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Impact of increased river discharge on water renewal in a tropical estuarine-bay system

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ABSTRACT

As economic development progresses and anthropogenic pressures intensify, estuaries become increasingly vulnerable, exhibiting higher levels of pollution, enhanced eutrophication, and reduced dissolved oxygen, which compromises the sustainability of these coastal environments. This study sought to better understand these features by applying the hydrodynamic, transport, and water quality modules of the image.pngmodel to evaluate water renewal in a tropical estuarine-bay System, Guaratuba Bay, located on the coast of Paraná, in southern Brazil, and its implications for oyster farming. Two scenarios were simulated: (i) the current condition, with regionalized river discharges; and (ii) an increased river discharge scenario, with tripled river discharges, identifying a decrease in salinity. The results indicated that water renewal is strongly influenced by river discharge and tidal dynamics, the renewal being more efficient in the inner part of the bay. In the scenario with increased river discharge, a significant reduction in water age was observed throughout the bay, indicating greater renewal efficiency. However, this intensification also resulted in a substantial decrease in salinity, especially in the inner and intermediate regions, where values dropped below 15 psu in the second scenario. Although water renewal may potentially favor the dilution of pollutants, a sharp reduction in salinity could compromise the viability of aquaculture, such as oyster farming.
Keywords: estuaries, oyster farming, salinity, SisBaHiA.

Impacto do aumento da descarga fluvial na renovação das águas em um sistema estuarino de baía tropical

RESUMO

À medida que o desenvolvimento econômico avança e as pressões antrópicas se intensificam, os estuários tornam-se cada vez mais vulneráveis, apresentando níveis mais elevados de poluição, intensificação da eutrofização e redução do oxigênio dissolvido, o que compromete a sustentabilidade desses ambientes costeiros. O aprimoramento da compreensão desses processos motivou este estudo, que aplicou os módulos hidrodinâmico, de transporte e de qualidade da água do modelo SisBaHiA® para avaliar a renovação das águas em um sistema estuarino de baía tropical, a Baía de Guaratuba, localizada no litoral do Paraná, sul do Brasil, e suas implicações para a ostreicultura. Foram simulados dois cenários: (i) condição atual, com vazões fluviais regionalizadas; e (ii) cenário de aumento da descarga fluvial, no qual as vazões dos rios foram triplicadas, resultando na diminuição da salinidade. Os resultados indicaram que a renovação das águas é fortemente influenciada pela descarga fluvial e pela dinâmica de maré, sendo mais eficiente na porção interna da baía. No cenário com aumento da descarga fluvial, observou-se uma redução significativa da idade da água em toda a baía, indicando maior eficiência de renovação. Entretanto, essa intensificação também levou a uma redução substancial da salinidade, especialmente nas regiões interna e intermediária, onde os valores ficaram abaixo de 15 psu no segundo cenário. Embora a renovação da água possa potencialmente favorecer a diluição de poluentes, a redução acentuada da salinidade pode comprometer a viabilidade da aquicultura, como a criação de ostras.

Palavras-chave: cultivo de ostras, estuários, salinidade, SisBaHiA.

1. INTRODUCTION

Economic growth and the intensification of anthropogenic activities have increased pressures on estuarine environments, including pollution, eutrophication, and reduced dissolved oxygen, thereby compromising the integrity of the ecosystem (Zhang *et al.,* 2021). Estuarine water quality is controlled not only by pollutant loads but also by the system's water renewal capacity, which governs dilution and dispersion processes, influences contaminant concentrations, and regulates dissolved oxygen availability (Liu, *et al.,* 2011; Sun *et al.,* 2014; Dalazen *et al.*, 2020). Water renewal is driven primarily by tidal forces, wind action, and river discharge, and is commonly quantified using metrics such as residence time, renewal rate, and water age (Dalazen *et al.*, 2020; Monse *et al.,* 2002). Among these factors, river discharge and tidal range at the estuary mouth play a dominant role in defining estuarine hydrodynamics, particularly in systems affected by upstream anthropogenic interventions, such as dam construction and flow regulation, which substantially alter circulation patterns (Sun *et al.,* 2023).

Systems with high renewal rates and short residence times tend to respond more quickly to external perturbations and are generally less susceptible to water quality degradation (Du *et al.,* 2024). In this context, increased river discharge can enhance water renewal and dispersion of pollutants, while also inducing significant changes in the physicochemical properties of the water column (Zhang, *et al.,* 2021). Recent studies indicate that high river flows and flood events can mitigate the effects of nutrient enrichment in estuaries (Du *et al.,* 2024); however, such events are also associated with increased nutrient input, resulting in substantially higher concentrations, particularly in the outer region of the estuary, compared to dry periods (Sun *et al.*, 2016).

Although increased water renewal is often associated with improved water quality, significant reductions in salinity can impose constraints on coastal uses that depend on relatively stable hydrodynamic and physicochemical conditions. Consequently, an integrated assessment of renewal rate, water age, and salinity patterns is essential for understanding the physical trade-offs associated with extreme hydrological scenarios in estuarine environments.

Hydrodynamic and transport models have been widely used to estimate renewal parameters in coastal systems. Dalazen *et al.* (2020) investigated the Paranaguá Estuarine Complex, Roversi *et al.* (2016) analyzed the Santos Estuarine System, and Zhang *et al.* (2021) applied water age modeling to the Pearl River Estuary under different hydrodynamic regimes. These studies highlight the robustness of numerical modeling as an effective tool for analyzing water circulation, dispersion, and water renewal processes in estuaries.

Nevertheless, many studies analyze renewal processes in isolation, without explicitly assessing their direct impacts on salinity stability or on the viability of economic activities that depend on specific physicochemical conditions, such as mariculture. This gap becomes particularly relevant in climate change scenarios, which are expected to increase the frequency and intensity of extreme hydrological events.

Guaratuba Bay, located on the southern coast of Brazil, is a tropical estuary covering approximately 50 km² and connected to the ocean by a channel about 500 m wide (Angulo, 1992; Trog-Ferreira *et al.,* 2025). The bay is home to extensive preserved mangrove forests and has a humid tropical climate, with precipitation concentrated during the summer months (Marone *et al.,* 2005). During this period, the local population increases from approximately 42,062 inhabitants to over one million, intensifying pollutant loads and pressure on water resources (Trog-Ferreira *et al.,* 2025).

Guaratuba Bay is an important mariculture area, particularly for the cultivation of the native oyster *Crassostrea brasiliana* (Ramos *et al.*, 2013). This species is characterized as euryhaline, exhibiting tolerance to a wide range of salinity conditions, generally between approximately 8 and 34 psu (Pereira *et al.*, 2001; Guimarães *et al.*, 2008). However, optimal growth performance is typically associated with intermediate salinity levels, ranging between 16 and 25 psu (Pereira *et al.*, 2001; Guimarães *et al.*, 2008).

Given the strong influence of salinity and overall water quality on oyster productivity, it is essential to understand the spatial and temporal variability of salinity in the estuarine system. This knowledge is fundamental for assessing the potential impacts of extreme hydrological events on the cultivation of *Crassostrea brasiliana*, particularly in cultivation zones more susceptible to freshwater intrusion.

In this context, the present study characterizes the water renewal processes in Guaratuba Bay, focusing on their implications for water quality and oyster aquaculture. Hydrodynamic and transport modeling was performed using the SisBaHiA® system. Two scenarios were simulated: (i) a reference scenario representing current conditions with regionalized river discharges, and (ii) a scenario with increased river discharge, in which river flows were tripled to represent critical conditions during the summer. Renewal rate, water age, and salinity patterns were analyzed to assess the impacts of extreme hydrological changes on estuarine dynamics and their implications for mariculture. Our hypothesis is that increased river discharge intensifies water renewal and pollutant dispersion, while simultaneously reducing salinity to levels that are potentially critical for aquaculture.

2. MATERIAL AND METHODS

The implementation of different simulation scenarios aims to understand how variations in hydrological conditions influence water renewal processes and salinity patterns in Guaratuba Bay. Given the characteristics of the bay and the intense river inflow, especially in summer, a period marked by population growth and increased pressure on water resources, it is essential to assess the estuarine system's response to different river discharge regimes. In this context, the proposed scenarios seek to represent distinct situations, with the aim of analyzing the impacts of extreme hydrological changes on water quality, particularly with regard to the viability of oyster farming.

Once a hydrodynamic model has been calibrated and validated, and assuming no significant changes in system geometry (e.g., bathymetry and bottom roughness), it can be applied to simulate different scenarios by updating external forces such as tides, wind, and river discharge. Calibration ensures that model outputs agree with observed data, while validation confirms its predictive capability under independent conditions (Williams and Esteves, 2017).

Accurate reproduction of water levels, particularly amplitude and phase, indicates that water exchanges within the domain are correctly represented, providing confidence in the simulated flow field. Consequently, transport processes, especially the advective component in Eulerian models, can be reliably estimated since they depend directly on the hydrodynamic solution (Rosman, 2025).

Under these conditions, calibrated models enable robust spatiotemporal analyses and scenario testing, making them essential tools for understanding estuarine dynamics and supporting environmental management in data-limited systems.

