ASSESSMENT OF PRIMARY PRODUCTIVITY AND NUTRIENTS FOR A COASTAL LAGOON IN SOUTHERN BRAZIL

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CHAPTER SYNOPSIS

Background
The present study was applied to a coastal lagoon, the Patos Lagoon, located in southern Brazil. Considered the largest strangled-type coastal lagoon in the world, it presents on its shores a population of approximately 7,000,000 inhabitants. The Port of Rio Grande, one of the most important in the Americas, is installed in its estuarine portion. The lagoon is home to fish and shrimp species of great commercial importance. Thus, the lagoon is an important water resource in economic and environmental terms. These activities provide the Patos Lagoon importance and prominence, but also make it susceptible to a large number of environmental damages, resulting from waste of domestic, industrial and agricultural activities. Several initiatives aimed at preserving the waters of this system have been performed, but most of these studies were carried out by means of field collection and / or as focus on the estuary portion of the Lagoon. Therefore, this paper presents a study on the Patos Lagoon water quality as a whole (using the numerical model MOHID as a tool) and the front differential to the other water quality works already done to the region using the same numerical model.

Results
Even with the complex dynamic of water quality parameters in the water column, the model showed that it can represent the reality well, with validations qualified between excellent and reasonable. Bidirectional winds parallel to the coast along with the river discharge, operating in the transport of freshwater to the coast and coastal water to the interior of the lagoon. The highest variations in salinity and ecological parameters (nitrate, ammonium, phosphate and chlorophyll-a) were found in the estuarine region. The lowest values of salinity and the highest concentrations of the ecological parameters are near the river mouths due to the high concentration of waste by river discharges. The analysis of the flows of such properties has shown that an input flow of dissolved inorganic nutrients and chlorophyll-a to the lagoon, by river discharge, is higher than the output from the lagoon to the coastal area.

Conclusions
The study has achieved the goals set besides contributing to the understanding of the main factors that control the water quality in the Lagoon. This study allowed quantifying flow properties, to characterize different sub-areas and to present more realistic results as well due to the use of a bathymetry consistent with the current morphology. The ecological parameters variations that rule the water quality are strongly influenced by the hydrodynamics of the system, which interferes in their releases for the water column. The decrease of flows of properties along the lagoon (from the north area of the lagoon to the coastal region) may be explained by flocculation processes and by grazing on phytoplankton which causes a reduction of chlorophyll-a and nutrients.

1 NUMERICAL MODELLING AND ITS APPLICABILITY IN WATER QUALITY

The ecological parameters governing the water quality of water bodies, such as biomass and dissolved inorganic nutrients have a short-scale temporal variation (few hours). The complexity of the interaction between physical, chemical and biological processes of water body, coupled with the difficulty of analyzing the parameters of water quality in the field indicates the need to work with tools that can overcome these difficulties, such as the numerical models.

Prognostic numerical models provide the possibility to simulate different scenarios and predict the short and long-term environmental response. The use of differential equations and empirical relations to represent the quantitative and qualitative aspects of the hydrological cycle is widely used technique for the simulation of hydrological processes and water quality [1].

Patos Lagoon is a water resource of high importance to the State of Rio Grande do Sul (RS), both ecologically (it generates high productivity in the coastal zone of the southern region, besides being an environment of high fishing activity) and economically (in its estuarine portion there is the Port of Rio Grande, the most southern seaport of Brazil, considered one of the most important in the Americas [2]). The growing development of the RS implies the need for better understanding of the processes occurring in the lagoon and influencing the degradation of its waters.

Since 1986 several initiatives aimed at studying the water quality of the Patos Lagoon have been developed in southern Brazil. However, these studies do not address the lagoon as a whole, focusing on specific stations due to the operating difficulty of sampling. In 2000 the project “Mar de Dentro” (Inside Sea) was developed – Program for Rational Development, Environmental Rehabilitation and Management of the Patos/Mirim Lagoon. Therefore, the first model of simplified water quality was applied taking the lagoon as a whole [2].

In 2003 a larger study was carried out aimed at assessing the water quality of the Patos Lagoon involving physical, chemical and biological events as well as their interactions, using the Delft 3D numerical model [2]. However, the study used a morphology that is inconsistent with the current configuration of the Patos Lagoon and does not provide an assessment of biomass transport and production. More recently there was an ecological modelling study of the Patos Lagoon [3] in which the water quality simulation period was very short (few months), preventing the stabilization of the ecological parameters in the system.

Therefore, it is clear the need to continue numerical studies on the water quality of the Patos Lagoon, taking into account the time required for stabilization of the ecological parameters and the new configuration of its access channel. Such a distinguishment makes it possible to obtain more representative values of nutrient concentrations and their variations throughout the year as well as to estimate the flow of ecological parameters between different regions of the lagoon and the overall ecological balance.

The numerical model chosen for this study was the MOHID (Water Modelling System), developed to support the management of aquatic ecosystems [4]. Besides having already been successfully used in numerous studies involving hydrodynamics and water quality of coastal environments, MOHID has the concept of integration boxes, designed to measure the flow of properties between different areas of the water body under study.

Through the MOHID numerical model this study presents an important ecological analysis of a lagoon located in the south of Brazil (Figure 1), based on varying concentrations of phytoplankton and dissolved inorganic nutrients governing water quality of such a water body over one year. Moreover, from the concept of flow measurement drawing on integration boxes it is possible to understand the importance of each area in the system’s ecological balance [6].

