

Hydro-morphodynamic characterization of areas with potential for nearshore wind farms using computational modeling.

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Abstract: The hydrodynamic and morphodynamic characterization of areas with potential for the installation of wind farms in Lagoa dos Patos is necessary as part of the planning for future wind energy projects. The aim of this study is to use computational modeling to describe the hydrodynamics of the lagoon system, focusing on areas with the greatest potential for wind farm installation. The three-dimensional hydrodynamic module TELEMAC-3D and the morphodynamic module SISYPHE, both from the Open TELEMAC-MASCARET system, were used in coupling for numerical simulations covering the period from 2005 to 2009. The analyses considered parameters that force the lagoon system, such as wind components and the intensity of river discharges into the system, and variables that respond to these forces, such as flow rate, current velocity, and bottom evolution. The results indicate significant seasonal variations in wind components and discharge events that respond to climatic events, but mainly to meteorological events that control hydrodynamic parameters such as currents and the free surface of the lagoon. This relationship controls sediment mobilization and bottom morphology evolution, highlighting the need for a deep understanding of these interactions for the proper planning of wind farm installation and maintenance operations, in order to minimize environmental impacts.

Keywords: Hydrodynamics; TELEMAC-3D; SISYPHE; Lagoa dos Patos.

1. INTRODUCTION

Energy is at the core of the solution to the climate challenge. The energy sector is responsible for more than two-thirds of global greenhouse gas emissions, reinforcing the need to place it at the center of any mitigation strategy according to the Intergovernmental Panel on Climate Change (IPCC, 2023, pp. 61–83). The United Nations (UN) warns that by the end of this century, global temperature could increase by 2.8°C, making it imperative for companies to adopt clean energy sources and abandon fossil fuels (SEI et al., 2023).

There are several reasons justifying the promotion of the development and use of alternative renewable energy sources. Renewable natural resources have become the focus of numerous studies, driven by the growing environmental concerns resulting from ecological impacts and global warming caused by the intensive use of fossil fuels. Among

the most well-known renewable sources today, wind energy stands out, especially in relation to wind farms located in flooded areas. These farms can employ nearshore and offshore technologies, aiming to take advantage of more favorable wind conditions, characterized by lower roughness and turbulence, as well as higher wind speeds compared to onshore areas (Gkeka-Serpetsidaki et al., 2024).

In view of these characteristics, the Lagoa dos Patos was included in a onerous concession, promoted by the Government of the State of Rio Grande do Sul, through the State Secretariat for the Environment and Infrastructure (SEMA), in December 2021, aiming at the implementation of wind energy generation parks by the private sector (Camargo-Schubert et al., 2014). Studies have shown that Lagoa dos Patos has an energy generation potential of 24.5 GW, and due to its shallow depth, it allows the use of jacket and monopile foundations, which are considered economically more viable and use technology similar to that employed in oil platforms. Globally, research using numerical modeling has been conducted to broadly assess nearshore and offshore wind energy projects in their processes (Zhang, J et al., 2023; Yin, Y et al., 2014; Defne, Z et al., 2011; Christie, E et al., 2012). In Lagoa dos Patos and its embayments, finite element techniques have been used to conduct studies on the system's hydrodynamics (Fernandes, 2001; Fernandes et al., 2001; 2002; 2004; 2005; Monteiro et al., 2006; Fernandes et al., 2007), hydrocarbon dispersion (Janeiro et al., 2008), and dredging activities (Martelo et al., 2019).

This article stems from the need to provide a detailed description of the hydrodynamics and morphodynamics of the areas described by Sena (2018) as suitable for expanding wind energy production in Lagoa dos Patos. This description must consider the high interannual variability of the system and the significant influence of the discharges from the two main basins, so that it will later be possible to identify and assess the potential environmental impacts associated with nearshore energy production in Lagoa dos Patos, in order to support the planning of installation and maintenance operations, as well as prevent or minimize the impacts of the project.

Furthermore, in light of the imminent need for an energy transition, and with the state of Rio Grande do Sul being a major wind energy investment hub for Brazil, studies like this will become increasingly frequent to ensure that the implementation of new technologies occurs in an equitable manner with low impact compared to oil and gas ventures. This study is just the beginning of a project that aims to understand how these changes in hydro-morphodynamics may impact the socio-spatial dynamics of those who rely on Lagoa dos Patos as a means of livelihood and for those enterprises already utilizing the lagoon system as part of their operations.

