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PROPOSAL OF A WATER QUALITY INDEX FOR GUANABARA BAY (RIO DE JANEIRO, BRAZIL) WITH A VIEW TO REDUCING COSTS RELATED TO THE ENVIRONMENTAL MONITORING

PROPOSIÇÃO DE UM ÍNDICE DE QUALIDADE DA ÁGUA PARA A BAÍA DE GUANABARA (RIO DE JANEIRO, BRASIL) COM VISTAS À REDUÇÃO DOS CUSTOS RELATIVOS AO MONITORAMENTO AMBIENTAL

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Resumo: Neste trabalho, foram utilizados métodos estatísticos multivariados no desenvolvimento de um Índice de Qualidade da Água específico para a Baía de Guanabara, de forma a possibilitar uma diminuição dos gastos realizados com o monitoramento ambiental deste estuário, sem perda da qualidade da informação. A área de estudo compreendeu catorze estações de monitoramento e dados relativos a treze parâmetros de qualidade da água selecionados, frequentemente monitorados durante 2010 a 2016. A Análise Fatorial foi aplicada aos parâmetros de qualidade da água para identificar as relações existentes entre eles, bem como os que são mais significativos. Consequentemente, o número de parâmetros monitorados foi reduzido para sete (DBO, Condutividade, Fósforo Total, Nitrogênio Amoniacal Total, Ortofosfato, Turbidez e Salinidade), que foram então considerados no Índice de Qualidade da Água da Baía de Guanabara (WQI_{GB}). O WQI_{GB} é um índice de fácil compreensão desenvolvido para a Baía de Guanabara que classifica a qualidade da água em três faixas (boa, regular e ruim), além de proporcionar uma redução significativa dos custos relacionados à amostragem e análises laboratoriais.

Palavras-chave: Baía de Guanabara; Monitoramento ambiental; Qualidade da água; Estatística multivariada; Análise Fatorial.

Abstract: In this work, multivariate statistical methods were used to develop a specific Water Quality Index for Guanabara Bay, in order to reduce the costs related to the environmental monitoring of this estuary, without loss of information quality. The study area included fourteen monitoring stations and related data of thirteen selected parameters frequently monitored during 2010 to 2016. Factor analysis was applied to the water quality parameters to identify the relationships between them and to identify the parameters that were most significant. Consequently, the number of monitored parameters was reduced to seven (BOD, electrical conductivity, total phosphorus, total ammoniacal nitrogen, orthophosphate, turbidity and salinity), which were then considered in the Guanabara Bay Water Quality Index (WQI_{GB}). WQI_{GB} is an easy-to-understand index developed for Guanabara Bay that classifies water quality into three ranges (good, fair and poor), as well as provides a significant reduction of costs related to sampling and laboratory analysis.

Keywords: Guanabara Bay; Environmental monitoring; Water quality; Multivariate statistics; Factor analysis.

1. INTRODUCTION

The ecological interpretation of surface water quality and the establishment of a monitoring system depend on the use of simple methods that provide objective and interpretable information according to their own criteria, taking into account the individual characteristics of water bodies. In this respect, water quality indexes (WQIs) are generally used in surface water monitoring programs to assess changes in water quality and identify trends over time (BARROS *et al.*, 2010; MOSTAFAEI, 2014; TOMAS *et al.*, 2017).

The concept of classifying water quality based on the degree of purity and pollution emerged in Germany in the mid-nineteenth century. At the same time, the importance of water quality for public health was recognized in the United Kingdom. However, numerical indices for water quality assessment were only developed more than a century later. They were pioneered by Horton, who presented a new method for classifying water quality in the form of a numerical index in 1965. He defined the WQI mathematical formula by simply selecting, classifying and integrating the main physical, chemical and biological parameters of water, namely dissolved oxygen, pH, fecal coliforms, electrical conductivity, alkalinity, chloride, sewage treatment (percentage of the population served) and carbon extracted by chloroform. It should be noted that Horton did not consider toxic substances in his index, since he felt that water bodies should not contain elements harmful to living beings under any circumstances (LUMB *et al.*, 2011; MEDEIROS *et al.*, 2017). Since then, several WQIs have been created worldwide using different formulations and models, each with its advantages and limitations.

