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Numerical study and proposal for the launch of domestic
effluents in the Patos lagoon and adjacent coastal area

Alejandra Bustillos Vega

Tutor: Prof. Dr. William Correa Marques (*in memoriam*)

Prof. Dr. Liércio André Isoldi

Profa. Dra. Juliana Costi

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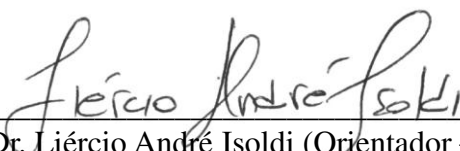
Alejandra Bustillos Vega

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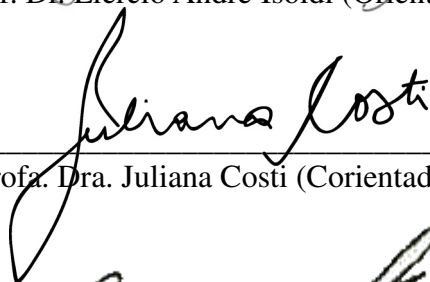
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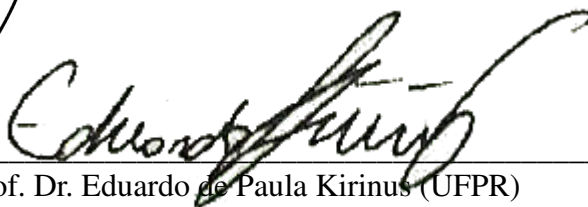
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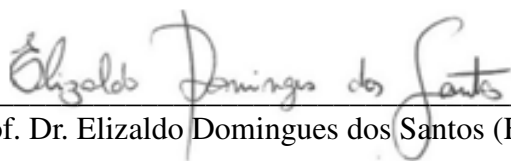
Prof. Dr. Liércio André Isoldi (Orientador – FURG)



Profa. Dra. Juliana Costi (Corientadora – FURG)



Prof. Dr. Eduardo de Paula Kirinus (UFPR)



Prof. Dr. Elizaldo Domingues dos Santos (FURG)

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ABSTRACT

As cities develop, water resources suffer from pollution problems. There is a paramount importance of adequately managing water resources as it is directly related to the economic and ecological development of the region. The city of Rio Grande has long suffered from inadequate coverage of its wastewater collection and treatment network, which favors the clandestine release of domestic and industrial effluents in the Patos Lagoon. Given the economic and ecological importance and the need for environmental protection in this place, studies to verify the behavior and destination of wastewater effluents are extremely important. Therefore, the main objective of the work is to analyze scenarios in order to mitigate pollution for the domestic effluent discharge points in the Patos lagoon estuary and its adjacent coastal area. This work presents the analysis of the behavior of pollutants produced by domestic discharges from the Patos lagoon estuary applying the numeric modelling system open TELEMAC-MASCARET. For hydrodynamic analysis, the three-dimensional TELEMAC-3D module is used and for the analysis of the behavior of contaminants, the contaminant module is coupled, which was developed in the Laboratory of Numerical Analysis of Dynamic Systems (LANSD). For which it is proposed to analyze the real situation as the first scenario, to later indicate and study 2 solution scenarios. The first solution scenario is based on the analysis described in the wastewater ATLAS of the Brazilian National Water Agency, and the second scenario is a solution with underwater outfalls as an ecological alternative. The model validation was carried out by comparing measurements and predictions for a reference station in the estuary area for the period of 2011 with the salinity and velocities parameters. Both solutions complied with the permissible limits of the CONAMA resolution. It was evidenced in the simulation that the first solution is the one with the lowest concentration of contaminants, however the effluent plume does not disperse. The second solution considers a dispersion of the contaminant plume together with the hydrodynamics of the estuary.

Keywords: Domestic effluents, Patos Lagoon, water quality, computational modeling.

RESUMO

À medida que as cidades se desenvolvem, os recursos hídricos sofrem com problemas de poluição. A gestão adequada dos recursos hídricos é de suma importância, pois está diretamente relacionada ao desenvolvimento econômico e ecológico da região. A cidade de Rio Grande sofre há muito tempo com a cobertura inadequada de sua rede de coleta e tratamento de esgoto, o que favorece o lançamento clandestino de efluentes domésticos e industriais na Lagoa dos Patos. Dada a importância econômica e ecológica e a necessidade de proteção ambiental neste local, estudos para verificar o comportamento e destinação dos efluentes são de extrema importância. Portanto, o principal objetivo do trabalho é analisar cenários para mitigar a poluição dos pontos de lançamento de efluentes domésticos no estuário da lagoa dos Patos e sua área costeira adjacente. Este trabalho apresenta a análise do comportamento dos poluentes produzidos pelas descargas domésticas do estuário da Lagoa dos Patos aplicando o sistema de modelagem numérica aberto TELEMAC-MASCARET. Para a análise hidrodinâmica é utilizado o módulo tridimensional TELEMAC-3D e para a análise do comportamento dos contaminantes é acoplado o módulo contaminante, que foi desenvolvido no Laboratório de Análise Numérica de Sistemas Dinâmicos (LANSD). Para o qual se propõe analisar a situação real como primeiro cenário, para posteriormente indicar e estudar 2 cenários de solução. O primeiro cenário de solução é baseado na análise descrita no ATLAS de águas residuais da Agência Nacional de Águas do Brasil, e o segundo cenário é uma solução com emissários submarinos como alternativa ecológica. A validação do modelo foi realizada comparando medições e previsões para uma estação de referência na área do estuário para o período de 2011 com os parâmetros de salinidade e velocidades. Ambas as soluções atenderam aos limites permitidos pela resolução do CONAMA. Ficou evidenciado na simulação que a primeira solução é aquela com a menor concentração de contaminantes, porém a pluma de efluente não se dispersa. A segunda solução considera uma dispersão da pluma contaminante em conjunto com a hidrodinâmica do estuário.

Keywords: Efluentes domésticos, Lagoa dos Patos, qualidade da água, modelagem computacional.

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LIST OF SYMBOLS

Acronyms

1D	ONE DIMENSION
2D	TWO DIMENSIONS
3D	THREE DIMENSIONS
ASGCM	Adriatic Sea General Circulation Model
Al	Aluminum
As	Arsenic
CO	Organic Carbon
CaCO ₃	Calcium Carbonate
Cd	Cadmium
CSC	Curved Surface Correction
CDOM	Color Dissolved Organic Matter
Cu	Copper
ENSO	South-El Niño Oscillation
Fe	Iron
IOPs	Inherent Optical Properties
NCOM 3d	Navy Coastal Ocean Model
Ni	Nickel
Mn	Manganese
O ₂	Oxygen
POM	Princeton Ocean Model
Pb	Lead
ROMS	Regional Ocean Modeling System
RG	Rio Grande
RS	Port of Rio Grande
SeaWiFS	Sea-viewing Wide Field-of-view Senso
SSS	Sea Surface Salinity
S	Sulfur
TASS	Turbidity Assessment Software
TELEMAC	Open TELEMAC-MASCARET
WST	Wastewater Treatment Stations
WWTP	Waste water treatment plant
WTS	Water treatment station Zn
Zinc	
AMR	Automatic Mesh Redistribution
CD	Calculated data CBM
Confluência Brasil-Malvinas	
CNRH	National Water Resources Council
CLIVAR	Variabile Predictability and Change
DEC	Department of Environmental Conservation
DELFT3D-FLOW	D-Water Quality 3D Flow
E	East
ERA-Interim ECMWF	European Center for Medium-Range Weather Forecasts interim reanalysis
GIS	Geographic Information System
HYCOM	HYbrid Coordinate Ocean Model
IBAMA	Brazilian Institute of Environment and Natural Resources
N	North
NE	Northeast

MARS3D	computation methods based on the use of a 3D numeric hydrodynamic model
OTIS	Oregon State University Tidal Inversion System
OD	Observed data
S	South
SMOS	Soil Moisture and Ocean Salinity
STWAVE	STeady State Spectral WAVE
SMS	Surface Water Modeling System
RSB	Southern Brazil
TSM	sea surface temperature
UFRGS	Federal University of Rio Grande do Sul
VES	Electric Electric Sounding
W	West
ZCAS	South Atlantic Convergence Zone

Greek Symbols

$\Delta\rho$	variation density (kg/m ³)
ρ_0	Reference density (kg/m ³)
$\Delta\rho$	Density difference
∂	Partial Derivative
ϕ	Heat flow (mW/m ²)
ρ	Water density (kg/m ³)
ρ_r	Relative density (kg/m ³)
ρ_{ref}	Reference density ($\rho_{ref} = 999,972$ kg.m ³)
ρ_s	Sediment density (kg/m ³)
σ	sigma coordinate
σ	Intrinsic or relative angular frequency
σ^2	Scatter ratio

Roman Symbols

f_u e f_v	Coriolis Force (N/m ³)
g	Gravitational acceleration (m/s ²)
g_o'	Density difference between fresh river water and salt water (kg/m ³)
Q_f	Flow
W_E	Estuary width
u_{tidal}	Tidal velocity
p	Pressure (Pa)
p_{ar}	Air pressure (Pa)
p_{atm}	Atmospheric pressure (Pa)
p_d	Dynamic pressure term (Pa)
g'	Low severity
t	Time (s)
F_x	Term source of momentum of the equation u
F_y	Term source of momentum in the equation v
G	Source due to gravitational forces
h	Water depth (m)
H_{mo}	Spectral significant wave height (m)
k	Turbulent kinetic energy of the fluid (m ² /s ²)
U	Velocity in X direction (m/s)
V	Velocity in Y direction (m/s)
W	Velocity in Z direction (m/s)
z	Depth of any layer (m)
Z_{ref}	Very thin layer concentrated near the bottom
Z_s	Surface elevation (m)
x	Spatial dimension
W_s	Wind Strength Index
y	Spatial dimension
z	Vertical space component

1. INTRODUCTION

Water is essential for the sustainable functioning of the ecosystems on which our socio-economic activities depend. For example, it is essential for agricultural production and power generation, as well as for industrial production and domestic use. Beyond the provision of water as a resource, aquatic ecosystems also provide other essential services, including water purification, flood mitigation, wildlife habitats, and recreational possibilities (UNEP, 2017). The importance of water care comes not only for the development of activities but also for maintaining the balance of an ecosystem. Water pollution resulting from industries, agriculture and domestic sources continues to grow in all regions, affecting rivers, lakes, estuaries and the coastal region (Palmer, 2001). This causes a series of challenges for the future of the ecosystems.

Estuaries located at the interface between rivers and sea are the site of great human development and biotic diversity (Chapra, 2008). Estuaries are one of the ecosystems most vulnerable to contamination. According to Kenov (2014), most estuaries are characterized by proximity to large cities and receive anthropogenic inputs from agriculture and urban waste with consequences on water quality. Estuary waters are normally used for aquaculture, fishing, recreation and navigation, hence the importance of focusing on the study addressed to estuary waters (Kenov, 2014).

Coastal areas, bays or estuaries are environments that are affected by pollution. In reality, many of the world's largest cities are located in coastal areas and more than 75% of people are expected to live within 100 km of the coast by 2025 (Kenov, 2014). Therefore, emphasis should be placed on these environments for the management and quality management of their waters.

In Brazil, according to the Sewer Atlas, launched by the National Water Agency (*Agência Nacional de Águas, 2017*), the deficit in the provision of sanitary sewer services has resulted in a significant portion of wastewater without treatment and without adequate disposal. Sometimes discarded directly into the water bodies, compromising water quality for different uses, with harmful implications for public health and environmental balance (*Agência Nacional de Águas, 2017*). Wastewater collection networks reach 61.4% of the Brazilian urban population, leaving 65.1 million people in cities in the country that do not have a collective system to eliminate sanitary wastewater. Not all collected wastewater is taken to a treatment plant. The portion served with wastewater collection and treatment represents 42.6% of the total urban population. Thus, 96.7 million people do not have collective wastewater treatment. The southern region of the country has collection networks that cover 54% of the total urban population of this region, and only 26 % with wastewater collection and treatment (*Agência Nacional de Águas, 2017*).

The municipality of Rio Grande, with its location in the southern region of the state of Rio Grande do Sul presents itself in a privileged location in relation to the other municipalities in the region, in addition to its strategic position in relation to the sea and the presence of the seaport, an important value for the southern region, projected by the municipality in state and

national scenarios. Therefore, the role in the economy played by Rio Grande and its maritime activities is an important factor for the development of the region. As for sewage coverage and wastewater management, the municipality of Rio Grande has only 25% of the population served by the sewage system (Engeplus engenharia e consultoria Ltda., 2013). According to the Sewer Atlas, the municipality of RG has 6 wastewater Treatment Stations (WTS) that cover 30.9% of collected water, 57.8% has an individual solution, and 11.3% does not count with wastewater collection. Therefore, according to information published by the National Water Agency ANA and research carried out at the Federal University of Rio Grande (FURG), the waters of the Patos lagoon estuary are contaminated due to the lack of collection and treatment of wastewater.

Within this scope, it is important that projects and actions are carried out for the management and monitoring of waters, especially when they are officially protected by state and municipal legislation. In this sense, it stands out in the estuary of the Patos lagoon - RS, which is located on the south coast of the RG city, due to its ecological importance for the region. Therefore, the importance of the Patos lagoon estuary generates a growing concern for the quality of its waters and the evaluation of the influence of anthropogenic actions. As a result, it is extremely important that there are projects and actions for the management and monitoring of this area, since in addition to being officially protected, it is also used in fishing activities.

As population growth with subsequent economic growth continues across the region, water resource managers must increasingly use analytical tools to help formulate sustainable water management strategies. A family of analytical tools that can be of great value are water quality prediction models (Palmer, 2001). The evaluation of water quality is carried out using monitoring tools (collection and measurement in the field) and modeling. In recent decades, there has been an increasing demand for modeling tools to support water quality management in estuary areas. Water quality models are effective tools to simulate and predict the transport of substances, pollutants (Kenov et al., 2014). At the same time, they have demonstrated an impressive ability to support important decisions about water resources in developed countries. Models are typically used to support development decisions and public policies in a variety of areas: simulation of discharges, drains, and intakes; changes in wastewater treatment systems; approval of changes in industrial processes; dam and reservoir operation; and allocations of water resources, among other uses. The modeling values are important in economic and financial terms with respect to determining individual project options and tiered investment programs.

Therefore, the economic and ecological importance of the estuary results in growing concern about the influence of anthropogenic actions. As a consequence, it is important that there are projects and actions for water management and monitoring, since in addition to being officially protected, it is also used in fishing activities. Therefore, the use of reliable collected data associated with the development of computational tools, helps to monitor these regions to assess the quality of their waters.

1.1. Justification

From the theoretical-scientific point of view, it is essential to know the existence and use of new technologies that facilitate a solution to the problem of water pollution in the estuary of the Patos lagoon. At the same time, the National Council for the Environment - CONAMA is the advisory and deliberative body of the National System for the Environment - SISNAMA, which establishes the National Environment Policy, regulated by Decree 99.274/90, the current legislation on quality of the natural waters that is the CONAMA Resolution No. 357 (2005) establish the care of aquatic environments.

For many years, domestic and industrial effluent discharges into the Patos lagoon estuary have become a problem that generates high levels of pollution, which to date have not been reduced. The lack of a tool to help establish where to locate the discharges and the treatment levels that should be applied, became a fundamental factor in decision-making for the region's comprehensive solution.

One of the most serious risks for human health related to water quality is that derived from microbiological contamination, particularly that of heat-resistant Coliforms, creating contamination of soils and agricultural products intended for human consumption, these being used by the inhabitants of the place for irrigation.

For this reason, there is a need to face the problem at a scientific level, so this research provides, from a theoretical point of view, the opportunity to describe, by evaluating treatment alternatives and using a mathematical model TELEMAC-3D And pollutant dispersion module, the behavior of water quality; and from a practical point of view it will cover points of interest in which decisions relevant to the required changes can be generated and contribute to the management of water resources of the municipality of Rio Grande.

Likewise, it is important to mention that, until now, few simulation analyzes of the behavior of water quality through mathematical models have been carried out in the Patos lagoon estuary and adjacent coastal areas.

1.2. Objectives

1.2.1. General Objective

The main objective of this work is to propose treatment solutions for the launch of domestic effluents in the Patos lagoon and adjacent coastal area through the use of a three-dimensional numerical model.

1.2.2. Specific Objectives

- Analyze the behavior and destination of the effluent plume of waste water.
- Propose solution scenarios for the discharge of wastewater from Rio Grande.
- Propose 2 solution scenarios for the discharge of wastewater from the Río Grande, in

which improvement of the existing treatment plants and the use of submarine outfalls are considered.

- Evaluate the use of outfalls as a mechanism in the discharge of wastewater.

2. STATE OF THE ART

This research focuses on the analysis of the water quality of the Patos Lagoon estuary and its adjacent coastal area, through the use of TELEMAC-3D models, as a decision-making tool. Therefore, it is important to mention the water quality models that have been disseminated and known worldwide through research.

2.1. Numerical Models

Numerical models have demonstrated an impressive ability to support important decisions about water resources in developed countries. Models are typically used to support development decisions and public policies in a variety of areas: simulation of discharges, drains, and intakes; changes in wastewater treatment systems; approval of changes in industrial processes; dam and reservoir operation; and allocations of water resources, among other uses. The value of modeling is important in economic and financial terms with respect to determining individual project options and tiered investment programs (Palmer, 2001).

World Bank in 2001, Palmer (2001), produced a guide describing the different types of water quality models offered and exemplified. Studies of water quality modeling over the years have been on the rise. However, not all models are appropriate in all conditions. They vary widely with respect to your analytical approach, underlying assumptions, data needs, and production capacity. In the context of developing countries, the usefulness of the models should be carefully examined in light of important limitations, such as the lack of experienced technical staff, low-quality data sets, and the lack of compliance with quality control protocols deficient.

The numerical models that the World Bank identified were: QUAL2E-UNCAS, WASP4f, HSPF, SWMM, WQRRS, CE-QUAL-W2, MIKE-XXFLOW 3D: XXPLUM-3D and TRISULA-DELWAQ DIVAST. Table 2.1 describes the variables and sectors that each of the mentioned models simulates.

It should be noted that in recent years numerical models have been increasing and/or were being developed and updated. To exemplify the use of the numerical models described above, The World Bank in the Palmer (2001) guide presents 7 studies from China, India and Philippines, case studies that were implemented. In each case, modeling work was necessary to allocate scarce financial resources to maximize environmental benefits.

HANGZHOU BAY ENVIRONMENTAL STUDY, 1993-1996 - Delft's TRISULA hydro-dynamic model, a two-dimensional finite element model using a curvilinear grid, was used to model. The best values for bottom roughness and eddy viscosities were determined. The model showed that predicted increases in biological oxygen demand, indicator bacteria, and nutrients will not exceed the assimilative capacity of the bay. However, because primary productivity is currently limited by high concentrations of suspended solids in the bay, any reduction in suspended solids concentrations will result in a greater biological mass of phytoplankton, which

Management Analysis	A	B	C	D	E	F	G	H	I
Receiving water									
Rivers	X	X	X	X	X			X	
Reservoirs & lakes		X			X	X	X	X	X
Estuaries, coastal areas		X				X	X	X	X
Attributes									
Dynamic		X	X	X	X	X	X	X	X
Stochastic	X								
Stormwater flow			X	X			X		
Sewer system				X					
Water Quality									
Dissolved oxygen	X	X	X		X	X	X	X	
Nitrogens	X	X			X	X	X	X	
Phosphoruses	X	X			X	X	X	X	
Indicator bacteria	X	X	X		X	X	X	X	X
Suspended Solids		X	X		X	X	X	X	
Heavy metals		X					X		
Dissolved Substances	X	X	X		X	X	X	X	X
Acidity									
Temperature	X	X			X	X	X	X	
Oils, grease, PAHs							X		

*A: QUAL2E-UNCAS; B: WASP4; C: HSPF; D: SWMM;
E:WQRRS; F: CE-QUAL-W2; G: 3D-XXPLUM3D;
H:TRISULA-DELWAQ; I: DIVAST

Table 2.1 – Numerical models of water quality.

could lead to increased appearance of undesirable algae blooms due to abundance of available nitrogen.

SECOND SHANGHAI SEWER PROJECT (SSPII), 1996 - The DHI MIKE model system was used for predictions which were used to evaluate different reduction options, with an emphasis on comparing model predictions for different options instead of comparing model predictions with water quality objectives or standards. The objective was to optimize the exploitation of this assimilative capacity, which is a direct function of the water quality standards for the estuary. The water quality model was also used in developing a long-term strategy for wastewater treatment, in particular the need to control nutrient loading in the Yangtze estuary.

SHANGHAI ENVIRONMENTAL PROJECT, 1994 - Tidal effects in the Shanghai area are important, so it was decided that a one-dimensional model designed to characterize tidal effects was appropriate to examine the suitability of a new site in Da Qiao. The water quality parameters modeled were BOD, ammonia, oxygen dissolved in nitrate and phenols. Phenols were included because there are high concentrations of phenols in the river and because there was an accidental spill of large amounts of phenols in 1989. Treatment failures or accidental spills in the industrial area would not affect the quality of the Huangpu River. The most important thing is to clearly define the objectives of the modeling; Keep the models as simple as possible; Use specialists to make assumptions and judgments.

SECOND MANILA SEWER PROJECT, 1996 - A hydrodynamic model was required to simulate the three-dimensional circulation in Manila Bay caused by surface winds, tides, and density gradients for different seasons. The model used for this project, MIKE 3 PA, consisted of four elements that satisfy the conservation of mass, momentum, salinity, and temperature, and the equation of state that relates local density with salinity, temperature, and pressure. The model predicted that the depth of solids deposition at the ocean floor would be negligible (0.04 mm for the three-year period, for a total of 58,950 tons of solids); the nutrients provided by the discharge could affect the primary productivity in the vicinity of the landfill and bacterial densities at recreational beaches and the coastal area northeast of the ocean spill site were slightly elevated.

TARIM II BASIN PLANNING PROJECT, 1997, CHINA - Each sub-basin had a separate model. In general, the water balance model consisted of modules for rivers, reservoirs, irrigation, groundwater and lakes, being different the formulation of the model in each module. The models were used to help decide which channels should be aligned, where well fields should be located, where drains should be installed, and where low-performance land improvement and reclamation activities should be conducted. The design of the Tarim Basin II Project was determined in part based on the model results. In addition, the modeling requirements for the next phase were identified, as well as monitoring and other data collection requirements to support the prediction models.

OCEANOGRAPHIC MODELING AND WATER QUALITY STUDIES IN MUMBAI, INDIA, 1997 - The Binnie and Partners model, DIVAST (Integrated Depth of velocity and Solute Transport) was used. The model was used to assess the impact of the treated primary and secondary effluent discharged at various distances into the high seas (3-88 km) for different conditions. Model simulations showed that the wastewater columns were larger during the non-monsoon periods. In two locations, the extension of the outfalls farther from the coast did not significantly reduce the size of the effluent columns due to patterns of circulation.