2. STUDY AREA

Lagoa dos Patos, located between 30° and 32°S and 50° and 52°W, is the largest coastal lagoon of the strangled type in the world and the largest coastal lagoon in Brazil, with a length of 250 km and an average width of 40 km. The lagoon has a total surface area of 10,360 km² and an average depth of approximately 5 m. It is connected to the ocean by a single channel that is 22 km long, 2 km wide, and 12 m deep. Despite its large size, it is considered a fairly shallow body of water (Kjerfve, 1986). The largest rivers in the southern part of the country discharge their waters into this lagoon, which are

subsequently released into the adjacent coastal zone. Thus, it has an extensive drainage basin of approximately 201,626 km². The tributary rivers belong to the Atlantic basin, which includes important sub-basins such as the Jacuí, Caí, Sinos, Gravataí, and Guaíba Rivers (Veeck, 1997).

Delaney (1962) geomorphologically divided Lagoa dos Patos into three regions: the estuarine region, located between the mouth of the lagoon and Ponta da Feitoria; the central region, formed by the area between Ponta da Feitoria and the entrance of Lagoa do Casamento; and the upper region, formed by Lagoa do Casamento and the area of the Guaíba River near the lagoon. The study area of this work focuses on the upper region of the lagoon, from the metropolitan capital of Porto Alegre to the boundary between the central and estuarine regions at Ponta da Feitoria (Figure 1).

Sena (2018) applied the Analytic Hierarchy Process (AHP) method, which uses scales of ratio, proportionality, and normalized ratio scales essential for the generation and synthesis of priorities. A multicriteria method that requires integrating comparison measures with its own scale, described in his work as a level divider that facilitates understanding and evaluation of the problem. The scenario chosen for application in this work was built from variables defined for the operationalization of a wind farm, assigning greater weight to the variables: kinetic energy and wind variation, while allowing flexibility in environmental conservation, heritage, and cultural aspects, alongside the development of a clean energy matrix, without overlooking environmental and legal restrictions