The available water level measurements correspond to the year 2023; therefore, the circulation model was calibrated and validated for this period. Following calibration and validation, hydrodynamic and transport simulations were performed for the period from November 1, 2021, to November 1, 2022. The selection of the years 2021 and 2022 was based on the availability of observed salinity and temperature data in the Guaratuba Bay region, which are essential for analyzing estuarine dynamics and for calibration of the transport model. Subsequently, simulations were performed for a three-month period representative of summer conditions (to December 01, 2021 to March 01, 2022, totaling 121 days). This study presents the data used for calibrating the transport model (November 1, 2021, to November 1, 2022), while the dataset used for calibrating the circulation model (2023) is available in Trog-Ferreira *et al.* (2025).

2.1. Study Area

Guaratuba Bay is located in the southeast coastal region of Brazil (25º 51.80' S and 48º 38.20' W), as shown in Figure 1. To the north lies an Environmental Protection Area (APA), which encompasses a region with well-preserved forests and watersheds, surrounded by mangrove ecosystems (Brandini *et al.,* 2022). In contrast, the southern part of the bay is occupied by urban agglomerations, which contribute to the discharge of effluents from the cities of Matinhos and Guaratuba (Marone *et al.,* 2005; Cotovicz Jr. *et al.,* 2013).

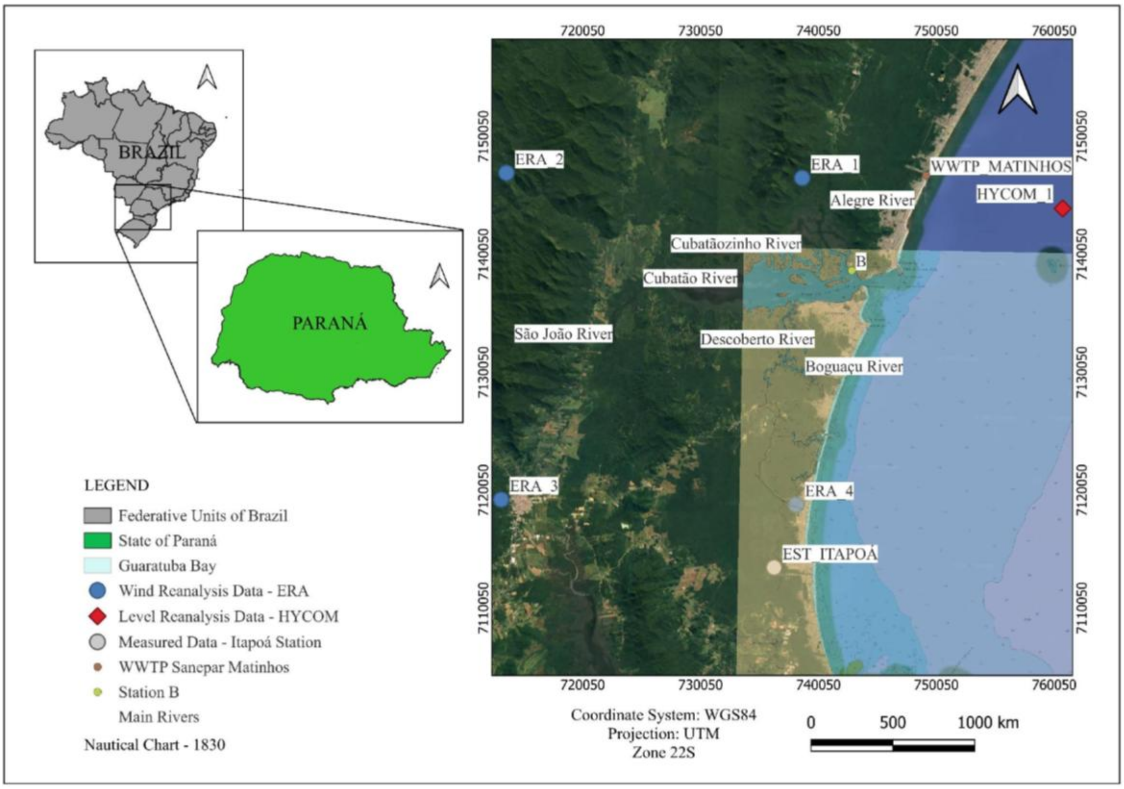

Figure 1. Geographical location of Guaratuba Bay, as well as the availability of hydrological data used in the models.

Guaratuba Bay covers an area of approximately 50 km², with a mouth about 500 meters wide (Zem, 2005). In the coastal region, tourism, fishing, and oyster farming are the main activities. In the river basin, banana and rice cultivation predominate, underscoring the economic importance of these practices in the region (Todeschini, 2004; IPARDES, 2024). These activities, while fundamental to local development, also directly influence the hydrological dynamics and water quality of the bay, especially in the areas closest to river's discharge points and urban centers.

2.1.1. Hydrological Data

The rainfall data (see Figure 2) used in this study were obtained from the Sanepar Matinhos WWTP station, code 2548089, managed by the Water and Land Institute, in Portuguese Instituto Água e Terra (IAT), for the period from November 1, 2021, to November 1, 2022.

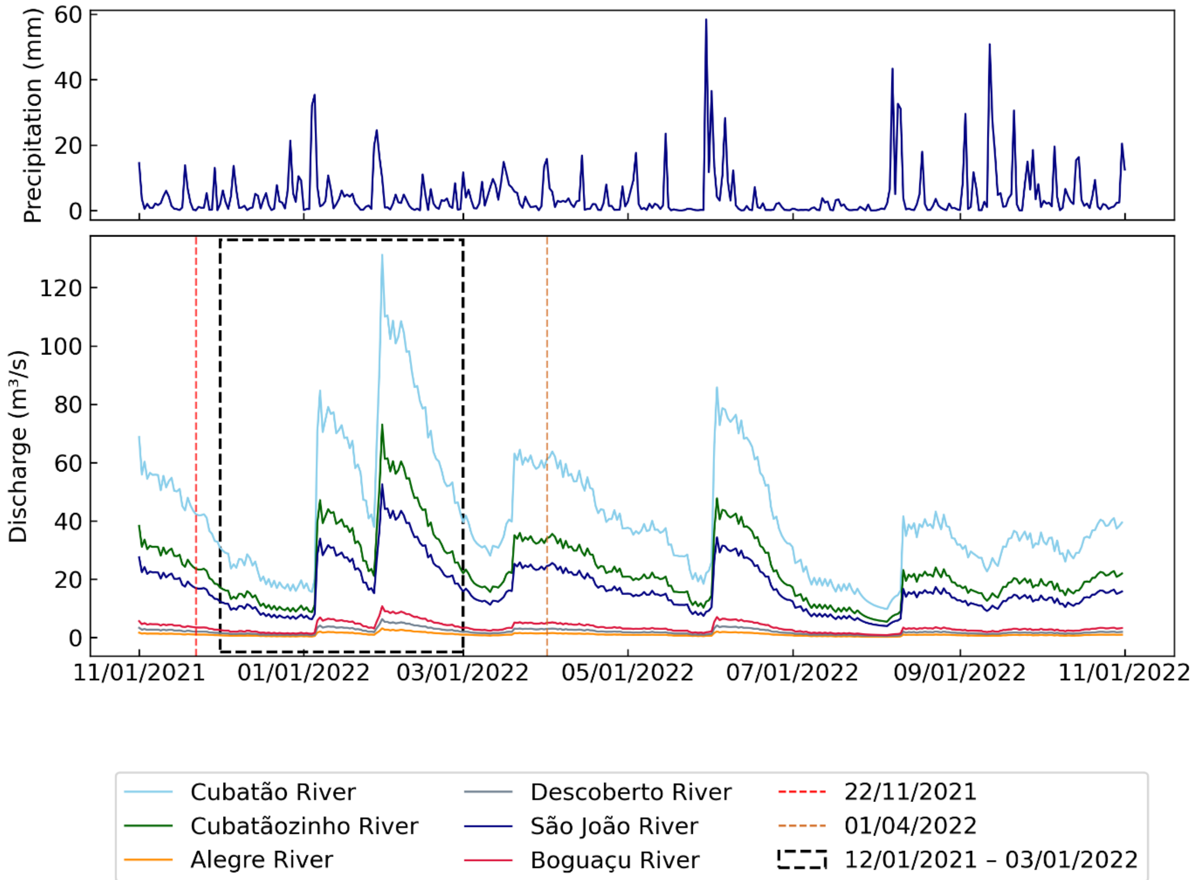

Figure 2. Time series of precipitation (mm) and regionalized flow rate between November 1, 2021, and November 1, 2022. The dashed lines correspond to the salinity and temperature measurement points for the periods of November 22, 2021, and April 1, 2022, respectively. The dashed rectangle corresponds to the simulation period of the analyzed scenarios.

Throughout the period analyzed, an irregular distribution of precipitation events was observed, with episodes of high intensity occurring at different times of the year. For example, the peaks observed in June and October 2022, with rainfall exceeding 50 mm, indicate significant intra-annual variability and the occurrence of extreme events even in periods considered drier.

Understanding this variability is essential for interpreting the flow regime of the region's rivers, whose hydrographic network is divided into two basins: the coastal plains and the Serra da Prata. Most of the region's rivers have their headwaters located on the mountain slopes, often near the summits, where they emerge as streams and brooks (Zem, 2005).