The following articles on hydrodynamics and water quality models were recorded in the last years:

In 2018, Al-Zubaidi and Wells (2020) verified analytically and with field data a hydrodynamic and water quality 3D number scheme based on the 2D formulation in CE-QUALW2. The CE-QUAL-W2 2D number scheme was expanded in three dimensions and modified to solve the elevation of the free surface. A time division technique was used to solve the impulse and the transport equation. The numerical formulation of the 3D scheme used a novel solution, which resulted in a tri-diagonal matrix form to solve the free surface equation rather than a more computationally intensive penta-diagonal matrix solution. For model hydrodynamics and temperature verification model predictions were compared with known analytical solutions and field data from Lake Chaplain, Washington, USA. There was good agreement on the solution of hydrodynamic equations to analytical solutions and field data.

Huang and Tian (2019) used numerical models to simulate the transport processes that are of primary importance to alleviate and control the problem of eutrophication in lakes.

This study presented an integrated graphical modeling system designed for three-dimensional hydrodynamic and water quality simulation in lakes. Called Lake Modeling System (LMS), the system provides the necessary simplified functionality for hydrodynamic modeling. The applicability of the LMS is demonstrated by a case study on Donghu Lake, which is a large urban lake in the middle reaches of the Yangtze River in China. The LMS was used to configure and calibrate a model for Donghu Lake. The model was then used to study the effects of a water diversion project on the change in hydrodynamics and water quality.

Tosic et al. (2019) analyzed the hydrodynamic behavior of the Bay of Cartagena, Colombia, at the same time that it carries out a study of pollutant discharges, water flow in the rainy season and analyzes the impact it has on water pollution. The hydrodynamic model calibrates and validates it with the 3D MOHID Water model. The results showed an evaluation of future scenarios: the first with the increase in freshwater runoff would result in a faster renewal of the water in the bay; and the second that plans to decrease freshwater discharge would result in slower water renewal in the bay. Therefore, it is imperative that any plan to reduce river flows in the bay be accompanied by control of local pollution sources, which are abundant and could worsen the bay's water quality problems if the renewal times of the water get longer.

de Oliveira (2012) used hydrodynamic and water quality variables to evaluate eutrophication in a tropical hydroelectric reservoir. Generalized linear models (GLM) were used to identify the influence of the operational phases of the reservoir on the water quality of its limnological zones. The results suggest that more eutrophic conditions occur during the operational phase of the water surge, and that the area most vulnerable to eutrophication is the transition zone. Demonstrating that the use of GLM is adequate to determine the areas and operational phases most vulnerable to eutrophication. It is provided that this information will be useful for decision makers when monitoring the water quality of hydroelectric deposits with dendritic patterns and dynamic operating phases.

Huang et al. (2020) performed a numerical study of hydrodynamics and water quality in the coastal waters of Qinhuangdao, China: implications for the management of pollutant loads. In this study, a polluting and hydrodynamic transport model (based on MIKE 21 modules) was established in the coastal waters of Qinhuangdao, China. The simulated hydrodynamic and water quality parameters were highly consistent with the measured values. The results of this study indicated that these waters were characterized by a weak tidal current, with average velocities varying in the range of 0 to 0.5 m/s. The results provided specific valuable information for controlling pollutants from rivers to coastal waters and managing the Qinhuangdao coastal water environment.

2.2. Numerical models in Brazil

Harari and Gordon (2001), carried out numerical simulations of dispersion of substances in the Port and the Bay of Santos, on the action of tides and winds. The work determines the evolution of the dispersion considering various hydrodynamic situations and numerical solutions,

all using advection-diffusion-decay current fields in vertical sigma coordinates. The Princeton Ocean (POM) model was used: MAPOM (dispersion model coupled to POM), MODIF (with vertical coordinates) and MOCAD (dispersion model that represents advection with the Lagrangian formulation and random diffusion and decomposition using the walk). This work made possible the implementation of computational routines that allow estimating the dispersion of remote discharge points, discharge combinations in various places, etc.

Pereira (2003) used the results of the "Pró Mar de Dentro" project to apply numerical models. In this work, the Delft3D model was also used as a tool, which shows that the circulation of the Patos lagoon depends fundamentally on the winds and the rain regime of the hydrographic basin, which ends up flowing towards the lagoon through the main tributary rivers.

For hydrodynamic modeling and phosphorus (P) concentration in the Iraí reservoir, Franz et al. (2005) also used SisBAHIA®. The SisBAHIA® water quality model considers nitrogen and phosphorous cycles and oxygen balance, in addition to temperature and salinity. Simulations were carried out to evaluate the degree of eutrophication in the Iraí river reservoir, considering the concentrations of organic and inorganic phosphorus as indicators. According to these authors, the model proved to be a useful tool for monitoring the water quality of the reservoir.

Barros (2008) performs the modeling of water quality in the hydrographic basin of the Ipojuca - Pernambuco river. Quantifying nutrient emissions from point and diffuse sources. The MONERIS model (modeling of nutrient emissions in river systems) was developed in Germany and was applied in more than 600 hydrographic basins in Europe.

Vasconcelos (2011), when evaluating the presence of submarine emissaries, investigated the dispersion conditions in the field near a possible Ocean Elimination System (SDO), in Enseada de Ingleses, on the island of Florianópolis - SC. For this, the author used the dispersion model called UM3 in Visual Plumes software, developed by the United States Environmental Protection Agency (USEPA - United States Environmental Protection Agency). As a result, the author obtained dilutions greater than 1: 100, recommended for projects, in all scenarios. However, due to the very high concentration values of the *Escherichia coli* indicator in the effluent, the plume did not obtain satisfactory rates, reaching values with potential for contamination. in primary contact with the population.

Ferreira et al. (2020), in the study of mathematical models to evaluate the effects of the dumping of organic waste on the sanitary conditions of environmental waters, evaluated the dispersion of organic matter from wastewater in the urban environment using the SisBAHIA® water quality model, developed by the Coastal and Oceanographic Engineering Area of the Oceanic Engineering Program at COPPE/UFRJ, considering the biochemical and dissolved oxygen demand as the main parameters. The authors highlighted the modeling of different types of emissions from the pollutant load, with the presentation of three types of emissions and the effects on the self-cleaning capacity of the water body. Considering the results obtained, the authors concluded that the model proved to be capable of simulating the transport of pollutants

in rivers, generating consistent results for environmental monitoring.

2.3. Analysis of contamination in the Patos Lagoon

In the lagoon estuary, Baumgarten (2010) studied the eutrophication of the Saco da Mangueira, based on the information gathered from other articles. It was evident that eutrophication is intense on the margins of the cove, due to the growth of phosphate and nitrogenous compounds from industrial emissions of fertilizers and clandestine emissions of domestic effluents.

Niencheski et al. (2006) evaluated organic contamination in the waters along the Patos lagoon, simultaneously considering the margin and channel areas. The authors took samples from 16 points along the Laguna, this sampling strategy is unprecedented for the region, since together with the hydrochemical parameters, the fecal and total coliform levels were analyzed for the first time. Fecal coliform bacteria rates showed a pattern similar to that of chemical parameters, increasing in waters near the cities of Rio Grande and Pelotas (São Gonçalo channel and Laranjal), both located south of the lagoon. No contamination was found in the channel areas along the axis of the lagoon, due to the greater hydrodynamics and the distance from the sources of urban contamination. The sampling was carried out in winter and summer, during the months of August and December 2001, respectively.

In addition to the previous work, Niencheski and Baumgarten (2007) analyzed parameters that characterize the water quality of Saco da Mangueira, in various places influenced by the discharge of effluents from different activities and under different salinity conditions. The parameters analyzed were salinity, temperature, pH, nutrients, suspended matter, oxygen, oxygen saturation, chlorophyll, total phosphorus, BOD5 (biochemical oxygen demand under standard test, carried out at constant temperature and during an incubation period, also days), fatty coliforms, oils, and bacteria. The evaluation indicated that the water contamination near the city of Rio Grande comes not only from domestic sources, but also from a local oil refinery.

In 2013, Baumgarten and Paixão (2013) calculated the Trophic Status Index (TSI) for the Patos lagoon estuary, selecting the representative variables of the estuary. The variables of chlorophyll a, total phosphate and total nitrogen are taken into account. The evaluation of the optimization efficiency was carried out by calculating the TSI using the estuary data, considering separately the channel waters (2006), with high hydrodynamics and shallow waters (2002) that directly receive eutrophic effluents rich in nutrients. In conclusion, the optimization was considered satisfactory for this estuary and the use of this index is recommended as a great complementary tool for the spatio-temporal evaluation of water quality. The TSI showed hypertrophy of the shallow waters of Saco da Mangueira in places close to the sewage discharges (TSI 67-85). The channels were predominantly mesotrophic (TSI <59), with additions to TSI (EIT 60-64 - eutrophic) in the fall, when seawater contained estuary water contaminated with anthropogenic inputs.

Campello (2006) carried out a study and identified the influence of wastewater release on

the behavior of benthic organisms on the north coast of the state of Rio Grande do Sul. In this study, it was detected that *Laeonereis acuta*, *Heteromastus similis*, and *Heleobia australis* are the most resistant wastewater species, while crustaceans showed a higher sensitivity. Also according to the author, the points under the influence of sewers showed a lower density of organisms and less wealth since the beginning of the summer season, a result that suggested a greater supply of wastewater due to the increase in population caused by the tourism.

Silva (2020), in 2020, presented an evaluation of the effect of the discharges of effluents on the magnitude of the concentrations of these variables and also indicators of the degree of contamination. This study was developed with the hydrodynamic model TELEMAC-3D, coupled to a pollutant module of advection - diffusion - decay. The results indicated that the Patos lagoon hydrodynamics is governed mainly by the performance of the wind and the river flow, factors which directly influence the behavior of the studied variables.

3. LITERATURE REVIEW

Water pollution is a modification of it, generally caused by humans, which makes it unfit or dangerous for human consumption, recreational activities, agriculture, etc. One of the most important reasons to treat wastewater is the elimination of all pathogens of human origin present in the excreta in order to avoid biological contamination by cutting the epidemiological cycle of transmission.

3.1. Biochemical Oxygen Demand - BOD

The organic matter present in water bodies and sewers is a characteristic of paramount importance, being the cause of the main problem of water pollution: the consumption of dissolved oxygen by microorganisms in their processes use and stabilization of organic matter (Von Sperling, 1996). In this context, BOD represents the necessary amount of oxygen used in the biochemical oxidation of organic matter in water. Therefore, the greater the amount of organic matter present in the water, the greater the BOD, and consequently, the greater the pollution, since there will be a decrease in oxygen dissolved in the water (Carmouze, 1994).

This parameter allows the quantification of the impact caused indirectly on the biota by the release of organic material. It should be noted that the impact is indirect because it decreases the oxygen in the environment, but BOD itself does not mean an indicator of toxicity, as it does not represent any direct damage to living beings (Leite, 2004). The BOD analysis method measures the amount of oxygen consumed in a liter of sample at a certain time and at a certain temperature. The standard used is for 5 days at $20 \pm C$, which represents 70% to 80% of the total BOD (Sawyer et al., 1978).

The typical BOD concentration in domestic sewage varies around 300 mg/l, reaching 20,000 mg/l for slaughterhouse effluents, due to the high volume of blood and animal tissue remains, or to be zero in industries of glass and cement, which have inorganic effluents (Von Sperling, 1996).

3.2. Ammonia

In natural waters, ammonia is found in two forms, such as: ammonium ion (NH_4) and ammonia (NH_3), and the ammonium ion can also be found in the form of NH_4OH . Ammonia or ammoniacal nitrogen is found in surface or groundwater as a result of the decomposition of organic matter. When plants and animals die, organic matter is consumed by bacteria that transform it into ammonia dissolved in water in the form of NH_3 and NH_4 . Domestic, industrial, and agricultural pollution is also an important source of ammonia contamination in aquatic systems. According to Benn and Mc Auliffe (1981), most of the nitrogen content in sewage comes from urine, in the form of urea. In agriculture, ammonia is formed from the

bacterial degradation of urea contained in manure, according to the ammonification reaction (O_2). High concentrations of ammonia can have ecological implications for aquatic systems, since in the nitrification process, the amount of dissolved oxygen decreases, being harmful mainly to fish. Concentrations of 0.25 mg/L or greater affect the growth of fish, but for their death to occur, the ammonia level must be greater than 0.5 mg/L (Esteves, 1998).

3.3. Nitrite and Nitrate

Nitrite occurs in natural waters, resulting from the reduction of nitrate or oxidation of ammonium, representing the intermediate state of oxidation between ammonium and nitrate, in the nitrogen cycle. In well-oxygenated media, the nitrite concentration does not exceed 0.14 $\mu\text{mol/L}$ of $N - N\text{O}_2$. Higher values, between 2 and 10 $\mu\text{mol/L}$, are recorded in both toxic and anoxic zones. In the exits of domestic sewage or polluted water, these values are even higher, and are used as indicators of organic pollution (Carmouze, 1994). Nitrate is the most stable form of nitrogen in the environment. Nitrates occur naturally in natural waters and lakes, around 1.0 $\mu\text{g/L}$ (Shelton, 2006). This amount can increase significantly when sources of nitrate are carried to rivers and lakes, from fertilizers, agricultural activities, or sewage. Worldwide the concentration of nitrate in rivers is correlated with the population density at the bases of the rivers (Berner and Berner, 2012).

3.4. Phosphor

Phosphorus is essential to life, similarly to nitrogen. In terms of water quality, this element is usually in low availability compared to other macronutrients (Von Sperling, 1996). This shortage, according to Chapra (2008), is due, for example, to the fact that phosphorus is not abundant in the earth's crust and does not exist in the gaseous form, among other factors. Although phosphorus is naturally scarce, several human activities lead to the contribution of this element to natural waters. The rain drainage of agricultural areas (fertilizers) and mainly of urban areas (chemical products containing phosphorus), and above all the loads carried by the sewage (physiological activities and detergents) can contribute to an increase in phosphorus levels in the aquatic environment (Von Sperling, 1996).

Domestic sewage usually represents the main point source of phosphorus in bodies of water, which is in the form of phosphates (Gujer et al., 1995). According to Von Sperling (1996), the importance of phosphorus in the aquatic environment is mainly associated with the fact that it is an essential nutrient for the growth of algae, and can therefore, under certain conditions, lead to the eutrophication of lakes and dams.

4. MATERIALS AND METHODS

4.1. Study area - Patos Lagoon and Adjacent Coastal Region

The study area of this work is located on the south coast of Brazil, between 30°—32°S and 50°—52°W (Fig 4.1), comprising the Patos lagoon and the adjacent coastal area. This area receives large contributions from continental waters and among the processes that take place in this region, there is the fertilization of the coastal zone by the plumes of the Rio da Prata and Patos lagoon, making this region one of the most important fishing zones in Brazil, so that the city of Rio Grande is the main fishing center in the southern region of Brazil (Seeliger et al., 1998). The Patos lagoon is considered a water resource of great economic, social, and environmental importance for the state of Rio Grande do Sul. In addition to generating high productivity in the coastal zone of the southern region of the state, it is home to numerous species of fish and shrimp of great commercial importance. This site was chosen for the study, due to its local importance, and because it is subject to severe anthropogenic impacts.

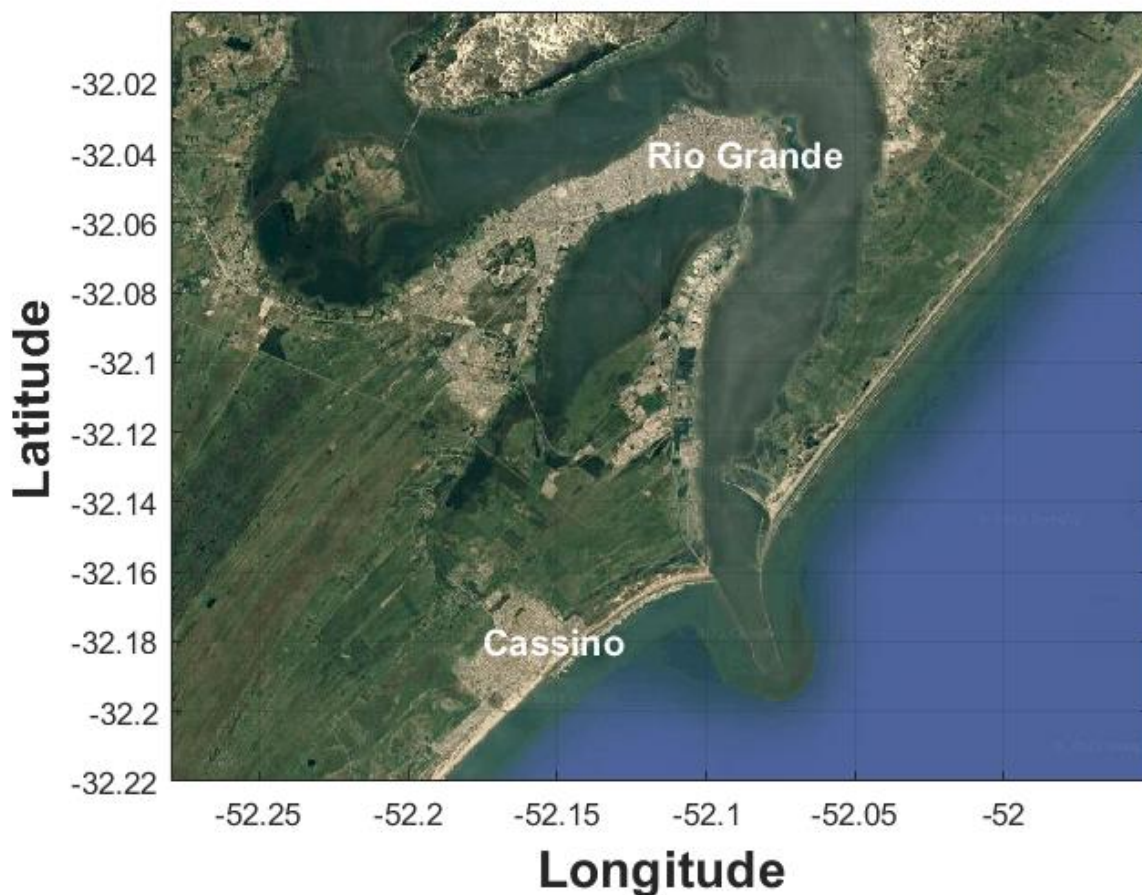


Figure 4.1 – Study Area, Patos Lagoon Estuary

Patos lagoon is considered the largest lagoon system in South America (Niencheski and Jahnke, 2002) and the largest strangled coastal lagoon in the world (Kjerfve, 1986), with an extension of approximately 250 km, an average width of 40 km and presenting an area of approximately 10.360 km² (Moller et al., 1996), however, it is a shallow lagoon, with a depth average of 5 m (Castelao and Moller Jr, 2006).

The topography of the main lagoon body is characterized by natural and artificial channels of 8-18 m, wide adjacent areas (> 5 m) and shallow marginal bags, so that its discharge into the ocean occurs between the cities of Rio Grande and São José do Norte (Fernandes et al., 2002).

Möller et al. (2009) consider that the main contributions of freshwater in the system originate from the Guaíba, Camaquã, and São Gonçalo rivers. When a low flow occurs, moderate (less than 2400 m³/s), the winds act with more evidence than the flow. These, in addition to controlling the entry and exit of saline water in the region, mean that, in addition to the fact that it is a shallow system, the lagoon remains well oxygenated throughout the year (Niencheski and Jahnke, 2002).

On the coast of Rio Grande do Sul, the flow of winds is strongly affected by the meteorological systems acting. Most of it is controlled by the Upper Atlantic Subtropical System of the Southern Atlantic (ASAS), causing predominant winds from the Northeast (NE) (Vera et al., 2006; Reboita and Kruche, 2018). Meteorological fronts of polar origin and transient cyclones also affect the region, causing winds from the southern quadrant to pass Reboita et al. (2010). During spring and summer Marques et al. (2009, 2010) verified through numerical modeling studies that, for the southern region of the coast of Rio Grande do Sul, the contribution of winds controlling the behavior of the Patos lagoon plume. On the other hand, the contribution of favorable winds to subsidy processes for increasing the mixing and dynamic control processes of the plume are most significant in autumn and winter.

Such processes occur mainly due to the action of the winds and their intensity depends on the configuration of the coastal zone. These processes are important for the control of mixing processes and stratification, as well as for the distribution of dissolved and/or particulate properties in the seawater, which contribute to the definition of patterns of behavior of marine organisms.

According to Moller et al. (1996), the Patos lagoon estuary is mainly controlled by two mechanisms, winds and fluvial discharge. The local effect of the wind acts directly on the surface inside the lagoon, by transferring the amount of movement through the friction, generating a lowering and elevating mechanism at the ends of Patos lagoon, which depends on the direction and intensity of the winds (Marques et al., 2009). The non-local effect of the winds is manifested in the coastal portion, causing an effect of increasing the level on the coast, transversely to the direction of the wind (Moller et al., 1996, 2001).

In periods of northeast winds, the action of the local effect of the wind promotes an increase in the elevation of the free surface in the region of *Feitoria*. The wind, in its non-local effect, causes a lowering the sea level close to the coast line, due to the Ekman transport, which

pushes the water towards the open ocean. The result of the combination of these two effects is the generation of a barotropic pressure gradient that forces the system to export water to the continental shelf. Under the action of a Southwest wind, Patos lagoon undergoes a lowering of level, in its southern portion (industrial region). In the coastal region, the Southwest wind generates an accumulation of water along the coast. The composition of these two movements produces a barotropic pressure gradient that tends to force the entry of salt water into the lagoon (Monteiro et al., 2006).

Tide events are prevalent in this estuary, mainly due to the effects of the north quadrant winds and the constant discharge of the tributaries that supply the Patos lagoon, resulting in an estuarine current that advances towards the ocean (Marques et al., 2010). The flood conditions, which are associated with the winds of the south quadrant, promote side effects, and the resulting direction of the current flows from the ocean into the estuary (Marques et al., 2011).

In addition to the aforementioned seasonal and annual events, the region suffers from inter-annual events such as El Niño southern oscillation (ENSO), directly affecting the fluviometric volumes of the tributaries of the Patos lagoon (Marques et al., 2014). In La Niña scenarios, due to atmospheric flow, drought situations occur over the south of the country, however, in El Niño episodes, atmospheric flow favors precipitation over the region (Reboita et al., 2010; Marques et al., 2014).

Patos lagoon receives a significant anthropogenic load resulting from the increase in population and industrialization along its margins. Due to the anthropogenic activities that border the lagoon system, among them: recreation and tourism, irrigation, discharge of domestic sewage, fertilizer production, fish processing and oil refining, artisanal fishing and aquaculture, agriculture and navigation industries, waters become subject to pollution (Tyrrell and George, 2006). In the estuarine region, in addition to the contribution via freshwater entry into the system - probably thought to be the main mechanism for the introduction of new nutrients in the estuarine region (Poersch et al., 2006), since the Guaíba river (a composition of the Jacuí, Sinos, Caí, and Gravataí rivers) accounts for 86% of the total freshwater entering this region, the rest being from the Camaquã River - the quality of the water in this region is the result of a complex interplay of factors including the movement of the water, the presence of nutrients, biogeochemical processes images, and anthropic entries (Niencheski and Windom, 1994).

