = 4 (indicated with the red colour); hypereutrophic = 5 (indicated with the purple colour).

Finally, the ALPI was calculated by crossing the IMPC and TSI results according to the following Equation 2:

$$\mathrm{ALPI} = (\mathrm{IMPC} \times 1.2) + \mathrm{TSI} \quad (2)$$

After the calculation, the following final rating is obtained: optimal = ALPI ≤ 2.5 (indicated with the blue colour); good = 2.6 ≤ ALPI ≤ 3.3 (indicated with the green colour); regular = 3.4 ≤ ALPI ≤ 4.5 (indicated with the yellow colour); bad = 4.6 ≤ ALPI ≤ 6.7 (indicated with the orange colour) and bad = 6.8 ≤ ALPI (indicated with the red colour).

2.3 Statistical Analyses

Different statistical analysis were applied to the data, including the Cohen D test, Standardized Odds Ratio and Logistic Regression (Cohen 1988; Agresti 2020) in order to verify the set of environmental variables that had the greatest potential to demonstrate the resulting acute and chronic toxicities in Guarujá drainage channels waters. This evaluation was carried out by cross-checking the 28 physicochemical and microbiological variables [available in the supplementary material from Roveri, Guimarães and Correia (2020)] with the results regarding the acute and chronic toxicities [obtained in Roveri, Guimarães and Correia (2021)]. These studies were carried out, simultaneously, in the Tombo, Enseada, Perequê and Iporanga channels, during February, March, May and July 2018 (Roveri, Guimarães & Correia 2020, 2021).

Initially, the average and standard deviation of select variables were calculated. Only variables that had results 100% above the limit of quantification (LOQ) were considered. The "Cohen D test" was thereafter calculated in order to categorize the levels of the toxicity of each selected variable. After the calculation, the following classification was obtained: Cohen d test < 0.50 = low effect (indicated with green colour); 0.50 ≤ Cohen test d < 0.80 = medium effect (indicated with yellow colour); Cohen test d > 0.80 = high effect (indicated with red colour) (Cohen

1988). Finally, for the variables that presented the highest effects (Cohen's d test > 0.80), the Standardized Odds Ratio and its respective lower and upper limits were calculated, through a Logistic Regression (Agresti 2020). From the Standardized Odds Ratio, it was possible to highlight the variables that present the greatest evidence of causing acute and chronic effects in the Guarujá channels waters. All analyses were performed using the statistical software R (version 3.6.1) (R Core Team 2017).

3 Results and Discussion

3.1 Water Quality Indexes

Assessment of urban surface runoff through physicochemical, microbiological and ecotoxicological variables, is strongly supported by the Environment Agencies of Europe and United States (EC 2000; USEPA 2002). In São Paulo state, CETESB (Environmental Agency of São Paulo) use *Escherichia coli* for the monitoring (through two annual campaigns) of 600 urban drainage channels flowing to the 290 beaches of the State (CETESB 2013). However, surprisingly, urban surface runoff monitoring is not yet requested by the Brazilian Water Resources Policy (Law No. 9433/1997) (Brazil 1997).

The most conventional methods to determine the quality of an aquatic ecosystem is to evaluate the physicochemical, microbiological and ecotoxicological variables and to compare the measured concentrations of pollutants with the national water quality standards (Shil et al. 2019; Ewaid et al. 2020; Son et al. 2020). However, the monitoring of this high number of critical environmental variables is costly and difficult to interpret (Shil et al. 2019; Ewaid et al. 2020; Roveri, Guimarães & Correia 2020, 2021). For example, Ewaid et al. (2020), during the development of a water quality index, were able to successfully reduce the number of variables used. As result, only 6 quality variables from 27 initial variables were selected to assess the quality of the Tigris River, Iraq (a basin that suffers from the strong development of municipal, industrial, and agricultural activities): (i) total dissolved solids, (ii) dissolved oxygen, (iii) chemical oxygen demand, (iv) total hardness, (v) chlorides, and (vi) total coliform. In this context, to integrate the different results previously obtained in Roveri, Guimarães and Correia (2020) and Roveri, Guimarães and Correia (2021), the IMPC, the TSI and finally the ALPI indexes were calculated (Zagatto et al. 1999).

The ALPI is one of the most complete indices to evaluate the quality of aquatic ecosystems, because it reports water quality scenarios based on the trophic status of the environment, determine the degree of toxicity for the aquatic biota, and indicates deficiency in essential parameters for the protection of the aquatic life (Zagatto et al. 1999; Lamparelli 2004). In this context, the raw analytical results of 4 essential variables: dissolved oxygen, pH and acute and chronic toxicities, and 7 toxic variables: surfactants and heavy metals: cadmium, lead, copper, chromium, nickel and zinc (that have different values and units), were transformed into a single value by a special type of mathematical averaging function (Table 1) (Zagatto et al. 1999).

