v. 5, n. 4, 2025

International Journal of Biological and Natural Sciences

Acceptance date: 24/10/2025

PHYSICAL AND CHEMICAL CHARACTERIZATION OF THE OUTER SECTOR OF GUARATUBA BAY, PARANÁ COAST, FACING ANTHROPIC AND METEOCEANOGRAPHIC CHANGES

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Abstract: Estuaries are transitional ecosystems where rivers meet the ocean, and in these areas long-term abiotic monitoring, both limnological and oceanographic, is essential. Guaratuba Bay (BG), located between two estuarine complexes that house ports in southern Brazil (Paranaguá -Paraná, and Babitonga -Santa Catarina), unlike these, has a scarcity of published abiotic data. Thus, our abiotic profile (2020-2021) provided seasonal data on temperature (seawater surface temperature/SST), salinity, pH, turbidity, and nitrogen and phosphate concentrations in the BG. This is relevant for conservation, because these biomarkers act as sentinels of agricultural expansion and effluent input, and also feed databases for assessing meteoceanographic changes. The minimum and maximum SST values of the outer sector of the BG ranged from 18 to 260C in winter (I) and summer (V), respectively. The average salinity ranged from 16.2 (V) to 27.4 (I) psu. The pH ranged from 6.11 to 7.24, in spring and summer. Turbidity ranged from 19 (I) to 34 (V) NTU. Phosphate concentrations ranged from 0.38 (spring) to 3.5 (summer) mg.L-1, ammonium from 0.12 to 0.45 mg.L-1 in autumn and spring; and nitrate from 0.04 to 0.53 mg.L-1 in autumn and summer. A novel approach and discussion of the observed differences in measured abiotic parameters was conducted, considering the northern and southern faces of the outer sector of the BG, i.é., the ferry berths in Caiobá and Guaratuba, respectively. Finally, this contribution compared some primordial differences in the physical and chemical profiles of Paranaguá Bay and BG, and over the past decades, suggesting that continuous monitoring of BG is highly recommended to track and mitigate current impacts and safeguard the ecosystem services provided by this estuary, which has been neglected in terms of limnoceanographic data.

Keywords: seawater parameters, SWAO, coastal monitoring, conservation.

INTRODUCTION

According to the US Environmental Protection Agency (EPA), National Estuary Program, an estuary is a partially enclosed, coastal water body where freshwater from rivers and streams mixes with salt water from the ocean. Estuaries, and their surrounding lands, are transition zones between land and sea. Although influenced by the tides, they are protected from the full force of ocean waves, winds and storms by landforms such as barrier islands or peninsulas. Estuarine environments are among the most productive on earth, creating more organic matter each year than comparably sized areas of forest, grassland or agricultural land. The sheltered waters of estuaries also support unique communities of plants and animals specially adapted for life at the margin of the sea.

The connection between these two ecosystems allows flows of higher-salinity seawater into the estuaries, generating dynamic circulation guided by the thermohaline gradients in these transitional areas. Estuarine environments constitute unique and diverse ecosystems, due to these exchanges of distinct water masses influencing the distribution of biota (Pellizzari 2005, Begon et al. 2006).

Furthermore, estuaries present high rates of sediment deposition and input of organic and inorganic nutrients from river discharges mixed with marine waters (Dalu et al. 2019). This eutrophic mixture is responsible for the high rate of primary production in these coastal environments (Hopkinson et al. 2005, Diatta et al. 2020). However, the accelerated urbanization process in coastal areas and the range of resources offered by estuarine environments continually attract economic and recreational activities, intensifying anthropogenic pressure and contributing to the input of additional nutrients and potential pollutants that compromise the quality of these ecosystems (Mitchell et al. 2015), justifying the relevance of limnoceanographic research and monitoring.

This is currently aggravated by climate change, disorderly population growth, and the unsustainable use of natural resources, which has magnified the loss of water quality in different coastal regions of the country and worldwide (Pellizzari et al. 2014, 2023). In the past decade, several studies have reported the presence of inorganic substances that promote eutrophication (Wang et al. 2019, Dalu et al. 2019), organochlorines and pesticides (Jayaraj et al. 2016, Carneiro et al. 2025), herbicides (Garrido et al. 2003, Parven et al. 2025), and trace elements (Xiao et al. 2019, Crini et al. 2022).

Furthermore, contamination of estuarine ecosystems is an issue not only related to coastal conservation but also to public health, being intrinsically linked to social and economic disruptions. Estuarine water quality is measured by physical, chemical, and biological variables. These abiotic parameters, if maintained within certain limit / basal concentrations, enable specific uses, e.g., for drinking, recreation and or aquaculture. These limits constitute the criteria (recommendations) or standards (legal rules) for water quality (Derísio 1992). In Brazil, the National Environmental Council (CONAMA) regulates these standards—in this case, Resolution 357/2005—for waters throughout the national territory, classified according to their salinity (freshwater, brackish, and marine). Thus, spatial and temporal monitoring of physical-chemical factors of estuarine waters that support the assessment of their quality is widespread and involves analyses of Surface Seawater Temperature (SST), salinity, pH, Biochemical Oxygen Demand (BOD), turbidity, Total Dissolved Solids (TDS), Dissolved Oxygen, nitrogen compounds, phosphate, among other inorganic and organic pollutants (Nascimento et al. 2021).