4.2. Numerical methods

This work was developed through three-dimensional numerical modeling using the open TELEMAC - MASCARET system, through the hydrodynamic module TELEMAC-3D (www.opentelemac.org). This module is used to study aspects related to the three-dimensional hydrodynamics of flows with free surfaces from rivers, estuaries, coastal, and/or oceanic regions. A complete description of the model and technique of the finite elements applied to Telemac-3D can be found in Hervouet (2007), but in this section only some more information is explained

relevant information about the mathematical description of the model, obtained from this author's book.

To describe the processes of effluents in the marine environment, the pollutant model developed at the Federal University of Rio Grande - FURG within the Laboratory of Numerical Analysis and Dynamic Systems - LANSO.

4.2.1. Hydrodynamic model - TELEMAC3D

The hydrodynamic module TELEMAC-3D solves the Navier-Stokes equations by applying the finite element method for later spatial representation and vertical reproduction in sigma coordinates, thus following the surface and bottom limits of water bodies (Hervouet, 2007).

The system is applicable in different fields of study, in which the main ones are related to marine environments through research in currents induced by tides or density gradients, with or without the influence of an external force such as wind or air pressure. It is also applicable in areas of great extension, for example the marine environment, or in relatively smaller areas, such as coastal regions, rivers, and estuaries, to assess the impact of sewage effluents from domestic discharges and industries, the study of thermal plumes or sedimentary transport. Related to continental waters, research involving analysis of thermal plumes in rivers, the general hydrodynamics in lagoon environments (natural or artificial) can be evaluated.

- Model equations

The system solves three-dimensional equations such as free surface flow (equations with or without the hydrostatic pressure hypothesis) and the transport-diffusion method, equations of intrinsic quantities (temperature, salinity, concentration). The main results, at each point in the mesh, are the velocity in all three directions and the concentrations of variable quantities transported.

TELEMAC-3D can be used in free surface flows in oceanic environments and rivers. In all cases the model can take into account different processes, including: the influence of temperature and salinity on water density, friction with the bottom, the influence of the Coriolis force, the influence of atmospheric elements such as pressure and wind, consideration of thermal exchanges with the atmosphere, sources for the amount of fluid movement within the domain, simple or complex turbulence models such as $(k - \varepsilon)$, dry areas in the computational domain characterized as tidal plains, and the advection and diffusion of tracers, with terms of generation or disappearance.

In its basic version, the code solves the three-dimensional hydrodynamic equations with the assumptions described in Hervouet (2007). The continuity equation (Eq. 4.1) and momentum equations (Eq. 4.2 and Eq. 4.3) are derived from geophysical fluid dynamics relations, and represented in a Cartesian coordinate system. In the three-dimensional module. the TELEMAC3D model considers the hydrostatic and Boussineq approximations for the Navier Stokes equations.

The hydrostatic approach considers the simplification of the source terms and the vertical

acceleration. Therefore, the terms that consider variations in hydrostatic pressure (Eq. 4.4) and gravity are kept in the vertical momentum equation, so that the pressure at a point depends only on the atmospheric pressure at the surface and the weight of the water column.

Continuity equation:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \quad (4.1)$$

Conservation of momentum equations:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nabla^2(vu) + F_x \quad (4.2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nabla^2(Vv) + F_y \quad (4.3)$$

Hydrostatic pressure equation:

$$p = p_{atm} + \rho_0 g(S - z) + \rho_0 g + \int_z^{Z_s} \frac{\Delta \rho}{\rho_0} dz \quad (4.4)$$

Where, h (m) is the water depth, S (m) free surface elevation, U, V, W (m/s) three-dimensional speed components, p (Pa) pressure, p_{atm} (Pa) atmospheric pressure, g (m/s²) gravity acceleration, v (m²/s) tracer diffusion coefficients, Z_f (m) bottom depth, ρ_0 (kg/m³) reference density, $\Delta \rho$ (kg/m³) density variation, t (s) time, x, y (m) components of horizontal space, z (m) component of vertical space, F_x, F_y (m/s²) source terms. In this system, h, U, V, W are the unknown quantities, and calculated by the model. In this situation, F_x and F_y are source terms that denote the wind, the Coriolis force and the bottom friction.

- $(k - \varepsilon)$ Model

The model of turbulent processes are solved by different means in TELEMAC-3D, in this study the model $(k - \varepsilon)$ was adopted, which is based on the calculation of the physical quantities that represent the turbulence in a flow, in this aspect the K and the ε are, respectively, the turbulent kinetic energy (Eq. 4.5) and its dissipation (Eq. 4.6).

$$K = \frac{1}{2} \overline{u'_i u'_i} \quad (4.5)$$

$$\varepsilon = \nu \overline{\frac{\partial u'_i}{\partial x_j} \frac{\partial u'_i}{\partial x_j}} \quad (4.6)$$

In this case, u'_i corresponds to the velocity fluctuation and the time-averaged operation. The model resulting from the coupling of the balance and dissipation equations to provide turbulent viscosity, in general, can be provided by the user. The representation of the model $k - \varepsilon$ is given by the Eqs. (4.7) and (4.8).

$$\frac{\partial k}{\partial t} + U \frac{\partial k}{\partial x} + V \frac{\partial k}{\partial y} + W \frac{\partial k}{\partial z} = \frac{\partial}{\partial x} \left(\frac{v_t}{\sigma_k} \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{v_t}{\sigma_k} \frac{\partial k}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{v_t}{\sigma_k} \frac{\partial k}{\partial z} \right) + P - G - \varepsilon \quad (4.7)$$

$$\begin{aligned} \frac{\partial \varepsilon}{\partial t} + U \frac{\partial \varepsilon}{\partial x} + V \frac{\partial \varepsilon}{\partial y} + W \frac{\partial \varepsilon}{\partial z} = & \frac{\partial}{\partial x} \left(\frac{v_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{v_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{v_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial z} \right) \\ & + C_{l\varepsilon} \frac{\varepsilon}{K} [P + (1 - C_{3\varepsilon})G] - C_{2\varepsilon} \frac{\varepsilon^2}{K} \end{aligned} \quad (4.8)$$

In this context, P is the turbulence energy production term (Eq. (4.9)) and G is a source term, due to gravitational forces (Eq. (4.10)).

$$P = v_t \left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right) \frac{\partial \overline{U_i}}{\partial x_j} \quad (4.9)$$

$$G = - \frac{v_t}{Pr_t} \frac{g}{\rho} \frac{\partial \rho}{\partial z} \quad (4.10)$$

- Tracer equation

The tracer represents the temperature or a physical quantity present in the water, interacting or not with the hydrodynamics of the flow. If there is interaction between these factors, the tracer is called active, otherwise it is commonly called passive.

The active tracers are mainly represented by temperature and salinity, in some cases sediments. Both types of tracers can be used in different studies, in the case of passive tracers, their main application is in the evaluation of physical-chemical parameters of water, for example, they can be applied in studies on temporal variability of water quality. The temporal evolution depends on the diffusive and advective processes, controlled mainly by the effects of currents, winds and turbulent processes.

A scalar can be defined as a substance, particle or property present in water, such as temperature, salinity, suspended sediments, nutrients, or non-nutrients. These can still be considered active, when there is interaction with hydrodynamics, or passive when they do not interact with hydrodynamic processes.

The temporal evolution of these scalars depends on the advective and diffusive processes, the former being controlled by the currents and action of the winds and the latter by the turbulent processes, in addition to sources and sinks. The advection and diffusion equation, in its non-conservative form, can be written as:

$$\frac{\partial(C)}{\partial t} + U \vec{\nabla} C = \text{div}(v_C \vec{\nabla} C) + F_{f\text{source}} \quad (4.11)$$

with v_C representing the turbulent diffusion coefficient associated with the considered tracer.

4.2.2. Pollutant transport model

The simulations with the consideration of domestic sewage effluents in different scenarios is carried out with a three-dimensional advection - diffusion - decay numerical model, with finite element scheme, which has been developed at LANSI using the FORTRAN95 language and which works directly coupled to the model hydrodynamic TELEMAC3D. Each of the properties of domestic sewage is considered as a differential tracer equation as in equation Eq. (4.11). A source term in the form of a decay is added to each of the properties. The modeled pollutant is considered inert and completely miscible in sea water (Gordon, 2001) and the concentration of constituents of the plume in the initial dilution is expressed according to District (2000). The model represents the concentration of specific properties and, in this context, is considered as properties indicating the degree of water contamination: faecal coliforms, water oxygen concentration related to biochemical oxygen demand (BOD), water oxygen concentration with respect to the demand associated with the nitrification process, and the evolution in the concentration of phosphorus.

- Thermotolerant Coliforms

As an indicator of the level of water contamination, the modeling of the concentration of bacteria (Thermotolerant Coliforms) is considered based on the use of a source term described by an ordinary differential equation according to (Kashefipour et al., 2006). The equation that represents the decay of coliform concentration is given by:

$$\frac{dC_o}{dt} = -k_C C_o \quad (4.12)$$

where, C_o represents the concentration of coliform bacteria (NMP: 100 ml⁻¹) and k_C represents the mortality rate (h⁻¹). The mortality rate of coliforms is considered to be a function of water temperature and salinity, in addition to the consideration of the sedimentation decay effect (Kashefipour et al., 2006). The mortality rate of coliforms can be described as:

$$k_{Ct} = k_{Ct,20} \lambda^{T-20} \quad (4.13)$$

$$k_{Cs} = 0.00014S^2 + 0.0024S + 0.0253 \quad (4.14)$$

$$k_{Cb} = \frac{0.04}{H} \quad (4.15)$$

with: $k_{Ct,20}$ representing the coefficient at a temperature of 20°C, λ with an empirical parameter ($\lambda = 1.190$) and H the local depth of the region where the submarine outfall is located.

- Biochemical oxygen demand (BOD)

In the analysis of water in natural environments, it is necessary to carry out some tests that prove its good quality. Biochemical oxygen demand (BOD) is a measure of the degree of pollution of a body of water.

BOD represents the necessary amount of oxygen used in the chemical oxidation of organic

matter in the water, while autotrophic bacteria perform the decomposition of organic matter using oxygen, which is reduced from the medium.

The rate of change in the amount of oxygen available in the water can be represented by an ordinary differential equation (Chapra, 2008) which is used as a source term in the form of:

$$\frac{dL}{dt} = -k_1 L \quad (4.16)$$

where, k_1 indicates the decomposition rate in the medium (h^{-1}), L represents the BOD remaining at the end of time in (mgO.l^{-1}) and t , the time (h). The consumption of dissolved oxygen in the liquid medium occurs simultaneously with the reoxygenation of this medium in which, by transfers through the interface, oxygen passes from the atmosphere to the water. This process is modeled by the following equation:

$$\frac{dD_o}{dt} = -k_2 D_o \quad (4.17)$$

with k_2 indicating the rate of reaction in the medium (h^{-1}) and D_o representing the oxygen deficit (mgO.l^{-1}). In this sense, the deficit of dissolved oxygen saturation corresponds to the result of the sum of the effects of deoxygenation and re-generation, which can be represented by the following differential equation:

$$\frac{dD_o}{dt} = k_1 L - k_2 D_o \quad (4.18)$$

Thus, the oxygen concentration in the CO_t time is given by the difference between the CO_s saturation concentration in the ambient conditions and the deficit of dissolved oxygen in a given time:

$$CO_t = CO_s - D_o \quad (4.19)$$

where, CO_s represents the oxygen saturation concentration in the medium in mgO.l^{-1}

- Nitrogen

In natural environment waters, nitrogen N is associated with several sources, but in general sanitary sewage represents its main source. Nitrogen can be found in reduced forms of organic nitrogen (from proteins) and ammoniacal nitrogen (urea hydrolysis), in addition to its oxidized forms of nitrite and nitrate. The release of sewers with high concentrations of nitrogen together with phosphorus and other nutrients can cause enrichment of the environment (eutrophication), favoring the proliferation of living beings, such as algae. Since, after carbon, nitrogen is the element required in higher concentrations by living cells. The increase in the concentration of living beings in marine environments can lead to problems in the use of this water by the population. In this sense, according to Chapra (2008) and Brandelero et al. (2010), a model, in the form of a system of differential equations, for the representation of the formation and disappearance of ammoniacal nitrogen

can be used as a source term for this property as:

$$\begin{cases} \frac{dN_o}{dt} = -k_{oa}N_o \\ \frac{dN_a}{dt} = k_{oa}N_o - k_{ai}N_a \\ \frac{dN_i}{dt} = k_{ai}N_a - k_{in}N_i \\ \frac{dN_n}{dt} = k_{in}N_i \end{cases} \quad (4.20)$$

where: o , a , i and n refer to the organic, ammoniacal, nitrite and nitrate plots, respectively. In these equations, k_{oa} represents the rate of conversion of organic nitrogen to ammonia, k_{ai} represents the rate of conversion of ammoniacal nitrogen to nitrite, k_{in} represents the rate of conversion of nitrite to nitrate. In this sense, the deficit in the oxygen balance can be written as:

$$\frac{dD_N}{dt} = 3.43k_{ai}N_a + 1.14k_{in}N_i - k_a D_N \quad (4.21)$$

so that D_N represents the deficit of oxygen saturation at time t in $mgO.l^{-1}$ and k_a represents the coefficient of reaction. Thus, the oxygen concentration over time is given by the difference between the saturation concentration under ambient conditions and the deficit in the oxygen balance at a given time:

$$CO_t = CO_s - D_N \quad (4.22)$$

- Phosphorus

The source of phosphorus (Ph) in natural waters can occur due to the presence of sanitary sewage, with superphosphated detergents being the main source, since they are used on a large scale domestically. There are three forms of phosphorus in water: organic phosphates, ortho phosphates and poly phosphates. Phosphorus, like nitrogen, is one of the main nutrients in biological processes, so it must also be monitored in natural waters, seeking to avoid enriching these environments. As a way of evaluating the phosphorus load in a body of water, an adaptation of the empirical model of Vollenweider et al. (1998) according to Chapra (2008) is used:

$$V \frac{dP_h}{dt} = W - QP_h - k_s V P_h \quad (4.23)$$

where, V represents the volume of the numerical domain in (m^3), P_h the total phosphorus concentration ($mg.m^{-3}$), to time (years), W the total phosphorus load introduced into the domain ($mg.year^{-1}$), Q the discharge exported outside the domain ($m^3.year^{-1}$) and k_s the first order sedimentation coefficient ($year^{-1}$). According to Chapra (2008), the sedimentation coefficient can be approximated by:

$$k_s = \frac{10}{H} \quad (4.24)$$

4.2.3. Modeling system coupling

The three-dimensional modeling system TELEMAC3D + POLLUTANT TRANSPORT MODULE works in a coupled manner using a data feedback system so that the numerical simulation occurs simultaneously for both modules used in this work (Fig. 4.2).

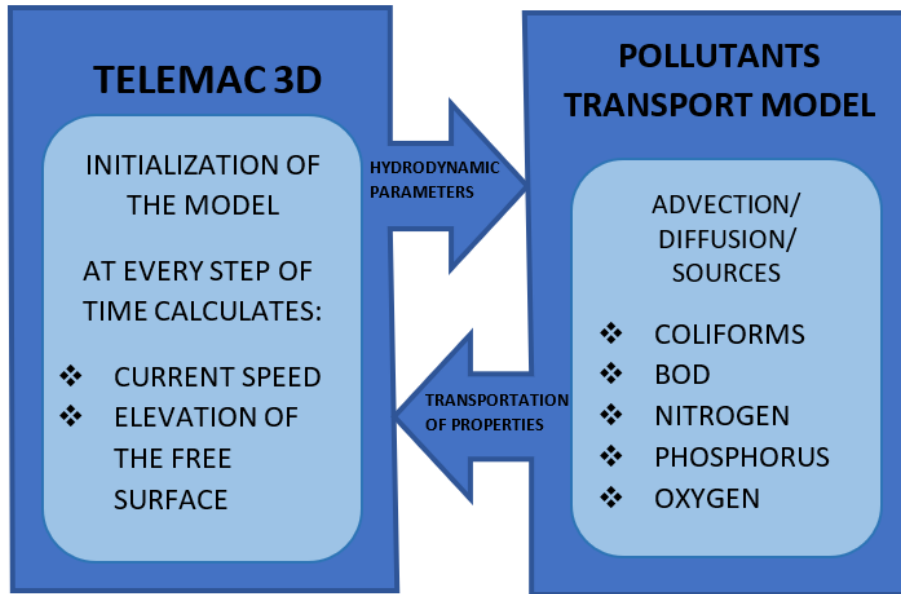


Figure 4.2 – System coupling

The TELEMAC3D model performs the simulation of the hydrodynamics of the environment based on the information of initial and contour conditions defined by the user. On the other hand, the pollutant transport module performs the transport, diffusion and decay simulation considering the different types of sources defined. These sources are: thermotolerant coliforms, carbonaceous BOD, which is the demand for oxygen to decompose organic matter, nitrogenous, BOD, which is the demand for dissolved oxygen due to the nitrification process, nitrification processes, the variation of the dissolved oxygen field in water as a function of carbonaceous BOD and nitrification, and the total phosphorus load imposed on the environment. The modeling system works in the form of a time loop with a defined time step common to both modules, so that the hydrodynamic and property transport processes are updated at each time step until the end of the numerical simulation.

4.3. Computational mesh

For the elaboration of the finite element mesh, software BlueKenue is used. This program is widely used for hydraulic modeling, allowing visualization and ease in handling georeferenced information and importing and exporting data in different formats.

The model generates triangular meshes specifying to the user line breaks and the possibility of manipulating points considered wrong within the study region. The procedure facilitates

adjustments to insert initial and boundary conditions. The density within the nodes is calculated based on information provided by the user, in wide formats. The software allows the extraction of time series at any point in the mesh within the domain analyzed by the model (Fig. 4.3).

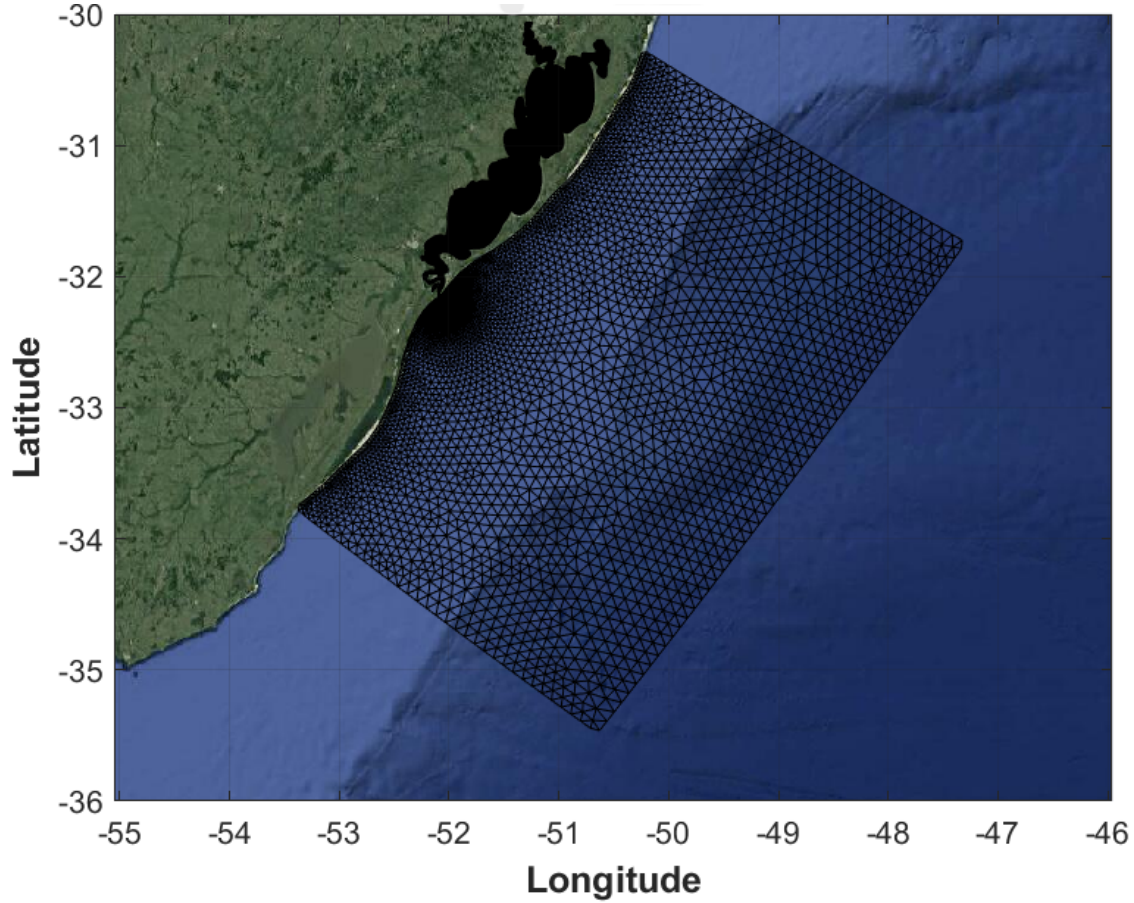


Figure 4.3 – Numerical domain.

To integrate the bathymetric data, the software Blue Kenue is used, generating a numerical grid of finite elements with the function *T3 Mesh Generator*, which allows the editing of lines and polygons to define the domains in the evaluated area.

In the process of creating the mesh, the aim is to intensify the refinement in regions considered shallower and a gradual reduction of this refining in the deeper portions of the complex, thus observing more coarse tendencies in these regions (Fig. 4.4). Specifically, in the present work, the constructed mesh has 49.353 nodes.