The fluviometric data used also correspond to the period from November 1, 2021 to November 1, 2022. Using this series, it was possible to perform a regionalization of the discharge (Figure 2). This procedure is based on the principle of hydrological homogeneity, according to which basins with similar physical characteristics (drainage area, slope, soil type, vegetation covers and rainfall index) exhibit comparable hydrological behaviors (Viola *et al.,* 2009).

Figure 2 shows that the rivers with the highest flow rates are the Cubatão River, the Cubatãozinho River, and the São João River, respectively. These rivers originate in the mountainous region of Paraná, where steep slopes accelerate water flow and increase runoff energy (Ramos *et al.*, 2013).

Due to the presence of the Serra da Prata mountain range, the climate of Guaratuba Bay is strongly influenced by the terrain and is classified as humid subtropical. In this region, summer is the rainiest season and winter the driest, with average annual precipitation ranging from 1,750 to 2,000 mm and temperatures around 21°C (Rosman, 2025).

2.1.2. Wind Data

The wind was obtained from four reanalysis points of the European Centre for Medium-Range Weather Forecast (ECMWF-ERA), covering the period from November 1, 2021, to November 1, 2022., as shown in Figure 1. The wind roses shown in Figure 3 indicate the predominance of northeast and south-southeast directions for station ERA 1 (A); east and south-southeast for station ERA 2 (B); north-northeast and south-southeast for station ERA 3 (C); and south-southeast and northeast for station ERA 4 (D). The average wind speeds are 2.06 m/s for A, 1.71 m/s for B, 2.33 m/s for C, and 1.66 m/s for D, thus demonstrating the minimal influence of wind in the region.

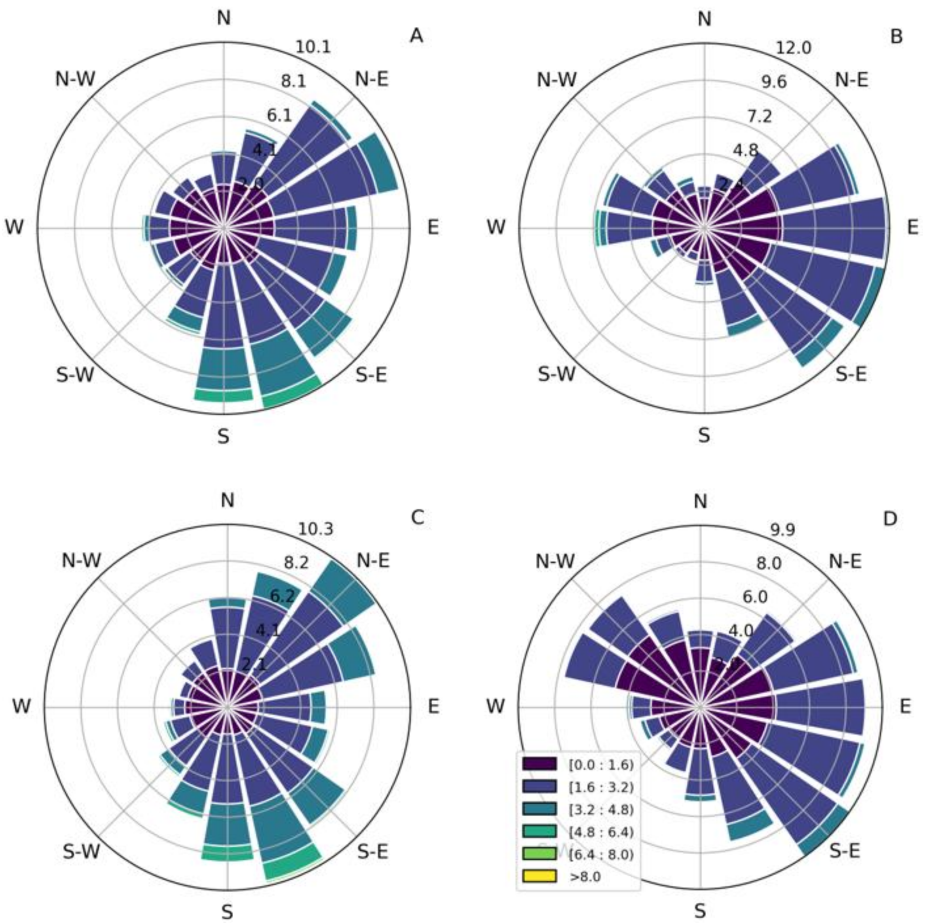

Figure 3. Wind roses for the seasons ERA 1 (A) ERA 2 (B), ERA 3 (C) and ERA 4 (D).

2.2. About the Models Used

The hydrodynamic, transport and water quality models used in this study are part of the Hydrodynamic Environmental System known as SisBAHIA®. The SisBaHiA® (in Portuguese, Sistema Base de Hidrodinâmica Ambiental) is a system developed by the Coastal and Oceanographic Engineering Department, Oceanic Engineering Program, Federal University of Rio de Janeiro (COPPE/UFRJ), that has been widely used to simulate coastal and estuary ecosystems. This system employs the finite element method for the spatial discretization and finite differences for the temporal discretization. The wind fields and bottom friction varied dynamically in time and space and the turbulent stress is parameterized according to filtering techniques derived from the approach known as Large Eddy Simulation (LES).

Computer simulations were conducted using the two-dimensional hydrodynamic model, the water quality model, considering salinity and temperature parameters, and the Eulerian transport model to calculate the renewal rate and water age.

Considering the circulation dynamics of Guaratuba Bay, and assuming that circulation is primarily driven by tidal currents and secondarily influenced by freshwater discharge, which introduces seasonal variability, an appropriate modeling approach can be defined. Under these conditions, the flow can reasonably be considered quasi-horizontal, and the horizontal pressure gradients associated with variations in water surface elevation are expected to be significantly greater than those associated with density variations. Therefore, a two-dimensional depth-integrated model was employed to investigate the circulation patterns within the bay.

In the literature, there are few studies addressing salinity distribution in Guaratuba Bay. Mizerkowski *et al.* (2012) observed salinity stratification in the middle and inner portions of the bay, with salinity gradients between bottom and surface waters reaching approximately 4,0 psu in regions close to the rivers during the rainy season. Marone *et al.* (2005) observed that bottom-layer salinity exhibits seasonal variations, with higher values during winter and lower values during summer.

The present study focuses on the large-scale horizontal response of the estuarine system to variations in freshwater discharge, specifically regarding water renewal, water age, and spatial salinity patterns relevant to estuarine water quality and mariculture management. In this context, the vertically integrated two-dimensional approach is suitable for representing the main circulation and transport processes associated with river discharge and tidal forcing, while maintaining computational efficiency for scenario-based analyses. Although this approach does not explicitly represent vertical stratification processes, it provides an appropriate framework for evaluating system-scale responses and comparing changes among different hydrological scenarios.

The two-dimensional hydrodynamic model solves the shallow-water equations using the hydrostatic approximation for pressure distribution and the Boussinesq approximation, in which the density is assumed constant, except for the terms related to buoyancy (Rosman, 2025).

The Eulerian transport model is especially adequate for determination of renewal rate and water age in natural water bodies, making it possible to obtain isoline maps of renewal rate and water age in different sectors of water bodies with complex geometry.

The water quality model is a Eulerian transport model vertically integrated for non-conservative scalars. Non-conservative scalars, which represent the majority of existing substances in water, have their concentrations modified by physical, biological and chemical processes, called kinetic reactions. These reactions are defined for each scalar and therefore by the differential equation associated with the scalar under investigation. Therefore, adequate representation of the hydrodynamic circulation pattern becomes a fundamental component of the computational framework used in modeling water quality parameters (Cunha *et al.*, 2006).

2.3. Hydrodynamic Circulation Model Data

The bathymetry of Guaratuba Bay, shown in Figure 4B, was obtained from the 1830 nautical chart provided by the Directorate of Hydrography and Navigation (DHN) and from data provided by the Paraná Environmental Monitoring and Technology System (SIMEPAR). The parameters used in the hydrodynamic simulations are described below:

1. The grid used in the domain discretization requires complex geometry and contains 1,268 elements and 5,492 nodes (Figure 4A). The time step used in the hydrodynamic circulation simulations was 10 seconds, which corresponds to an average Courant number of 1.18.

2. Initial condition: The model underwent a warm-up period of two tidal cycles to minimize any influence of initial conditions on the results obtained.

3. Open boundary: The position of the free surface is prescribed by applying the total tide curve (astronomical + meteorological). The imposed astronomical tide levels were obtained from the Harmonic Constants of FES2014 – Finite Element Solution. Figure 5 shows the tide curve between November 1, 2021 and November 1, 2022.

4. Land boundary: All land nodes were assumed to be impermeable, with zero normal flow, except for the nodes corresponding to the Cubatão, Cubatãozinho, São João, Descoberto, Boguaçu, and Alegre rivers, where the flow rates shown in Figure 3 were prescribed.

