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Spatial and Seasonal Characterization of Water Quality in Guanabara Bay (Rio de Janeiro, Brazil)

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ABSTRACT: *This study aimed at the spatial and seasonal characterization of the water quality in Guanabara Bay, an estuarine system in southeastern Brazil from 2010 to 2016, to identify the main factors that contribute to the pollution of these waters. Fourteen monitoring stations were assessed, and seven physical-chemical parameters (BOD, total phosphorus, total ammonia nitrogen, dissolved orthophosphate, turbidity, electrical conductivity and salinity) were statistically analyzed. The northwest area is the most polluted, due to organic load and nutrients from the improper disposal of domestic and industrial effluents. The main indicator for the spatial characterization of the estuary is salinity, since its concentration is inversely proportional to pollution levels. The influence of seasonality on the water quality of the estuary was assessed and worse conditions were observed in the wet season in almost all the monitoring stations.*

KEYWORDS: *Spatial characterization, seasonal characterization, water quality assessment, environmental monitoring, Guanabara Bay.*

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I. INTRODUCTION

The emblematic and urgent challenges for the sustainable management of water resources are anchored by increasing human demands and for environmental quality conservation, fundamental health and life quality factors for urban and rural populations. Monitoring is vital to the formation of a database that provides greater knowledge of the quality of water resources to ensure proper management, in addition to identifying and preventing the main sources of pollution. Quantifying the pollutant load in bodies of water is a key element in management practices that focus on the conservation and sustainable use of water. The integrated analysis of water quality data and the characteristics of land use and occupation in a river basin, combined with the distribution of the urban population and availability of urban and industrial infrastructure make it possible to define the cause and effect relationship between land occupation and estuarine water quality [1,2].

The physical, chemical and biological parameters that characterize the water quality of a water body undergo significant spatial and temporal variations, prompting the need for studies and investments aimed at monitoring different regions of interest. Water quality monitoring programs are essential to a better understanding of a water body's behavior. Brazil's Ministry of Environment defines environmental monitoring as "the systematic monitoring of the condition of environmental resources of physical and biotic means, with the aim to environmental quality recovery, improvement or maintenance", which "is related to the management of environmental variables when they are altered due to anthropogenic sources or to natural changes" [3].

Guanabara Bay is surrounded by the metropolitan region of Rio de Janeiro, which is characterized by a high population density and is home to Brazil's second largest industrial park. In recent decades, the water quality of this estuary has undergone great deterioration, with evidently serious pollution problems due to the disorderly urban growth associated with construction of industrial complexes, including alterations in the original contour of the islands due to successive landfills; increased sedimentation rates; destruction of mangrove vegetation; and disposal of domestic sewage, urban and industrial waste, causing pollution by organic matter, highly toxic metals, phenols, organic micropollutants, oils and greases [4,5].

In the present study, the spatial and seasonal characterization of water quality in Guanabara Bay (Rio de Janeiro, Brazil) was carried out from 2010 to 2016, identifying the main factors that contribute to deteriorating water quality in the estuary and support the necessary adjustments to the current management model of the region around its drainage basin.

II. METHODOLOGY

2.1 Study Area

Guanabara Bay is located in the center of the metropolitan region of Rio de Janeiro, in southeastern Brazil, with 7 municipalities on its shores. It is the second largest estuary on the Brazilian coast (131 km of perimeter), with a total area of 384 km², average depth of 6 meters and maximum of 50 meters at the mouth. Its waters are largely brackish, except near the mouth of the bay, where saline water predominates. The Guanabara Bay region contains around 40 beaches, most deemed unfit for bathing [5,6,7,8].

Guanabara Bay should not be limited solely to its water mirror, but rather its entire hydrographic region should be considered, since pollution in the estuary comes largely from the rivers and mainland in the form of surface water drainage and highly polluted water. The Guanabara Bay basin consists of 55 rivers that cover 16 municipalities, with an approximate area of 4,000 km². The climate in the bay region is hot, humid and tropical with a warm rainy season in summer, from December to April, and a dry cool season in winter from June to August [6,7,8,9,10,11,12].