Therefore, by comparing the individual analysis of the 30 environmental variables obtained in urban drainage channels of Guarujá (Roveri, Guimarães & Correia 2020, 2021), with the hereby results of IMPC, TSI and ALPI indexes (that combined results of only 11 variables), it confirmed that channels of Tombo, Enseada and Perequê (areas with greater anthropic interference) presented the worst water quality scenarios. IMPV and ALPI indexes presented "terrible" rating for the three channels (Table 1) (Zagatto et al. 1999). Moreover, the TSI index results indicated that the waters have eutrophic characteristics (total phosphorus enrichment) (Lamparelli 2004).

Historically, the discharge of total phosphorus into coastal areas in globally has compromised the ecological integrity of estuaries and receiving seas (Abal et al. 2001; Galloway et al. 2003; Yang & Toor 2017). Therefore, these channels showed a potential risk to the local fauna and flora (Table 1). For example, the blooming of toxic cyanobacteria, caused by the high enrichment of total phosphorus, has already been responsible for the extinction of aquatic species in Moreton Bay, Queensland (one of Australian's most important coastal resources) (Abal et al. 2001), and in Chesapeake Bay (the largest estuary in the United States and third largest in the world) (Galloway et al. 2003). On the other hand, Iporanga showed the best water quality, as the IMPC and ALPI indexes presented "good" and "great" ratings, respectively. Moreover, the TSI index results indicated that Iporanga urban channel water have oligotrophic characteristics (low content of total phosphorus) (Table 1) (Lamparelli 2004).

Therefore, similar to the already reported in other studies, such as in Umgeni River, South Africa (located along the Indian Ocean coastline) (Banda & Kumarasamy 2020b), in Tigris River, Iraqi (Ewaid et al. 2020), and in Cau River, Vietnam (whose basin is under the strong anthropic pressure) (Son et al. 2020), the application of these indexes for the assessment of the Guaruá urban drainage channels, brought more clarity and understanding regarding the interpretation of the runoff water quality, making its use recommended for both non-technical individuals and environmental agencies (Banda & Kumarasamy 2020b; Ewaid et al. 2020; Son et al. 2020).

Table 1 Results of the various water quality indexes calculated for the urban drainage channels of Tombo, Enseada, Perequê and Iporanga beaches, located in Guarujá, Brazil. The table describes the groups of variables (essential or toxic), the levels and the respective ranges of variation and weighting of these variables, as well as the results of the weighting obtained in each of the four drainage channels. Legend: Water Quality Index for the Protection of Aquatic Life and Aquatic Communities (WQI-PALAC), Index of Minimum Variables for the Preservation of Aquatic Life (IMVPAL) and Trophic State Index (TSI). and the WQI-PALAC. For more details see M&M.

Groups	Variables	Levels	Variation range	Weighting	Tombo	Enseada	Perequê	Iporanga
Essential variables	Dissolved Oxygen	A	≥ 5.0 mg/L	1	–	–	–	1
		B	3.0 to < 5.0 mg/L	2	–	–	–	–
		C	< 3.0 mg/L	3	3	3	3	–
	pH	A	6.0 to 9.0	1	1	1	1	1
		B	5.0 to < 6.0 and > 9.0 to 9.5	2	–	–	–	–
		C	< 5.0 and > 9.5	3	–	–	–	–
	Toxicity	A	Non-toxic	1	–	–	–	–
		B	Chronic effect	2	2	2	2	2
		C	Acute effect	3	–	3	3	
Toxicity variables	Cadmium	A	≤0.001 mg/L	1	1	1	1	1
		B	> 0.001 to 0.005 mg/L	2	–	–	–	–
		C	> 0.005 mg/L	3	–	–	–	–
	Chrome	A	≤0.05 mg/L	1	1	1	1	1
		B	> 0.05 to 1.0 mg/L	2	–	–	–	–
		C	> 1.0 mg/L	3	–	–	–	–
	Copper	A	≤0.009 mg/L	1	–	1	1	1
		B	> 0.009 to 0.05 mg/L	2	2	–	–	–
		C	> 0.05 mg/L	3	–	–	–	–
	Lead	A	≤0.01 mg/L	1	1	1	1	1
		B	> 0.01to 0.08 mg/L	2	–	–	–	–
		C	> 0.08 mg/L	3	–	–	–	–
	Nickel	A	≤0.025 mg/L	1	1	1	1	1
		B	> 0.025 a 0.16 mg/L	2	–	–	–	–
		C	> 0.16 mg/L	3	–	–	–	–
	Zinc	A	≤0.18 mg/L	1	1	1	1	1
		B	> 0.18 a 1.0 mg/L	2	–	–	–	–
		C	> 1.0 mg/L	3	–	–	–	–
	Surfactants	A	≤0.5 mg/L	1	–	–	–	1
		B	> 0.5 a 1.0 mg/L	2	–	–	–	
		C	> 1.0 mg/L	3	3	3	3	
IMVPA					6 (terrible)			1 (good)
TSI					3(eutrophic)			1 (oligotrophic)
WQI-PALAC					10 (terrible)			2 (great)