In another instance, inorganic nitrogen and phosphate compounds, also input by human activities in the estuaries, limit the growth of autotrophs (phytoplankton, macroalgae, and seagrasses). High concentrations may cause algal blooms (both, phytoplankton and seaweeds), further affecting the physical and chemical behavior of the water column and biota. Algal blooms (whether harmful – HAB- or not) block the penetration of sunlight into the water column, which is naturally turbid in these areas, generating hypoxia or anoxia (Pellizzari et al. 2014, Mafra et al. 2024), and consequently altering estuarine homeostasis and ecosystem services.

Matinhos and Guaratuba municipalities, located in the surrounds of Guaratuba Bay, Paraná State, Southern Brazil, Southwestern Atlantic Ocean (SWAO), attract thousands of tourists during summer, resulting in a great increase of local population, and several environmental problems. The main issue is the increase in sanitary sewage loads reaching the bay, besides aquicultural, and agricultural endeavors. The accumulation and persistence of effluents constitute a threat to estuarine biota, coastal communities and severely degrades the environment.

Unfortunately, Guaratuba Bay (GB) stands out for its scarcity of published abiotic parameters. Hence, the present study aims to present a physicochemical database based on seasonal monitoring (2020-2021). Physico-chemical parameters of the waters from external sector of the GB (SST, salinity, pH, turbidity, TDS, phosphate, ammonium, and nitrate) were measured spatiotemporally. Historical comparisons were used to discuss the data, as well as the possible impacts of these changes on abiotic patterns in the estuarine system. These insights and the seasonal reference/basal data generated here are essential for medium- and long-term monitoring, especially facing anthropogenic impacts and/or the current meteoceanographic changes.

METHODOLOGY

STUDIED AREA

Guaratuba Bay (GB), an Environmental Protection Area, is located between coordinates 25°32'41"S // 26°00'29"S and 49°08'22"W // 48°32'18"W (Figure 1). This estuary (50.19 km²) is characterized by a single, narrow channel of communication with the SWAO (ca. 500 m), and presents distinctive physical, chemical, and biological conditions, with high concentrations of nutrients and organic matter that support high primary productivity (Brandini 2008). GB has a subtropical and transitional climate, in addition to unique geological and landscape attributes.

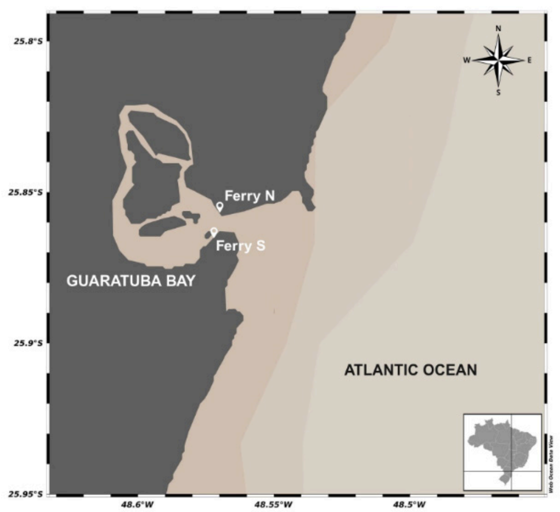

Figure 1. Map of Guaratuba Bay (BG, Paraná State, Southern Brazil), and the sampling sites plotted in the outer sector of the estuary: to the north (Ferry N - Caiobá) and to the south (Ferry S – Guaratuba Municipality), Southwestern Atlantic Ocean (SWAO). Map generated using Ocean Data View software (ODV web).

The BG includes, among others, runoff from the São João and Cubatão rivers, the main source of freshwater to the estuary. The abiotic characteristics of GB and its unique biota enable activities that boost the economy, such as tourism (Scheuer et al. 2022), oyster farming, sport and artisanal fishing, and agriculture, particularly the cultivation of bananas and citrus fruits (Chaves 2021).

The development of these activities over the years has led to an increase in the local population and associated impacts, such as the irregular dumping of domestic effluents and solid wastes, in addition to the consequent increase in agricultural demand and excessive use of fertilizers in the vicinity of the BG. These factors interfere in the natural dynamics of the estuarine system and adjacent beaches. Therefore, monitoring the area is essential to assess and mitigate potential environmental impacts.

SAMPLING AND LABORATORIAL ANALYSIS

Eight subsurface water sampling sites were established in the outer sector of GB, at the access docks for the Matinhos-Guaratuba Ferry crossing. Four were arranged adjacent to the dock at the Caiobá Beach (Ferry North: FN) and 4 on the opposite bayside, in the municipality of Guaratuba (Ferry South; FS). Samplings were performed seasonally in the following months of the Austral Hemisphere: spring (September 2020), summer (December 2020), autumn (March 2021), and winter (June 2021).