5. Wind: assumed to be non-permanent and variable (Figure 3).

6. Bottom roughness amplitude: The bottom friction coefficient in SisBaHiA® is established by the Chèzy coefficient, which depends on the equivalent bottom roughness amplitude and is established based on the composition and distribution of bottom sediments. Bottom roughness amplitude values (ξ) for Guaratuba Bay were obtained from Zem (2002) (Figure 4C). Guaratuba Bay bed is predominantly composed of fine (ξ = 0.015 m) and medium (ξ = 0.020 m) sand; in the river mouths, medium (ξ = 0.020 m) sand predominate.

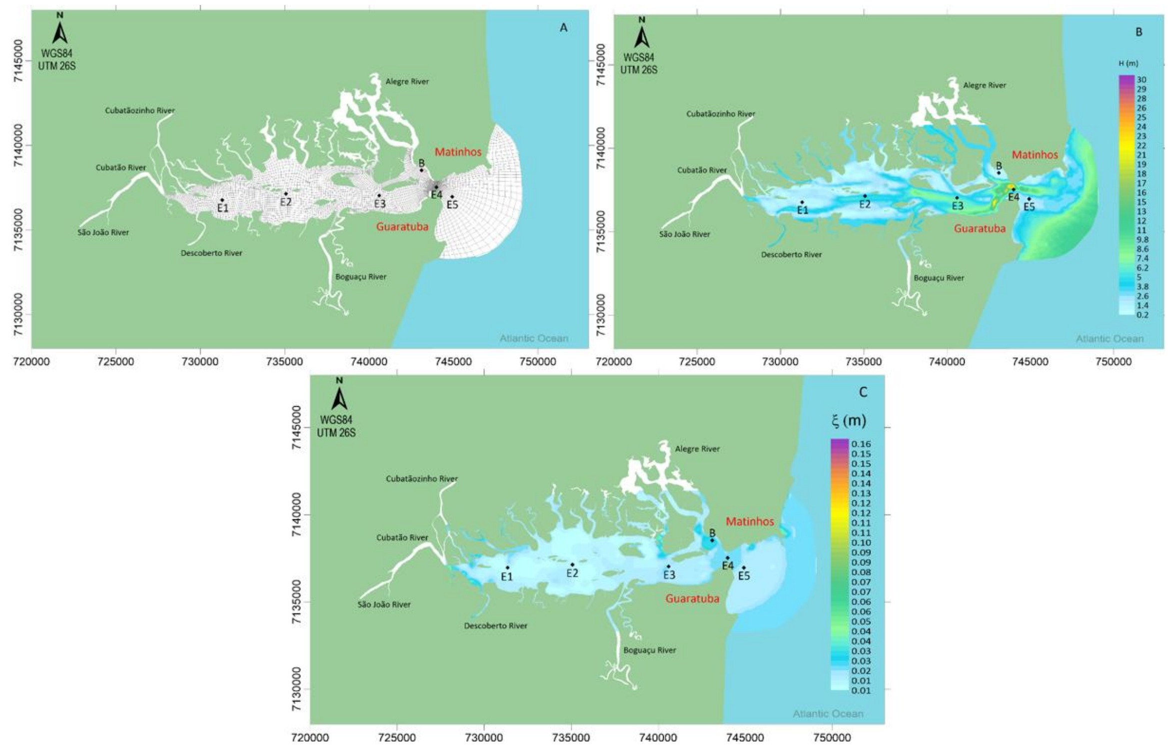

Figure 4. Modeling domain together with the finite element mesh (A), bathymetry isolines (B) and isolines of the equivalent bottom roughness amplitude (C) of Guaratuba Bay.

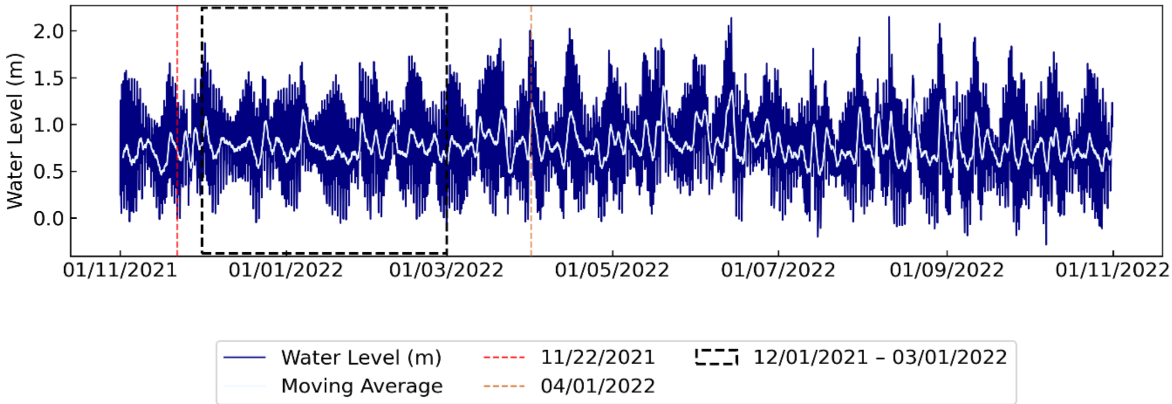

Figure 5. Tidal curve (astronomical + meteorological) for the period November 1, 2021 to November 1, 2022. The red line corresponds to the moving average for the 36-hour period. The dashed lines correspond to the salinity and temperature measurement points for the periods November 22, 2021 and April 1, 2022, respectively. The dashed rectangle corresponds to the simulation period of the analyzed scenarios.

2.4. Water Quality Model Data (Salinity and Temperature)

Salt and heat transport modeling in the Guaratuba Bay was developed for the same hydrodynamic circulation period (November 1, 2021, to November 1, 2022) using the Water Quality model. However, the results presented refer only to the interval corresponding to the scenarios analyzed. The simulations considered the following parameters:

1. The grid is the same as that used in the hydrodynamic circulation model.
2. Initial condition: the model had a warm-up period of three tidal cycles.
3. Open contour: in the case of influx, a salinity of 35 ups and a temperature of 25°C were adopted, based on data obtained from the HYCOM (Hybrid Coordinate Ocean Model).
4. Land boundary: At the boundary nodes corresponding to the Cubatão, São João, Descoberto, Boguaçu, and Alegre Rivers, salinity data were specified as shown in Table 1. Temperature values ranged from 20°C to 25°C. The other boundary nodes were considered impermeable, with zero normal flow.
5. Meteorological data: Radiation, air temperature, and humidity data (Figure 6) were obtained from the Itapoá Station -A851 (the location of the station can be observed in Figure 1 with a 1-hour time step.

Table 1. Salinity data for the Cubatão, São João, Descoberto, Boguaçu and Alegre rivers, interpolated for the period from November 1, 2021 to November 1, 2022.

Month	Cubatão (psu)	São João (psu)	Descoberto (psu)	Boguaçu (psu)	Alegre (psu)
November*	24.5	24.50	25.20	26.10	26.30
December	24.5	24.50	25.20	26.10	26.30
January	24.5	24.50	25.20	26.10	26.30
February	15.35	15.35	19.82	22.10	28.30
March	13.52	13.52	18.00	20.27	26.47
April*	11.70	11.70	16.80	19.30	26.50
May	13.52	13.52	18.00	20.27	26.47
June	15.35	15.35	19.82	22.10	28.30
July	17.18	17.18	21.65	23.92	30.12
August	19.01	19.01	23.48	25.75	31.95
September	20.84	20.84	25.31	27.58	33.78
October	22.67	22.67	27.14	29.41	35.61

*In the months of November and April, the prescribed salinity data correspond to the measured data obtained from the EIA/RIMA Ponte de Guaratuba (Consórcio Maia Melo, 2022).

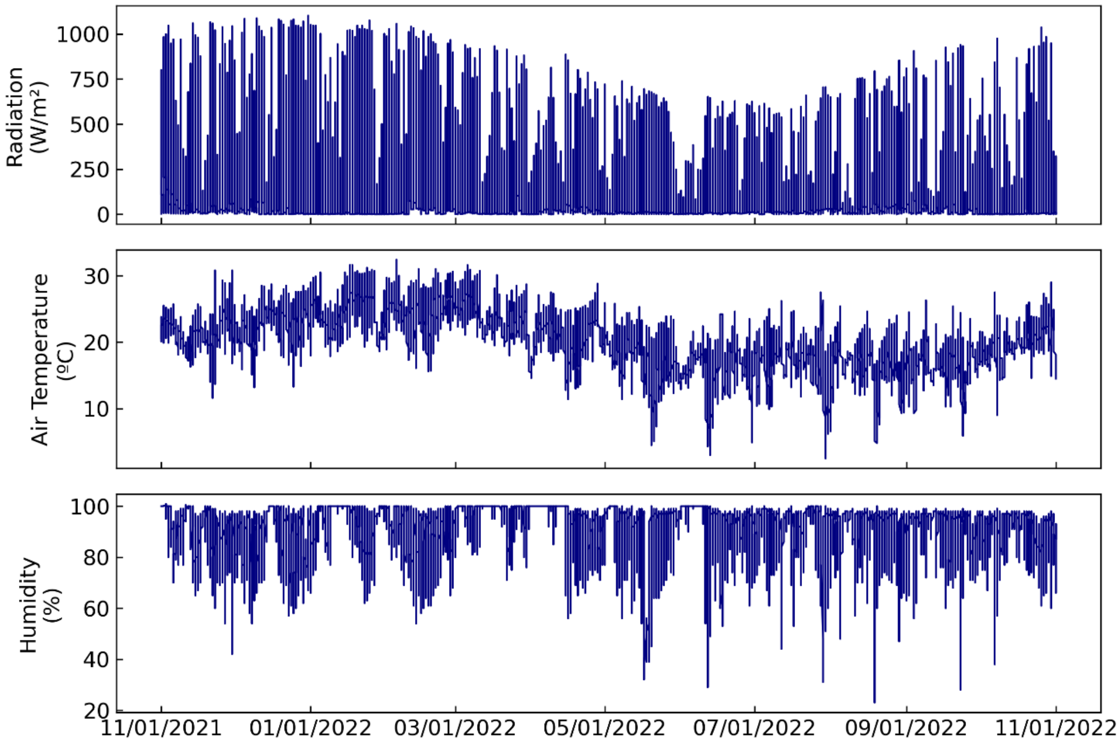

Figure 6. Radiation, air temperature and humidity at Itapoá Station.