Guanabara Bay is characterized by its high demographic density and contains the second largest industrial park in Brazil. In recent decades, the water quality of this estuary has declined significantly, with severe pollution due to disorderly urban growth and industrial development. Industries (responsible for most of the toxic contaminant load in the bay, such as metals), clandestine landfills, domestic effluents, atmospheric emissions, oil pollution (primarily from shipping activities) and surface runoff are the main point and diffuse (non-point) sources of pollution in the bay (AGUIAR *et al.*, 2011; ABREU *et al.*, 2016). Another contributing factor in the deterioration of the estuary is siltation in certain areas due to the solid load resulting from the disordered occupation of the headwaters, deforestation and landfills. This restricts hydrodynamic circulation and reduces the dilution of pollution, worsening water quality (KCI, 2017).

The Rio de Janeiro State Environmental Agency (*Instituto Estadual do Ambiente* - INEA) is responsible for monitoring the region's water bodies. However, WQIs have never been used to assess Guanabara Bay due to the lack of a suitable instrument. Thus, a large number of water quality parameters is monitored, generating high costs in the collection (greater quantity of flasks and reagents for storing and preservation of samples) and analytical tests (greater quantity of reagents and expenses with maintenance of equipment), underscoring the need for a specific WQI with parameters that actually influence the dynamics of the bay.

The aim of this work is to use multivariate statistical techniques to develop a specific WQI for Guanabara Bay, allowing a significant reduction of the costs involved in the environmental monitoring of this estuary without loss of information quality.

2. METHODOLOGY

2.1. Study Area

Guanabara Bay, located in Southeastern Brazil, has 384 km² with 7 municipalities on its shores, including the state capital, Rio de Janeiro. Its average depth is 6 meters, and the maximum depth reaches 50 meters at the mouth. Its drainage basin, consisting of 34 rivers, covers an area of 4,000 km² and receives raw or partially treated sanitary sewage from 2/3 of Rio de Janeiro's metropolitan region. Of the 8,570,000 inhabitants in the drainage basin, only approximately 30% are served by sewage collection and treatment systems (FEEMA, 1998; ABREU *et al.*, 2016).

2.2. Database

The database of the Water Quality Monitoring Program of INEA, which contains data from fourteen monitoring stations in Guanabara Bay (Figure 1), during 2010 to 2016, was used to carry out this work. Thirteen physicochemical and microbiological parameters often monitored by the environmental agency were evaluated: thermotolerant coliforms, electrical conductivity (EC), biochemical oxygen demand (BOD), total phosphorus (TP), nitrate (NO_3^-), nitrite (NO_2^-), total ammoniacal nitrogen (NH_3), dissolved oxygen (DO), orthophosphate (PO_4^{3-}), pH, salinity, temperature and turbidity. All parameters were analyzed in a laboratory using standard methods (APHA, 2012), except temperature, which was measured on site.

The database of the available data from each of the monitoring stations was organized into a single matrix. Twenty-four sampling campaigns were performed at each monitored station, totaling 4,368 analytical tests.