3.2 Statistical Analysis

Considering that water quality is generally described using physicochemical and microbiological variables, statistical analyses can ideally transform complex data matrices (e.g., 28 physicochemical and microbiological variables obtained in Guarujá urban runoff) in a minimal and manageable number of factors without losing relevant information (Shil et al. 2019; Banda & Kumarasamy 2020b; Ustaoğlu et al. 2020). In this context, after the application of Cohen's D test followed by the Standardized Odds Ratio and Logistic Regression, it was possible to identify the most prevalent groups of physicochemical and microbiological environmental stressors responsible for the acute (Table 2) and chronic toxicities (Table 3) resulting from the Guarujá urban runoff (Cohen 1988; Agresti 2020).

As indicated in section 2.3, of the 28 physicochemical and microbiological variables present in Roveri, Guimarães and Correia (2020) database, only 19 were selected (i.e., all the variables that had results 100% above LOQ) (Tables 2 and 3). As a result of the applied statistics, 8 of 19 quality variables were selected: conductivity, total dissolved solids, total phosphorus, phosphate, surfactants, ammonia, dissolved oxygen, and total coliforms (Tables 2 and 3), and therefore, deserve attention, as they can have a great deleterious impact on the aquatic biota when their values have deviations from normality.

High conductivity recorded in Guarujá urban surface runoff can be the result of a complex mixture of pollutants generated along the beaches of Tombo, Enseada and Perequê (Roveri, Guimarães & Correia 2020). Moreover, conductivity it is an indirect measure of total dissolved solids, and therefore may indicate the nutrients presence (e.g., total phosphorus, phosphate- including surfactants and ammonia) (CETESB 2019). In Tombo, Enseada and Perequê beaches, where sewage discharge is the main source of pollution in coastal waters, the pressure in the coastal ecosystem is high, as result of nutrient's water enrichment (Lamparelli 2004). In Guarujá urban drainage channels, total phosphorus occurs mainly in the form of phosphate, originated from surfactants, that are commercial products widely used in household cleaning, and therefore, reinforces the sanitation deficiency of the municipality (Ghose et al. 2009; Renzi et al. 2012; Roveri, Guimarães & Correia 2020).

The presence of surfactants also warns about the potential ecological risks, because many studies have already demonstrated their toxicity on algae, crustaceans, and fish (Kusk & Petersen 1997; Nunes et al. 2016; Zhu et al. 2020). Moreover, the bioavailability of total phosphorus, phosphate and ammonia can cause hypoxia and anoxia (reduction of the dissolved oxygen levels) with direct consequences on the survival of Guarujá aquatic biota (Lusk & Toor 2016; Yang & Toor 2017; Roveri, Guimarães & Correia 2020). For example, the discharge of the nutrients into coastal areas of San Andres, Colombia, and in the island of Culebra, Puerto Rico, has seriously compromised the ecological integrity of the receiving seas, jeopardizing the seagrass and coral ecosystems (Gavio et al. 2010; Hernandez-Delgado et al. 2017).

The Guarujá urban surface runoff quality, which often receives domestic sewage, is also of concern due to the introduction of allochthonous pathogenic microorganisms (e.g., total coliforms, *Enterococci* and *Escherichia coli*) in areas of intense human recreation (Roveri, Guimarães & Correia 2020). These pathogenic are responsible for the systematic loss of bathing water quality standards, with serious repercussions in the public health, tourism, and other economy sectors of the municipality (Hernandez-Delgado et al. 2017; Roveri, Guimarães & Correia 2020).