The main source of pollution in the Guanabara Bay hydrographic region is domestic sewage from urban areas, accounting for 84.26% of the total biochemical oxygen demand (BOD) load and 58.14% of the total chemical oxygen demand (COD) load. The infrastructure for sewage collection and treatment in the municipalities within the basin region is highly deficient. Of its 8,570,000 inhabitants, only 23.6% are connected to sewage collection and treatment systems [8]. As a result, the population lives under precarious and adverse conditions, with alarming rates of waterborne diseases [12,13].

Guanabara Bay is home to Brazil's second largest industrial park containing approximately 14,000 industries from different sectors, primarily the commercial, service, food and processing sectors, with extractive industries being the most productive in the region [12]. Industrial effluents are also a significant source of organic pollution related to BOD and COD, and are responsible for almost all chemical pollution by toxic substances and heavy metals [7,14].

2.2 Data Base

The database of the Water Quality Monitoring Program of the Instituto Estadual do Ambiente (INEA), the environmental agency of the state of Rio de Janeiro, was used to carry out this work. The database contains data from a systematic monitoring program with 14 monitoring stations in Guanabara Bay, during 2010 to 2016 (Figure 1).

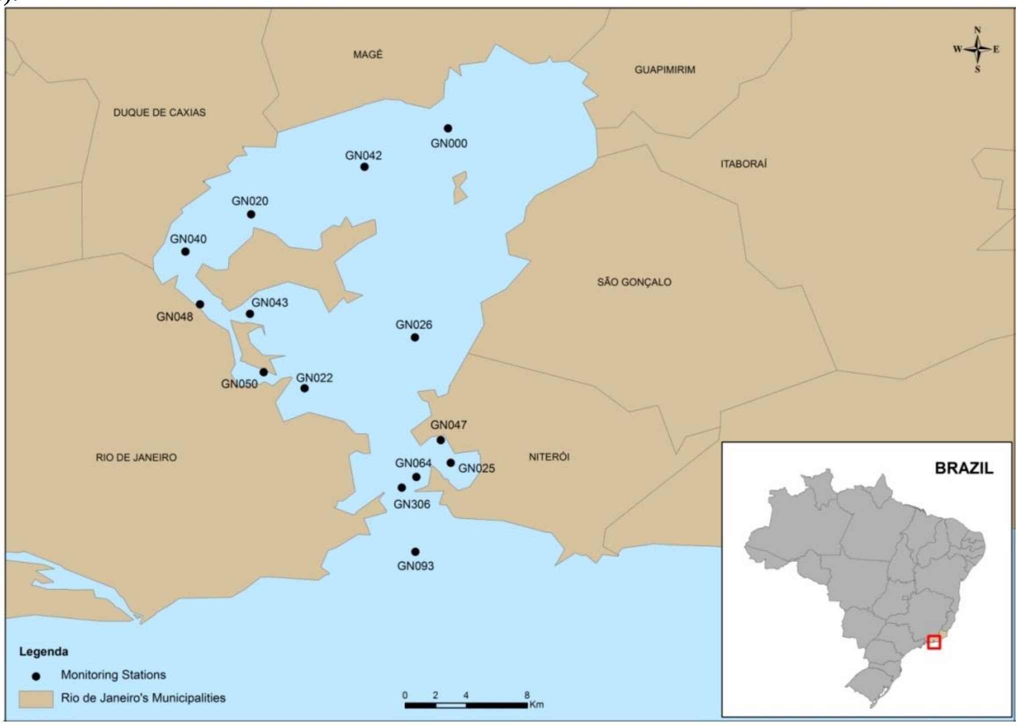

Figure 1. Study area and respective monitoring stations

The physical-chemical parameters that compose the Guanabara Bay Water Quality Index equation (WQI_{GB})[1] were analyzed, which are: BOD, total phosphorus (TP), total ammonia nitrogen (NH_3), dissolved orthophosphate (PO_4^{3-}), turbidity, electrical conductivity (EC) and salinity (Equation 1) [15]. The first five parameters represent pollution related to domestic waste discharge, and the last two are directly related to the degree of water exchange between the bay and the ocean. WQI_{GB} is an easy-to-understand index that classifies Guanabara Bay water quality into three ranges (good: $WQI_{GB} \leq$ -0,38; fair: -0,38 $< WQI_{GB} \leq$ 0,05; poor: $WQI_{GB} >$ 0,05), as well as provides a significant reduction of costs related to sampling and laboratory analysis due to the reduction in the number of frequently monitored parameters (from 13 to only 7).