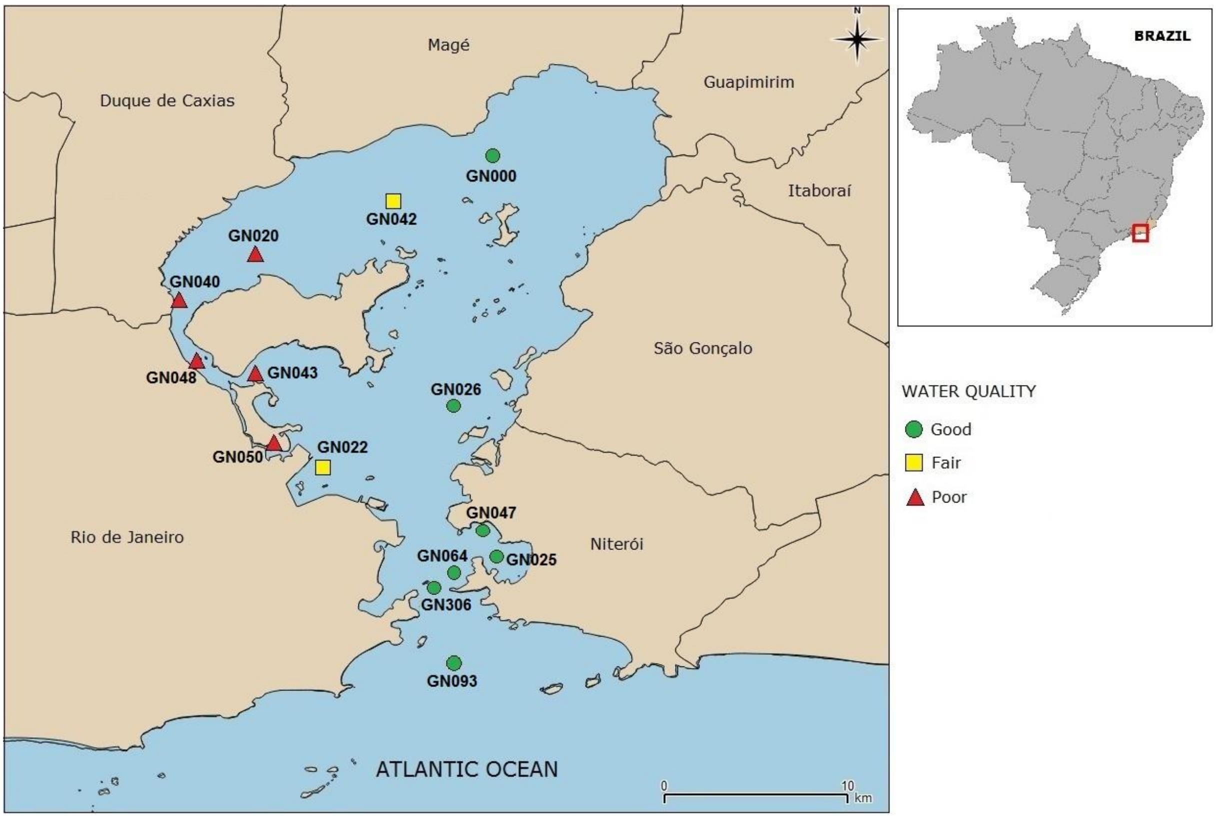

Figure 1. Location map of Guanabara Bay monitoring stations

2.3. Compiling the Water Quality Index (WQI_{GB})

The water quality index for Guanabara Bay (WQI_{GB}) was created using factor analysis (FA). This multivariate statistical technique considerably reduces the size of large datasets and describes their variability using a small number of factors without information loss. It makes it possible to identify the parameters that most affect water quality variations and groups the variables studied according to their characteristics and affinities (MAHAPATRA *et al.*, 2012; AL-MUTAIRI *et al.*, 2014). The process was carried out in five steps, as follows: a) standardization of data; b) preparation of the correlation matrix; c) factor extraction and possible reduction of the variables; d) rotation of the factor axes, with a view to ensuring easier interpretation; e) calculation of the factor score coefficient matrix (TOLEDO & NICOLELLA, 2002; COLETTI *et al.*, 2010). Calculations were performed using *Statistical Package for the Social Sciences* (IBM® SPSS® Statistics 19) software and the factor extraction method was principal component analysis.

3. RESULTS AND DISCUSSION

Table 1 shows the correlation matrix for the 13 variables studied. Values above 0.5 are highlighted red, indicating certain trends subsequently confirmed by FA. Variables with positive correlations can be found under the same factor, and those with negative correlations under different factors. Some variables (temperature, NO_3^-, NO_2^-, pH, DO and thermotolerant coliforms) showed weak correlations and were therefore not retained in the extracted factors.

Table 1. Correlation matrix of the variables

	EC	BOD	TP	NH_3	PO_4^{3-}	Turb.	Sal.	Temp.	NO_3^-	NO_2^-	pH	DO	Coli.
EC	**1.000**												
BOD	-0.282	**1.000**											
TP	-0.485	0.581	**1.000**										
NH_3	-0.397	0.258	0.651	**1.000**									
PO_4^{3-}	-0.379	0.386	0.834	0.710	**1.000**								
Turb.	-0.432	0.656	0.717	0.425	0.489	**1.000**							
Sal.	0.989	-0.286	-0.480	-0.381	-0.366	-0.430	**1.000**						
Temp.	-0.431	0.240	0.374	0.243	0.274	0.309	-0.453	**1.000**					
NO_3^-	0.074	-0.001	-0.014	0.022	0.009	-0.016	0.067	-0.110	**1.000**				
NO_2^-	-0.288	0.013	0.207	0.260	0.153	0.244	-0.293	0.119	-0.025	**1.000**			
pH	0.181	-0.198	-0.272	-0.321	-0.320	-0.217	0.174	-0.012	-0.040	-0.079	**1.000**		
DO	0.005	0.146	-0.008	-0.181	-0.188	0.120	-0.022	0.071	-0.060	0.007	0.239	**1.000**	
Coli.	-0.274	0.150	0.258	0.368	0.222	0.235	-0.259	0.125	0.114	0.238	-0.259	-0.163	**1.000**

Turb. = turbidity; Sal. = salinity; Temp. = temperature; Coli. = thermotolerant coliforms

Several general intercorrelation measures were analyzed to ensure the adequacy of the data structure for FA. Bartlett's Test of Sphericity showed significance of less than 0.05, and the Kaiser-Meyer-Olkin (KMO) test exhibited sampling adequacy of 0.743 (KMO values above 0.50 are considered acceptable), demonstrating sufficient correlations between the variables (FILHO & JÚNIOR, 2010; TAHERDOOST *et al.*, 2014). The values of the individual KMO guidelines obtained for NO_3^- and DO and the commonalities (common variance) for NO_2^-, temperature, pH and thermotolerant coliforms were less than 0.5, indicating their exclusion for continuation with FA (HAIR JR. *et al.*, 2009).