Water samplings were performed in previously sterilized 1.5L polyethylene bottles with handles and a launch cable submerged at a depth of 20-30 cm. After sampling, the bottles, properly labeled, were stored in cooler boxes, and transported to the laboratory for further analysis. Seawater surface temperature (SST) and atmospheric temperature (AT) were the only factors measured in situ with a digital thermometer.

In the laboratory, samples were stored in a refrigerator and analyzed within 48 hours. Salinity was analyzed by conductivity, and the appropriate transformations were conducted. Conductivity was measured with an Akso conductivity meter. Potentiometric tests were performed using a PHTEK PHS-3E pHmeter after calibration with pH 7.0 and 4.0 buffer solutions. Total dissolved solids (TDS) were measured with a Milwaukee CD-600 portable meter. Turbidity determinations were performed with a TU2106 AKSO portable digital turbidimeter after calibration with 0 and 100 NTU solutions.

All chemical analyses for dissolved inorganic nutrients were performed with analytical--grade reagents and Milli-q ultrapure water in a temperature-controlled room (22±2°C). Phosphate (PO4) concentration was determined using colorimetric technique analyzed by a Bel single-beam UV-vis spectrophotometer, wavelength 660 nm. The Molybdenum Blue Method (https://oceanbestpractices.org) was used to obtain both sample and standard solutions. This method involves the reagents ascorbic acid, glycerin, ammonium molybdate, and nitric acid; when combined with orthophosphate ions it forms the molybdenum blue complex (Masini 2008).

For the determination of nitrogen compound ammonium (NH4+), the indophenol blue method was used with reads in spectrophotometry at 630 nm which consists of the gas diffusion/acid-base indicator procedure, and the Nessler reagent method (Rice et al. 2012). For Nitrate (NO_3^-) analysis, a reduction step to nitrite (NO_2^-) was initially performed on the water sample. The concentration was determined by the Griess reaction (Corrêa et al. 2016). The reduced sample was then analyzed by UV-vis spectrophotometer, at wavelength 545nm (Ramos et al. 2006).

STATISTICAL ANALYSIS

This study measured two abiotic features in situ (SST, AT), besides another seven parameters of water quality (Salinity, pH, Turbidity, TDS, Phosphate, Ammonium, and Nitrate). Analysis of variance (one and two-way ANOVA) were applied on these sampling datasets to investigate ($p< 0.05$) differences among seasons (spring 2020 to winter 2021), sampling points (Ferry N and S).

The multivariate Principal Component Analysis (PCA) was used to investigate the most important correlation significance considering these abiotic parameters among seasons, and sampling sites. These results were graphically represented in a hyperspace established by perpendicular axes, whose relative contributions represent the data variation.

RESULTS AND DISCUSSION

The abiotic variations between the two sampling sites on the outer sector of BG presented a seasonal pattern with maximum values in the summer/autumn seasons and minimum values in the winter/spring (Figs. 2 - 8). Among the parameters analyzed, only turbidity did not show significant differences (md = 23.1 NTU). The pH varied between 6.3 (spring-winter, Ferry N-S) and 7.0 (summer--autumn, Ferry S). TDS showed a minimum value of 21,589.0 mg.L-1 and a maximum of 30,090.3 mg.L-1 (Ferry S) during spring. Nitrate showed low variation and only for Ferry S, 0.05 (autumn) and 0.11 mg.L-1 (winter).

The atmospheric (AT) and sea surface temperatures (SST) data measured in situ are detailed in Table I. SST varied seasonally from 18 to 26°C during winter and summer, respectively. The SST data analyzed by a two-way ANOVA considering south and north faces from the outer sector of BG (Figure 2), did not show significant variation between faces, nor among seasons.

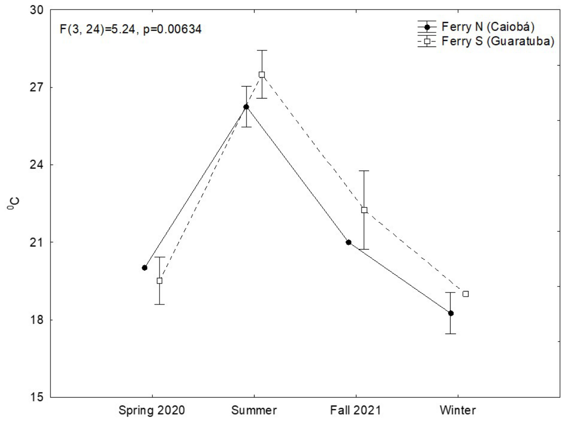

Figure 2. Seasonal variation of sea surface temperature (SST), using a two-way ANOVA analysis, considering two sampling sites (Ferry North and South) along the outer sector of Guaratuba Bay, Southern Brazil.