$$WQI_{GB} = 0.145\, EC + 0.271\, BOD + 0.304\, TP + 0.229\, NH_3 + 0.301\, PO_4^{3-} + 0.253\, Turbidity + 0.149\, Salinity \quad (1)$$

Surface water samples were taken in quadrature ebb tides to understand the impact from the drainage basin. All parameters were analyzed in a laboratory using standard methods [16], except temperature, which was measured on site. Twenty-four sampling campaigns were performed at each monitored station, totaling 336 samples.

2.3 Water Quality Assessment

Water quality in Guanabara Bay was assessed in three stages. First, the WQI_{GB} was applied to all the water samples collected at the monitoring stations during the study period, in order to classify them according to quality.

Next, water quality was spatially evaluated by analyzing the variability of the monitoring data set for the entire period (2010 to 2016), in order to identify the main sources of pollution in each area of the estuary.

The final stage consisted of seasonal assessment. To that end, box plots were constructed using the monitoring data for the parameters of the WQI_{GB} equation to determine the effect of dry and wet seasons on water quality. The impact of seasonality was analyzed using data from November 2012 to October 2013, since the highest number of monthly samplings (nine) occurred in this period.

III. RESULTS AND DISCUSSION

3.1 Application of WQI_{GB} and Spatial Evaluation

These two steps were carried out together because they provide complementary information for water quality assessment: the WQI_{GB} classifies the water quality of each monitoring station and spatial assessment makes it possible to identify the factors responsible for changes in water quality. The mean, standard deviation and minimum and maximum values calculated for all WQI_{GB} parameters are presented in Table I.

Table I. Mean, standard deviation and minimum and maximum values of the parameters studied