Similar conditions were observed in coastal areas of several developing countries of Latin American, e.g. Mexico (Curiel-Ayala et al. 2012), Cuba (Larrea-Murrel et al. 2013), Puerto Rico (Hernandez-Delgado et al. 2017) and Colombia. In São Paulo state, according to the criteria established by Board Decision No 112/2013/E of 2013, CETESB monitors 600 channels affluent to the 290 beaches (through two annual campaigns), and in 2018, the microbiological analysis revealed that only 13% of them complied with the legislation [600 CFU (Colony Forming Unit) *Escherichia coli* /100mL]. This result is 9% lower than in 2017 (CETESB 2013, 2019). Therefore, our study suggests that, in addition to the microbiological parameters, Cetesb should carry out ecological analyses of these channels (through these 8 representative variables).

4 Conclusion

The most conventional methods to determine the quality of an aquatic ecosystem is to evaluate its physicochemical, microbiological and ecotoxicological variables. However, the present study indicates that the use of complementary water quality indexes (including IMPC, TSI and ALPI indexes) supported by appropriate statistical analyses (including Cohen D test, Standardized Odds Ratio and Logistic Regression) is a useful tool for the assessment of the water quality of the urban surface runoff.

This approach successfully reduced the number of physicochemical, microbiological and ecotoxicological variables needed to assess the water quality of Guarujá urban surface runoff. Of an initial list of 30 environmental variables provided by previous studies, 9 chemical variables

Table 2 Results from the set of environmental variables that have the greatest potential to cause acute toxicity in the urban drainage channels of the beaches of Tombo, Enseada, Perequê and Iporanga, in Guarujá, Brazil. The table presents: (i) the set of 19 environmental variables used for the calculations (N number of samples, X mean and SD standard deviation), in two distinct conditions (without and with acute toxicity); (ii) result of Cohen's D Test; (iii) result of the Standardized Chance Ratio (and their respective lower and upper limits) calculated only for those variables that indicated a high toxicity effect (Cohen's d test > 0.80, flagged in red). For more details, see M&M.

Variables	Unit	Without acute toxicity			With acute toxicity			Cohen's D test	Standardized Odds	Lower limit	Upper limit
		N	X	SD	N	X	SD				
Water temperature	ºC	11	24.10	2.36	4	24.08	2.41	0.01	–	–	–
Conductivity	µS/cm	11	379.36	203.75	4	580.50	293.95	0.85	2.61	0.65	10.54
Total Dissolved Solids	mg/L	11	196.55	75.96	4	249.25	113.02	0.61	–	–	–
Dissolved Oxygen	mg/L	11	2.5	2.40	4	0.86	0.55	0.75	–	–	–
pH	pH	11	6.72	0.19	4	6.73	0.32	0.06	–	–	–
Turbidity	NTU	11	38.22	37.09	4	57.83	37.03	0.53	–	–	–
Colour	mg Pt/L	11	54.00	24.44	4	73.00	12.11	0.62	–	–	–
Sedimented solids	ml/L	5	0.10	–	3	0.10	–	–	–	–	–
Biological Oxygen Demand	mg/L	7	26.70	19.62	4	29.48	38.74	0.11	–	–	–
Ammonia	mg/L	11	1.36	1.27	4	2.38	0.24	0.87	4.21	0.44	40.14
Nitrite	mg/L	11	0.17	0.27	4	0.24	0.26	0.26	–	–	–
Nitrate	mg/L	11	1.8	0.62	4	1.40	0.54	0.30	–	–	–
Phosphate	mg/L	11	0.64	0.52	4	1.05	0.23	0.83	4.00	0.42	37.74
Surfactants	mg/L	11	0.76	0.56	4	1.34	0.28	1.03	10.35	0.34	320.03
Total Phosphorus	mg/L	11	1.45	1.10	4	2.50	0.47	0.98	9.63	0.28	334.80
Aluminium	mg/L	4	0.13	0.10	4	0.10	0.11	0.33	–	–	–
Total coliforms	CFU/mL	11	9,73E+07	1,28E+08	4	2,85E+08	1,77E+08	1.17	3.90	0.90	16.91
Escherichia Coli (*E.coli*)	CFU/mL	11	1,39E+07	2,17E+07	4	2,11E+07	1,26E+07	0.37	–	–	–
Enterococci	CFU/mL	11	3,81E+06	6,95E+06	4	4,27E+06	8,48E+06	0.07	–	–	–

Table 3 Results from the set of environmental variables that have the greatest potential to cause chronic toxicity in the urban drainage channels of the beaches of Tombo, Enseada, Perequê and Iporanga, in Guarujá, Brazil. The table presents: (i) the set of 19 environmental variables used for the calculations (N number of samples, X mean and SD standard deviation), in two distinct conditions (without and with chronic toxicity); (ii) Cohen D test result; (iii) Standardized odds ratio result (and their respective lower and upper limits) calculated only for those variables that indicated high toxicity effect (Cohen d test > 0.80, indicated in red).