Salinity ranged from 16.2 to 27.4 psu during summer and winter, respectively. Higher salinity is expected during the winter months, which are less rainy than the summer months. Salinity data (Figure 3) varied significantly between sites (N and S Ferry) of the outer sector of BG only during the summer, suggesting distinct tidal flow between the south and north faces of the estuary. In addition to other associated parameters, such as rainfall, geomorphology, the presence of sandbanks, and distinct bathymetries (Brandini 2008) along the outer and inner sectors of the GB, as well as along the N/S axis analyzed.

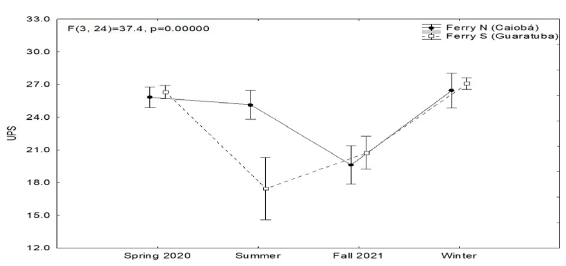

Figure 3. Seasonal variation of salinity data (expressed in practical salinity units PSU) using a two-way ANOVA analysis, considering two sampling sites (Ferry North and South) along the outer sector of Guaratuba Bay, Southern Brazil.

The pH values (Figure 4) ranged from 6.11 (spring) to 7.24 (summer), with no significant variations between sampling sited, being within the expected patterns for an outer sector's estuary (Pellizzari 2005).

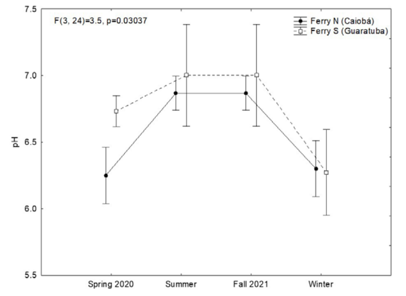

Figure 4. Seasonal variation of pH values using a two-way ANOVA analysis, considering two sampling sites (Ferry North and South) along the outer sector of Guaratuba Bay, Southern Brazil.

Overall, turbidity data (Figure 5) varied more at the N ferry (Caiobá), possibly due to stronger tidal flow on this side. Averages ranged from 21 NTU (winter, summer, and spring) to 27 NTU (fall). Although summer has the highest rainfall, it was also the season with the lowest turbidity on both sides. The higher turbidity values in fall and winter are possibly associated with the frequent arrival of weather fronts in these seasons, which destabilize the water column, increasing the estuary's turbidity with bottom sediments.

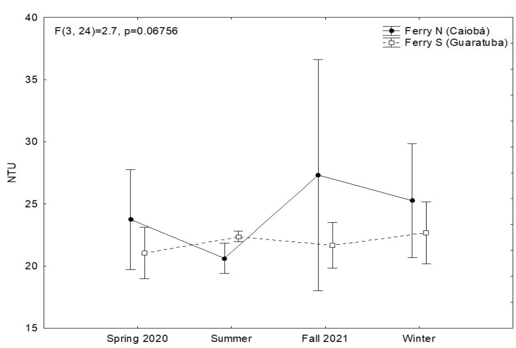

Figure 5. Seasonal variation of water turbidity using a two-way ANOVA analysis, considering two sampling sites (Ferry North and South) along the outer sector of Guaratuba Bay, Southern Brazil.

Total dissolved solids (TDS) varied significantly between N and S faces but only during the summer (Figure 6). During this season, a lower TDS value was recorded at Ferry S (Guaratuba), coinciding with the turbidity data, although this was unexpected for summer given the typically higher rainfall rates. However, 2021 was an atypical year due to the La Niña phenomenon, which remained strong in the Pacific Ocean, impacting rainfall patterns in Brazil, with higher volumes in the North and Northeast, and less rainfall in the South. This phase of the El Niño-Southern Oscillation (ENSO) was characterized by the cooling of the waters of the Equatorial Pacific, affecting global weather patterns (Ramos et al. 2021).

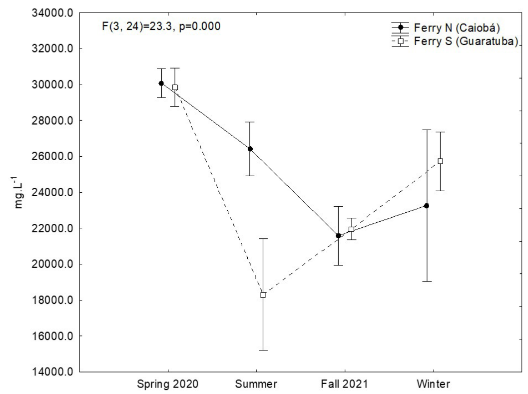

Figure 6. Seasonal variation of total dissolved solids (TDS) using a two-way ANOVA analysis, considering two sampling sites (Ferry North and South) along the outer sector of Guaratuba Bay, Southern Brazil.