MONITORING STATION	EC (µS/cm)	BOD (mg O_2/L)	TP (mg P/L)	NH_3 (mg N/L)	PO_4^{3-} (mg P/L)	Turbidity (NTU)	Salinity (‰)
GN000	40455±9913 (12840-51900)	9,2±15,8 (2,0-80,0)	0,21±0,18 (0,07-0,98)	0,39±0,61 (0,01-2,87)	0,06±0,10 (0,01-0,53)	7,62±6,19 (1,70-32,00)	26,53±7,13 (7,49-35,85)
GN020	34577±11232 (12250-57100)	9,6±7,4 (2,4-32,0)	0,51±0,24 (0,21-1,20)	2,50±1,65 (0,10-5,90)	0,20±0,17 (0,02-0,80)	12,82±9,65 (2,70-44,20)	22,55±8,03 (7,12-37,99)
GN022	45278±9490 (13960-58000)	8,8±10,8 (2,0-48,0)	0,27±0,14 (0,04-0,80)	0,67±0,56 (0,01-2,40)	0,08±0,05 (0,01-0,21)	4,47±2,42 (0,98-9,00)	29,80±6,70 (8,21-38,65)
GN025	47727±9704 (15140-59400)	5,3±5,7 (2,0-28,0)	0,1±0,08 (0,03-0,41)	0,43±1,17 (0,01-5,40)	0,04±0,06 (0,01-0,31)	2,65±1,84 (0,20-9,20)	31,67±6,90 (8,97-39,66)
GN026	45533±9915 (13460-58400)	8,2±6,8 (2,0-20,0)	0,26±0,30 (0,04-1,60)	0,32±0,31 (0,01-1,31)	0,11±0,28 (0,01-1,40)	5,39±4,98 (0,84-19,00)	30,02±7,01 (7,89-38,94)
GN040	31883±9975 (11200-48330)	12,5±7,0 (2,6-28,0)	0,72±0,26 (0,32-1,34)	4,20±2,83 (0,10-10,00)	0,36±0,25 (0,04-0,90)	13,38±6,07 (4,90-28,00)	21,00±7,13 (6,46-32,31)
GN042	41708±9479 (13280-51800)	12,6±18,2 (2,2-88,0)	0,39±0,42 (0,07-2,21)	0,64±0,57 (0,01-1,84)	0,12±0,16 (0,01-0,78)	10,94±0,74 (2,00-67,00)	27,32±6,71 (7,77-34,75)
GN043	38913±10126 (10840-53200)	6,8±4,9 (2,0-21,0)	0,50±0,21 (0,19-0,91)	2,23±1,45 (0,10-6,20)	0,22±0,10 (0,02-0,43)	7,18±3,24 (1,40-15,20)	25,27±7,02 (6,23-35,18)
GN047	47492±9471 (14980-55300)	5,3±3,7 (2,0-16,0)	0,11±0,07 (0,04-0,34)	0,14±0,17 (0,01-0,83)	0,04±0,03 (0,01-0,13)	2,81±1,99 (1,10-10,00)	31,46±6,72 (8,86-36,87)
GN048	35673±8003 (17520-55300)	8,5±5,1 (2,0-20,0)	0,64±0,18 (0,31-1,00)	3,41±1,87 (0,10-8,00)	0,34±0,14 (0,10-0,61)	9,20±3,60 (3,80-16,00)	22,89±5,58 (10,51-36,69)
GN050	36490±8958 (17560-52200)	13,5±8,9 (2,0-36,0)	0,68±0,29 (0,08-1,19)	4,68±2,91 (0,33-11,00)	0,45±0,25 (0,01-0,94)	11,21±7,70 (1,40-31,00)	23,85±6,61 (10,54-34,46)

[1] WQI_{GB} was formulated and validated by the authors of this paper in another component of this project and all the detailed steps of its development were described in the paper *"Proposal of a water quality index for Guanabara Bay (Rio de Janeiro, Brazil) with a view to reducing costs related to the environmental monitoring"* [15].

GN064	47355±9484 (14910-56400)	3,0±1,2 (2,0-5,4)	0,10±0,05 (0,03-0,34)	0,51±1,61 (0,01-8,00)	0,04±0,03 (0,01-0,09)	2,01±1,15 (0,20-4,80)	31,44±6,77 (8,82-37,49)
GN093	48732±9576 (15910-55700)	2,2±0,5 (2,0-4,4)	0,07±0,05 (0,02-0,22)	0,42±1,38 (0,01-6,90)	0,03±0,02 (0,01-0,08)	1,32±0,71 (0,17-3,73)	32,46±6,84 (9,46-37,88)
GN306	47365±9577 (14890-57700)	2,8±1,0 (2,0-5,0)	0,09±0,02 (0,07-0,12)	0,67±2,42 0,01±12,00	0,04±0,02 (0,01-0,10)	1,76±1,06 (0,10-4,30)	31,44±6,82 (8,80-38,43)

The WQI_{GB} of each monitoring station was calculated using the results obtained in the 24 monitoring campaigns, applying the concentrations of the parameters studied after standardization to Equation 1. A graph was constructed depicting the annual medians of WQI_{GB} monitoring stations to facilitate result interpretation (Figure 2). Figure 3 presents the Box Plots for the seven parameters of the WQI_{GB}, used to spatially assess water quality in Guanabara Bay. The reference standards of each parameter were established according to national and international legislation and the technical literature [7,17,18,19,20].