4.4. Initial and boundary condition

4.4.1. Hydrodynamic model

The data used as initial and boundary conditions were extracted from different sources for the model domain, and then interpolated and prescribed for each point on the finite element

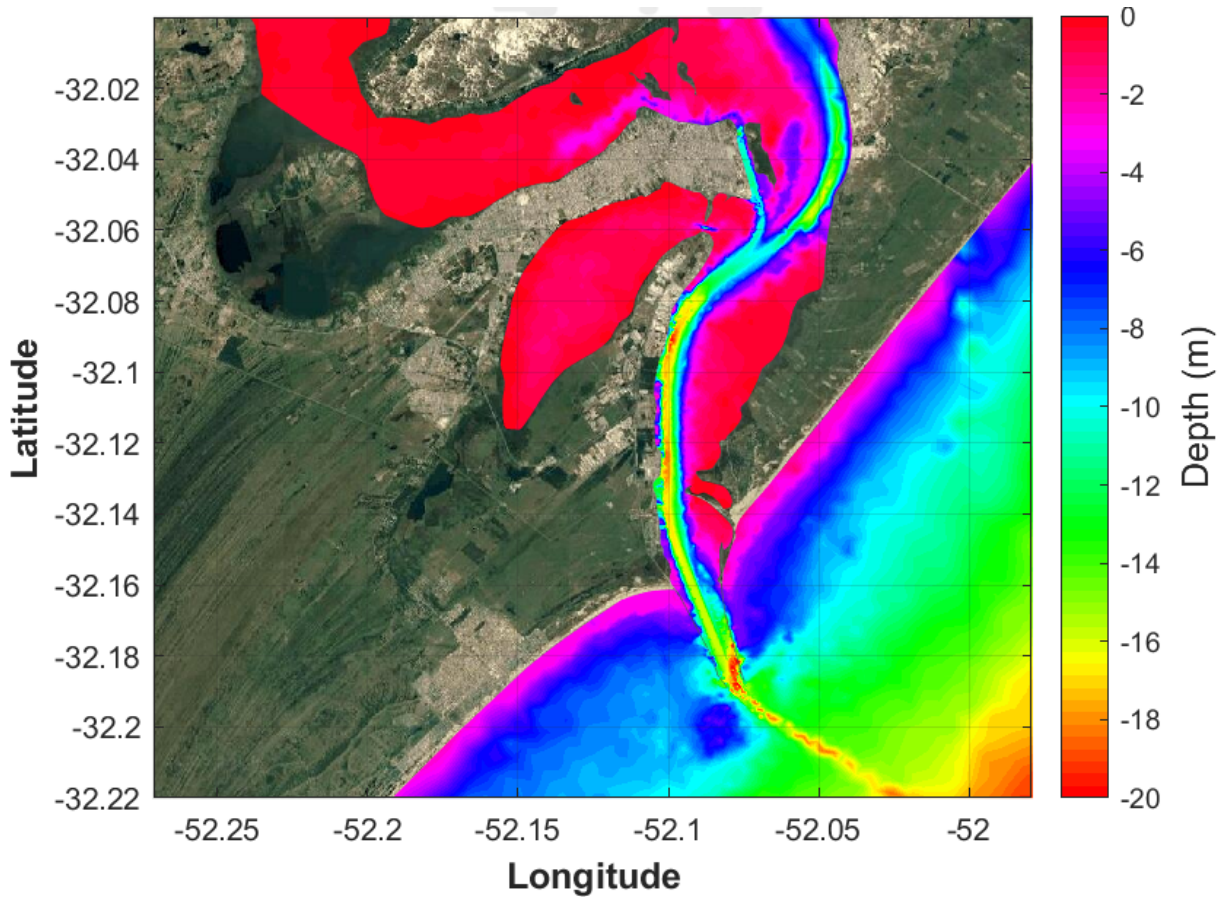


Figure 4.4 – Bathymetric estuary mesh

mesh. The data sources for the hydrodynamic model come from four different databases: global ocean circulation data from the HYCOM (HYbrid Coordinate OceanModel) model, global and atmospheric circulation data, from ERA-Interim Reanalysis, amplitude and phase data calculated by GrenobleModel FES2004 and river discharge data from the Guaíba and Camaquã rivers provided by the National Water Agency (ANA).

- HYCOM

The oceanographic data, represented by the components of current velocity, salinity and seawater temperature, used to define the initial conditions of the model, were obtained through the HYCOM model (Hybrid Coordinate Ocean Model), which is the set of multi-institutional efforts sponsored by the National Ocean Partnership Program (NOPP), as part of the Global Ocean Data Assimilation Experiment (GODAE), to develop and evaluate the isopycnal-sigma-pressure hybrid assimilation method. The spatial resolution of the data being used in the simulation is 0.083 (7 km) of latitude and longitude, with a time scale of 24 h.

- ERA-Interim

Available from 1979 to the present, ERA-Interim (Global Atmospheric Reanalysis) was developed by ECMWF (European Center for Medium-term Weather Forecasting), which provides daily and updated meteorological data for analysis and forecasting. Data as-

simulation systems use observations measured in situ, at land and sea stations, on board airplanes, probes, rockets and satellites, the majority of the data being obtained by the latter. These observations are combined with forecast models, through data assimilation systems, to provide various meteorological parameters (Reis, 2015). The spatial resolution of the data set is $0,125^\circ$ (approximately 14 km) (spectral T255) at 60 vertical levels of the surface up to 0,1 hPa (Berrisford et al., 2011).

- Fes

Under liquid boundary conditions, at the ocean boundary, tides are prescribed at each nodal point on that boundary using the amplitude and phase of each of the five major tidal components for the area (Fernandes et al., 2004), that is, the components K1, M2, N2, O1 and S2, obtained from the Grenoble Model (Model, 2004).

- ANA

In the liquid limit conditions, on the continental border, time series of river discharge from the Guaíba and Camaquã rivers, extracted from the ANA page, were prescribed for the year 2011. Data were obtained for fluviometric stations of these rivers in the form of measurements daily and linearly interpolated for each time step of the model. The discharge data from the São Gonçalo Canal were considered constant at $390 \text{ m}^3/\text{s}$ throughout the simulation, due to the lack of time series for this river (de Oliveira, 2012).

The acquired results form a set of information that considers the average of the daily data used as initial limit conditions and considers the seasonal cycles for the region, thus generating time series and average field information that address different parameters. In the study, the parameters used in the modeling system were salinity, temperature, currents, astronomical tides, air temperature, atmospheric pressure, and wind velocities.

4.4.2. Pollutant transport model

The data used as initial conditions for the pollutants module will be based on the concentration values indicated in Von Sperling (1996) and data taken by CORSAN, the table (4.1), describes the concentrations of the most representative parameters in domestic discharges.

Pollutant	Von Sperling (1996)	CORSAN (2018)
Coliforms	$5.10 \cdot 10^7$ NMP/100ml	7913739,13 NMP/100ml
BOD	300 mg/l	124.69mg/l
Organic nitrogen	20 mg N/l	-
Ammonium	25 mg $\text{NH}_3\text{-N}$ /l	38.09mg $\text{NH}_3\text{-N}$ /l
Nitrite	0	-
Nitrate	0	-
Oxygen	0	0
Phosphorus	7 mgP/l	5.30mgP/l

Table 4.1 – Physico-chemical concentrations of domestic wastewater

For all scenarios, a full year will be simulated. The chosen year was 2013, so all the initial

and limit conditions used will refer to this year. Other information inserted into the model for initialization can be seen in Table 4.2

Configuration Telemac-3D	Simulation 1, 2 and 3
Simulation Period	2011, 2010, 2013 and 2015
Saving results	24 h
Parallelism	90
Time step	90
Save step	Daily
Geographic projection	WGS-84
Coriolis coefficient	-7.70735×10^{-5}
Horizontal turbulence model	$k - \varepsilon$
Vertical turbulence model	$k - \varepsilon$
Bottom friction law	Manning
Lateral friction law	No friction
Tidal Flats	Yes
Sigma levels	15
Wind influence coefficient	5×10^{-6}

Table 4.2 – Parameterization

4.5. Modeling system validation

As a way of evaluating the quality of the results of the hydrodynamic model, validation was performed through the comparison between the data observed in the field and those simulated by TELEMAC-3D. The validation was based on the work of Marques et al. (2009), Marques et al. (2011), and Marques et al. (2017)

The hydrodynamic simulation used to validate the results was carried out during 365 days, from 01/01/2011 to 12/31/2011. The results obtained were compared with the observations of the current velocities, salinity and temperature measured in the access channel to Patos lagoon, in the Piloting Station "Practicagem", Fig.4.5 for the period from 06/01/2011 to 12/15/2011.

The practicagem data was obtained with a Doppler-ADCP acoustic current processor placed in the navigation channel anchored at a depth of 12 m. The salinity data were obtained using a conductivity and temperature (CT) sensor placed at the same point of the navigation channel, at a depth of 3 m.

To evaluate the presented comparisons, performance indicators were used, as in Sutherland et al. (2004), Marques et al. (2017), and Oleinik et al. (2017). The performance indicators used are:

- Root of the Mean Quadratic Error (RMSE): used to express the precision of the numerical results, where the RMSE presents error values in the same dimensions of the analyzed variables (Fox, 1980);
- Mean Absolute Error (MAE): because it is less affected by points with anomalously extreme values (outliers), the MAE is considered accurate and robust as a measure of the

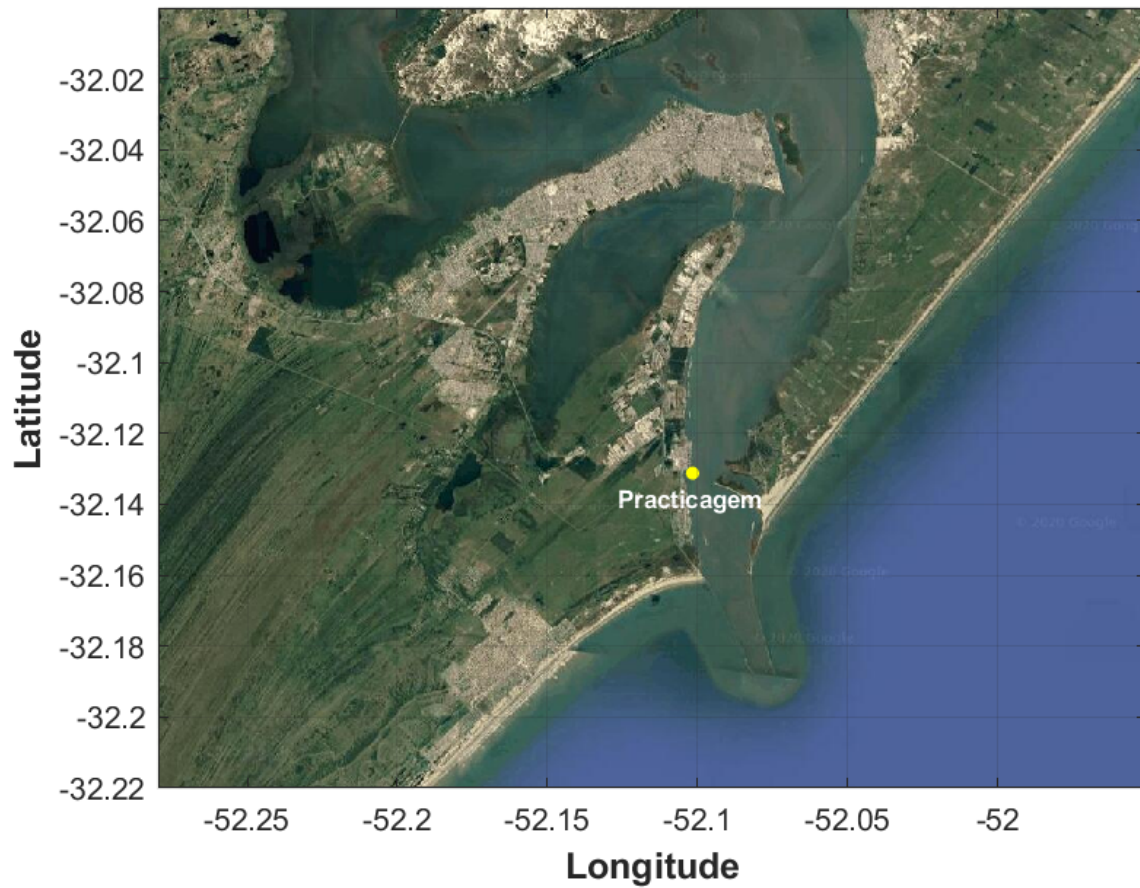


Figure 4.5 – Equipment Position: Point indicates the position of the ADCP on the access channel to Lagoa dos Patos

ability of numerical models to reproduce reality (Fox, 1980);

- Variance Relationship (RVAR): lists the model and the observation indicating overestimation or underestimation.

5. RESULTS AND DISCUSSION

This section presents the results of the model validation analysis, then the study case scenarios that were carried out according to the methodology description.

5.1. Modeling system validation

Current data were obtained with a Doppler-ADCP acoustic current processor placed in the navigation channel anchored at a depth of 12 m. The salinity data were obtained using a conductivity and temperature (CT) sensor placed at the same point of the navigation channel, at a depth of 3 m. Figure 5.1 shows the comparisons between time series with observed data (OD) and calculated data (CD), obtained by numerical simulation.

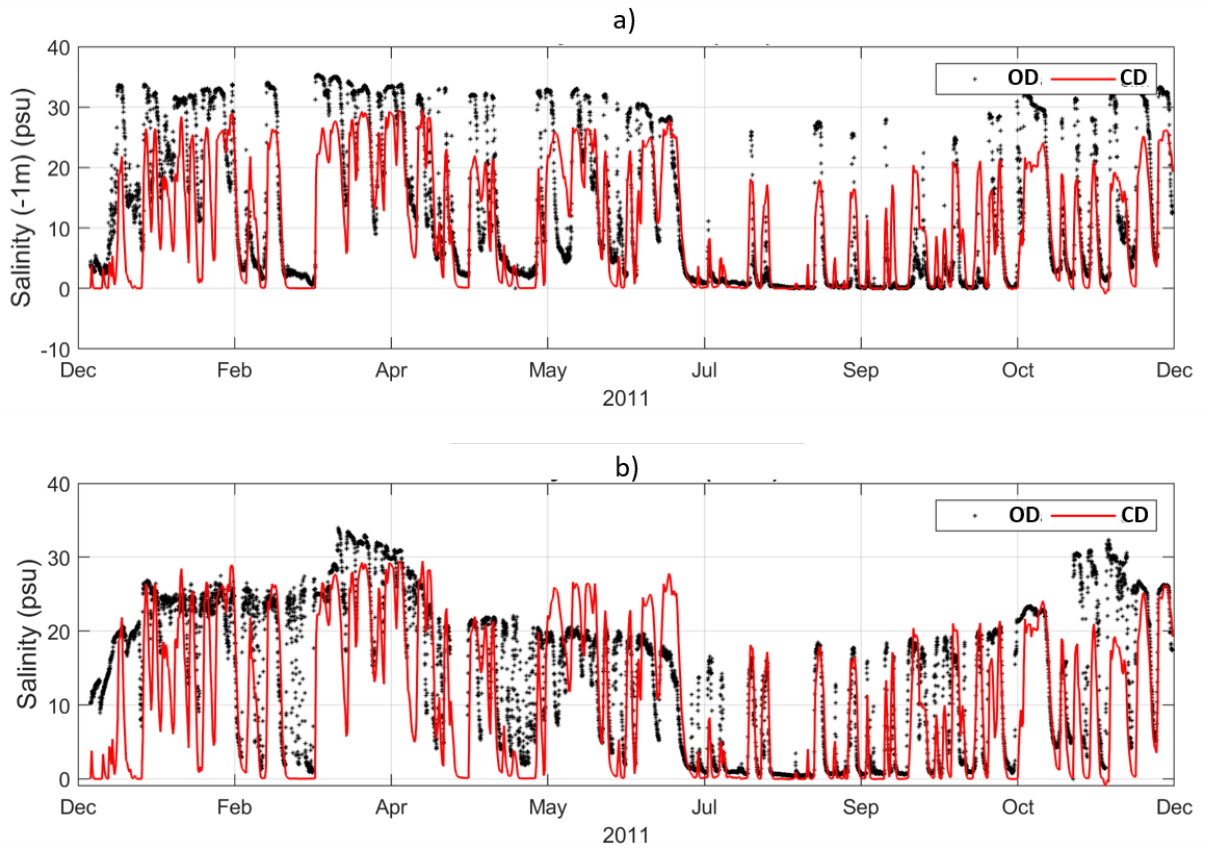


Figure 5.1 – Salinity validation. a) 1 m depth b) 10 m depth

Comparison between the calculated and observed salinity time series at 1m and 10m depth indicates that the model can reproduce trends in salinity field data in the estuary channel. Likewise, the comparison between the observed current velocity time series and those calculated by the model also indicates that it can reproduce the trends of the velocity signal in the Patos lagoon channel (Figs. 5.2, 5.3 and 5.4).

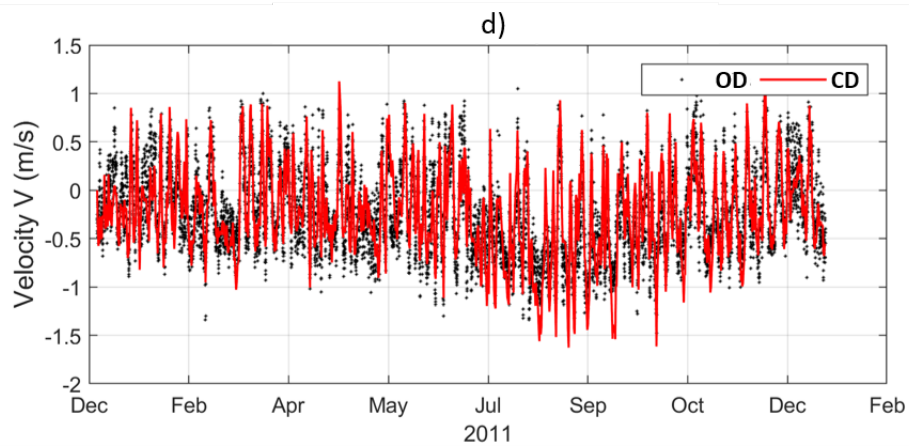
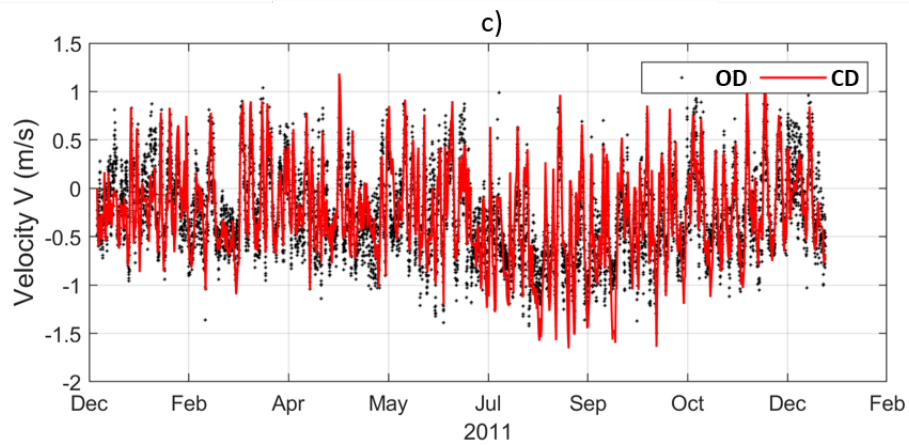
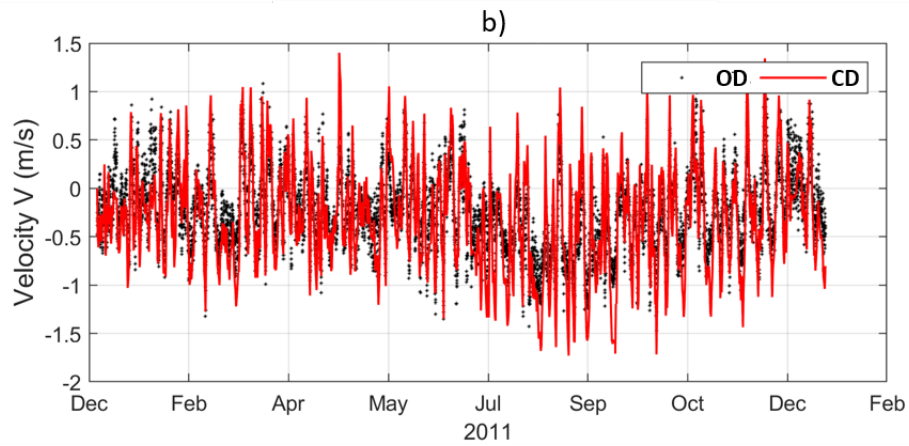
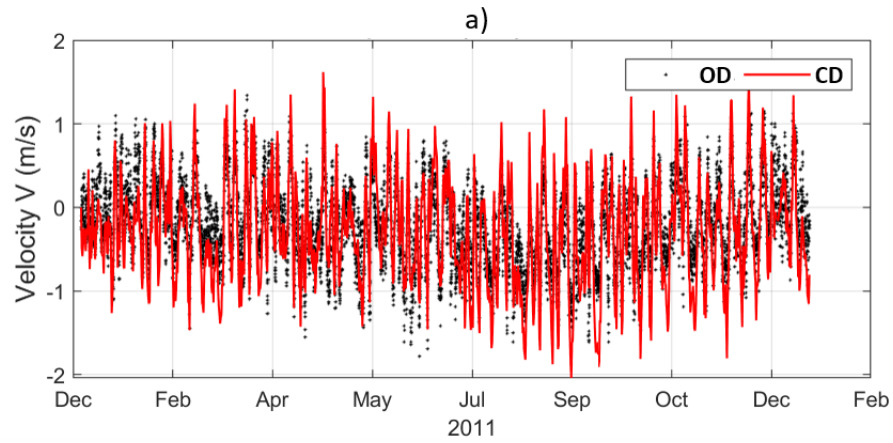


Figure 5.2 – Velocity Validation a)at 0m depth b)at -1m depth c)at -3m depth d)at -4m depth

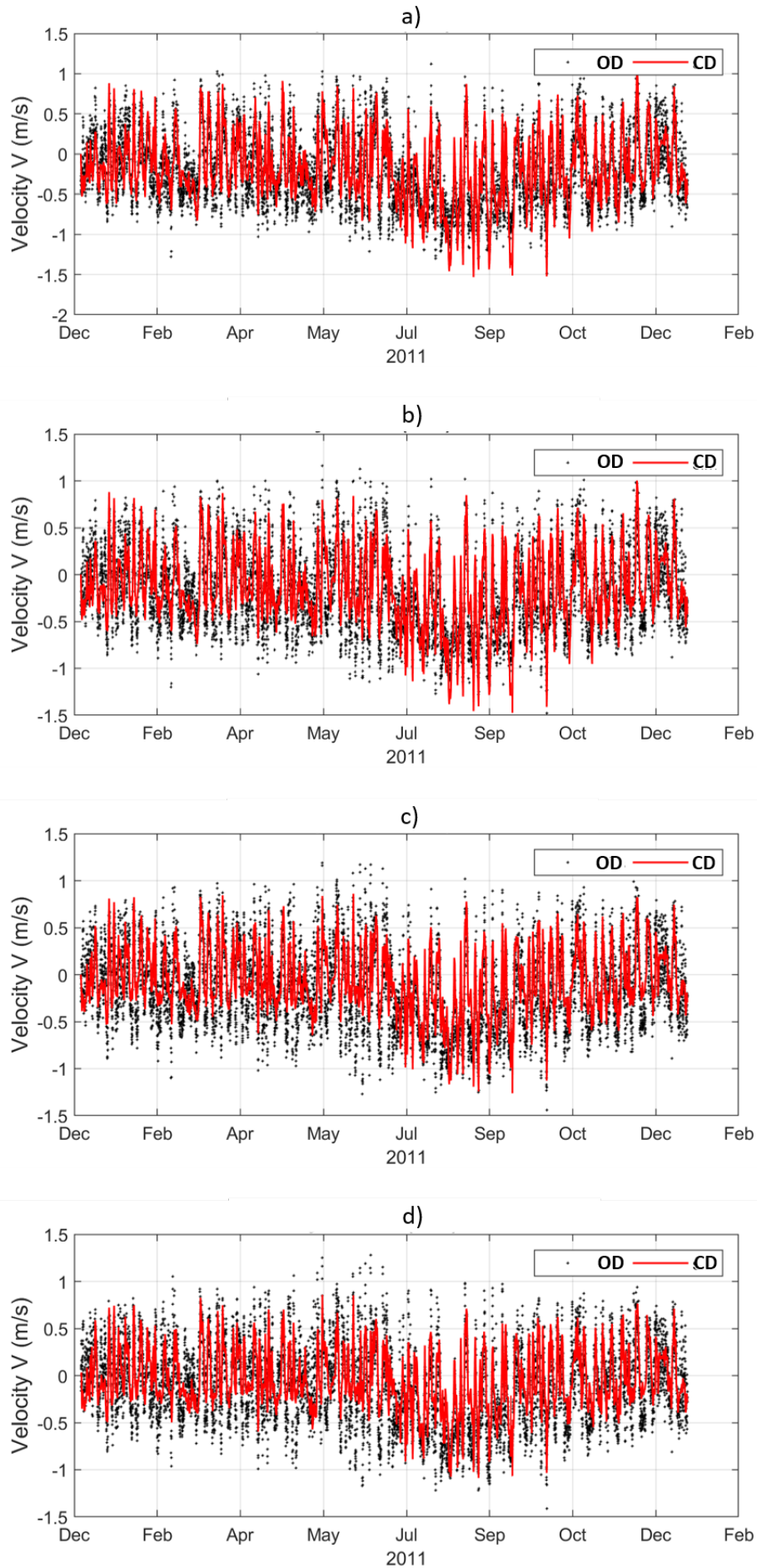


Figure 5.3 – Velocity Validation a) at -6m depth b) at -7m depth c) at -9m depth d) at -10m depth