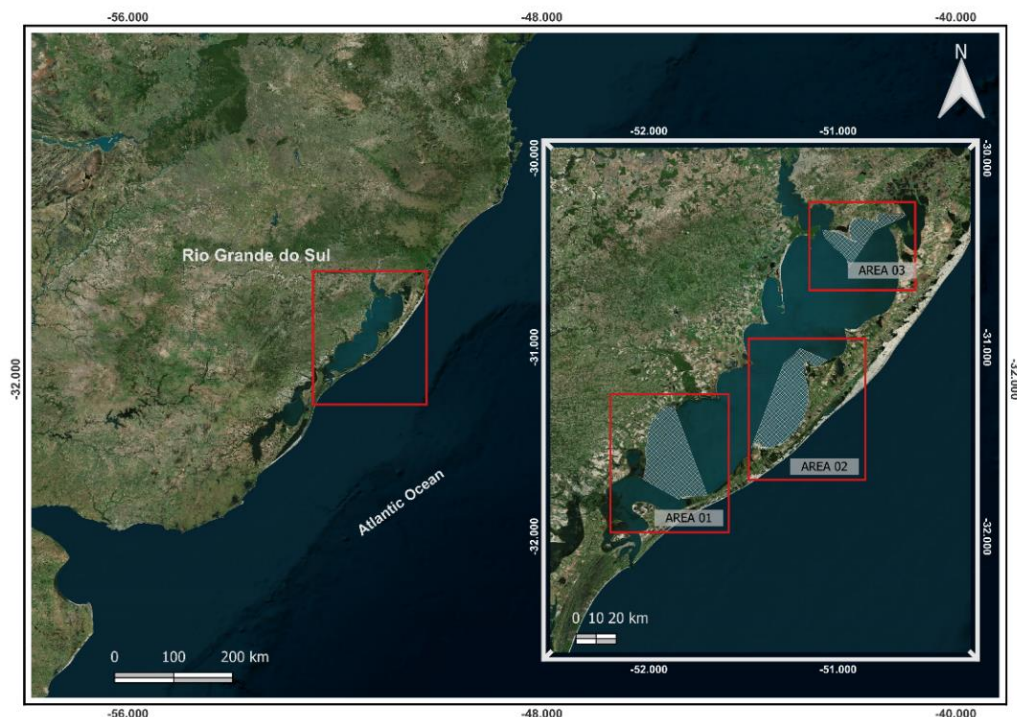


Figure 1: Study area in the Lagoa dos Patos. Area 01: Lagoon portion bordering the estuarine portion, near the municipalities of Pelotas and São Lourenço do Sul, RS. Area 02: Eastern coastal portion of Lagoa dos Patos, near the municipality of São José do Norte, RS. Area 03: Northern lagoon portion, near the metropolitan region of Porto Alegre, RS.

The lagoon portion is formed by interconnected elliptical cells, shaped by the action of wind and waves. The topography is more regular with smaller bathymetric gradients, consisting of larger basins deeper than 5 m in their central parts and shallow margins along their edges (Toldo Jr, 1994). Seven types of bottom sediments can be identified along the main body of Lagoa dos Patos (Martins & Villwock, 1987; Toldo Jr, 1994). Very coarse, coarse, and medium sand are found in the northern portion of the lagoon and on the sandbars located in its central portion. The lagoon has a slope gradient of approximately 1 m for every 120 km, and an average elevation difference of 2 m between the Guaíba River and the Rio Grande channel (Delaney, 1962).

The action of river discharge and winds are the most important forces driving circulation in Lagoa dos Patos (Möller et al., 2001). The effect of winds on coastal lagoons can be separated into local and non-local effects, with the local wind action blowing over the lagoon portion being the main controlling factor of circulation. The local action of northeast winds causes an increase in water levels in the Feitoria region, inducing flows towards the estuary, while southwest winds cause flooding in the lagoon portion, raising water levels in the headwater region of Lagoa dos Patos. The effect of high river discharge can intensify the elevation pattern associated with the local action of northeast winds (Möller Jr, 1996).

3. MATERIALS AND METHODS

The methodological process was structured to understand the realistic hydrodynamics of the lagoon system by coupling the SISYPHE morphodynamic module and the TELEMAC-3D three-dimensional hydrodynamic module of the Open TELEMAC-MASCARET system.

TELEMAC-3D solves the Navier-Stokes equations, considering or not hydrostatic pressure conditions, and models the evolution of the free surface over time. For the transport of tracers such as salinity, temperature, or suspended sediments, the model uses advection-diffusion equations. The main results obtained at each point of the computational grid include the velocity in the three directions and the concentration of transported substances, while the main result on the surface layer is the free surface elevation.

SISYPHE calculates sediment transport rates, divided into bedload and suspended load, at each grid node, taking into account flow parameters such as velocity, water depth, and wave height, as well as sediment characteristics such as grain diameter, relative density, and settling velocity. Bedload is estimated using classical formulas from the literature, while suspended load is determined by solving a transport equation for suspended sediment concentrations in depth. Bed evolution, described by the Exner equation, can be solved through either finite element or finite volume formulations (Tassi & Villaret, 2014).

The simulations conducted over five years used SISYPHE to calculate the suspended load of cohesive sediments and bed evolution based on hydrodynamic parameters

provided by TELEMAC-3D. The cohesive sediment suspended load was calculated using a concentration-based approach that satisfies the depth-averaged advection-diffusion transport equation (Tassi & Villaret, 2014; Rijn et al., 2007). Bed evolution was calculated using the Exner equation, which considers changes in bed elevation due to sediment fluxes above the bed. It assumes an equilibrium state where bed changes are linked to sediment transport and flow interactions (Tassi & Villaret, 2014).

In this study, a hydro-morphodynamic simulation was performed covering the period from January 1, 2005, to December 31, 2009, with a domain encompassing the Lagoa dos Patos and the adjacent coastal region, delimited by latitudes 30.05°S to 35.45°S and longitudes 53.23°W to 47.38°W. The mesh contains 93,050 nodes in each of the 11 vertical planes, with spatial resolution varying from 10 meters in regions of complex coastline to 10 km in the ocean region. The time step adopted was 10 seconds. The model was previously calibrated and validated by Martelo et al. (2019).