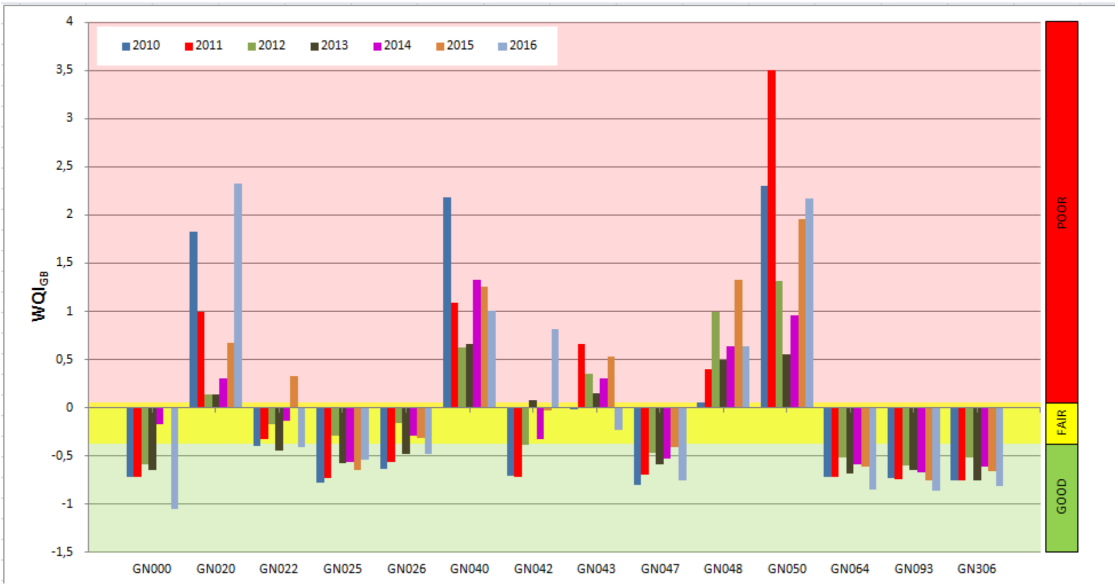

Figure 2. Annual medians for the WQI_{GB} monitoring stations

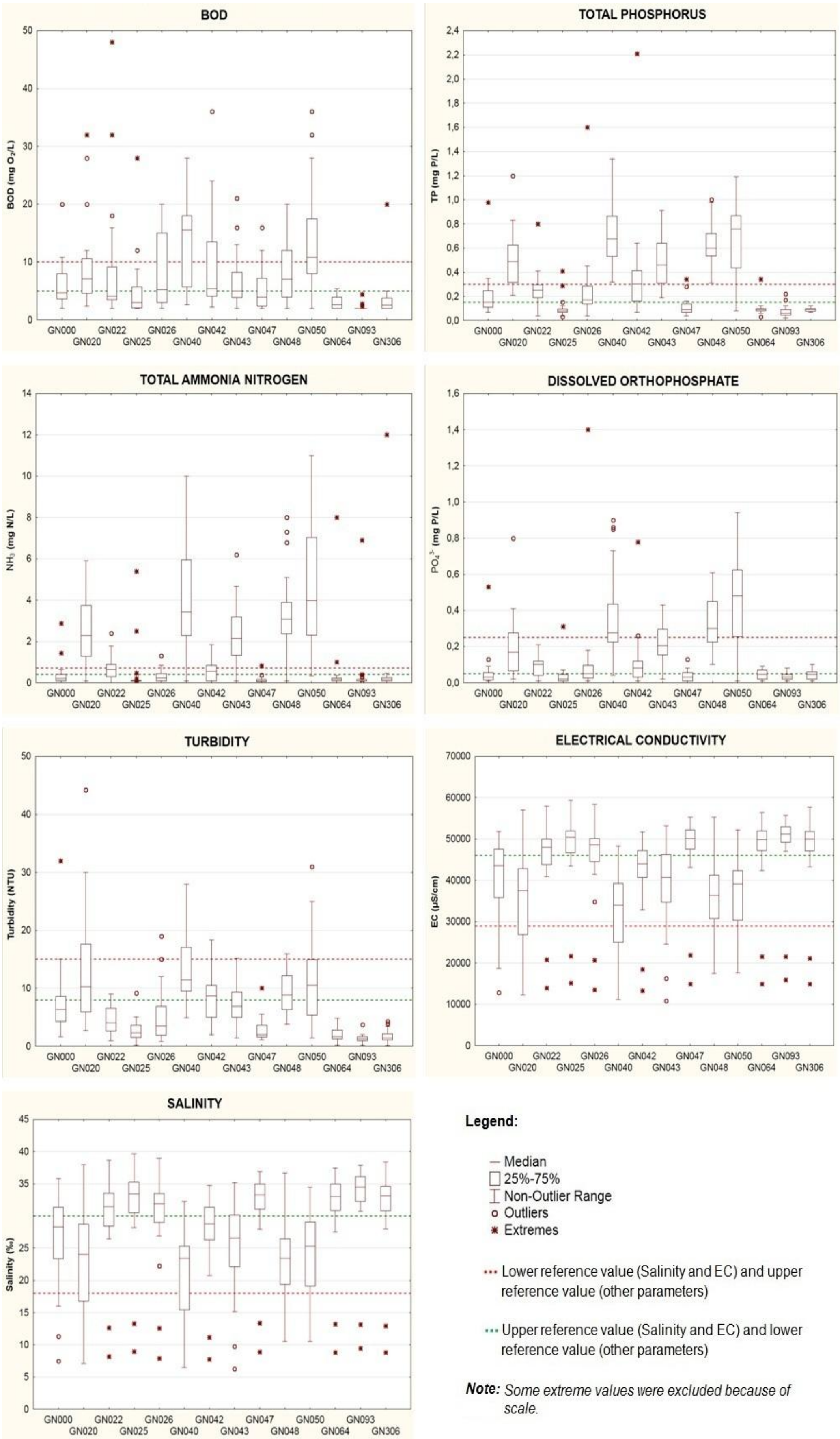

Figure 3. Box plots for the water quality parameters of the WQI_{GB} equation (2010 to 2016)

The northwestern area, which includes the monitoring stations GN020, GN040, GN043, GN048 and GN050, was the most polluted in terms of organic load and nutrients, with an advanced level of degradation due to the presence of several sources of pollution, a high urbanization rate, siltation and embanking of the water body, which contributed to poor water circulation in the region. The highest levels of BOD, NH_3, TP, PO_4^{3-} and turbidity were found at monitoring stations GN040 and GN050, located in the channel between the islands of the northwestern area and the continent. The region displays extremely low circulation and water renewal is practically non-existent, since tidal movement has a limited influence due to sediment deposition, which has reduced the cross-sections of the channel. Additionally, the rivers in this region contain very poor water quality and are subject to high pollutant loads from domestic and industrial effluents. Elevated PO_4^{3-}, TP and NH_3 concentrations indicate extremely high levels of raw or partially treated effluents discharged from low-income residential areas north of the municipality of Rio de Janeiro. The water quality in this area is similar to that of partially treated domestic sewage and exudes odors typical of anaerobic water bodies during low tide. The high loads of organic matter (BOD) and nutrients combined with the low water clarity in this region have exacerbated the degradation of the Guanabara Bay ecosystem. Nitrogen and phosphorus compounds are also directly related to BOD because nutrients are responsible for eutrophication, increasing organic matter levels due to algae growth and, consequently, turbidity.

The high degree of eutrophication has spread to other regions from the highly urbanized northwestern area, threatening water quality throughout the estuary [7]. This is evident in the fair classification of the WQI_{GB} for monitoring stations in the intermediate region between the northwestern area and the central and entry areas (GN022 and GN042). The BOD was lower and water quality higher at GN022, since it is closer to the mouth of the bay. Although GN000 in the northern area displays fair EC and salinity, which indicates less influence from ocean waters because it is farthest from the mouth, it is classified as good by the WQI_{GB} due to the presence of wetlands and mangroves at the mouths of the rivers in the northeastern area of the basin, factors that positively influence water quality [10]. Point GN026 displays fair BOD and TP conditions, possibly because it is located in a region mildly affected by domestic sewage discharge into a river whose mouth is on the east coast, bordering the municipalities of São Gonçalo and Niterói.