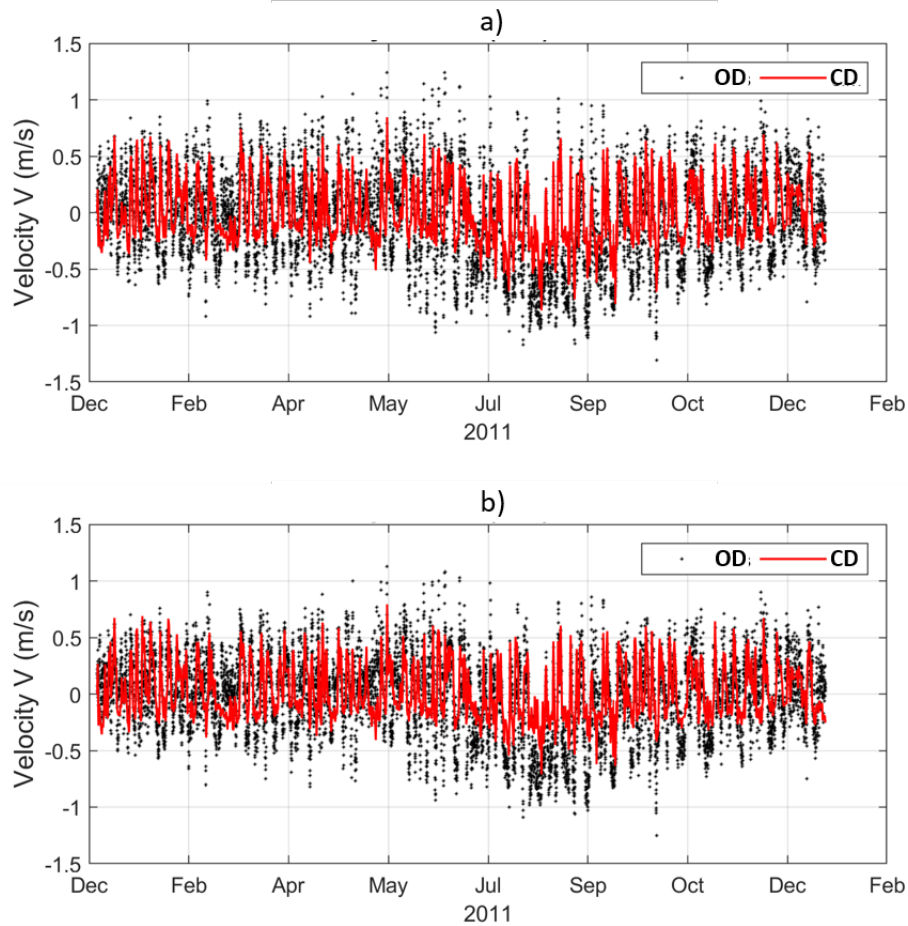


Figure 5.4 – Velocity Validation a)at -12 m depth b)at -13m depth

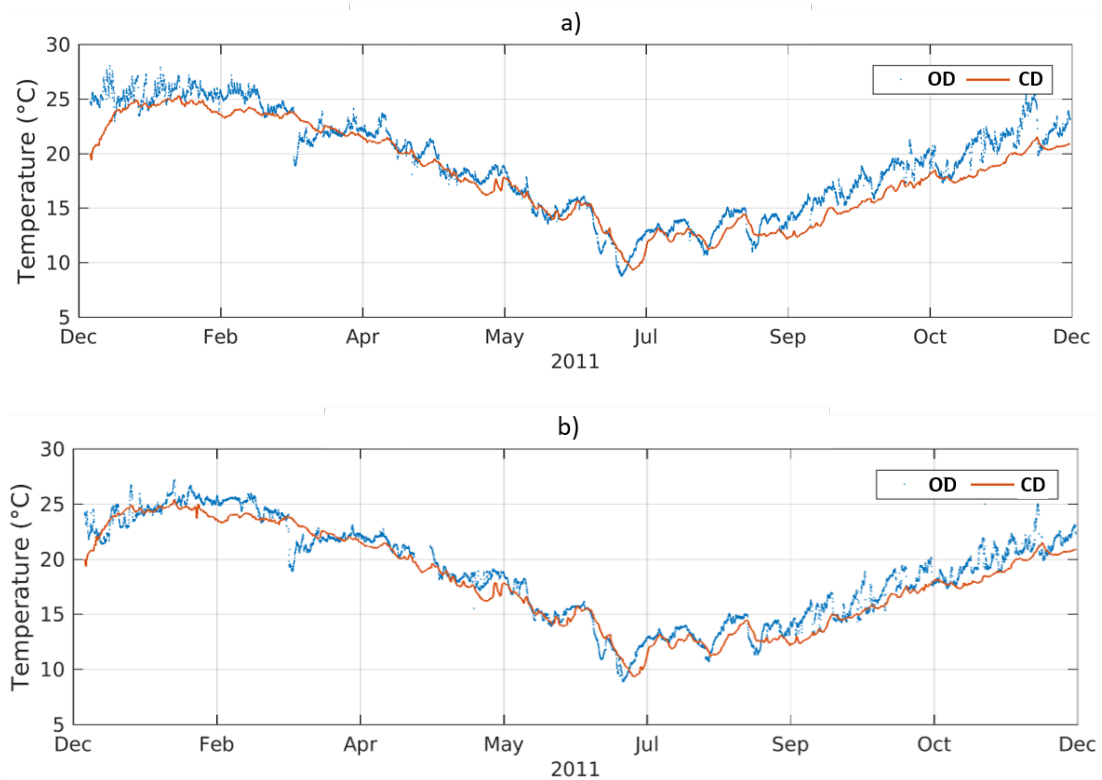


Figure 5.5 – Temperature Validation a)at -1 m depth b)at -10m depth

For salinity, temperature and current velocity, it is possible to observe some differences between the observed and calculated data (see fig. 5.1, 5.2, 5.3, 5.4 and 5.5). This underestimation of the calculated time series, according to Marques et al. (2017), may be related to the use of a constant spatial influence coefficient of the wind, the absence of wind-generated waves in hydrodynamics or due to the use of data sets with low-spatial-temporal resolution reanalysis. Ruti et al. (2008) attributed the low spatial resolution of the reanalysis data as the main source of errors in a comparison with the wind fields analyzed over the Mediterranean basin.

According to Table 5.1 and 5.2, it is possible to observe that for both salinity and velocity, the means between the observed and modeled data were very close. Temperature has a greater variation between observed and simulated data.

The standard deviation, which represents the measure of dispersion around the average, also presented close values, between observed and modeled, however, it is worth mentioning that the salinity values are high, due to the great variation that occurs within the lagoon. Between the periods of entry and exit of seawater, between the processes of flood and ebb, resulting in periods of high and low salinity interspersed. Therefore, the salinity values are well distributed around the average. As for velocity, since it does not present large variations, the opposite occurs, they are more condensed around it. Both the RMSE and MAE for salinity and velocity are within the expected value ranges and are consistent with the results obtained by Marques et al. (2017), Oleinik et al. (2017), and Leal et al. (2019).

Variance is a measure of dispersion that shows how far apart the mean values are, so if RVAR equals 1, it means that both data, observed and modeled, have the same distance relationship between the means. Therefore, the RVAR values demonstrate that the variance of the observed data is greater than the variance of the modeled data, and the reverse is also true for salinity and velocity, respectively. For both salinity and velocity, the RVAR values were satisfactory, close to, the temperature indicates that there is still a difference in values between simulated and observed.

	Sal1m	Sal10m
MAE	5.57	6.02
RMSE	7.51	8.66
RVAR	0.61	1.01
Coef	0.83	0.68

Table 5.1 – Salinity statistics of hydrodynamic simulations.

	-13m	-12m	-10m	-9m	-7m	-6m	-4m	-3m	-1m	0m
MAE	0.238	0.248	0.245	0.242	0.238	0.239	0.246	0.252	0.271	0.356
RMSE	0.291	0.306	0.306	0.303	0.299	0.299	0.309	0.317	0.341	0.432
RVAR	0.436	0.437	0.581	0.649	0.834	0.931	1.120	1.203	1.874	1.621
Coef	0.586	0.643	0.695	0.726	0.748	0.758	0.763	0.764	0.789	0.747

Table 5.2 – Velocity statistics of hydrodynamic simulations.

The analysis of the results indicates that, even with the limitation of the observed data used, the model presented good reproducibility for salinity and current velocity, compared to observations in the channel of the Patos lagoon estuary. Therefore, it is possible to use the model to evaluate the influence of the hydrodynamics of the region with respect to the effluent contamination in the study region, since the contaminants are intrinsically associated with the dynamics of the region defended and diffused by the dominant processes in the hydrodynamics of the study region.

5.2. Hydrodynamic analysis in the years 2010, 2013 and 2015

Aiming to understand the dominant processes in the dispersion of contaminants. For the hydrodynamic study of the Patos lagoon estuary, the analysis was carried out at 4 points, which were identified in strategic sectors in order to observe the behavior of the estuary in different sectors 5.6).

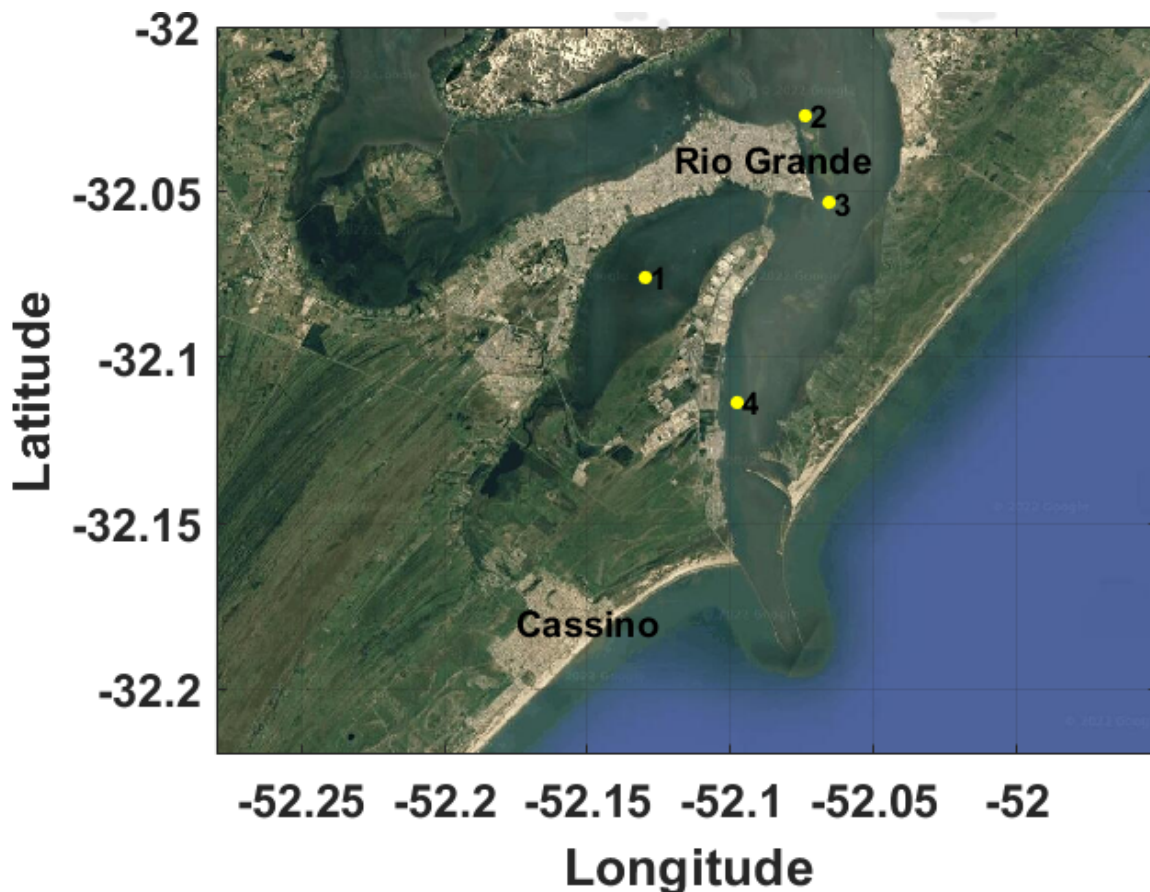


Figure 5.6 – Study points in the Patos Lagoon estuary

At the same time, for the hydrodynamic analysis of the sector under study, it is important to analyze the discharges, which, according to what is stated in the boundary conditions section, consider 3 rivers that enter in the Patos lagoon with different flows during the year. These discharges in the different years were taken from the Agência Nacional de Águas (ANA) web.

The data was obtained for fluviometric stations of these rivers. The São Gonçalo channel discharge data was considered constant at $760 \text{ m}^3/\text{s}$ throughout the simulation Oleinik et al. (2017).

Making a comparison of the 3 years that were simulated, the discharges of these rivers become important to be able to identify the trend of rainfall in the sector and the intensities in the different years. In the Guíba River, it was possible to identify that in 2010, the discharges are constant during the months of January to October with flows that vary from 1000 to 6000 m^3/s . In the months of October to December there is evidence of a decrease in discharge from 500 to 1000 m^3/s . In 2013, it was identified that there are discharges that vary from 1,000 to 2,000 m^3/s between the months of January to July and a variation of 1,000 to 7,000 m^3/s from July to December. Finally, in 2015, a variation from January to June of 1,000 to 4,000 m^3/s was identified, and in the months of July to December discharges reached up to 11,000 m^3/s .

In the Camaquã river, it was evidenced that the discharges have a similar trend in the years 2010 and 2015, in which there are low discharges in the months of January to June and in the year 2015 between the months of June to July the discharges vary from 200 at 3000 m^3/s ; In 2010 discharges vary between the months of July to September with flows of 200 to 3000 m^3/s . In 2013 it was evidenced that there are discharges that reach 2300 m^3/s between the months of October to November and in the rest of the year the discharges are low, ranging from 0 to 500 m^3/s .

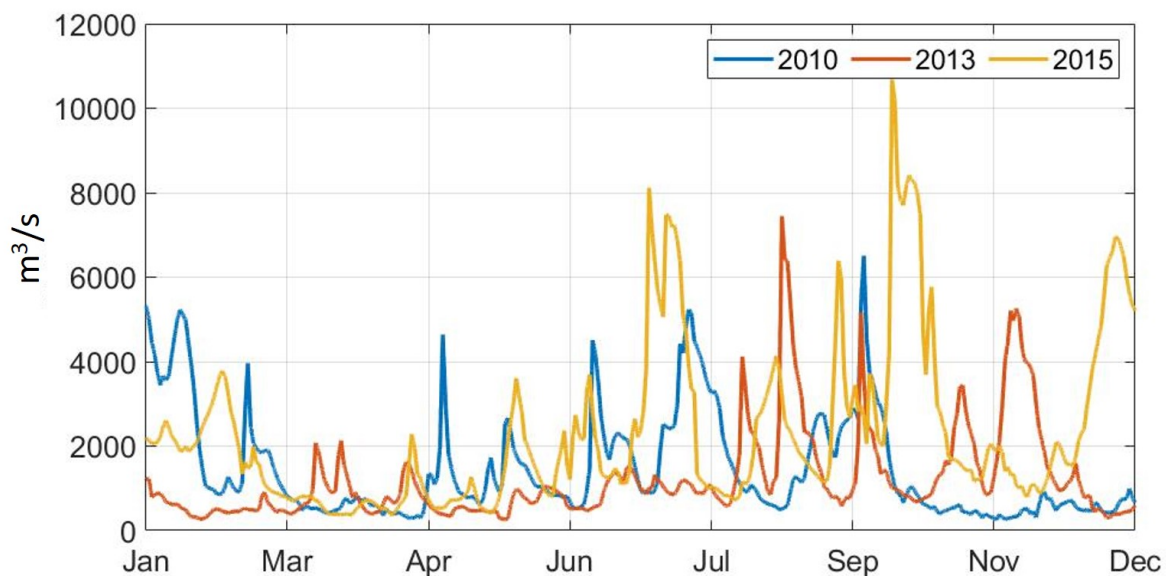


Figure 5.7 – Time series of Guaíba river discharges during the years 2010, 2013 and 2015.

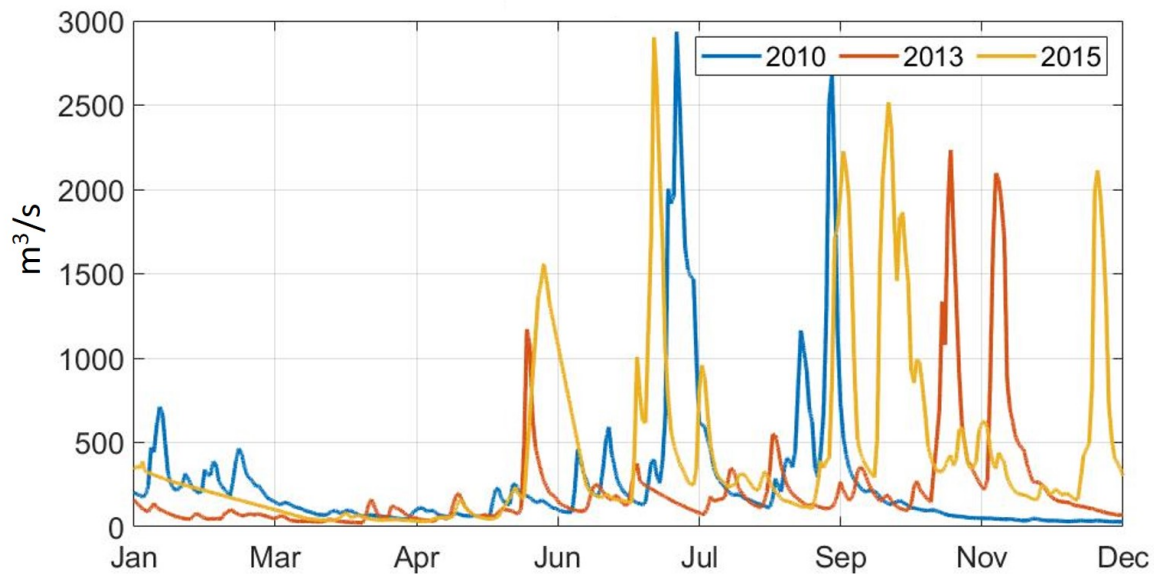


Figure 5.8 – Time series of Camaquã river discharges during the years 2010, 2013 and 2015.

This analysis of discharges allows us to observe that in the different simulation years there were different behaviors of discharges in the rivers.

The variation of the wind in the study region is represented by the figure of intensity and direction of the wind, which was determined for the 4 study points in the 3 years of analysis (Fig. 5.9), with a minimum scale of 0 - 2 m/s and maximum scale greater than 10 m/s, which vary in all quadrants, however, the predominance in the northeast direction is evident. In the same graph it can be seen that in the course of the years 2010, 2013, and 2015, the direction in the northeast quadrant varies minimally, being that in the year 2010 the intensities reach 12 m/s and there is a distribution of the intensity of wider wind in the northeast quadrant that can be identified from the east to northeast direction. In 2013, the average wind intensity reaches 10 m/s, in a northeasterly direction. And in 2015, the intensity of the wind reaches 8 m/s with a punctual direction to the northeast (Fig. 5.9).

According to Machado et al. (2010) the variability of wind direction in all the quadrants of the southern region of Brazil is due to the geographical position, which is associated with extra tropical and inter tropical cyclones.

Fernandes et al. (2007) affirm that the response to the action of the local wind covering the instantaneous area is much more important for the internal circulation where the circulation from one end to the other controls the oxygenation and resuspension of sediments and nutrients according to the direction of the wind. The combined action of internal circulation and exchanges between the Saco da Mangueira and the main access channel prevents the occurrence of anoxic conditions.

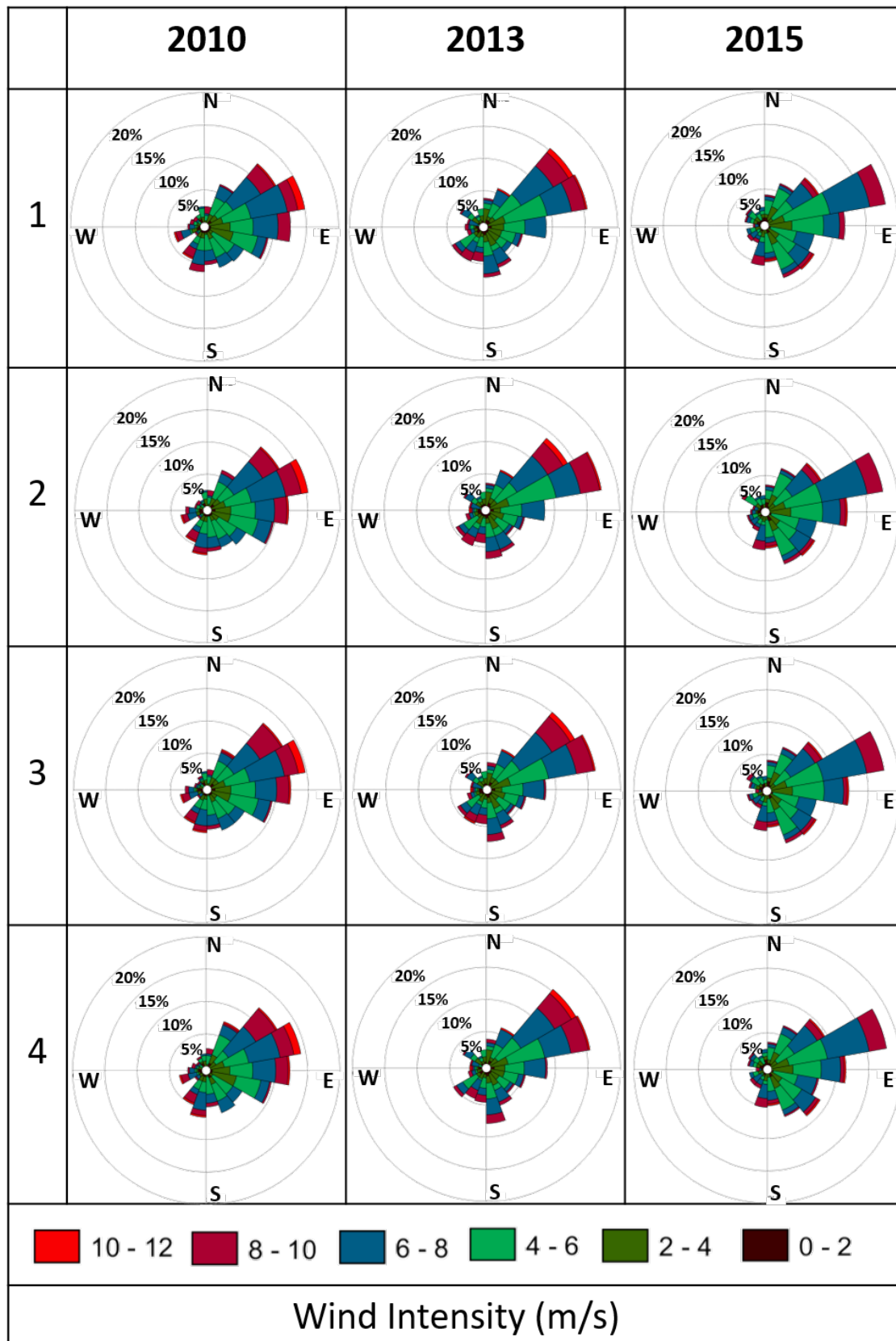


Figure 5.9 – Average wind variation in the 4 study points in the 2010, 2013 and 2015 administrations. 1) North of the port of Rio Grande. 2) South of the port of Rio Grande. 3) Estuary channel. 4) Saco of Mangueira.