Ammonium concentrations (Figure 7) ranged from 0.12 to 0.45 mg.L-1, with significant differences detected only for Ferry N, and between the subsequent seasons (spring: 0.04 and summer: 0.38 mg.L-1). This pattern is unprecedented for the outer sector of GB and is possibly associated with coastal runoff, with different discharges along the south and north faces at the entrance of the estuary. Despite these differences, concentrations are within the limits established by CONAMA for estuarine water quality (<0.70 mg.L-1).

Nitrate concentrations ranged from 0.04 to 0.53 mg L-1 during autumn and summer, respectively, and significant variations were recorded only for Ferry S (fall 0.05, summer and winter 0.11 mg L-1). The average value for Ferry N was 0.10 ± 0.02 mg L-1. Although no measurable concentrations were obtained for spring (Table I), the values obtained for both sampling sites are within the limit established by CONAMA Resolution 357/2005 (< 10 mg L-1).

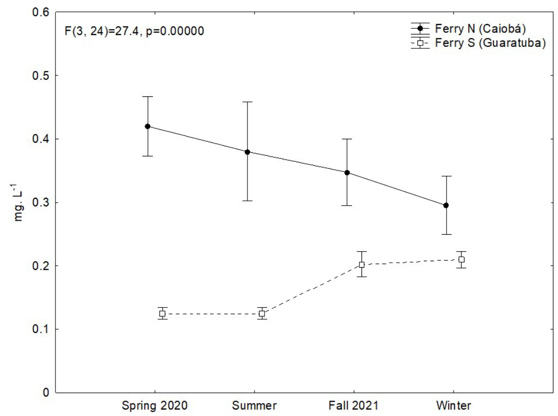

Figure 7. Seasonal variation of Ammonium (NH3) concentrations using a two-way ANOVA analysis, considering two sampling sites (Ferry North and South) along the outer sector of Guaratuba Bay, Southern Brazil.

Phosphate (PO4) concentrations (Figure 8) obtained in the outer sector of the GB varied widely between the N and S faces only during summer, ranging from 0.38 mg.L-1 in the spring and 3.5 mg.L-1 in the summer. According to CONAMA Resolution 357/2005, phosphate concentrations should not exceed 0.150 mg.L-1 in estuarine waters. Therefore, all our samples were above the established threshold, possibly associated with coastal runoff, fertilizer input from agricultural endeavors adjacent to the GB, tourism and population increase during summer, and possible clandestine discharges of untreated effluents.

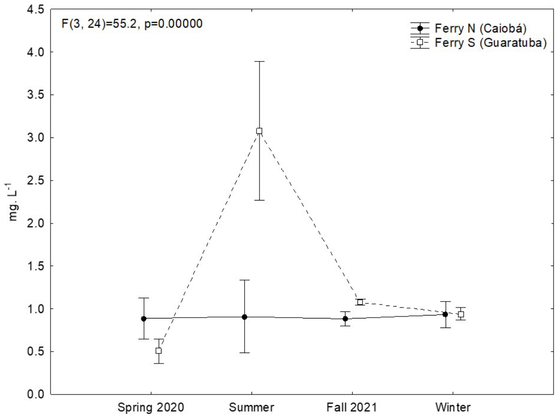

Figure 8. Seasonal variation of Phosphate (PO4) concentrations using a two-way ANOVA analysis, considering two sampling sites (Ferry North and South) along the outer sector of Guaratuba Bay, Southern Brazil.

In general, atmospheric temperature (AT) and sea surface temperature (SST) data showed significant seasonal variations ($p < 0.05$) expected with minimum values during winter and maximum values during the austral summer. AT and SST were the only abiotic variables whose comparisons between sampling sites and seasons did not show significant variation (Table I).

The integrated analysis of the results considering abiotic factors along the outer sector of GB and the correlation matrix obtained from the PCA I are presented in Tables II and III. The first and second axes of PCA I explained 51.27% and 19.18% of the total variance, respectively (Figure 9, Table II). Axis 1 was positively correlated with Salinity (Sal) and Total Dissolved Solids (TDS). It was also negatively affected by Phosphate (PO4), Sea Surface Temperature (SST) and pH. The second axis was negatively correlated with Ammonium (NH4+) and weekly with Turbidity (Turb). Data analysis revealed three groups that were negatively related with each other: group I (PO4, pH and SST), group II (Sal and TDS) and group III (Turbidity and NH4).

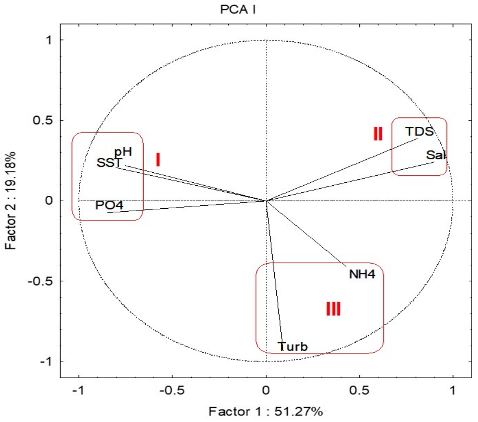

Figure 9. Principal Component Analysis (PCA) based on the water quality parameters analyzed along the outer sector of Guaratuba Bay, Southern Brazil.