As mentioned previously, on November 22, 2021 and April 1, 2022, temperature and salinity measurement campaigns were carried out in Guaratuba Bay as part of the Environmental Impact Assessment (EIA/RIMA) studies for the Guaratuba Bridge (Consórcio Maia Melo, 2022). On these occasions, measurements were taken at five points (E1, E2, E3, E4, and E5), as illustrated in Figure 4A. Table 2 presents the data obtained during these campaigns.

Guaratuba Bay has well-defined compartments, and the sampled points were selected because they gathered available measured data and because they represent these different regions: (i) the internal region (stations E1 and E2), strongly influenced by river discharge; (ii) the intermediate region (stations E3 and E4), under the combined influence of river discharge and tide; and (iii) the external region (station E5), predominantly under the action of tidal forces.

Table 2. Measured temperature (ºC) and salinity (ups) data at five stations (E1, E2, E3, E4 e E5) distributed throughout Guaratuba Bay [25].

Stations	Date	Temperature (ºC)	Salinity (ups)
E1	November 22, 2021	24.1	24.5
	April 1, 2022	22.3	11.7
E2	November 22, 2021	25.5	25.2
	April 1, 2022	21.7	16.8
E3	November 22, 2021	23.8	26.1
	April 1, 2022	21.4	19.3
E4	November 22, 2021	24.0	26.1
	April 1, 2022	22.3	25.5
E5	November 22, 2021	23.8	26.3
	April 1, 2022	22.0	26.5

Salinity measurements taken on November 22, 2021 (late spring) and April 1, 2022 (late summer) indicate variations consistent with expected seasonal behavior, in which greater river inputs in late summer reduce salinity in the innermost regions of the bay, while relatively higher salinity is observed in early autumn due to lower river discharge.

However, the precipitation time series for the analyzed period does not exhibit a well-defined seasonal pattern, unlike typical rainfall concentrations in the summer months. There is an irregular distribution of rainfall events over time, with high-intensity episodes recorded at different times of the year, such as in June and October 2022 (Figure 2), whose volumes exceeded 50 mm.

This variability and the occurrence of extreme events even in traditionally drier periods indicate that the observed salinity patterns may be more closely associated with specific or cumulative hydrological events than with typical seasonality.

2.5. Eulerian Transport Model Data (Water Renewal Rate and Water Age)

The Eulerian transport model is used to simulate both water age and water renewal rates, using the same spatial discretization as the hydrodynamic model. The simulation of non-conservative or reactive substances requires the definition of decay or transformation coefficients for these substances. In the specific case of water age, the T90 parameter is used, which represents the time required for the substance's concentration to reach 10% of its initial value, that is, for 90% of its mass to be dissipated (Rosman, 2025).

According to Rosman (2025), for water age estimates being consistent, the T90 value should be equivalent to the total simulation duration. Therefore, for a 90-day model, such as the one performed in this study, a T90 equal to 90 days should be adopted, ensuring consistency between the decay time and the modeled period.

As an initial condition, a uniform concentration of 1.0 mg/L was assumed throughout the domain. At the river inlets and in the open boundary, in cases of inflow, a concentration of 1.0 mg/L was also set. Over time, the combined effects of advection, diffusion, and decay allow us to estimate the water age at each point in the domain.

In addition to water age, the Eulerian model also allows us to simulate the water mass renewal rate. In this case, the initial conditions are different: a zero concentration was assigned throughout the domain, representing zero renewal, while a concentration of 100.0 mg/L was adopted at the river inlets, corresponding to 100% renewal. During the simulation, the substance propagates and the concentration values gradually decrease, allowing the renewal rate, expressed as a percentage, to be estimated over time and space.

2.6. Scenarios

To investigate the influence of hydrological variability on water renewal and salinity distribution in Guaratuba Bay, a set of numerical scenarios was implemented. Particular attention was given to summer conditions, when increased river discharge and seasonal population growth intensify anthropogenic pressure on the estuarine system.

Two river discharge scenarios were defined. The reference scenario (Scenario 1) represents typical summer conditions and was simulated over a three-month period (December 1, 2021, to March 1, 2022; 121 days), using observed atmospheric and hydrodynamic forces. The second scenario (Scenario 2) represents a hypothetical stress condition, in which river discharge was increased threefold relative to the reference values. Although not based on observed conditions, this scenario was designed to assess the sensitivity of the system to extreme freshwater input.

In Scenario 1, wind forcing, bathymetry, tidal conditions, and average river discharge were prescribed based on available data. Scenario 2 maintained identical wind, bathymetric, and tidal conditions, with only river discharge modified.

The transport model associated with the reference scenario was calibrated using observed salinity and temperature data, ensuring consistency between simulated and measured hydrographic conditions.

3. RESULTS

3.1. Model Calibration and Validation

The hydrodynamic model was calibrated for the period from February 02, 2023 to February 27, 2023 and validated for the period from March 01, 2023 to March 31, 2023. Figure 7 shows the comparison between the water levels observed at Station B (the location of the station can be observed in Figure 1) and the results simulated by the SisBaHiA® model.

The calibration statistics indicate a correlation coefficient (R^2) of 0,8663, demonstrating good agreement between the measured and modeled values. Additional details on the calibration process can be found in (Trog-Ferreira *et al.,* 2025). In the validation phase, the model presented a correlation coefficient (R^2) de 0.8344, confirming the good performance of the fit, as illustrated in Figure 7.

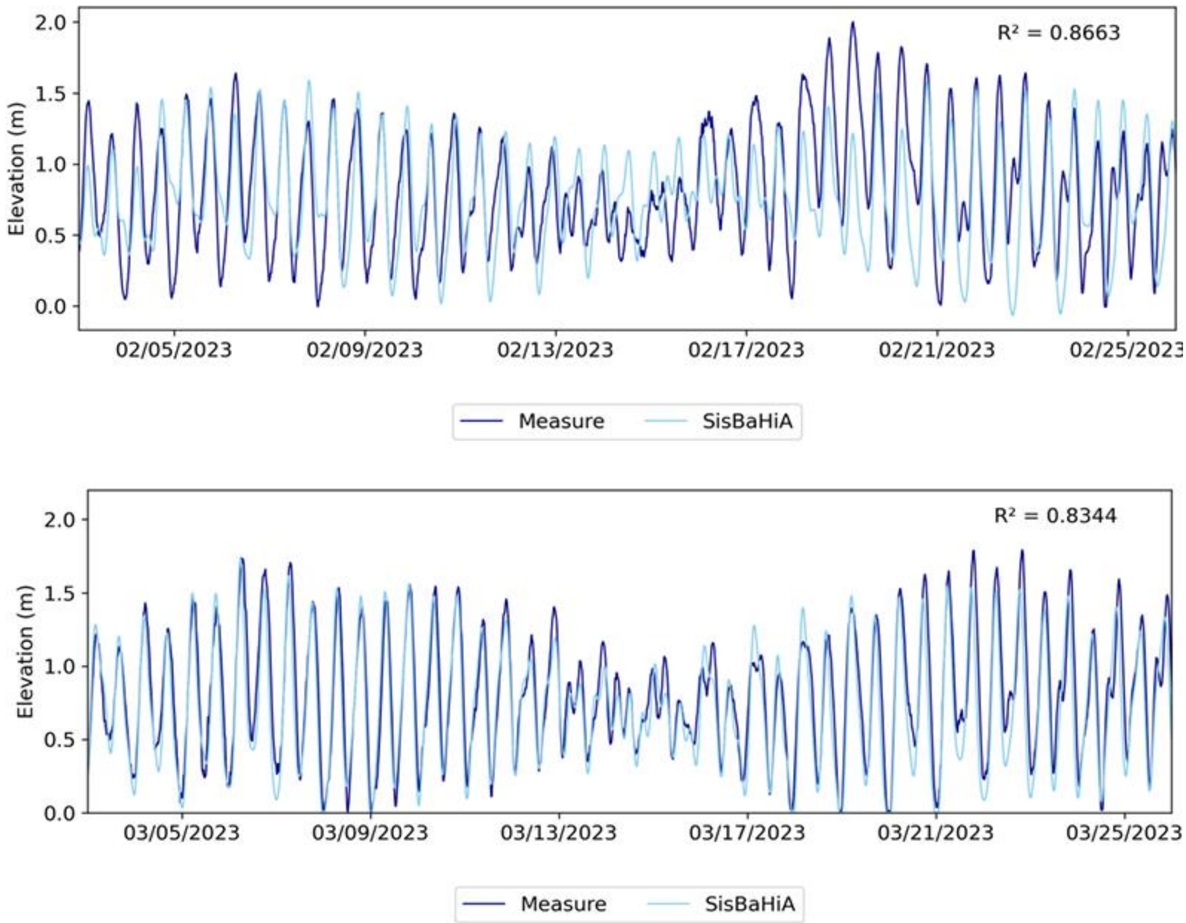

Figure 7. Water level simulated vs. field data.