In relation to the saline structure of the Patos lagoon, according to Moller et al. (1996) and Moller et al. (2001), it is related to the combination of the local and non-local action of the wind, since it is the main mechanism for introducing salt into the estuary.

For the hydrodynamic analysis, the salinity at the entrance of the Barra breakwaters was compared (5.10), which describes the constant saline intrusion and outflow throughout the year. Fig. 5.10a describes the saline ingress in the Saco da Mangueira of 2-6 salinity for the year 2013. For the year 2010, the saline ingress is constant throughout the year, maintaining a salinity of 1-2. For the year 2015, fresh water is identified for the months of October to January. Greater saline contributions are identified in the months of March to July, especially in the month of May for the year 2013,

In the study points near the city of Rio Grande, the same constant entry and exit behavior is identified throughout the year.

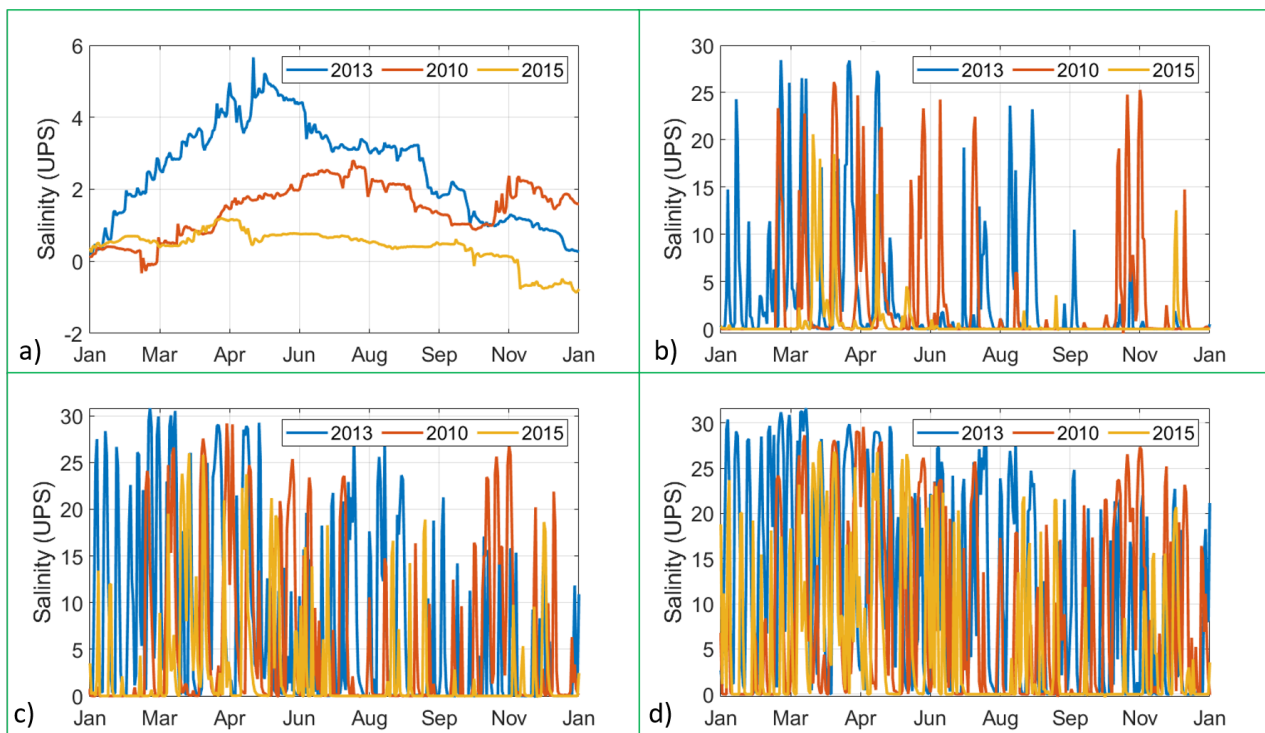


Figure 5.10 – Salinity time series for the years 2010, 2013 and 2015: a) Point 1, b) Point 2, c) Point 3, and d) Point 4

The comparison of the intensity of the wind in different months of the year was made (see Fig. 5.11). The months of April, June, September and November were taken into account, since they were identified with a variation and similarity in the salinity analysis. It was identified that the intensity of the wind varies from 0 to 2.5 m/s and that there is a greater variation in the month of June, since for the years 2010 and 2013 the intensity decreases radically. At the same time, the wind direction was identified for the average mean of the month of June for the year 2013, a direction to the southeast, contrary to that of the year 2015 that has a north-west direction.

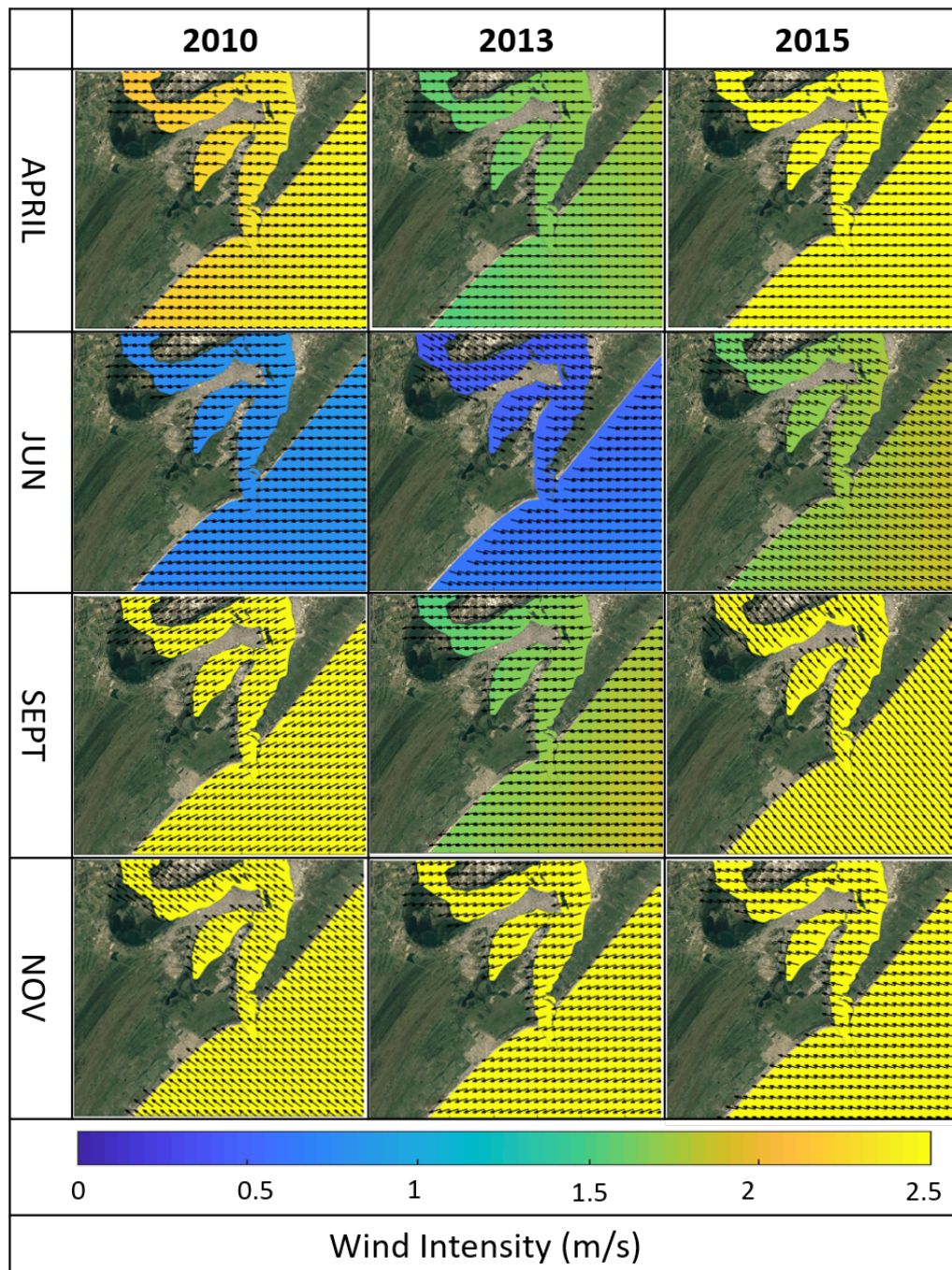


Figure 5.11 – Wind intensity in the months of April, June, September, and November for the years 2010, 2013, and 2015.

Regarding salinity, the comparison of the average was made in the months of April, June, September and November, in which a greater saline intrusion was identified in the month of April for the year 2010, for the month of June in 2015 a decrease in saline intrusion and in the month of November a greater saline intrusion for the year 2010 (see Fig. 5.12).

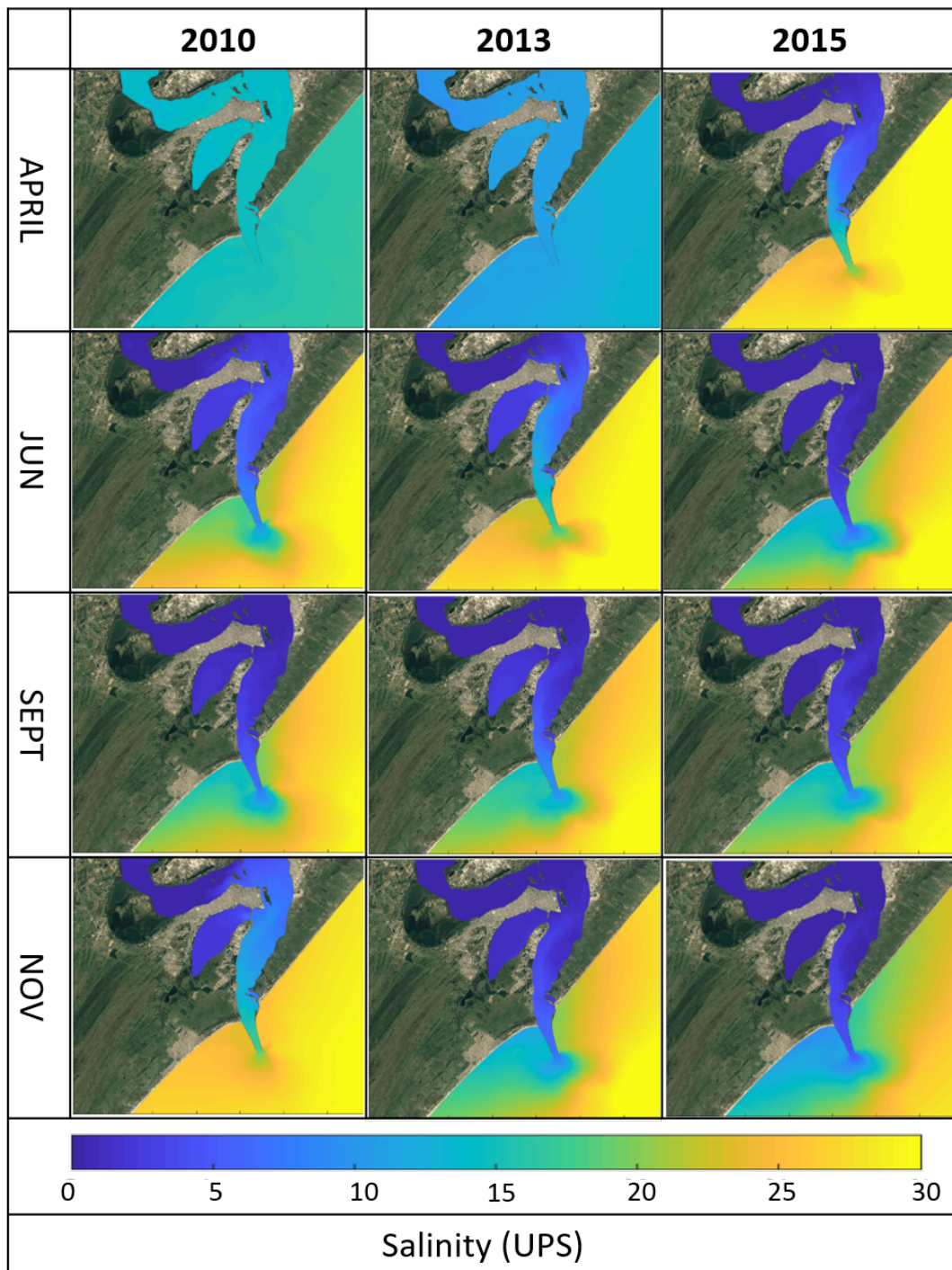


Figure 5.12 – Salinity in the months of April, June, September, and November for the years 2010, 2013, and 2015.

For the study of the intensity of the current, the annual average analysis was carried out in the 4 study points for the 3 years (2010, 2013, and 2015). Figure 5.13 and Figure 5.14 describes similar trends in the 3 years of study, with current intensities that vary up to 0.0125 m/s. Figure 5.14 shows that the intensity of the current has a greater magnitude in the year 2015 for the months of April, June and November. For the month of September, it was possible to identify that in 2010 there is a greater intensity of the current.

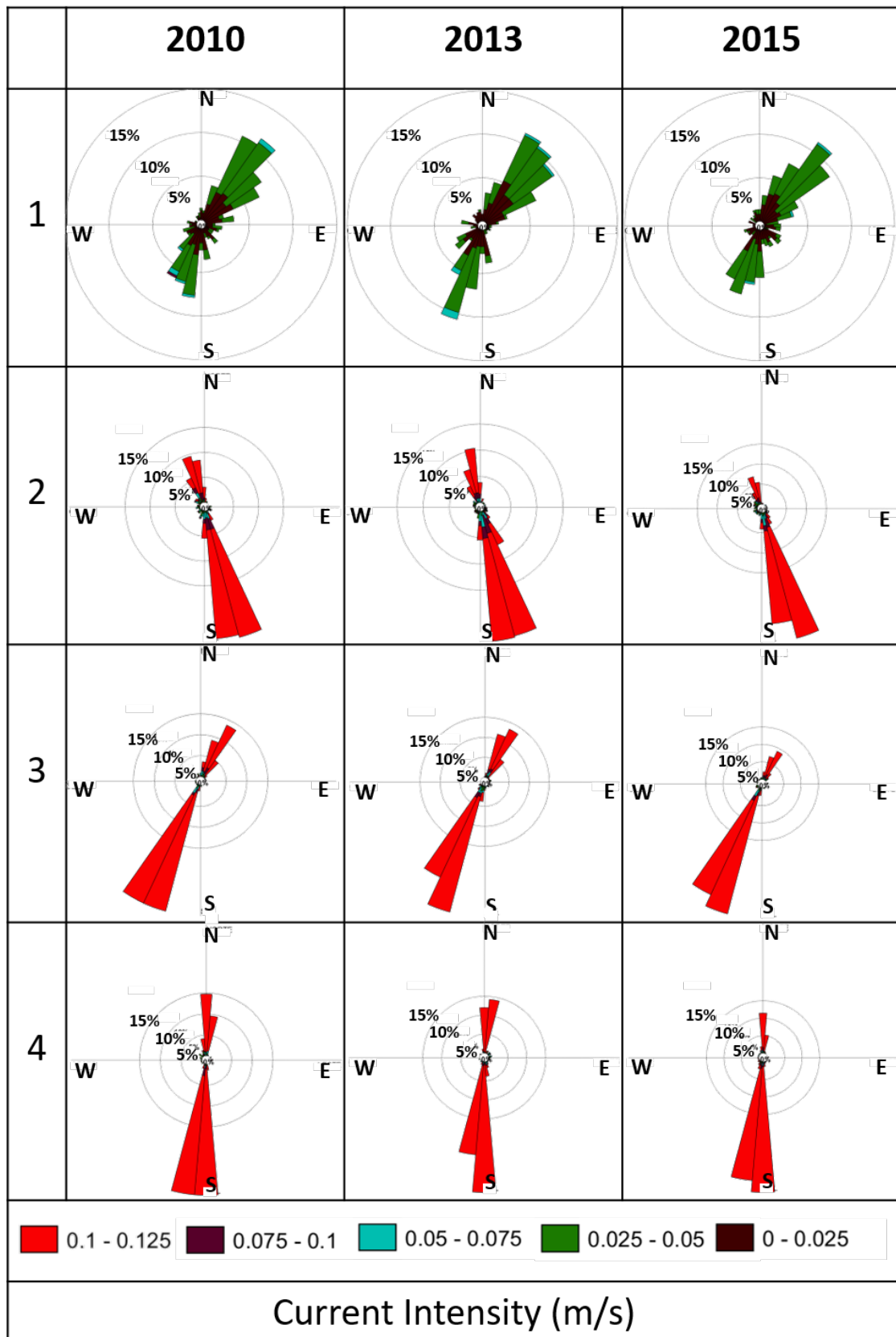


Figure 5.13 – Average current intensity at the 4 study points in the 2010, 2013 and 2015 administrations. 1) North of the port of Rio Grande. 2) South of the port of Rio Grande. 3) Estuary channel. 4) Saco da Mangueira.

Monteiro et al. (2006); Moller et al. (1996, 2001); Fernandes et al. (2002) state that due to the hydrodynamics of the lower estuary, it is controlled by the non-local wind, which has a direct effect on the Saco da Mangueira.

Regarding the temperature analysis, Fig. 5.15 describes its variation on a 17-25 degree scale. It is evident that in the month of April in the year 2015 there is a greater variation with respect to the years 2010 and 2013.

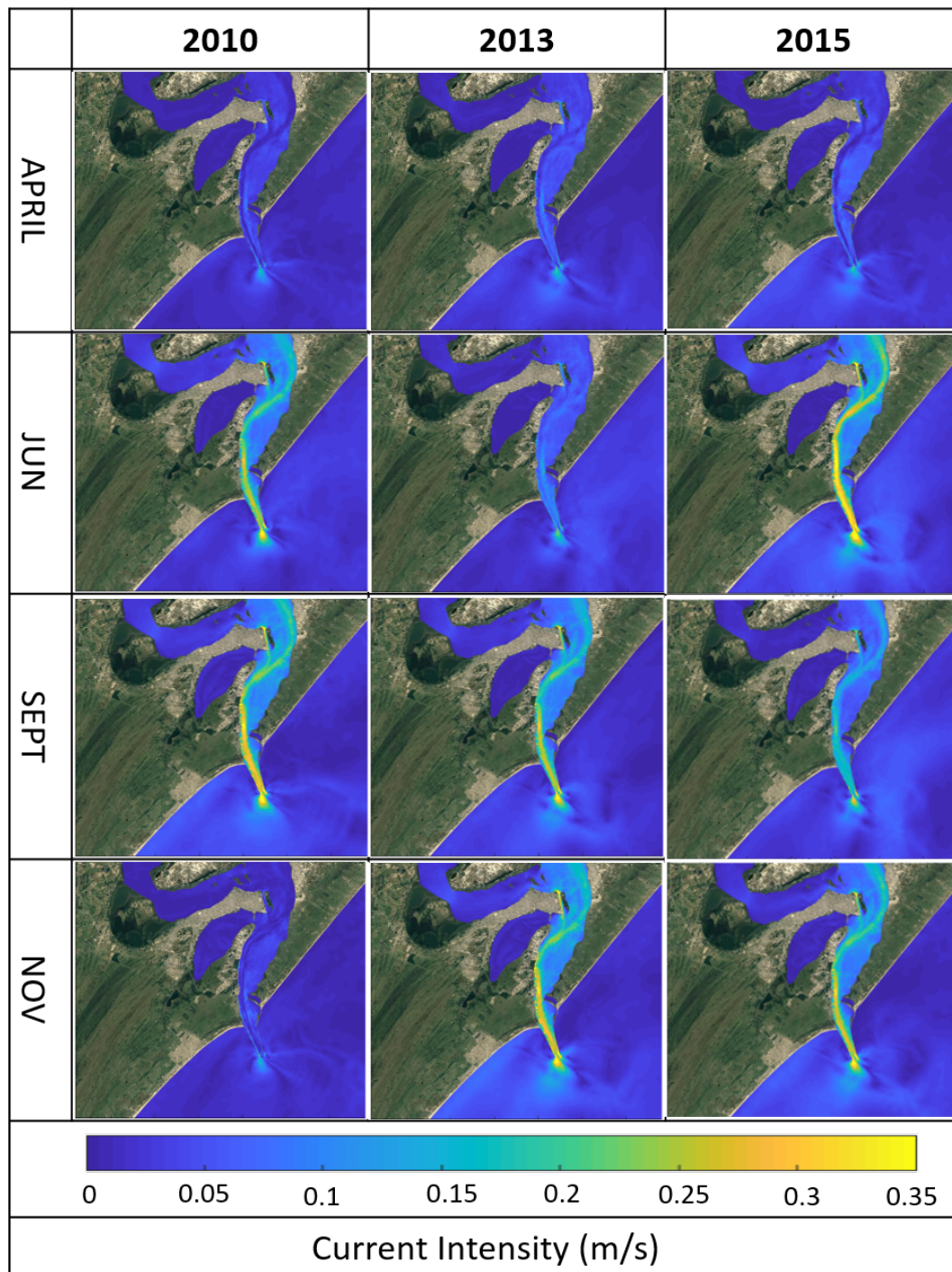


Figure 5.14 – Intensity average of the current in the months of April, June, September and November for the years 2010, 2013 and 2015.