Variables	Unit	Without chronic toxicity			With chronic toxicity			Cohen's D test	Standardized Odds	Lower limit	Upper limit
		N	X	SD	N	X	SD				
Water temperature	ºC	3	22.81	1.83	12	24.41	2.34	0.70	–	–	–
Conductivity	µS/cm	3	238.33	83.56	12	481.67	240.64	1.02	6.27	0.57	68.54
Total Dissolved Solids	mg/L	3	124.33	27.06	12	232.17	82.46	1.25	16.27	0.51	519.92
Dissolved Oxygen	mg/L	3	4.01	2.5	12	1.57	1.90	1.12	0.32	0.08	1.28
pH	pH	3	6.76	0.14	12	6.71	0.24	0.22	–	–	–
Turbidity	NTU	3	9.43	4.87	12	51.95	36.45	0.45	–	–	–
Colour	mg Pt/L	3	37.00	15.62	12	64.58	21.66	0.69	–	–	–
Sedimented solids	ml/L	1	0.10	–	7	0.10	–	–	–	–	–
Biological Oxygen Demand	mg/L	1	7.50	–	10	29.73	26.63	0.55	–	–	–
Ammonia	mg/L	3	0.74	1.27	12	1.85	1.09	0.95	2.76	0.67	11.4
Nitrite	mg/L	3	0.30	0.27	12	0.18	0.27	0.22	–	–	–
Nitrate	mg/L	3	1.57	0.42	12	1.52	0.63	0.08	–	–	–
Phosphate	mg/L	3	0.26	0.38	12	0.87	0.45	1.24	4.04	0.81	20.04
Surfactants	mg/L	3	0.44	0.50	12	1.04	0.52	1.07	3.21	0.73	14.05
Total Phosphorus	mg/L	3	0.74	0.93	12	1.98	0.98	1.16	3.56	0.79	16.07
Aluminium	mg/L	2	0.03	0.04	6	0.14	0.10	0.40	–	–	–
Total coliforms	CFU/mL	3	7,69E+07	1,33E+08	12	1,65E+08	1,67E+08	0.55	–	–	–
Escherichia Coli (*E.coli*)	CFU/mL	3	9,67E+06	1,67E+07	12	1,73E+07	2,06E+07	0.39	–	–	–
Enterococci	CFU/mL	3	6,05E+03	1,04E+04	12	4,92E+06	7,64E+06	0.70	–	–	–

[i.e., dissolved oxygen, pH, surfactants, heavy metals (including cadmium, lead, copper, chromium, nickel, and zinc)], and 2 ecotoxicological variables (namely, acute, and chronic toxicity tests with microcrustacean *Daphnia simillis* and *Ceriodaphnia dubia*, respectively), were able to indicate potential risks to local biota.

Following statistical analyses, eight variables alone (i.e., conductivity, total dissolved solids, total phosphorus, phosphate, surfactants, ammonia, dissolved oxygen, and total coliforms) were able to demonstrate the greatest potential to cause the acute and chronic toxicities in the waters of Guarujá surface drainage channels. Moreover, the application of water quality indexes and statistical analyses, corroborated the information that Tombo, Enseada and Perequê channels presented the worst water quality scenarios.

Ultimately, the advantages of a combined approach using water quality indexes and statistical analyses are: (i) in a local and regional scale, this approach generated user-friendly interpretative data, and thus, very useful to support the stakeholders (e.g., public planners, civil society and field engineers) during implementation the best management practices of water (BMP) in São Paulo coastal zone; (ii) moreover, this combined approach provides a simpler means for water quality assessment, which could help Environmental Agency of São Paulo to plan and perform low-cost monitoring programmes in São Paulo coastal zone (limited human, technical and financial resources region for a water quality monitoring programme); (iii) in global scale, the results of this study could be valuable for water quality monitoring agencies worldwide (mainly in poor and developing countries) looking for a cost-effective, and thus, more effectively approach for monitoring urban surface runoff in costal zones.

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Author contributions

Vinicius Roveri: conceptualization; formal analysis; writing – original draft. **Luciana Lopes Guimarães**: writing review and editing. **Alberto Teodorico Correia**: funding acquisition, supervision, writing review and editing.

Conflict of interest

The authors declare no potential conflict of interest.

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All data included in this study are publicly available in the literature.

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