4. RESULTS AND DISCUSSION

The results presented in graphs 1, 2, and 3 indicate a strong influence of river discharge and wind components on the hydro-morphodynamics. Current velocity, free surface elevation, bed evolution, and suspended sediment concentration are represented for each area (01, 02, and 03), directly responding to these forces, with peaks observed during events of high river discharge and intensified winds.

Wind velocity in the "u" direction (east-west) predominantly ranges between -10 m/s and +10 m/s, with occasional peaks reaching values of +15 m/s. This behavior is irregular, with sharp wind peaks both to the west (negative values) and east (positive values), suggesting strong wind events interspersed with periods of calm, typical of a coastal region subject to varying meteorological systems, such as cold fronts driven by high-pressure systems over the ocean, pushing winds from the coast inland. The graph shows high-frequency variations, with rapid changes in wind direction, as well as low-frequency variations, with prolonged periods of wind.

The behavior of wind speed in the "v" direction (north-south) shows a more regular pattern, though still with considerable fluctuations, indicating seasonal variations. The graphs exhibit constant oscillations between positive and negative values, but predominantly with strong winds coming from the south, due to the increased frequency of frontal systems, which raises the frequency of southerly winds (Möller Jr., 1996).

Authors such as Costa et al. (1988), Kjerfve (1986), and Möller (2001) agree on the importance of the longitudinal wind component as a driving force for circulation in the lagoon system, primarily affecting water level fluctuations, while the transverse component of the sea breeze plays a secondary role. According to Möller (2001), the three areas chosen for analysis in this study have different relationships with wind patterns. In the lagoon's entrance zone, from the mouth to the São José do Norte station, circulation is driven by remote wind action. In the intermediate region, located between São José do Norte and Ponta da Feitoria, local winds dominate the circulation with low influence from remote winds. Meanwhile, the central and interior regions of the lagoon are exclusively driven by local winds through the oscillatory set-up and set-down mechanisms.

Northeast (NE) winds prevail throughout the year. However, during spring and summer, there is also a notable presence of east (E) winds, indicating the influence of the sea breeze. Southwest (SW) winds become more significant in the autumn and winter due to the higher frequency of frontal systems in the region (Tomazelli, 1993). Wind action, which depends on water depth, results in weaker currents in deeper areas, which may even be counterbalanced by opposing currents induced by river flow. During southwest wind events, river discharges enhance the return flow in the direction of the wind, while during northeast wind events, freshwater reinforces wind-induced surface currents, forming weak currents in the same direction of the wind at the bottom (Möller, 2001).

The flow of the Guaíba River shows greater variability over time, with significant peaks at different periods, reaching values close to 10,000 m³/s during some events. Between these peaks, although the flow of the Guaíba decreases, considerable fluctuations are still observed, associated with wetter and drier periods, as well as the influence of climatic variabilities such as El Niño and La Niña. In contrast, the flow of the Camaquã River remains at significantly lower levels throughout the period, rarely exceeding 1,000 m³/s, with sporadic peaks around 1,500 m³/s, likely due to local precipitation events in the basin. It is observed that, at certain times, there is a relationship between the flow peaks of the Guaíba and Camaquã rivers, suggesting that both rivers respond to simultaneous climatic events.

However, during other periods, the flows appear to be independent, indicating significant variations in meteorological and drainage conditions between the two river basins. Furthermore, a seasonal flow pattern becomes evident, associated with the mid-latitudes that influence the river discharges. The graphs suggest that periods with higher flow correspond to the end of winter and the beginning of spring, when rainfall events are more common, while during the summer and autumn months, flow tends to decrease, reflecting lower precipitation levels—patterns previously described by Rochefort (1958) and Möller et al. (2001), respectively. Therefore, it is expected that freshwater discharge will dominate circulation during periods of higher flow, leading to positive modulations of the "free surface height (m)," observable during the periods between September and December of the five simulated years.