One of the outputs derived from the circulation modelling is the isoline map showing the occurrence of current velocities below 0.10 m/s over a 121-day period, which allows the identification of potential stagnation zones. In Scenario 1 (Figure 8), the highest occurrence of velocities below 0.10 m/s was observed in the adjacent coastal region (50–100%), where water exchange driven by tidal action is relatively limited, and in the inner region of the bay (80–100%). The lowest occurrence (~35%) appeared in the central part of the bay, and even lower values (~20%) were found near the mouth, indicating the absence of areas prone to pollutant accumulation and confirming an effective exchange between water masses in this region. However, the left margin areas present conditions favorable to stagnation. In Scenario 2 (Figure 8), a slight intensification of the currents is observed, though this variation does not exceed 7%, as can be seen in Figure 8.

A similar result was observed for the percentage of occurrences of current velocities below than 0.05 m/s (Figure 8). The central region of the bay will exhibit velocities greater than 0.05 m/s for almost the entire period. In the inner region of the bay, a high percentage of time with low velocities is still observed, but only in the areas near the river mouths. Additionally, the left margin of the bay exhibits very low flow velocities, indicating a high susceptibility to stagnation. As previously noted, Scenario 2 shows a slight intensification of the currents, particularly at the mouth of the Cubatãozinho River.

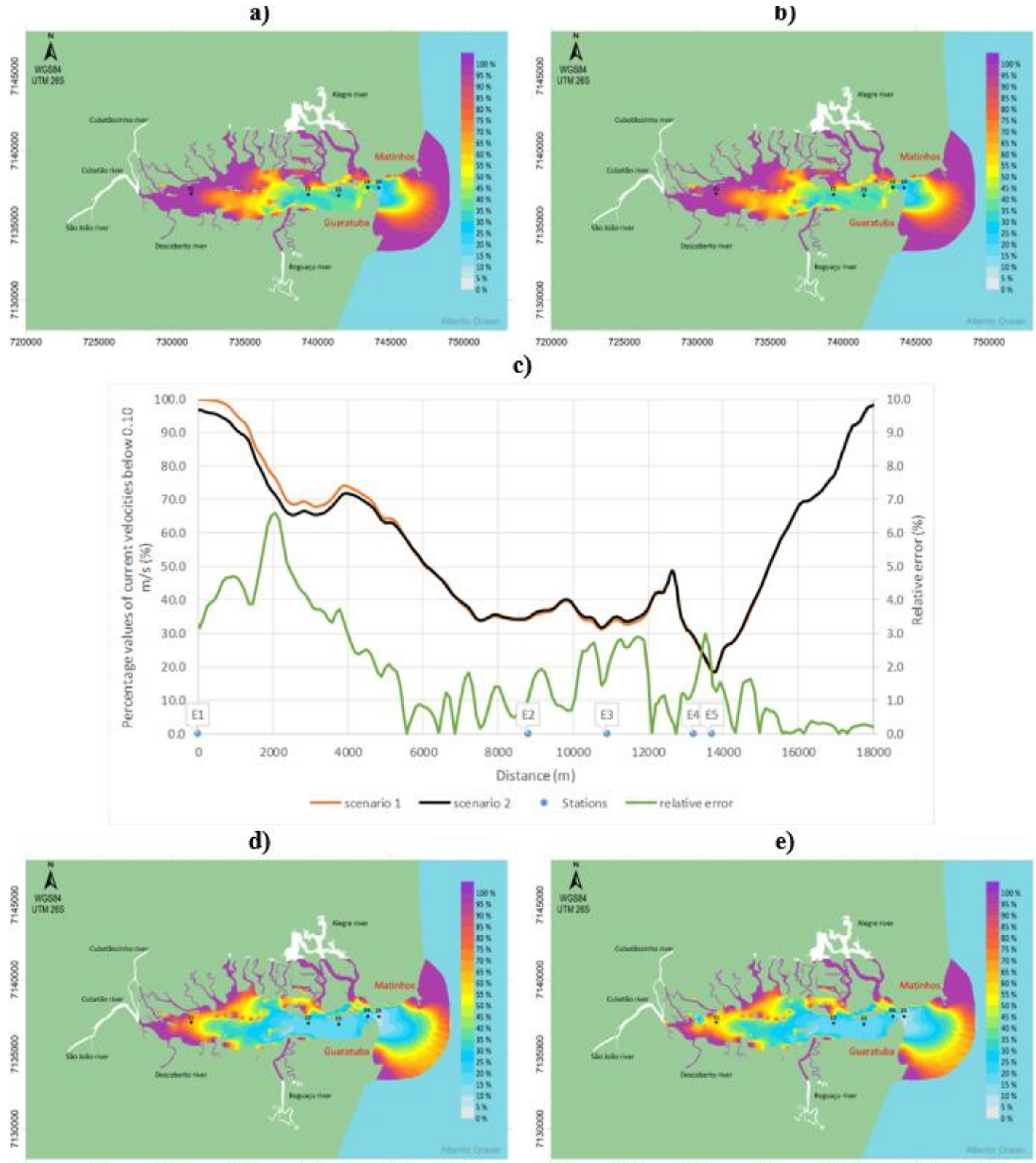

Figure 8. Occurrence isoline map of current velocities below 0.10 m/s to December 01, 2021 to March 01, 2022, totaling 121 days, in Scenario 1 (a), Scenario 2 (b), and percentage values of current velocities below 0.10 m/s along the longitudinal axis of the bay for both scenarios (c). An occurrence isoline map of current velocities below 0.05 m/s from December 01, 2021 to March 01, 2022, totaling 121 days, in Scenario 1 (d) and Scenario 2 (e).

The salinity model was calibrated based on data measured for the periods from November 20 to 25, 2021 and March 30 to April 3, 2022 for all sampling stations. The salinity data, as presented in Table 1, are insufficient for a comprehensive model calibration, as they correspond only to monthly averages. Given that the prescribed river discharges exhibit daily variability, it is necessary to establish salinity values at a daily temporal resolution. Accordingly, daily salinity values were derived through interpolation based on the monthly dataset. The results can be seen in Figure 9.

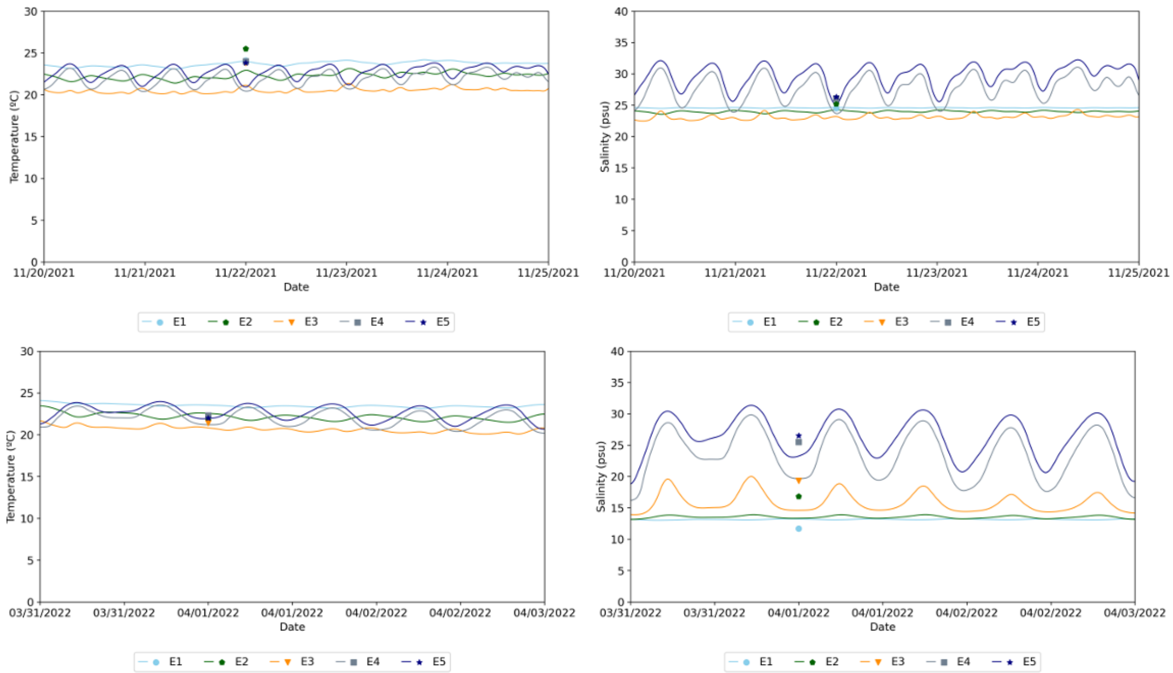

Figure 9. Salinity (psu) and temperature (^{0}C) data obtained by the model at Stations E1, E2, E3, E4 and E5 and the points measured at the same stations for the period November 22, 2021 and April 01, 2022.