Water quality at the mouth of the bay (GN025, GN047, GN064, GN093 and GN306) is classified as good according to the WQI_{GB}, which is directly related to the contribution of ocean water. However, less favorable BOD conditions were observed at monitoring stations GN047 and GN025, possibly because they are located in densely populated coves with reduced water circulation when compared to the other monitoring stations.

In short, considering the different spatial patterns, the north/south pollution gradient is a function of the estuarine characteristics of the bay, such as changes in salinity, and reflects continental contributions in the north and the ocean in the south, while the east/west pollution gradient is a reflection of urbanization in the coastal areas of the bay [12].

It can be deduced that salinity is a major indicator for the spatial characterization of Guanabara Bay, since increased salinity indicates less pollution. In regions of high salinity, such as the mouth, PO_4^{3-} and NH_3 levels remain low, demonstrating greater assimilation capacity. On the other hand, at monitoring stations located near the western margin, these nutrients increase as salinity declines, confirming greater degradation and recent pollution [7].

3.3 Seasonal Evaluation

Figure 4 shows the box plots of the water quality parameters of the WQI_{GB} equation in the wet (November 2012 to April 2013) and dry seasons (May 2013 to October 2013), confirming the influence of seasonality.

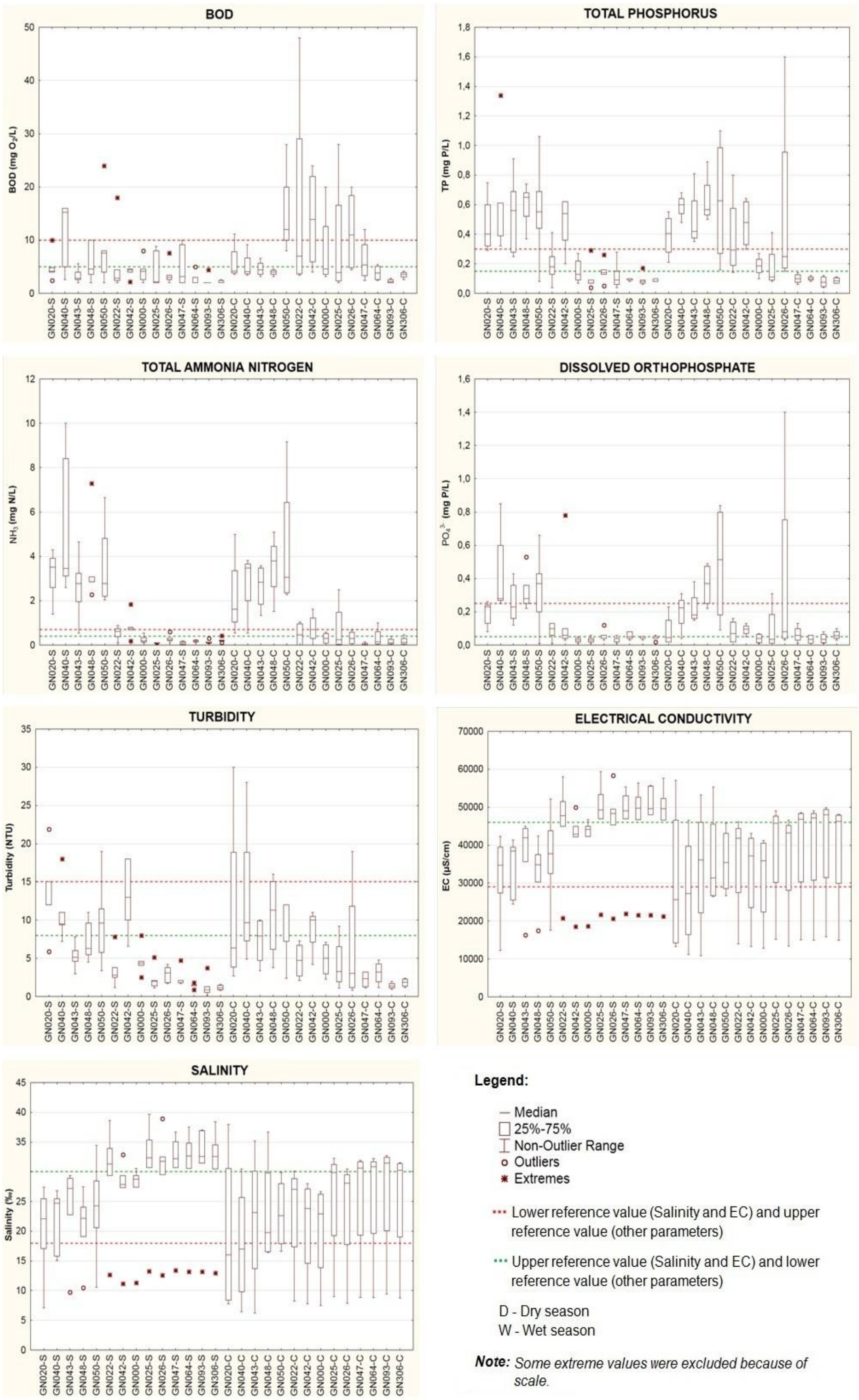

Figure 4. Box plots for the water quality parameters of the WQI_{GB} equation (wet and dry seasons from November 2012 to October 2013)

The BOD results obtained in the wet season showed higher maximum and median concentrations than those recorded in the dry season, with the exception of GN040 and GN048. Additionally, there was a greater variation in BOD levels in the wet season, especially at monitoring stations that generally exhibit good and fair water quality (mouth, central area and northern area). These changes occur due to the rise in organic matter from domestic sewage and industrial effluents discharged into the rivers that flow into the bay, especially in the wet season.

With respect to nutrients (NH_3, TP and PO_4^{3-}), both maximum concentrations and variations rose during the wet season, except for points GN020 and GN040. This was most noteworthy in the central and at the mouth, particularly at GN026. Similarly to BOD, the increase in fluvial discharge in the wet season results in higher levels of these domestic sewage nutrients.