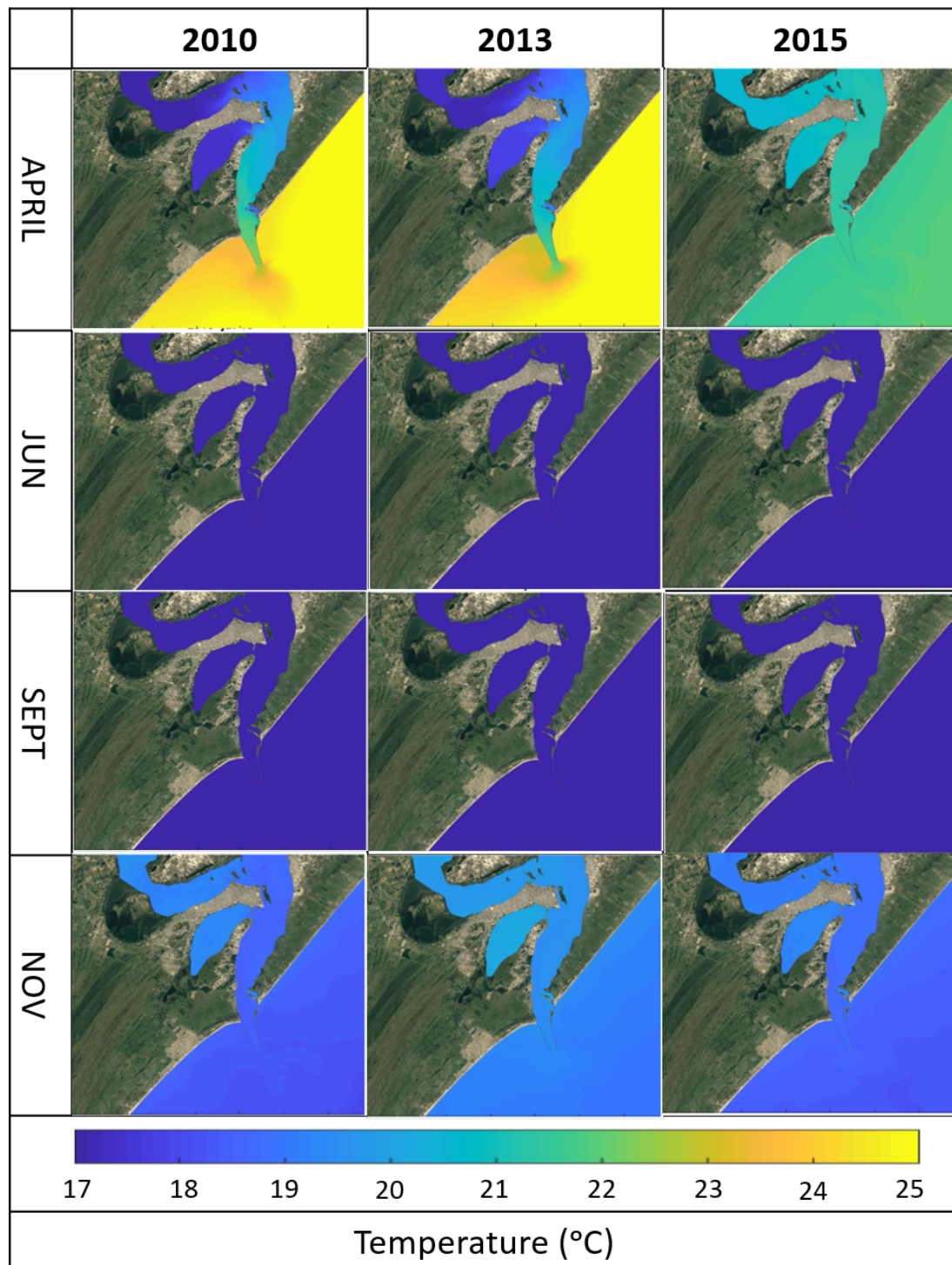


Figure 5.15 – Temperature in the months of April, June, September, and November for the years 2010, 2013, and 2015.

Through the analysis of the time series of temperature in the 4 study points (see Fig. 5.15), it is evident that the trend is usually the same, that is, with lower temperatures for the months of May to September. Figure 5.16 describes that, in the year 2015 for the 4 study points, there is a rise in temperature for the month of August, reaching a temperature of 20 °C, which in the years 2010 and 2013 reach 10 °C. At the same time, it is identified that in Saco da Mangueira

the oscillations of temperature change are greater during the year (Fig.5.16).

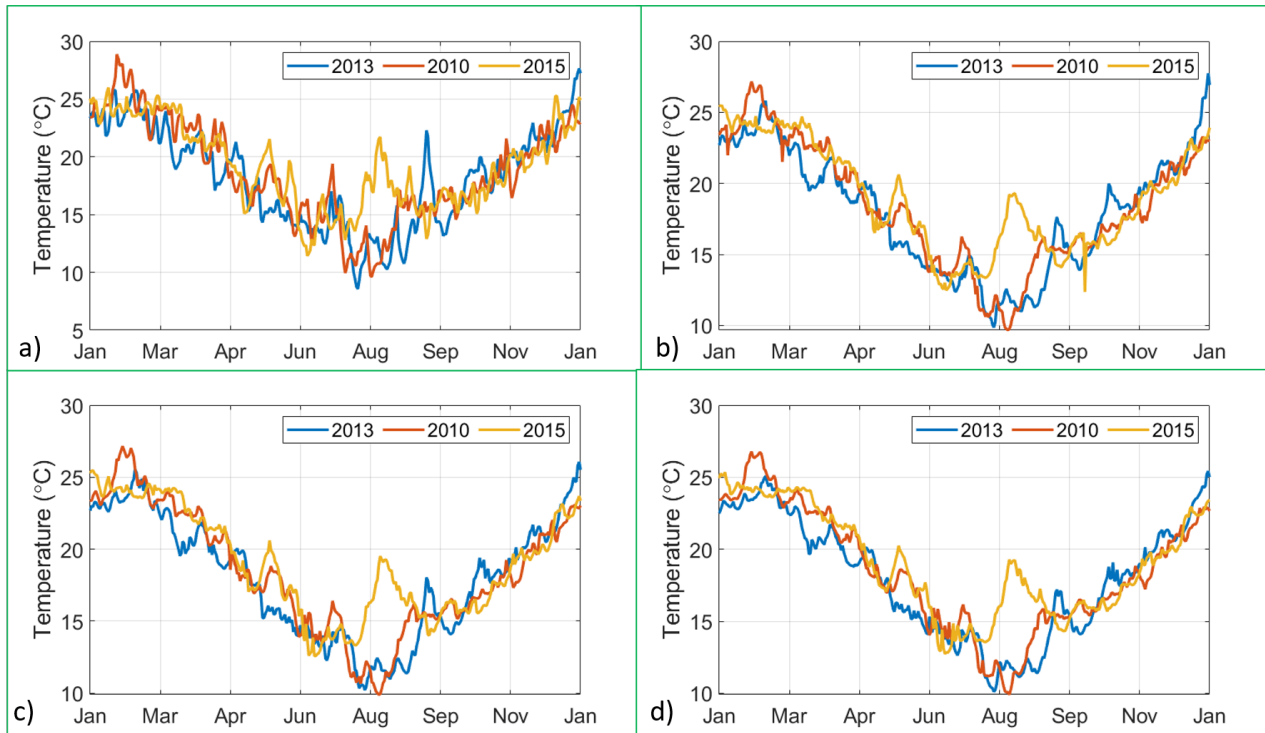


Figure 5.16 – Temporal time series for the years 2010, 2013, and 2015: a) Point 1, b) Point 2, c) Point 3, and d) Point 4.

The elevation of the surface (Fig. 5.17) was analyzed in the months of April, June, September and November, in which it is identified that in 2015 there is a greater elevation of the free surface, reaching values at 1.5 m in the estuary, especially in the months of June to November, with respect to the years 2010 and 2013. It is evident that in the month of April the behavior of the free surface is maintained with an average value of 1 m.

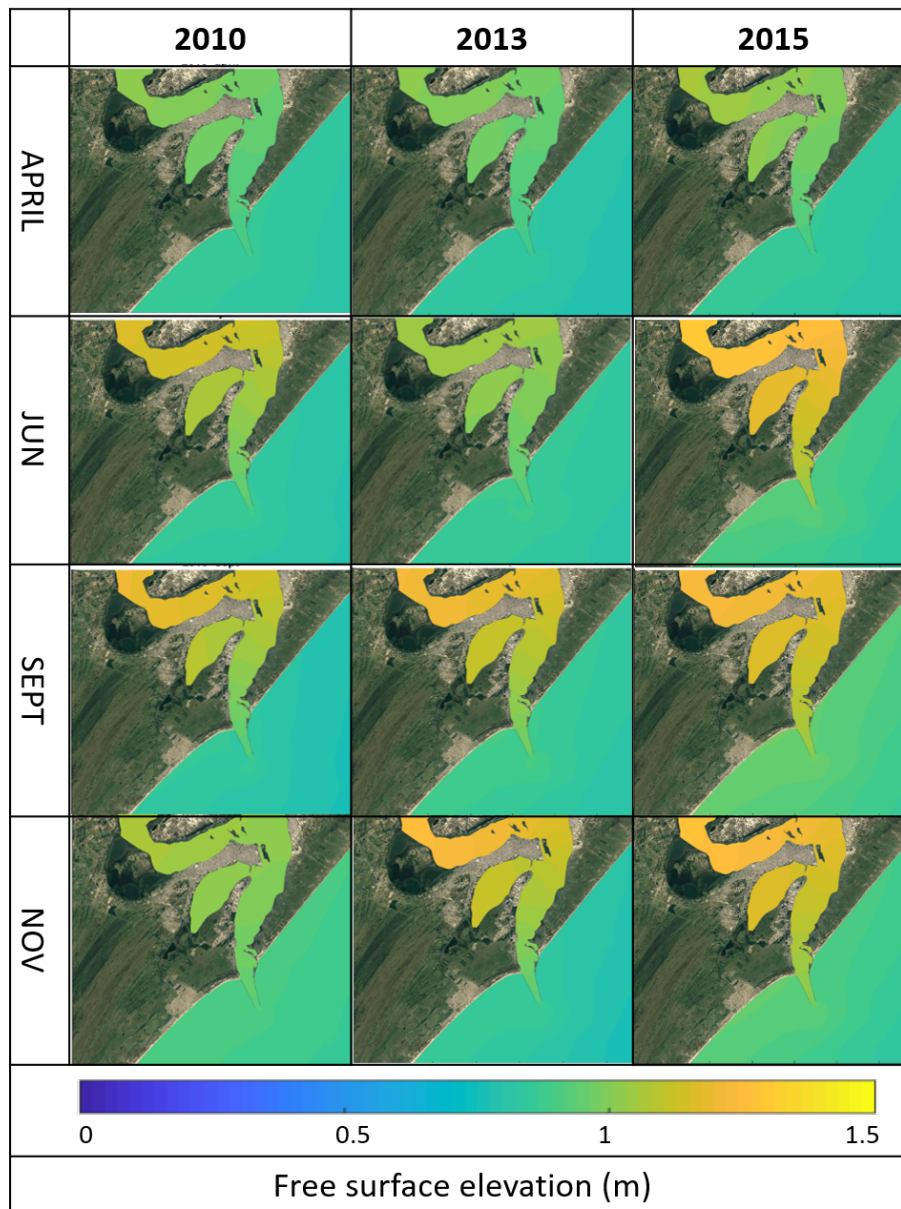


Figure 5.17 – Free surface elevation in the months of April, June, September, and November for the years 2010, 2013, and 2015.

5.3. Pollutant transport model

In this section, the scenarios that were simulated for pollutant concentration are presented to assess the fate of the effluent column in the Patos lagoon estuary and the adjacent coastal area.

5.3.1. Methodology

To carry out the case studies, it is necessary to have data on the concentration of water quality in the estuary and in the adjacent coastal zone. At the same time, the domestic residual water concentration values of the discharges from the treatment stations are required.

The case studies that are implemented are based on:

- 1st Scenario - Current status of the water quality of the Patos lagoon and Cassino beach estuaries, identifying discharge points according to the Brazilian sewerage Atlas and information on existing treatment stations. It should be noted that the data collected from the download points were identified with Google earth and that the information on clandestine downloads was taken into account as explained in the sewage atlas of Brazil Agência Nacional de Águas (2017), in Baumgarten (2010) and in the diagnosis of basic sanitation of the municipality of Rio Grande Engeplus engenharia e consultoria Ltda. (2013)

The data received are analytical results of the Effluent Quality Control (RCE) No. 13/2019 (Navegantes WWTP), No. 14/2019 (Parque Marinha WWTP), No. 15/2019 (Molhes/Cassino WWTP), which contains data from effluents (untreated wastewater) that reaches CORSAN's wastewater treatment plants in Rio Grande by 2018.

- 2nd Scenario - Preliminary solutions according to the ANA sewage atlas of Brazil in which solution proposals were identified, which describe capturing all the domestic discharges in 3 treatment stations and increasing the efficiency of the treatment stations. For which, the Atlas proposes a removal with efficiency between 80% and 96% with a captured population of 198.577 inhabitants. Adjustments in uptake were made according to Table 5.3.

	WWTP	Population
1	Navegantes	142.758
2	Parque Marinha	25.326
3	Cassino	30.493

Table 5.3 – Population served at treatment station

- 3rd Stage - Solution implementing submarine outfalls that are 500 to 2000 m from the coast or land limit. This solution was conceived based on criteria from international organizations such as:

The Panamerican Center for Sanitary Engineering and Environmental Sciences (CEPIS) and the Panamerican Health Organization (PAHO) conceptualize that: "The discharge of wastewater into the sea through Submarine Emissaries and diffuser systems represent a viable alternative for coastal cities, especially in developing countries with limited financial resources. These systems can take full advantage of the natural assimilation capacity of the sea, which functions as a Treatment Plant without producing any undesirable impact on the marine waters. The alternative of the submarine outfall with pretreatment is a more attractive disposal method in relation to secondary treatment with near-shore disposal, in terms of reliability, efficiency, cost and low operation and maintenance requirements. The sea is capable of assimilating, diluting and even disinfecting biodegradable waste naturally, under optimal mixing, aeration and sedimentation conditions".

ESSBIO from Chile states that: "The levels of technical, economic and environmental efficiency shown (in their experiences) allow us to affirm that a well-designed submarine outfall meets all the requirements for effective and true treatment. The submarine outfall is, from a technical point of view, one of the simplest disposal and treatment solutions for wastewater, therefore less subject to failure, which gives guarantees in the operation of the system. Of which, it was proposed to discharge the domestic wastewater into the Saco da Mangueira, estuary channel and on the shoreline of Cassino beach. Each discharge captures the total population of Rio Grande and the preliminary treatment has an efficiency of 80%.

All results will be analyzed according to CONAMA, the official body responsible for establishing norms and standards related to environmental quality control with a view to the rational use of environmental resources, mainly water. The values used will be those described in CONAMA Resolution No 357, of 2005, which establishes the quality conditions for the structure of aquatic systems and also the conditions and standards for the discharge of effluents in Brazil.

5.3.2. Current assessment of water discharges

This section will address the analysis of current discharges in the Patos lagoon estuary and surroundings of the city of Rio Grande. It is considered as scenario 1, since it is the first simulation carried out with the water quality module.

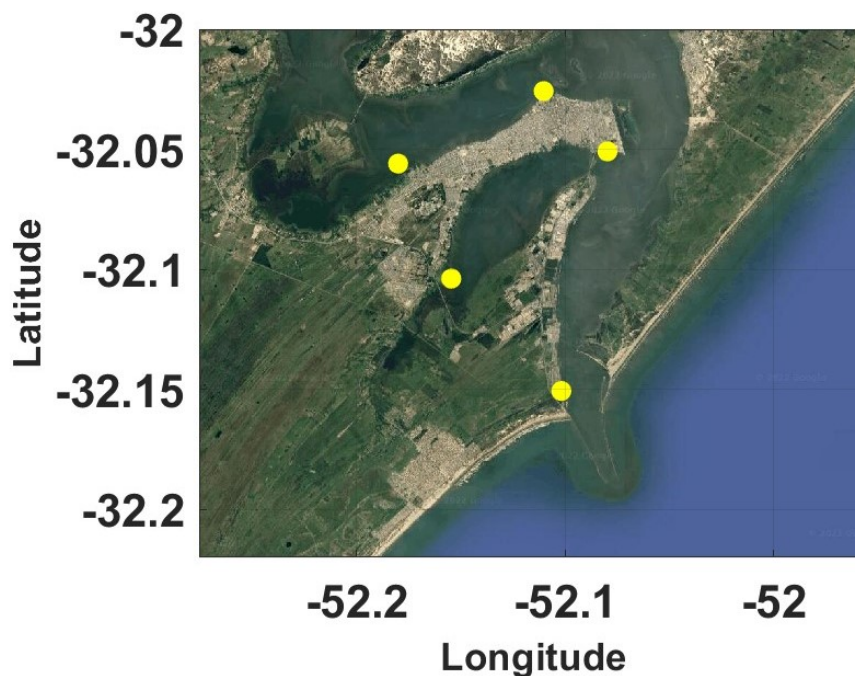


Figure 5.18 – Discharge points scenario 1

Figure 5.18 presents the points at which the discharge were made. The existing waste water treatment plants (WWTP) of Navegantes and Parque Marinha were taken into account.

At the same time, 3 clandestine discharge points were considered. According to Silva (2020); Niencheski and Baumgarten (2007), there are many clandestine discharges in Saco da Mangueira and around the city of Rio Grande. Once the discharge points were identified, the simulation was carried out taking into account the discharge flow based on the existing population in the city of Rio Grande. Considering 1 year of simulation (2013), it was possible to perform the analysis of coliforms, biochemical oxygen demand and oxygen deficiency. These being compared with salinity, intensity and wind direction. For the analysis of these parameters, the monthly average of all the months was determined. In which, the months of January, April, July, September, and November were the months with the greatest movement in the parameters analyzed.

Figure 5.19 describes the months analyzed and the parameters in those months. It has been identified that in the months of January, April and July brackish waters dominate. At the same time for the analysis of contaminants in the months of July, September and November, the dispersion of coliforms forms a plume at the outlet of the estuary in a southwesterly direction. This behavior can also be evidenced by the deficiency of dissolved oxygen.

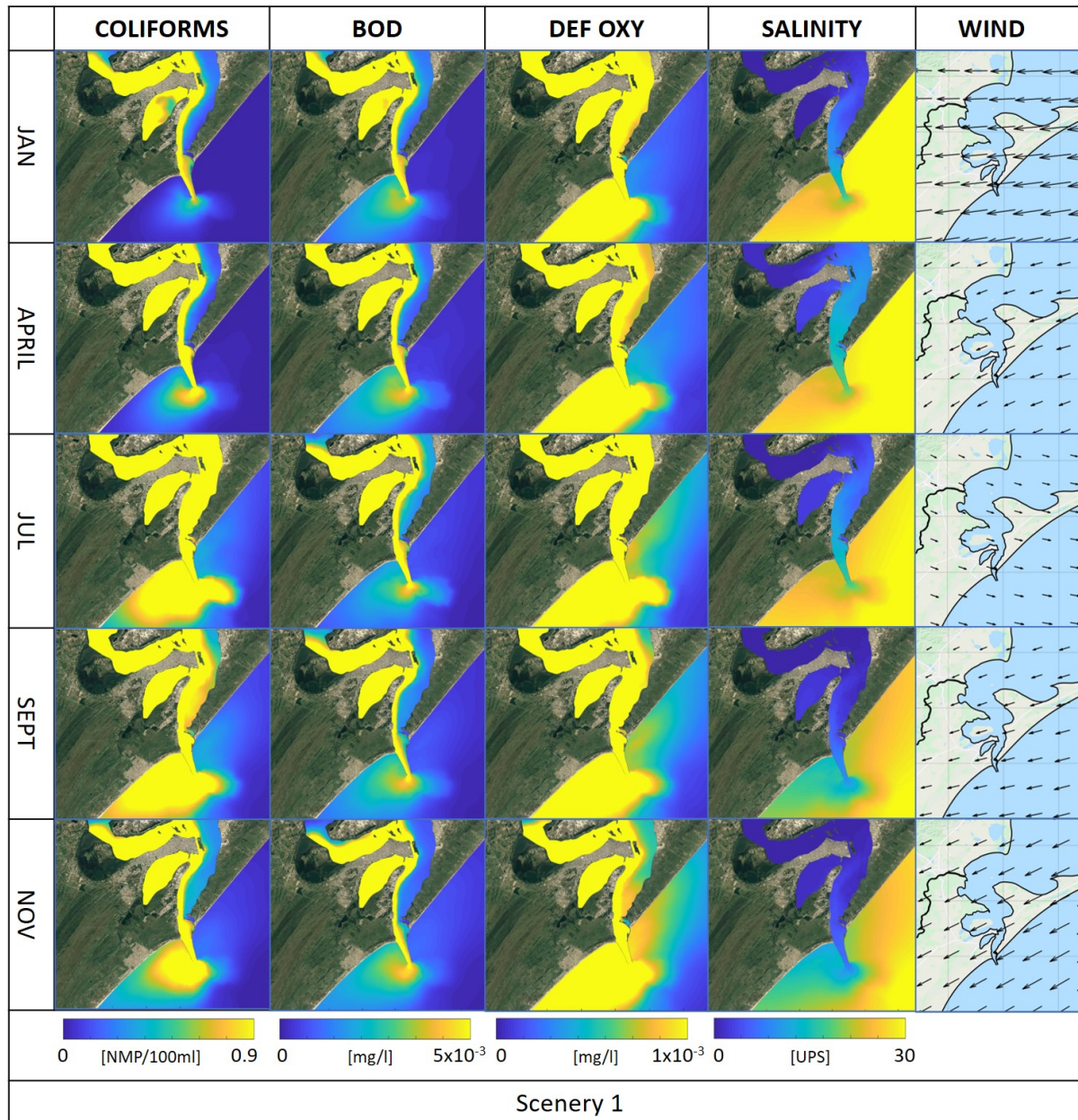


Figure 5.19 – Comparison of scenario 1 of coliform contaminants, BOD and oxygen deficiency with salinity and magnitude and direction of wind in the months of January, April, July, September, and November 2013.

5.3.3. Solution Scenario Analysis

To analyze of solution scenarios, 2 alternatives were proposed. Which consider in the first instance the discharge of water at the same discharge points of the treatment plants (Marinha Park and Navegantes), considering an efficient treatment that removes 80% of contaminants. A second solution scenario considers submarine outfalls at 5 points in the adjacent zone of the estuary.