Two factors were extracted, which together explain 76% of the total variance. Better distribution of the factor loadings was obtained after Varimax factorial rotation, allowing better interpretation of the factor loading matrix (Table 2).

Table 2. Factor loading matrix

Variables	**Factor**			
	Before rotation		**After rotation**	
	1	2	1	2
TP	0.904	0.268	0.901	-0.278
PO_4^{3-}	0.796	0.312	0.836	-0.181
Turbidity	0.781	0.210	0.766	-0.258
NH_3	0.724	0.182	0.703	-0.250
BOD	0.635	0.319	0.705	-0.087
EC	-0.739	0.668	-0.245	0.966
Salinity	-0.733	0.674	-0.237	0.967
Variance explained	58.2%	17.8%	45.8%	30.2%

The factor loading graph (Figure 2) shows variable distribution for the two extracted factors after Varimax rotation, according to their factor loadings, with two distinct groups observed. The first group contains the parameters BOD, PO_4^{3-}, TP, turbidity and NH_3, and represents pollution related to domestic waste discharge. Elevated PO_4^{3-} (and consequently

TP) and NH_3 levels, as well as high turbidity, may be the result of domestic sewage discharge, since PO_4^{3-} is an important component of detergents, and NH_3 occurs through the decomposition of organic compounds that contain nitrogen, such as proteins and urea, thus indicating a strong correlation with BOD, which expresses organic matter pollution (VEGA *et al.*, 1998; WU *et al.*, 2010, SCHAFFELKEM *et al.*, 2012; JHA *et al.*, 2015). The second group, composed of salinity and EC, is directly related to the degree of water exchange between the bay and the ocean (KIM *et al.*, 2016).