Data presented in Table III provide the correlation matrix of the abiotic water quality parameters obtained using PCA. Only few parameters exhibited significant relationships. Positive correlation ($r \sim 0.7$) can be observed within group I (SST, pH, and PO4) and group II (TDS and Sal) ($r = 0.780$). Negative correlation ($r \sim -0.7$) was observed between group II and PO4. Seasonal antagonism observed between summer/fall versus winter/spring seems to be responsible for these patterns.

PCA II displays data from sampling sites along the outer sector of GB in relation to the most strongly correlated parameters: SST, Sal, pH, TDS and PO4. Axes 1 and 2 represent, 59.72% and 15.73% of the total variation, respectively (Figure 10). There was a pattern along the second axis in which summer and fall samples of Ferry N (≠ 5-12) and Ferry S (≠ 21-28) are opposed to spring (≠ 1 from Ferry S); and these data overlap (spring and winter) for Ferry S suggest a homogeneous behavior in these seasons at southern face of the GB entrance. These differences are reported here for the first time.

Variables	Season	Ferry N	Ferry S	p p-station1 p-station2 p-station X season
		x±SE		
SST °C	Spring 2020	20±0.0[b]	19.5±0,6[a]	0.0000
	Summer	26.2±0.5[d]	27.5±0.6[c]	0.0000
	Fall 2021	21.0±0.0[c]	22.2±1.0[b]	NS
	Winter	18.2±0.5[a]	19.2±0.0[a]	
pH	Spring 2020	6.3±0.1 a	6.7±0.1 a	0.0000
	Summer	6.9±0.1 b	7.0±0.2 a	0.0007
	Fall 2021	6.9±0.1 b	7.0±0.2 ab	0.0303
	Winter	6.3±0.1 a	6.3±0.2 b	
NH_4	Spring 2020	0.04±0.03 a	0.13±0.01 a	0.0025
	Summer	0.38±0.05 a	0.13±0.01 a	0.0000
	Fall 2021	0.35±0.03 ab	0.20±0.01 a	0.0000
	Winter	0.30±0.03 b	0.21±0.01 a	
Turbidity	Spring 2020	23.7±2.5	20.6±0.8	NS
	Summer	27.3±5.8	25.3±2.9	NS
	Fall 2021	21.1±1.3	22.4±0.3	NS
	Winter	21.7±1.1	22.7±1.6	
DTS	Spring 2020	30090.3±507.7 c	21589.0±1030.7 d	0.00002
	Summer	29848.5±675.2 b	21961.0±374.2 a	0.0000
	Fall 2021	26425.3±938.6 a	23271.8±2656.7 b	0.000
	Winter	18304.3±1955.0 ab	25727.6±1030.10 c	
salinity	Spring 2020	25.8±0.6 a	26.3±0,4 a	0.0000
	Summer	25.2±0.8 a	17.5±1.8 b	0.0000
	Fall 2021	19.6±1.1 b	20.8±1.0 c	0.0000
	Winter	26.5±1.0 a	27.1±0.3 a	
PO_4	Spring 2020	0.89±0.15	0.51±0.09 a	NS
	Summer	0.91±0.27	3.08±0.51 c	0.0000
	Fall 2021	0.88±0.05	1.08±0.02 b	0.0000
	Winter	0.90±0.1	0.90±0.0 ab	
NO_3	Spring 2020	-	-	0.0000
	Summer	0.11±0.02 a	0.10±0.01	NS
	Fall 2021	0.09±0.04 b	0.05±0.02	0.00002
	Winter	0.10±0.01 a	0.11±0.01	

- not detectable

Table I. Spatio-temporal results of ANOVA (faces of the outer sector, season, station X season), mean stand± error and probability (p) of de water variables in Guaratuba Bay, Paraná State, South Brazil. Where: Air Temperature (AT), Sea Surface Temperature (SST), Salinity (Sal), hydrogen potential (pH), Turbidity (Turb), Total Dissolved Solids (TDS), Phosphate (PO4), Ammonium (NH4+) and Nitrate (NO3-).

Parameters	Factors	
	1	2
SST	-0,806	0,208
pH	-0,754	0,220
Turb	0,091	-0,932
Sal	0,899	0,242
TDS	0,809	0,389
PO_4	-0,847	-0,073
NH_4	0,429	-0,409

Table II. Results of the PCA I considering abiotic factors along the outer sector of GB.