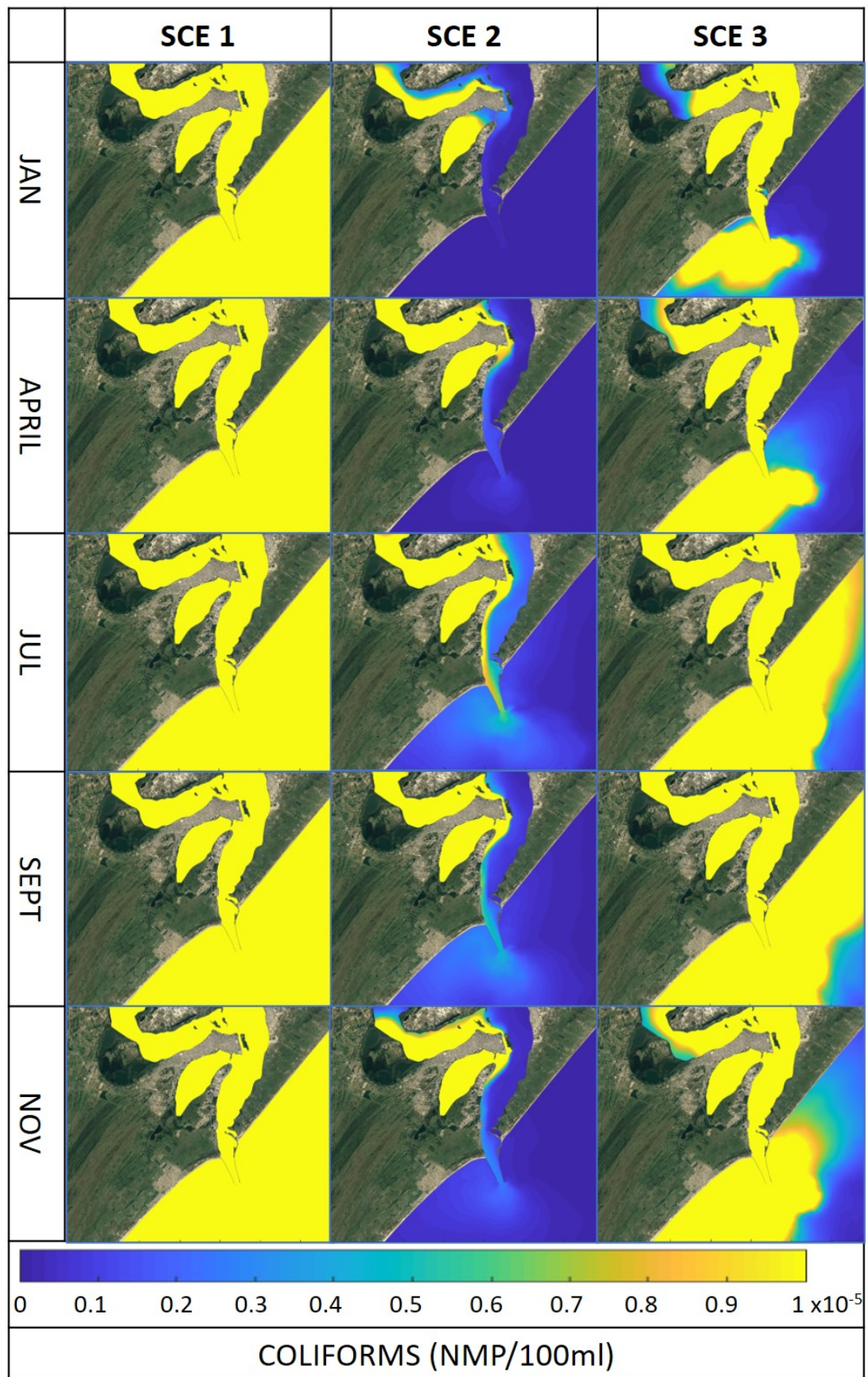


Figure 5.20 – Comparison of Coliforms of 3 simulated scenarios for the year 2013

In the same way, the analysis of the monthly average of the months of January, April, July, September, and November was carried out. The 3 scenarios were compared, being the first scenario, the current situation of contamination in the estuary; the second scenario the first proposed solution, in which the removal efficiency in the existing treatment plants is increased; and the third scenario the alternative of the implementation of submarine outfalls. It should be noted that the simulation carried out was for the entire year 2013, a year of normal weather conditions.

From the total coliform analysis of the 3 scenarios (Figure 5.20), it was possible to identify that scenario 2 describes the dispersion of the coliform contaminant as the most favorable in terms of dispersion and intensity of the coliform plume. This is due to the percentage of removal that the treatment plants have.

At the same time, it was identified that in the months of July to November there is a greater dispersion of coliforms, due to the dispersion plume identified in the channel and at the outlet of the Barra breakwaters.

Regarding the biochemical oxygen demand, it was possible to identify that scenario 2 is the most favorable, since the dispersion of the pollutant is lower (see Fig. 5.21). In the BOD analysis, scenario 3 constitutes a greater dispersion, since it has a greater removal than scenario 1; however, it is important to take into account that the use of submarine outfalls increases dispersion in the estuary. Regarding the monthly analysis of the BOD dispersion, a slight dispersion was identified in the months of September and November.

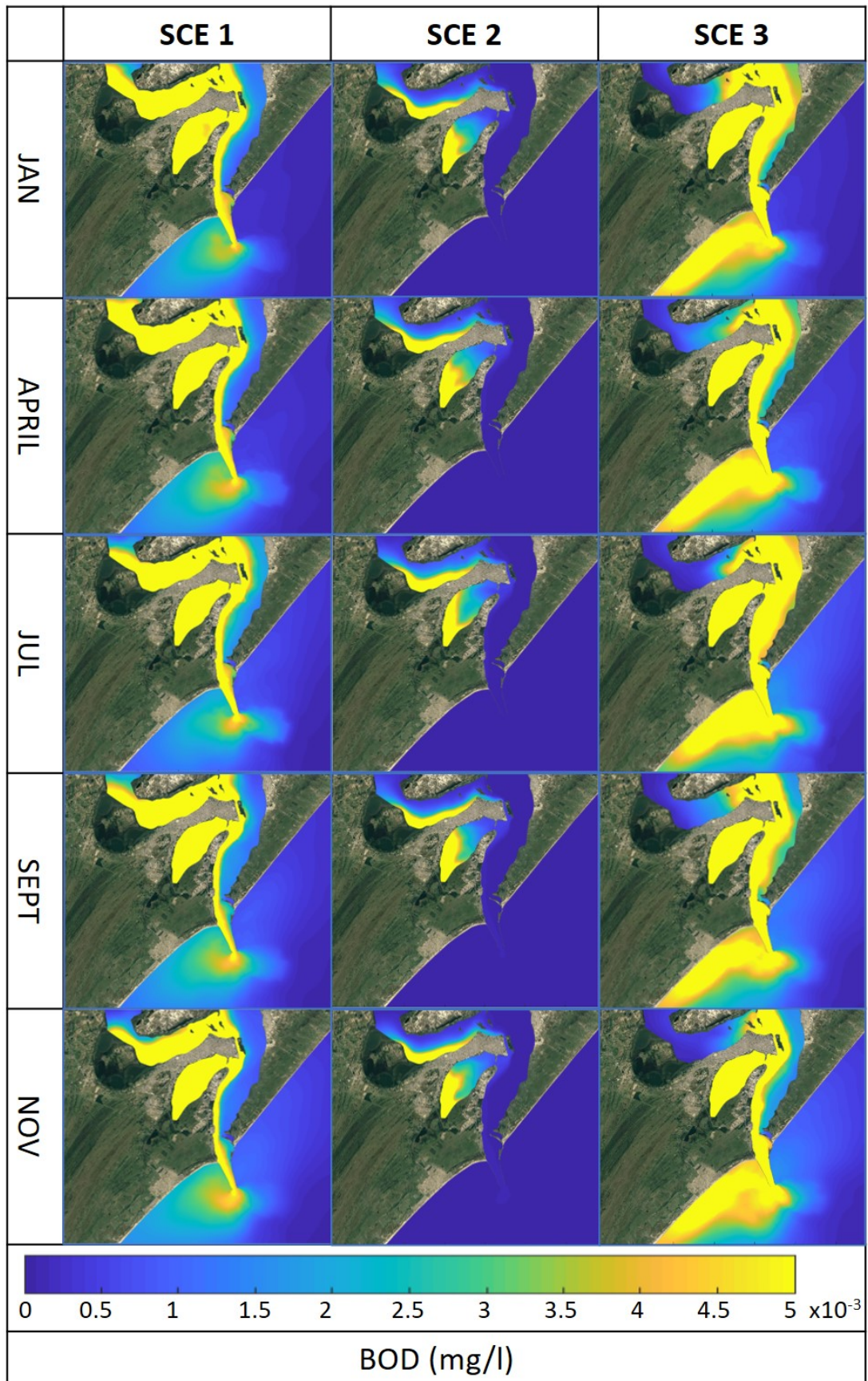


Figure 5.21 – Comparison of BOD of 3 simulated scenarios for the year 2013.

Time series analysis were performed at two points in the estuary. In the middle of Saco da Mangueira and near the city of Rio Grande. In Figs. 5.22, 5.23, 5.24, and 5.25 it was possible to identify that in scenarios 2 and 3, they comply with the minimum discharge concentration, according to CONAMA Resolution 357. It was confirmed that scenario 2 has a lower concentration of Coliforms and BOD in both points, reaching a concentration maximum of 0.0006 MPN/100 ml for scenario 2 and 0.045 MPN/100 ml for scenario 3.

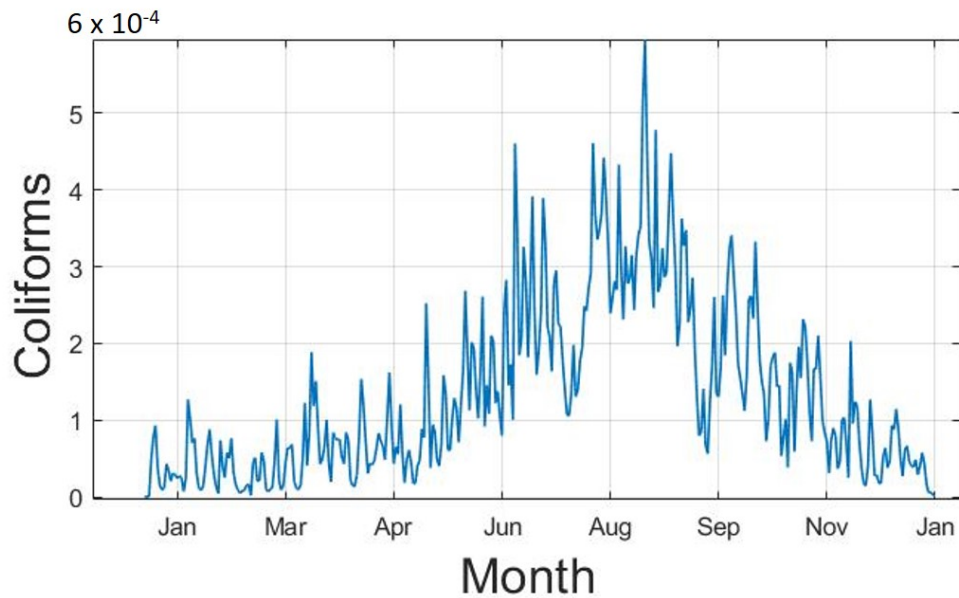


Figure 5.22 – Temporal serie of Coliforms - Scenario 2, Saco da Mangueira

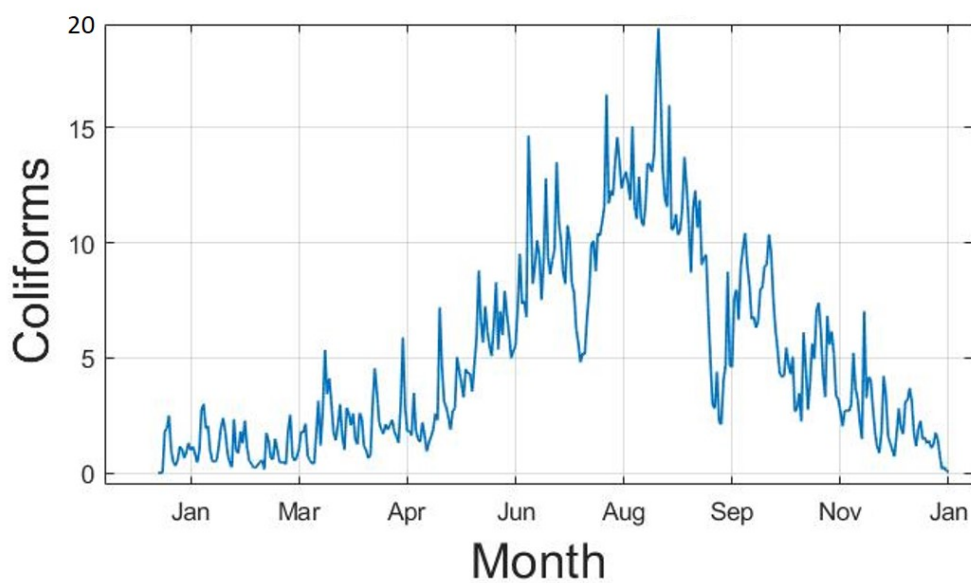


Figure 5.23 – Temporal serie of Coliforms - Scenario 3, Saco da Mangueira

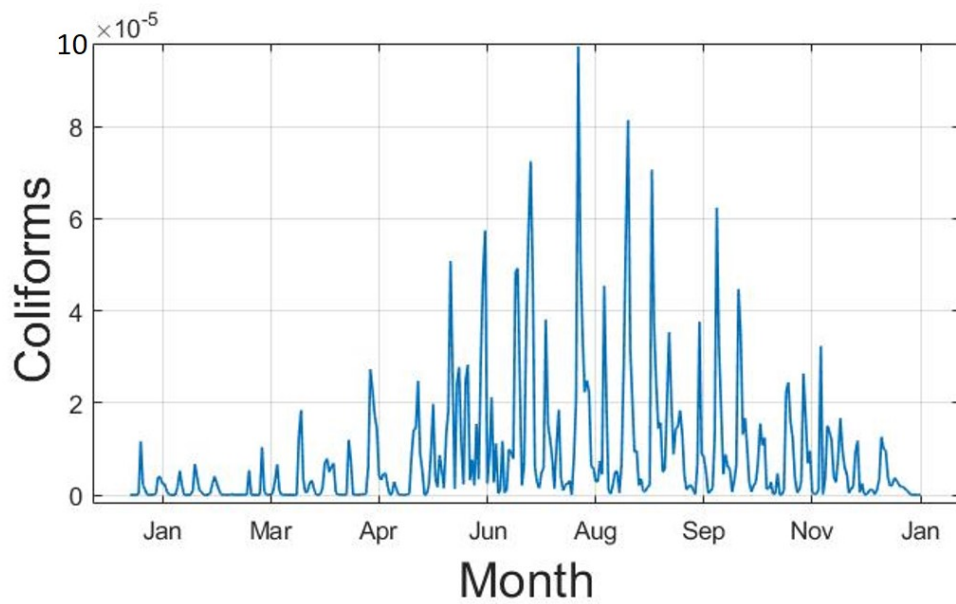


Figure 5.24 – Temporal serie of Coliforms - Scenario 2, RG

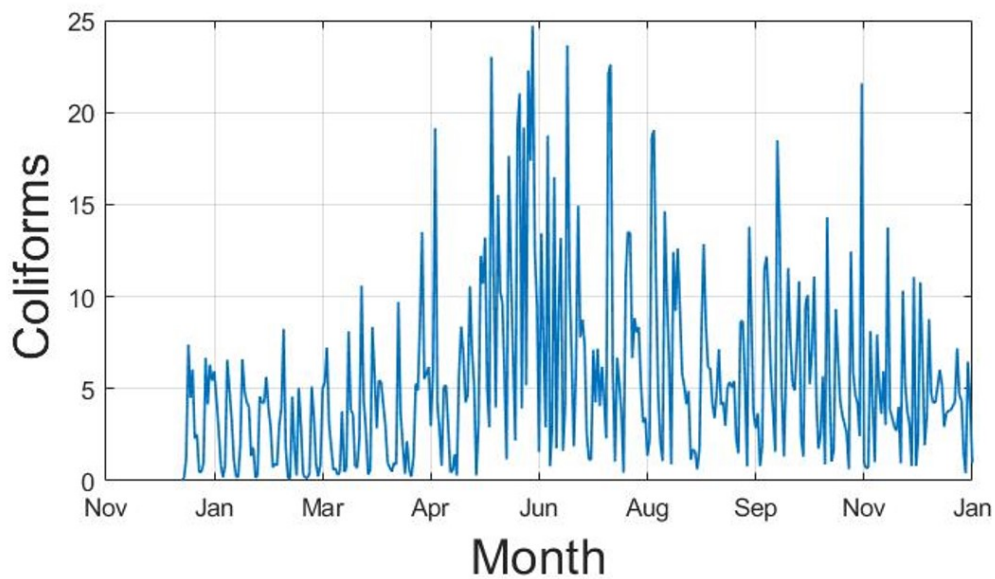


Figure 5.25 – Temporal serie of Coliforms - Scenario 3, RG

At the same time, it was possible to identify that there is a higher concentration of coliforms in the months of July to November. August being the month of highest concentration for total coliforms. In Figs. 5.26 and 5.27, the concentrations at both points are variants throughout the year. Scenario 2 shows a lower BOD concentration, reaching a maximum concentration of 0.013 mg/l in January. For scenario 3 (Figs. 5.26 and 5.27) it has a rising point for the month of March, reaching a concentration of 2.35 mg/l.

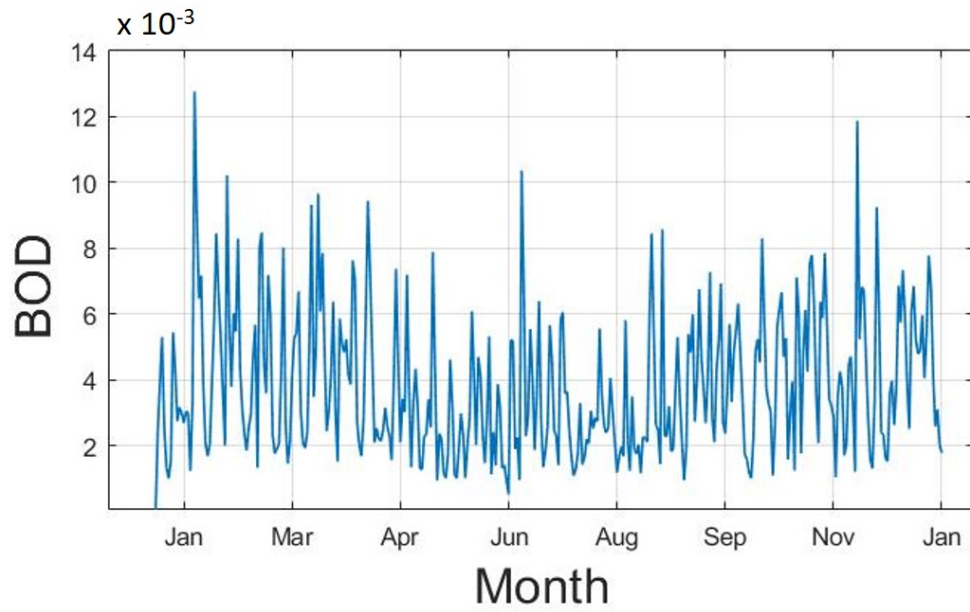


Figure 5.26 – Temporal Serie of BOD in Saco da Mangueira - Scenario 2

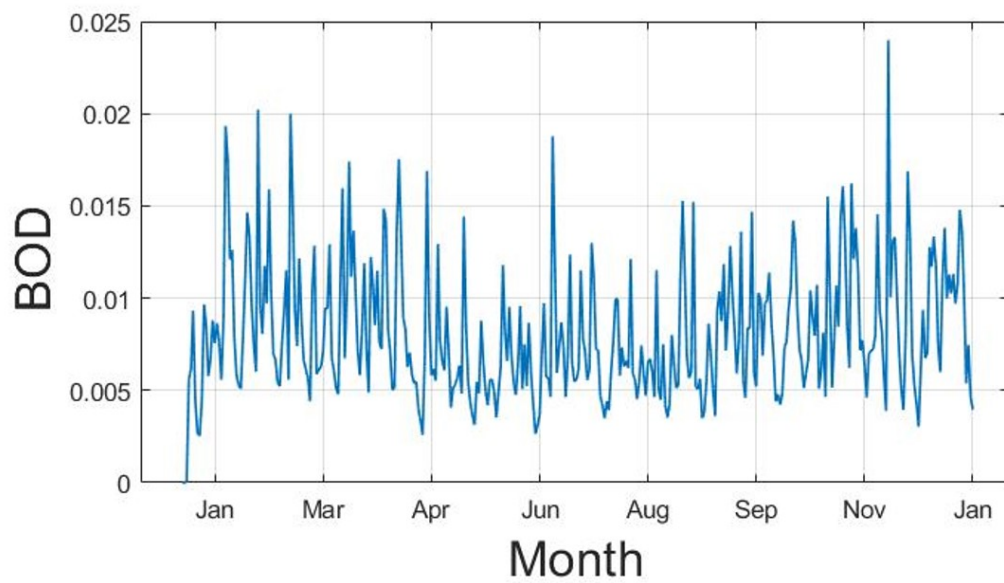


Figure 5.27 – Temporal Serie of BOD in Saco Mangueira - Scenario 3

6. CONCLUSION

This study performed numerical modeling in the estuary of the Patos lagoon using the TELEMAC-3D MASCARET system for the hydrodynamic model and the domestic contaminant dispersion model coupled to the hydrodynamic model for the year 2013.

It proposed treatment solutions for the disposal of wastewater from domestic discharges in the Patos lagoon and in its adjacent area through the use of a three-dimensional numerical model in 2013.

The analysis of the fate of the effluent plume was carried out through a three-dimensional advection-diffusion simulation model of domestic contaminants with a finite element scheme.

For the safe disposal of waste water in the city of Rio Grande, an analysis of 2 solution scenarios was carried out:

- The first solution proposed in the study considers the same points of discharge from the existing treatment plants in Rio Grande. Taking into account a secondary treatment, it considers improving the removal efficiency of current treatment plants in Rio Grande and performed a global collection system in the city of Rio Grande, to be able to capture all the discharges clandestine.
- The second solution considers the use of submarine outfalls inside the channel of the estuary, in the Saco da Mangueira and in the Cassino beach. For the hydrodynamic analysis, it was identified that the action of the winds plays a very important role in the circulation of the lagoon. At the same time as the discharge of the rivers, they act in the direction and magnitude of the currents. It was possible to identify that scenario 2 is the one with the lowest concentration and dispersion, because the solution proposes to improve the efficiency in the existing treatment plants. However, it was possible to show in the Fig. 5.20 that the contaminant is concentrated in the shores of Saco da Mangueira.
- The formation of the Coliform dispersion plume is the most evident in the diffusion survey in the Patos Lagoon. This is because in the months of July, September and November an expansion of the contaminant plume was identified in scenario 1 (Fig. 5.20). Considering the work carried out by Silva (2020), which demonstrates the efficiency of the applicability of the numerical modeling in variables indicating water contamination, it was possible to validate the use of a contaminant simulation module in the estuary of the Patos lagoon.
- In the case of the Patos lagoon estuary, when identifying entrances and exits of saline water, the current is variable throughout the year. Therefore, it is considered to take a submarine outfall off the coast of the Cassino beach, so the diffusion of the contaminant is widened.

6.1. Considerations

It must be taken into account that an exact mapping of all the existing clandestine discharges was not carried out. Therefore, it was considered only 3 points of clandestine discharges in the Saco da Manguera for the three-dimensional simulation.

It should be taken in account of the currents, carrying out a study on the hydrodynamics of the sector. In this way to propose the points of discharge in the submarine outfalls, since in the case of the proposal of solution 2, only the launch distances were considered. If industrial effluents are not considered, the location implies that the simulated water quality is not 100% true, according to the model. The contaminant contamination module considers a single flow rate for all points, where it is impossible to consider the actual flow rate at the discharge points. If I consider the maximum flow for all discharge points.

6.2. Proposal for future research

Consider industrial discharges in the simulation of the contaminant model. For submarine outfalls, consider the currents of sea water for the discharge of residual water. Analyzing the plume dispersion of the contaminates.

Carry out a comparison of the dispersion of contaminants in different years, from La Niña, El Niño and normal weather conditions.

Consider other analysis of other contaminants in the simulation module.

Comparison between other models water quality.

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