For both periods, the salinity values at Stations E4 and E5 show little change, as they are predominantly controlled by external boundary conditions, characterized by smaller fluctuations. The same behavior can be observed for temperature values.

The salinity values observed at Stations E1, E2, and E3, located at the inner part of the Bay, showed different behaviour for the two periods, due to the direct influence of freshwater discharge. In November, due to low discharges, salinity values are high, showing little variation. During this period, the model adequately reproduces the measured data. In April, a significant increase in freshwater discharges is observed (Figure 2), resulting in a reduction in salinity values during this period. The salinity observed at Station E1 showed greater deviations from the measured data. Thus, the model cannot adequately reproduce the measured values, certainly due to inaccuracies associated with the imposed boundary conditions, that is, the definition of river discharges. On the other hand, the temperature values performed better, since their main influence comes from heat exchange processes, predominantly through radiation. In this case, the data used came from direct measurements, allowing for a more accurate simulation of the system's thermal variation.

3.2. Renewal Rates, Water Age, and Salinity Patterns

Renewal rates in bays and estuaries reflect the differences in water exchange capacity of their various compartments, thereby allowing the identification of spatial and temporal fluctuations caused by external driving mechanisms and morphological characteristics.

Figure 10 shows the temporal evolution of renewal rates and salinity at Stations E1, E2, E3, E, and E5 in Scenarios 1 and 2 over a three-month simulation period. It can be observed that water renewal occurs more slowly at all stations in Scenario 1. This difference is less pronounced at the outer stations, since they are located closer to the open boundary and are therefore less influenced by river discharge.

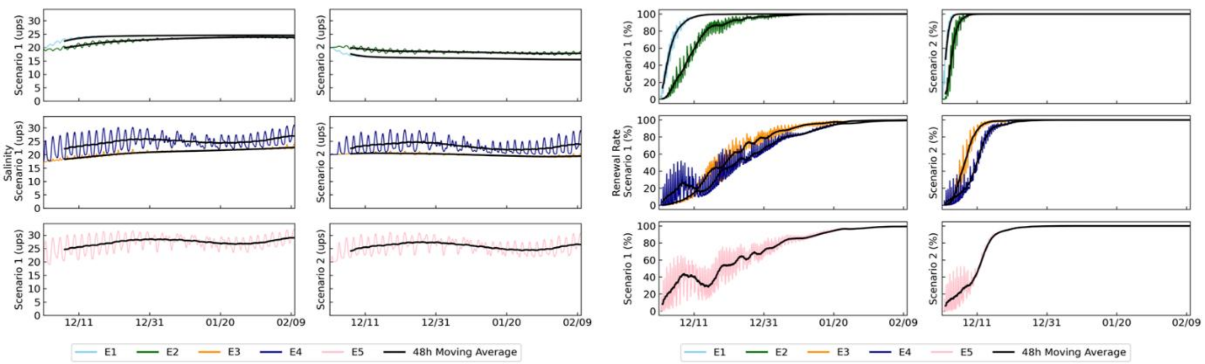

Figure 10. Time series for the water renewal rate and salinity for Scenarios 1 and 2. The black curve corresponds to the 48-hour moving average.

In Scenario 2, river discharge proves to be a decisive influencing factor in the renewal process, particularly in regions near tributaries. Its inclusion leads to a significant increase in renewal rates compared to Scenario 1, underscoring its important role in promoting water exchange in these areas.

With regard to salinity, only minor differences are observed, which are mainly limited to the inner parts of the bay. In Scenario 2, a slight decrease in salinity is observed compared to Scenario 1. At Stations E3 and E4, the differences between scenarios are negligible, since these locations are farther from the mouths of the major rivers, making the influence of river discharge relatively insignificant.

Figure 11 illustrates the temporal evolution of water age in Guaratuba Bay under both scenarios over the simulation period from December 1, 2021, to March 1, 2022. Under baseline conditions (Scenario 1), water age exhibits a marked spatial gradient, increasing from the inner estuary toward the mouth of the bay, which indicates progressively reduced renewal efficiency toward downstream regions. In contrast, under enhanced discharge conditions (Scenario 2), water age decreases significantly throughout the system, particularly within the intermediate and outer sectors. This pattern demonstrates that increased freshwater input strengthens estuarine flushing processes, extending its influence beyond regions directly affected by river discharge.

In Scenario 2, reduced variability is observed in renewal rates, salinity, and water age compared to Scenario 1, which can be attributed to the increased freshwater input. After three months of simulation, both water age and renewal rates exhibit oscillations around characteristic values governed by variations in the primary hydrodynamic forcing mechanisms, such as tidal dynamics and river discharge. This behaviour reflects the inherently dynamic nature of equilibrium in natural systems. After this period, only the Cubatão River region (E1) reaches a dynamic equilibrium state in both scenarios.

Table 3 summarizes the renewal rates after 10 days of simulation, along with water age and salinity after 90 days, for both scenarios across the five monitoring stations (E1, E2, E3, E4, and E5). A significant enhancement in water renewal processes is observed under the condition of tripled river discharge, particularly at Stations E2, E3, E4, and E5. Across all stations, both renewal rates and water age exhibit markedly lower values in Scenario 2 compared to Scenario 1. A similar pattern is observed for Salinity, with consistently lower values in Scenario 2 at all stations, indicating a stronger influence of increased freshwater input in the bay.

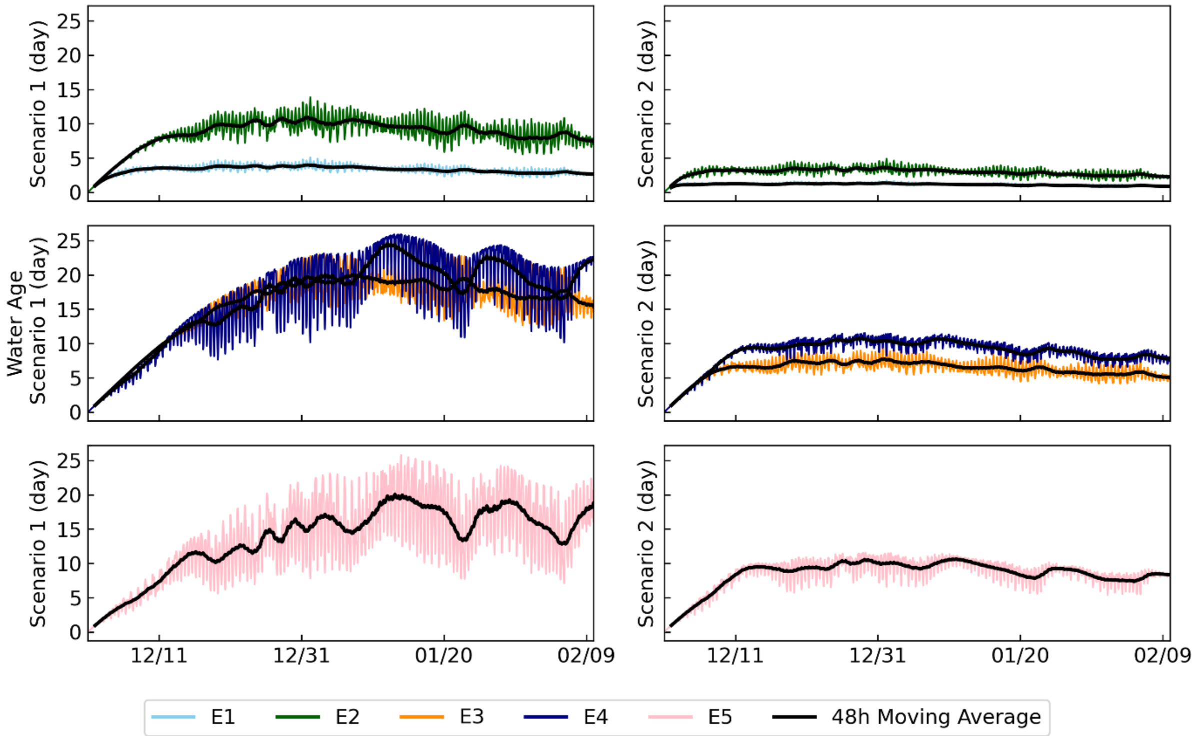

Figure 11. Time series for Water Age (day) for scenarios 1 and scenario 2. The black curve corresponds to the 48-hour moving average.

Table 3. Values of renewal rate (R), after 10 days of simulation, and water age (A) and salinity (S), after 90 days of simulation, for both scenarios at Stations E1, E2, E3, E4, and E5.