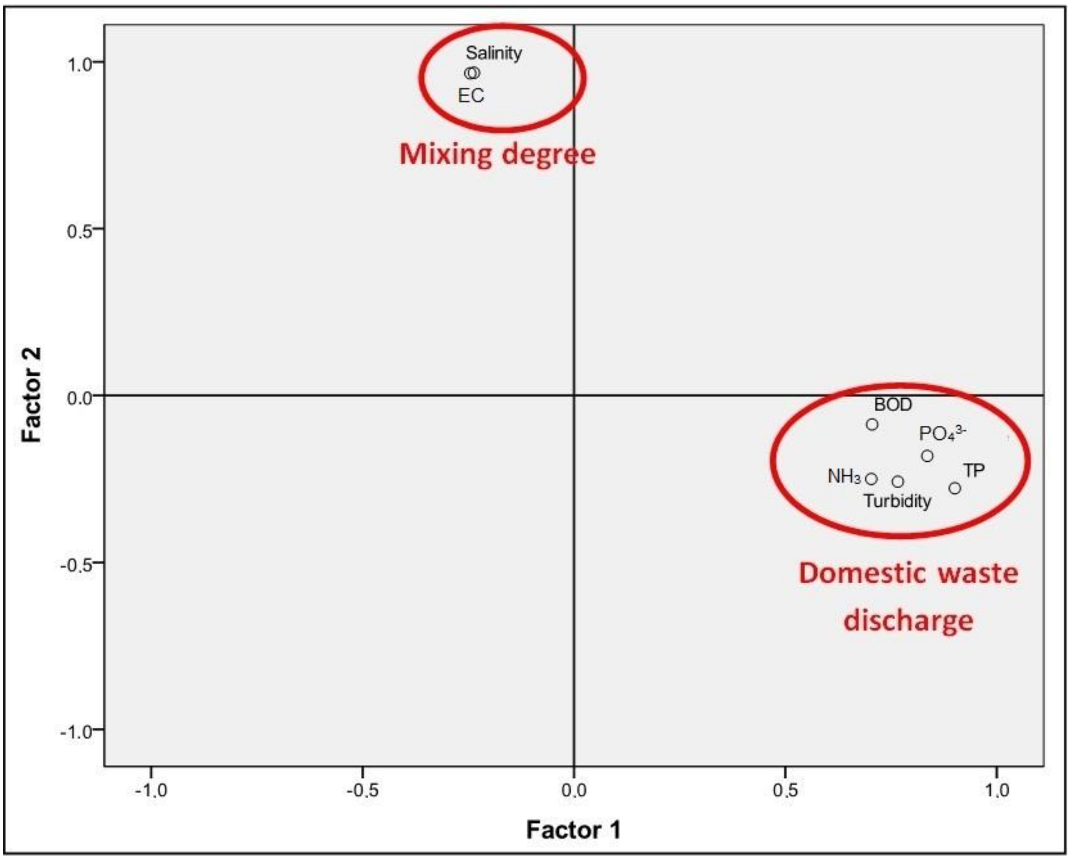

Figure 2. Factor loadings: Factor 1 x Factor 2

Given that the first factor always explained the greatest data variability and represents the most common elements of the variables studied, it was adopted as the Guanabara Bay Water Quality Index (WQI_{GB}) (DEVEREL, 1989; FEPAM, 2005; COLETTI *et al.*, 2010). The WQI_{GB} equation terms (Equation 1) are composed of the variables (parameters) retained in FA and their respective weights, which are the coefficients of the first factor scores obtained from the factor score coefficient matrix, calculated using Bartlett's method. The WQI obtained using this equation exhibited zero mean and unit variance, and previous standardization of the variables was performed.

$$WQI_{GB} = 0.145 \cdot EC + 0.271 \cdot BOD + 0.304 \cdot TP + 0.229 \cdot NH_3 + 0.301 \cdot PO_4^{3-} + 0.253 \cdot Turb + 0.149 \cdot Sal \qquad (1)$$

The WQI_{GB} results were divided into three water quality ranges: good, fair and poor (Table 3). The limits of each range were defined based on the reference standards of each parameter, established according to national and international legislation and the technical literature (Table 4) (CONAMA, 1986; EPA, 1988; FEEMA, 1998; CONAMA, 2005; EPA, 2006).

Table 3. WQI_{GB} water quality ranges

Water quality	Range
GOOD	$WQI_{GB} \leq -0.38$
FAIR	$-0.38 < WQI_{GB} \leq 0.05$
POOR	$WQI_{GB} > 0.05$

Table 4. Reference standards for WQI_{GB} parameters

Parameter	Good	Poor	Reference
BOD (mg O_2/L)	< 5	> 10	CONAMA, 1986; FEEMA, 1998
TP (mg P/L)	< 0.15	> 0.3	FEEMA, 1998
NH_3 (mg N/L)	< 0.4	> 0.7	CONAMA, 2005
Turbidity (NTU)	< 8	> 15	EPA, 1988
Salinity (‰)	> 30	< 18	EPA, 2006
EC (µS/cm)	> 46000	< 29000	EPA, 2006
PO_4^{3-} (mg P/L)	< 0.05	> 0.25	FEEMA, 1998

The WQI_{GB} of each monitoring station was calculated using the results obtained in the 24 sampling campaigns, and expressed as the medians of the entire study period in Figure 1. The northwestern area, which includes the monitoring stations GN020, GN040, GN043, GN048 e GN050, has the worst water quality. This region contains rivers that run through municipalities with serious health infrastructure problems and a large number of industries. The northern area (GN000 e GN042), which displays lower population density and consequently receives a lower effluent pollution load, and the central area (GN022 e GN026), which is strongly influenced by tidal currents, show fair to good water quality. All the monitoring stations at the mouth (GN025, GN047, GN064, GN093 e GN306) have good water quality because water exchange with the sea and renewal of estuary waters occur in this region.

4. CONCLUSIONS

In this work, the reduction of costs related to the systematic monitoring of Guanabara Bay water quality was achieved by applying FA to physical-chemical and biological parameters. Two factors were extracted that together, after applying the Varimax orthogonal rotation, explain 76% of the total variance. The first factor, composed of the variables BOD, total phosphorus, orthophosphate, total ammoniacal nitrogen and turbidity, represents the pollution related to untreated sanitary effluent discharge, while the second factor, which contains the variables salinity and electrical conductivity, is related to the degree of water exchange between the bay and the sea. The seven parameters considered in the FA, with their respective weights (coefficients of the first factor scores), compose the terms of the WQI_{GB} equation, an index developed to provide an easy interpretation of this estuary's water quality without loss of information based on three ratings: good, fair and poor. The evaluation of the water quality index showed that in half of the monitoring stations water quality is good, while 35.7% have poor quality, and 14.3% have fair quality. Reducing the number of parameters allows for a significant reduction in costs involved in all stages of Guanabara Bay water quality monitoring, making the current environmental management model of this estuary more economically viable.

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