	SST	pH	Turb	Sal	TDS	PO4	NH4
SST	1,000	**0,674**	-0,275	**-0,622**	-0,452	**0,689**	-0,105
pH		1,000	-0,194	**-0,659**	-0,460	0,356	-0,290
Turb			1,000	-0,111	-0,217	-0,033	0,269
Sal				1,000	**0,780**	**-0,709**	0,249
TDS					1,000	**-0,690**	0,275
PO_4						1,000	-0,397
NH_4							1,000

Table III. Results of PCA I - correlation matrix.

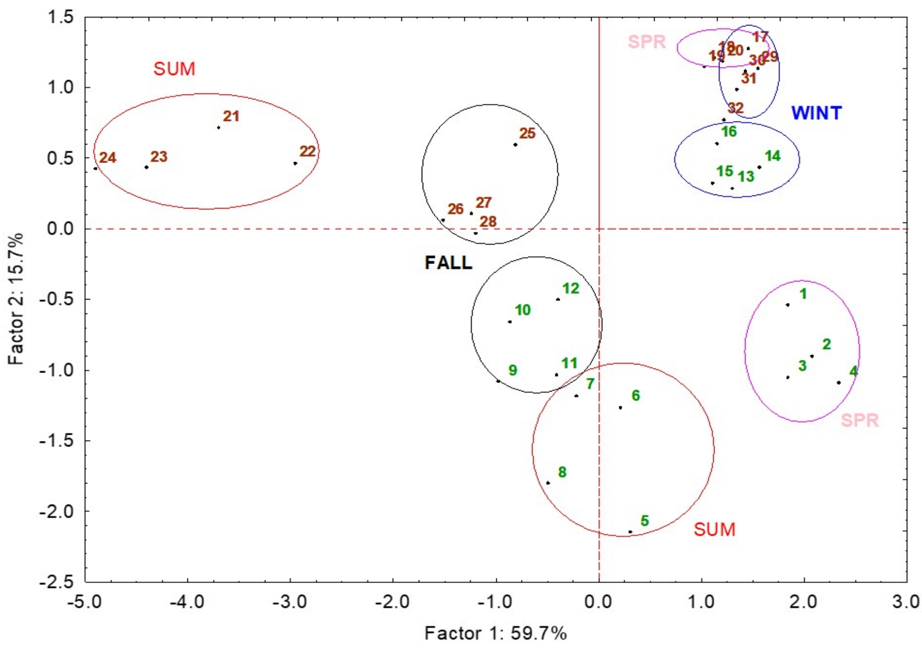

Figure 10. Principal Component Analysis (PCA) considering abiotic parameters measured in the outer sector of Guaratuba Bay based on each sample (≠ 1-32; Ferry N in green and Ferry S, brown), and where 1-16 (Ferry North, Caiobá), 17-32 (Ferry South, Guaratuba), and seasons (SPR: spring; SUM: summer; FALL and WINT: winter).

International Journal of Biological and Natural Sciences ISSN 2764-1813 DOI https://doi.org/10.22533/at.ed.8135425100711

It is noteworthy that Ferry S (Guaratuba), along the outer sector of GB, is protected by Caieiras Beach, while the Ferry N (Caiobá) is exposed to the open sea. This may partially explain the similarity only during winter for most parameters between S and N samples (except ammonium). This similarity may be associated with water mixing and the consequent higher homogeneity and destratification of the water column during the meteorological fronts, common during winter. On the other hand, -salinity, NH4+, TDS and PO4- showed significant differences between the south and north samples during summer (SST, turbidity, and pH were exceptions for this pattern).

The higher phosphate concentrations observed here suggest a higher potential for harmful microalgae blooms (HAB), which could affect oyster aquaculture in the GB. Tibiriça (2013), studying the spatial and temporal distribution of phytoplankton in GB (October 2010 to May 2012), during the same period of the present study, emphasized potentially harmful species and determined the environmental factors that control their composition and abundance. In the outer sector of BG (estuary mouth), the same author reported turbidity values between 10 and 13, which were about twice the values recorded in the present study (same sampling date).

However, it is noteworthy that the water sampling sites of our study compared to Tibiriça (2013) in the outer sector of GB are different, since our sampling was performed near the ferry docks (and not in the middle of the channel), where particulate matter (including sediment from the propellers) is constantly being resuspended to the water column. The same author reported values for phosphate (0.44 and 0.50), DIN (0.3 and 11 µM, with no defined seasonal pattern), and silicate concentrations (averages of 19.0 µM). The higher phosphate (and silicate) concentrations reported in the summer by Tibiriça (2013) were also observed in our study.

The same author also reported that the average chlorophyll-a concentration in the outer sector of the estuary was 2.1 µg.L-1, with higher abundance of marine species, including the potentially toxic diatom Pseudo-nitzschia spp. Notably, in the inner sector of GB, the abundance of dinoflagellates was also high, despite the lower salinity, including the toxic species Dinophysis acuminata.