Scenarios		1			2	
Stations	R (%)	A (days)	S (psu)	R (%)	A (days)	S (psu)
E1	100	3	8	100	1	1
E2	75	7	3	100	3	2
E3	20	16	20	63	5	5
E4	20	22	22	92	8	8
E5	37	18	18	50	8	8

To evaluate the influence of increased river discharge on hydrodynamic exchange at the bay mouth, the mean bidirectional fluxes (inflow and outflow) were computed, and the net volumetric exchange was subsequently determined from hydrodynamic model outputs extracted along the bay-mouth transect. Figure 1 illustrates the cross-sectional segments used in the analysis, and Table 4 summarizes the volumetric exchange budget for both simulated scenarios over the summer period.

The results indicate that increased freshwater discharge substantially alters the exchange dynamics between the estuary and the adjacent coastal zone. Although the difference between inflow and outflow volumes does not directly correspond to river discharge, since part of the tidal prism is re-exported during tidal exchange, Scenario 2 showed a marked increase in freshwater contribution relative to the seaward flux. This contribution increased from 12.1% in Scenario 1 to 33.5% in Scenario 2, reinforcing the ebb-dominant character of the system.

Table 4. Inflow and outflow volumes at the mouth, river supply volume, percentage of fluvial discharge input compared with outflow at the mouth and percentage of "new" water originated in the ocean in the two simulated scenarios.

	Volume (hm^3)			Percentage	
	Inflow at the mouth	Outflow at the mouth	River supply	Fluvial discharge input compared with outflow at the mouth	"New" water is originated in the ocean
Scenario 1	6770.90	7177.50	865.8	12.1	93.3
Scenario 2	6182.20	7748.84	2597.4	33.5	83.2

Additionally, the fraction of "new" ocean-derived water decreased from 93.3% in Scenario 1 to 83.2% in Scenario 2, indicating that elevated fluvial discharge reduces oceanic water renewal and increases the relative retention of freshwater-influenced water masses within the bay. These results demonstrate that extreme discharge conditions significantly modify estuarine exchange processes, with implications for residence time, salinity distribution, and ecological functioning.

Under baseline conditions (Scenario 1), water age exhibited a clear spatial increase from the inner estuary toward the bay mouth, indicating progressively lower renewal efficiency in downstream regions. Under increased discharge (Scenario 2), water age decreased substantially throughout the system, particularly in the intermediate and outer sectors, demonstrating that enhanced freshwater inflow intensifies estuarine flushing beyond areas directly influenced by river discharge.

Figures 12A and 12B illustrate the spatial distribution of salinity after 21 days of simulation under both scenarios, highlighting areas designated for oyster aquaculture. In Scenario 1 (Figure 12A), salinity remained elevated throughout much of the estuary, with values exceeding 25.0 psu dominating the outer and mid-bay regions. In contrast, Scenario 2 (Figure 12B) showed a pronounced reduction in salinity, particularly in the inner and central portions of the bay, where values dropped below 15.0 psu and, in regions influenced by the Cubatão and Descoberto Rivers, below 10.0 psu.

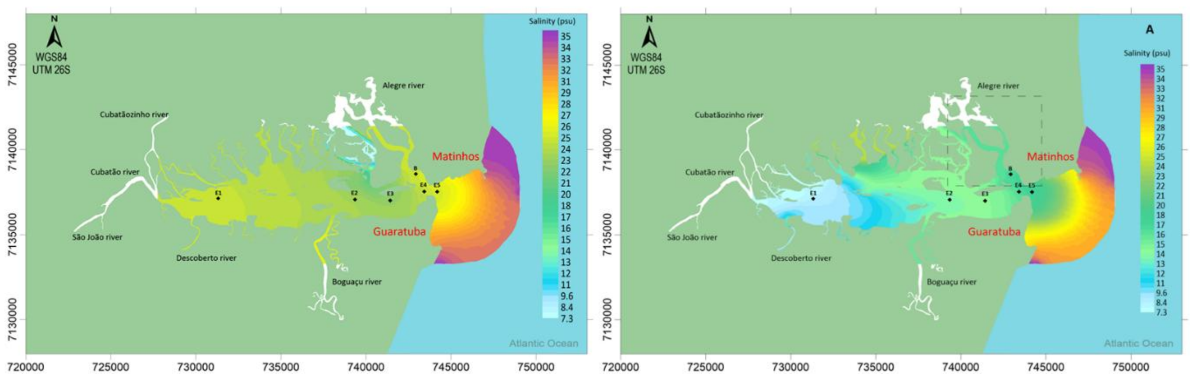

Figure 12. Salinity (psu) for the Guaratuba Bay after 21 days of simulation, highlighting areas designated for oyster aquaculture, for Scenario 1 (A) and Scenario 2 (B).

In the oyster farming region, under the freshwater stress scenario, salinity levels approach values near the lower threshold considered optimal for the reproduction of these organisms (16.0 psu). Consequently, the increased fluvial input is likely to impair the optimal growth performance of the oyster *Crassostrea brasiliana*, which is typically associated with intermediate salinity conditions ranging from 16.0 to 25.0 psu.

4. DISCUSSION

The results of this study indicate that alterations in the fluvial regime exert a controlling influence on the mixing dynamics and salinity distribution within Guaratuba Bay. Enhanced river discharge accelerates water renewal throughout the system, particularly in the inner- and mid-estuary regions. Increased fluvial inflow strengthens the exchange between water masses but concurrently decreases salinity. Moreover, higher river discharge may elevate nutrients and organic matter contribution, as well as diffuse pollutant loads, potentially degrading water quality, especially in zones adjacent to the river mouths. These findings underscore the critical role of fluvial dynamics in governing estuarine circulation, flushing efficiency, and the physico-chemical environment of the bay (Williams and Esteves, 2017).

The main evidence observed is that the increase in river-derived water volume leads to a reduction in the tidal prism. In this context, an improvement in water renewal efficiency occurs. These effects become more pronounced during the rainy season, due to higher river discharges. These processes are also associated with the intensification of advective flows, which substantially modify salinity gradients and the dynamic balance between fluvial and marine contribution.

In addition to the effects on hydrodynamics, changes in salinity can have significant biological im-plications. Laboratory studies indicate that the oocyte fertilization rate of the mangrove oyster (*Crassostrea rhizophorae*) increases with salinity, with the ranges being 20-25 mg/L (Rampersad and Ammons, 1992), 28-30 g/L (Rodríguez and Frías, 1992), 25-30 (Miranda and Guzenski, 1992), or 25-37 psu (Dos Santos and Nascimento, 1985). Thus, although water renewal is favored, water quality for aquaculture purposes can be compromised by excessive salinity reduction.

Similar effects have been observed in other ecosystems. Marshall *et al.* (2019) evaluated the effects of freshwater input variability on a restored oyster reef in the Gulf of Mexico, combining analyses of community abundance, biomass, and diversity with stable isotopes to identify changes in organic matter composition and quality. After the first major salinity reduction, the resident community shifted from a dominance of small gastropods to larger, more resilient crustaceans, while the second, smaller-scale event did not produce significant changes. In Guaratuba Bay, the salinity decrease observed in Scenario 2, with higher flow, can directly affect sensitive species, such as oysters, altering the structure and balance of local communities.

Results reported by Loiseau *et al.* (2024), who investigated how freshwater input, intensified by climate change and land-use changes, affects benthic substrate communities in small estuaries in Quebec, Canada. The authors found that increased freshwater inputs significantly reduced biomass, taxonomic and functional richness, and the presence of filter feeders and long-distance dispersers. At low salinities, macroalgae were smaller and functional redundancy was low, indicating greater vulnerability of these communities.

A similar situation may occur in Guaratuba Bay, where increased river discharge tends to reduce average salinity and, consequently, the ecological resilience of the system.

These results demonstrate that, despite the benefits of increased water renewal promoted by increased river flow, changes in salinity can impose significant limitations on the viability of aquaculture in estuarine environments, especially for sensitive species such as oysters.

5. CONCLUSIONS

This study demonstrated the applicability of the SisBaHiA® hydrodynamic, transport, and water quality models in analyzing renewal processes, water age, and salinity patterns in Guaratuba Bay. Computational modeling proved to be an effective tool for representing estuarine circulation and assessing the effects of river flows on the region's dynamics.

The simulation of different scenarios highlighted river flow as one of the main drivers responsible for the renewal of water masses. The results indicate that, under current conditions, river flow exerts a significant influence on renewal in the inner portion of the bay, especially near the Cubatão River, whose discharge exceeds that of other tributaries. With the threefold increase in flow, a significant acceleration of water renewal processes was observed throughout the estuary, accompanied by a substantial reduction in water residence times.

However, this increase in river flow also led to a sharp decrease in salinity values, which could compromise aquaculture activities such as oyster farming, which are sensitive to saline variations. A comparison between the scenarios revealed a marked change in salinity distribution: while, under the current conditions, high salinities predominate in the outer and middle portions of the bay (above 25 psu), the scenario with tripled flow showed a widespread reduction in salinity, especially in the innermost regions. This change represents a retreat of the saline interface toward the ocean, resulting from the greater dilution of saltwater.

The redistribution of saline zones significantly alters the ecological conditions of the estuary, with potential impacts on habitats and the viability of mariculture practices. Therefore, the findings reinforce the need for systematic monitoring and management strategies that consider the role of river flows in maintaining the balance between environmental conservation and the sustainable use of estuarine resources.

6. DATA AVAILABILITY STATEMENT

Data availability not informed.

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