In Figure 2, the current velocity shows significant variability over time, with peaks associated with increased river discharges, especially during flood events, and with the increase in wind shear during periods of strong winds from a predominant direction. The free surface, on the other hand, exhibits frequent and consistent variations with relatively low amplitudes. These variations indicate that the water level in the Lagoa dos Patos fluctuates continuously in this region. The set-up varies around 1 meter, with a maximum of up to 2 meters, associated with meteorological events that intensify wind and/or discharge forces, increasing the water level. This can lead to the formation of waves towards the Lagoon's coast, which modulate gravitational circulation and alter the vertical velocity profile, reducing ebb currents and shear flow, as described by Herz (1977).

Regarding the bed evolution in area 01, the graph shows a continuous increasing trend over the five years of simulation, indicating that, over this period, the lagoon's bottom was gradually elevated in a cumulative manner. This suggests that the dominant process was sediment deposition. The variations over time are very small, on the order of millimeters, indicating that the deposition process is slow but continuous. There are no abrupt peaks, suggesting that there were no sudden events of massive deposition or

significant erosion, at least not enough to considerably alter the bed profile. Although the graph shows a trend of accumulation, it is relatively smooth, which indicates that, for most of the time, the lagoon's bed remained stable, with slow and gradual sediment deposition.

The cumulative variation of the bed is a parameter linked to sediment transport processes, which predominantly occur in suspension due to the action of currents, winds, and river flows. Sediment transport and deposition are largely controlled by the intensity of the currents and wind action. More intense currents, as evidenced by the current velocity data, increase the transport capacity, moving sediments to areas of lower energy or more protected zones. In the graphs, it can be observed that the suspended sediment concentration remains low for most of the time, with small fluctuations coinciding with more intense meteorological events, especially winds. Additionally, a higher river discharge event stands out, contributing to a significant increase in current velocity. These data reaffirm that larger volumes of water and faster currents mobilize sediments more efficiently, resulting in their transport in suspension.

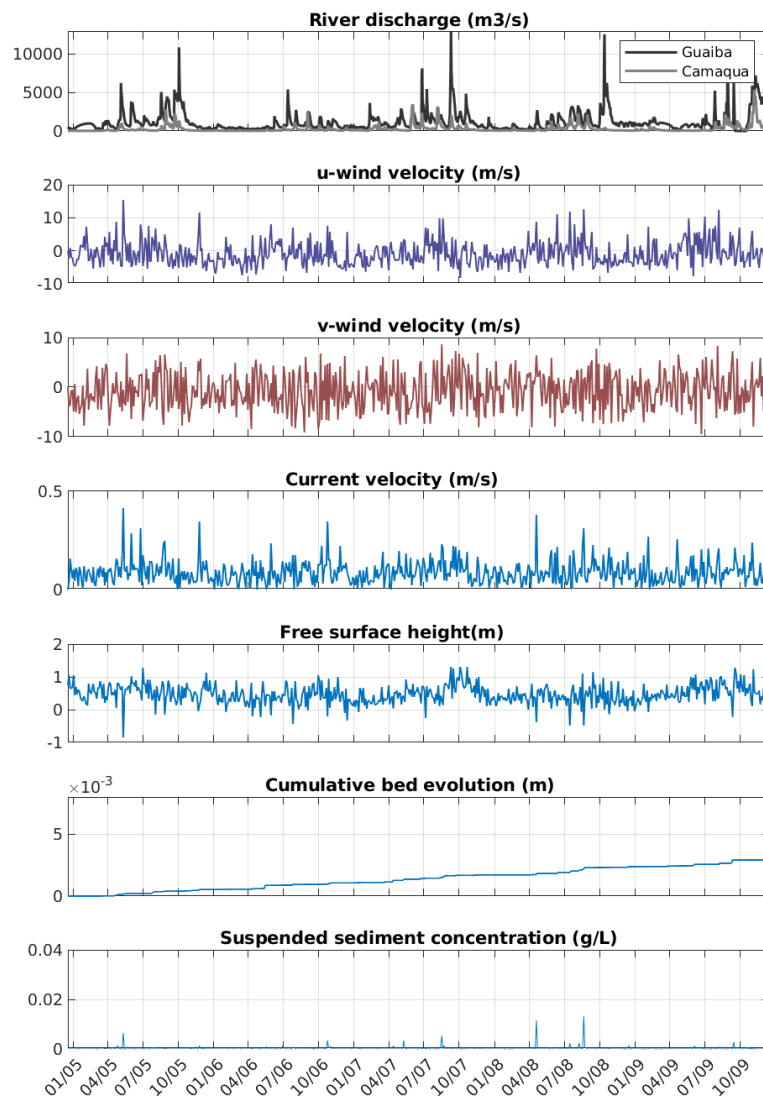


Figure 2: Area 01. Temporal variation of meteorological forcing on hydrological parameters in a region of the Lagoa dos Patos.