Previous data on estuarine metabolism, biomass balance, and biogenic matter in relation to the hydrodynamic and meteorological drivers along the GB were also reported by Brandini (2008). According to the author, rivers and mangroves input the largest amount of nutrients influencing its entire spatial distribution, and primary productivity, in this estuarine system (e.g., nitrate) and influence variations in pH, DO, NID, and N/P ratios. Also, Brandini (2008) reports that the seawater mean residence time along the GB is ca. one week, and that the mean annual biomass balance along GB suggests the predominance of autotrophic metabolism. Nitrogen fixation generally exceeds denitrification, however, when segmented, Brandini (2008) observed net nitrogen fixation only in the inner sector of the estuary, confirming that the main source of N in the system is continental input by river drainage. According to the δ13C isotope used in Brandini's experiments, the terrestrial/mangrove contribution in surface samples was 80-90% in the inner sector, 50-70% in the middle, and 25-50% in the outer sector.

Also regarding organic input into the GB, Trog-Ferreira et al. (2024) evaluate the effects of sewage discharge using an environmental modeling tool, using hydrodynamic and water quality models developed to simulate long-term transport and evaluate effluent pollution in the GB. One of the main impacts in the environment is the oxygen deficit, which is caused by the consumption of oxygen by bacteria to oxidize the organic matter, indicated by biochemical oxygen demand (BOD), present in sewage. For the analysis, simulations used variations in sewage load (low and high) and seasonality (summer and winter), considering the implication for pollutant loads on the resident population and a projected population with tourists during the summer. For both scenarios, a 60% removal of BOD load was assumed. The results showed that the sewage discharged in the channels reaches the bay, accumulates along the regions near the estuary and compromises water quality, with the outer sector of GB being less negatively influenced by discharges.

Still considering organic pollution in Guaratuba Bay, recently Toledo-Netto et al. (2024) performed validation of methods for the quantification of emerging contaminants: natural (E1, E2, and E3) and synthetic (EE2) estrogens in surface waters and suspended particulate matter (SPM) using liquid chromatography coupled with a fluorescence detector. The method proved accuracy at the studied concentrations (ng g -1 and µg L-1), which ranged from 10 to 177 ng L-1 in surface waters, and from 392 to 4108 ng g-1 in SPM. The E2, EE2, and E3 were found in SPM at different seasons and population occupancy. EE2 was determined in all sampling surveys, especially during summer, when the tourism increases considerably. The presence of EE2 in the SPM of GB raises concerns about potential implications for coastal conservation and public health, as similarly observed in our study driven by the higher concentrations of phosphates.

Finally, and comparatively, Pellizzari (2005) performed physical and chemical characterization of the outer sector of the Paranaguá Estuarine Complex (PEC), aiming to generate data for a mariculture program of the edible green seaweed Gayralia (Ulvophyceae/Ulotrichales), traditionally cultivated in Japan for its nutritional value. The author characterized and related the algal growth rates with the abiotic features of the Maciel intertidal bed, recording the following, and very distinct concentrations when compared to GB, abiotic variables: SST (winter min 21.2°C and summer max 27°C), salinity (ranged from 27 to 34 psu, higher during winter), rainfall (autumn: 62 and summer: 287 mm). For dissolved inorganic nutrients, NH3 (0.53 to 7.60 ug/L), DIN (0.84 to 8.02 UM) and PO4 (0.28 to 0.60), the maximum coverage and growth rates of Gayralia (which also occurs in GB, though with lower biomass), coincided in PEC with higher salinities (peak of up to 34 psu) and lower SST (20-22oC), mainly during winter and spring.

Therefore, we present here a new approach to the observed differences in measured abiotic parameters and compare main differences in the physical-chemical profiles of Guaratuba Bay, specifically for the N-S axis of the estuary mouth (outer sector), generating baseline data for decadal comparisons. Furthermore, we reinforce the need for long-term monitoring in the area aiming to track and mitigate the current impacts and safeguard the ecosystem services provided by this estuary, which has been neglected in terms of limnoceanographic data in the past decades.

CONCLUDING REMARKS AND FUTURE PERSPECTIVES

PO4 concentrations above the limits set by CONAMA Resolution 357/2005 suggest over-eutrophication of Guaratuba Bay due to changes in limnological and oceanographic patterns of the estuary. Tides strongly influence the abiotic patterns of these areas, suggesting the imminent need of continuous monitoring of several abiotic and biotic indicators, including to track potential of HABs formation due to estuarine stratification in different sectors of the estuary (outer, middle, and inner). Higher concentrations of dissolved inorganic nutrients suggest critical periods, especially in the summer, due to higher precipitation levels. Furthermore, GB is home to many oyster farmers and seafood restaurants, and summer is the higher harvesting and consumption season for oysters, being a critical public health warning. Based on our observations, the N-S axis at the estuary mouth should also be analyzed more carefully. Data from monitoring, and virtual platforms should be encouraged to establish a database that would contribute to long-term plans, as well as government actions supporting territorial planning, tourism control, food security, public health and the recovery of coastal areas, mainly considering the intensification of climate change multiple side effects and coastal zones impacts.

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