With the exception of points GN042 and GN050, turbidity increased significantly in the wet season, possibly due to a greater contribution by suspended solids from sediment transport in the river basin caused by erosion, as well as surface runoff and resuspension of particulate material from the bay.

Salinity and EC varied significantly in the wet season, with far lower minimum values than those recorded in the dry season. This is because increased flow in tributaries leads to greater freshwater intake in the estuary, in addition to dilution of the bay waters by rainwater.

IV. CONCLUSIONS

In the present study, water quality in Guanabara Bay was spatially and seasonally characterized by statistically analyzing its physical and chemical parameters. All the monitoring stations in the northwestern area exhibited poor water quality, while quality at the mouth was good. With respect to the central and northern areas, the monitoring stations closest to the east coast showed good water quality, while in those located further west quality was fair. The highly urbanized and industrialized northwestern area was the most polluted due to organic load and nutrients from domestic and industrial effluent discharge, with the highest levels of BOD, NH_3, TP, PO_4^{3-} and turbidity recorded at monitoring stations GN040 and GN050, located in a region of low circulation and water renewal. The high degree of eutrophication in this region is already evident in the northern and central areas, where fair water quality points are found (GN022 and GN042). Less favorable BOD conditions were observed at some points with good water quality (GN025, GN026 and GN047) due to their proximity to densely populated regions. The spatial pattern of pollution identified is related to the estuarine characteristics of the bay (north/south) and the anthropic activities in the coastal areas (east/west). Additionally, salinity was found to be important in the characterization of the environment, since its concentration is inversely proportional to the degree of pollution.

Seasonality influences water quality in the estuary since, in general, the maximum concentrations and variations of all the parameters rose at almost all the monitoring stations in the wet season due to increased flow in tributaries. This was most significant at monitoring stations that normally had good or fair water quality, located at the mouth, and in the central and northern areas of the bay.

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