In Figure 3, the graphs reveal more pronounced variations in current velocity, with a higher frequency of more abrupt positive peaks compared to the "Current velocity (m/s)" graph in Figure 2. The water level continues to fluctuate under the general influence of local winds, between 1 and 2 meters of free surface. The lagoon bottom was gradually elevated in a slightly more cumulative manner in area 02, due to the sediment deposition process occurring along the eastern coast. The variations over time are also very small, on the order of 10^{-3} meters, indicating that the deposition process in this area is also slow and continuous. Although the amount of suspended material remains low, variations occur with slightly more frequency and exhibit somewhat more abrupt peaks. These peaks coincide with episodes of increased river discharge and strong wind conditions, which resuspend sediments from the bed into the water column.

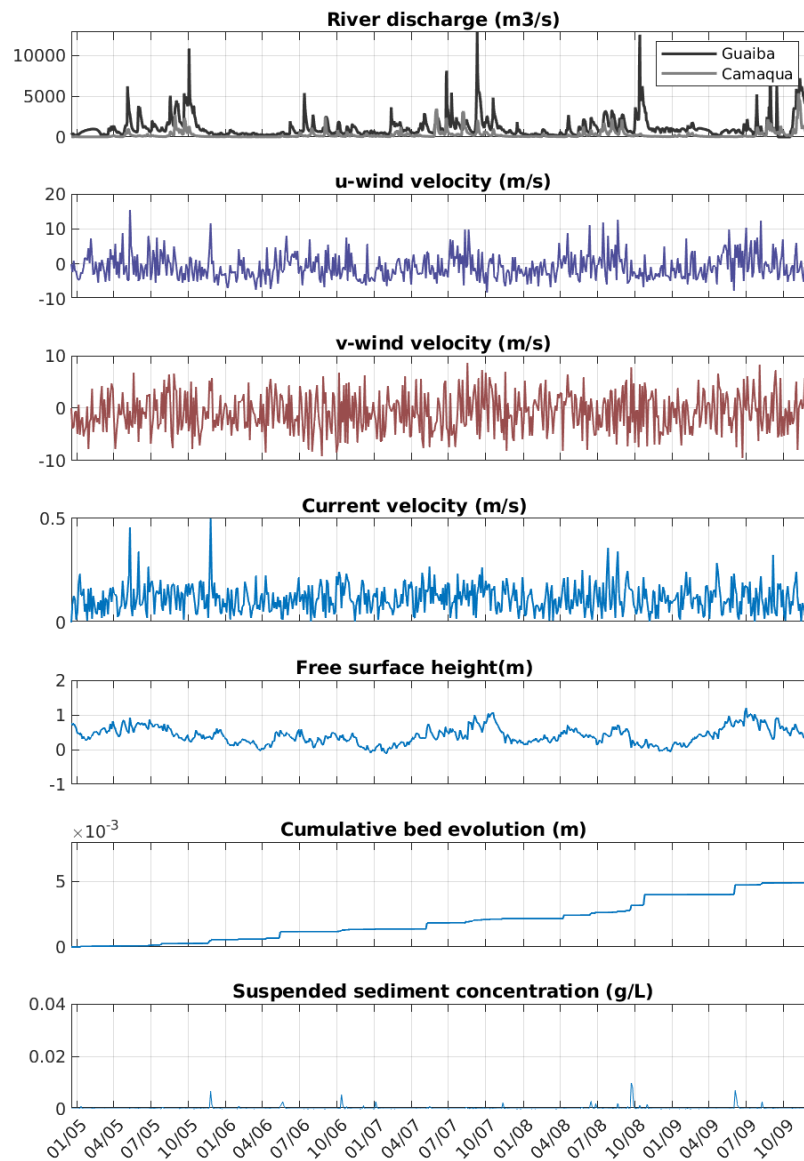


Figure 3: Area 02. Temporal variation of meteorological forcing on hydrological parameters in a region of the Lagoa dos Patos.

In Figure 4, during periods of high river discharge, more intense and frequent current velocity peaks are observed compared to the first two graphs, as the additional water volume accelerates the flow after the narrowing at the mouth of the Guaíba River and reaches the high-energy region of area 03. The free surface levels exhibit a similar pattern to the other scenarios, and the wind components (u and v) further enhance circulation, contributing to variations in current velocity and the pronounced peaks of suspended material visible in the graph. The concentration of suspended sediments remains low most of the time, with peaks coinciding with periods of high current velocity and intense river discharges. This region has a more dynamic and complex hydrodynamic regime than the other areas, resulting in a more pronounced cumulative bed evolution and higher sediment concentration.

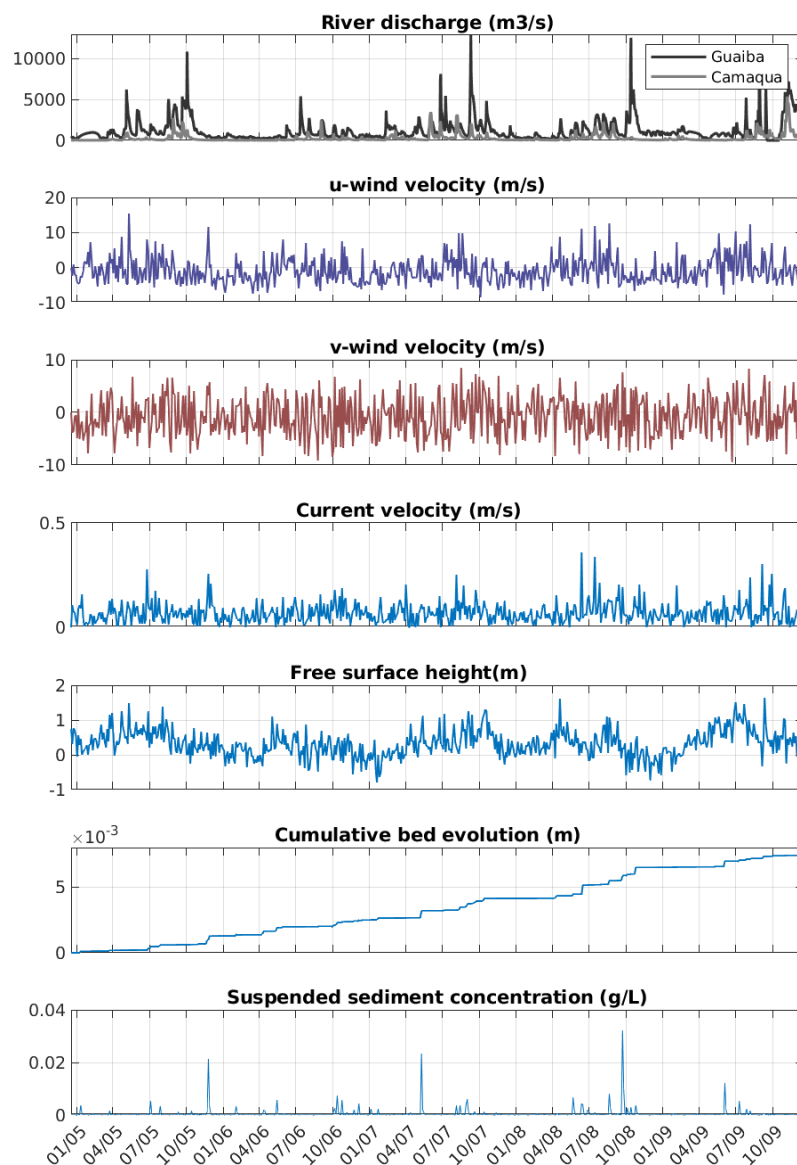


Figure 4: Area 03. Temporal variation of meteorological forcing on hydrological parameters in a region of the Lagoa dos Patos.

Figure 5 illustrates the seasonal variation of current velocity in the study area of the Lagoa dos Patos. During summer (Figure a), currents are less intense, with velocities ranging from 0.05 m/s to a maximum of 0.15 m/s in specific regions of the lagoon, as indicated by the color scale. The vectors show a predominantly southward (ebb) flow, but it is disorganized, causing water to pile up along the shores and form circulation cells due to the influence of bathymetry, similar to the patterns observed in previous "Current Velocity (m/s)" graphs.

In autumn (Figure b), current velocities slightly increase, and the vectors indicate a more defined ebb flow as atmospheric temperatures gradually decrease, cooling the surface and reducing the energy transferred to the system during the transition from summer to winter. In winter (Figure c), the currents become faster, and the ebb flow starts to vary in direction, particularly in the northern region of the lagoon. By spring (Figure d), although current velocities remain higher, the ebb flow becomes disorganized again, leading to water accumulation along the shores. This is attributed to the irregularity of the u and v wind components caused by the gradual rise in atmospheric temperature, as well as the increased contribution of discharge from the Guaíba River.

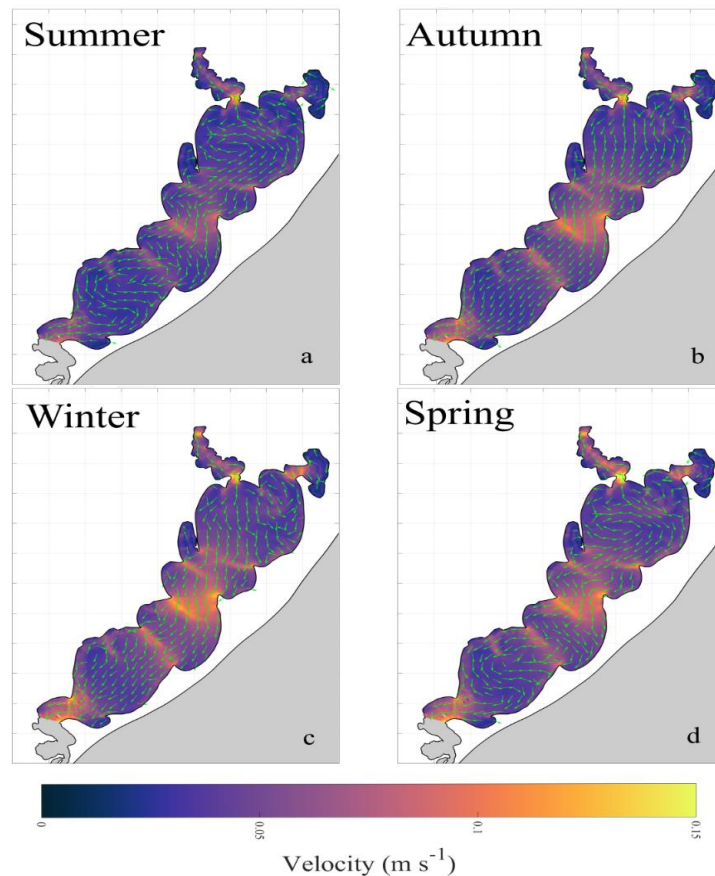


Figure 5. Seasonal averages of current speed in the lagoon portion of the Lagoa dos Patos, from 2005 to 2009.

5. CONCLUSIONS

The hydrodynamic modeling of the Patos Lagoon highlights the complexity of coastal processes in the region. The results obtained demonstrate a significant influence of wind variability and the discharges of major tributaries, which supply water and sediments to the system, on the behavior of currents and the free surface elevation of the lagoon. These factors underline the critical interdependence in sediment mobilization and the morphological evolution of the lagoon bed. The TELEMAC-3D and SISYPHE modules employed in the modeling proved to be effective tools for representing the flow patterns in the three areas analyzed, showcasing their potential to support future planning and implementation of wind farms. This integrated approach aims to provide insights for more informed and balanced decisions, aligning economic development with environmental preservation.

Furthermore, it is essential to recognize that the Patos Lagoon acts as a natural regulator of energy exchanges between the continental shelf and the lagoon itself due to its morphology, emphasizing the importance of the data collected for the installation and operation of wind turbines. Future research may explore potential changes in wind patterns and assess how the operation of *nearshore* wind farms could impact this energy balance, particularly in the context of climate change.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

USE OF AI FOR WRITING ASSISTANCE

Used only to check the writing of the text in English.

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