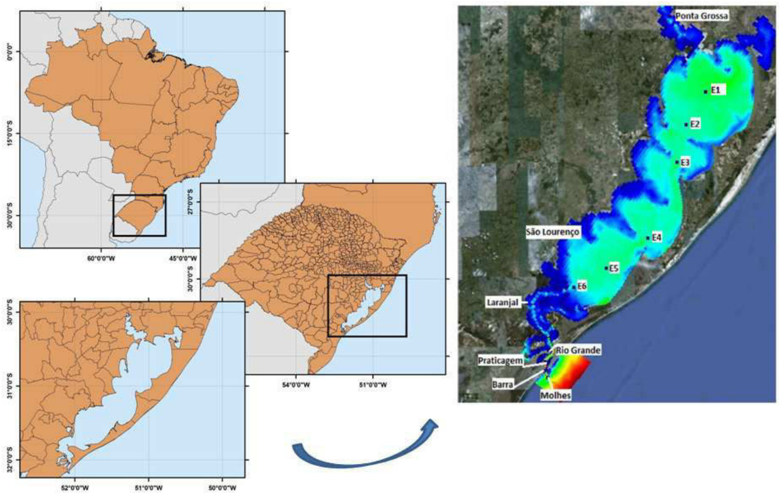


Figure 1. *Location of the Patos Lagoon; bathymetric mesh and stations for results analysis.*

1.1 Objectives

The main objective of this study is to understand the key events controlling the water quality in the Patos Lagoon. This will focus on an analysis of Biogeochemical Cycles (oxygen, nitrogen, and phosphate), Primary and Secondary Production, flow properties among different regions of the lagoon, and the determination of limiting factors for phytoplankton growth.

2 METHODOLOGY

2.1 Bathymetric mesh

In order to discretize the domain for the numerical model of the Patos Lagoon, a bathymetric mesh representative of the new configuration of the Port of Rio Grande was generated for this study. This new mesh included the extension of 500 and 900 m at the East and West breakwaters, respectively, as well as the progressive deepening of the access channel [5]. As this study focuses on the lagoon as a whole, the new mesh no longer used the nesting concept of a parent model (lower resolution) with a child model (of higher resolution) [3, 7, 8]. Instead it created a single varied resolution domain. This modification enabled integration boxes to be created along the field to measure the flow properties of the lagoon from the northern to the coastal region.

For creating the bathymetric mesh, data were used in UTM coordinates of scanned letters of the Directorate of Hydrography and Navigation (DHN) [9] as well as recent data from the region of the Access Channel and Porto Novo obtained from the bathymetric survey conducted by the company *Jan de Nul do Brazil Dragagem Ltda*. The spatial domain has a mesh of irregular cell spacing, ranging from 90,000 m^2 (the highest resolution in the estuary region) and 4,000,000 m^2 for the rest of the lagoon, and a declination of 37° to the North (to follow the inclination of the lagoon in relation to the Geographic North). In total, the grid has 210 cells in the x direction and 100 cells in the y direction.

2.2 Hydrodynamics

For the hydrodynamic simulation, time series of wind, sea level rise and river discharge in the open border of system were used. Data on level variation were obtained from the Meteorological Station of Pilots at Barra do Rio Grande [10]. The series of wind speed and direction were obtained from the Project Reanalysis of the Earth System Research Laboratory, NOAA, through the Monitoring System of Oceanographic Data from the Southern Brazil Coastal Zone (SISCONSUL) [11] of the Universidade Federal do Rio Grande – FURG, which makes this type of data available for the coastal region of southern Brazil. These data consist of u and v wind components every 6 h. After processing the data for its time variation, the wind stress was calculated using the Bulk equation that determines the transfer between wind and water/water properties.

Data on river discharge were obtained from the Brazilian National Water Agency (ANA) [12], which provides gauged stations with time series of flow. Two hourly time series have been imposed as initial conditions of the model, one representing the discharge of Guaíba River, a composition of the discharge of Taquari-Jacuí system, and another representing the discharge of Camaquã River. For this study the following considerations were made: the role of the Coriolis force; horizontal initial velocity of 0 m/s; horizontal turbulent viscosity of 10 m^2s^{-1} and vertical one of 0.0010 m^2s^{-1}; and sediment roughness coefficient of 0.0025. The output of results calculated by the model was established for certain sites along the lagoon (Ponta Grossa, E1, E3, E4, E6, São Lourenço, Laranjal, Rio Grande, Barra, and Molhes – Figure 1).

2.3 Water quality

The initial conditions of the water quality module were: constant salinity of 8 psu, concentration of nitrite (0.02 $mgN\,L^{-1}$), nitrate (0165 $mgN\,L^{-1}$), ammonia (0.11 $mgN\,L^{-1}$), phosphate (0.07 $mgP\,L^{-1}$), oxygen (8 $mg\,L^{-1}$), phytoplankton (0.125 $mgC\,L^{-1}$), zooplankton (0.01 $mgC\,L^{-1}$), particulate organic nitrogen (0.05 $mgN\,L^{-1}$), dissolved organic nitrogen non-refractory (0.002 $mgN\,L^{-1}$), dissolved organic phosphorus non-refractory (0.019 $mgP\,L^{-1}$), dissolved organic phosphorus refractory (0.008 $mgP\,L^{-1}$), organic phosphorus particles (0.011 $mgP\,L^{-1}$). Values of salinity, temperature, nitrite, nitrate, ammonia, dissolved oxygen, and phosphate were provided by the Laboratory of Hydrochemistry at the Universidade Federal do Rio Grande (FURG). These data were obtained by quarterly sampling of surface, half and bottom water. In this study only the superficial means are used. The remaining parameters were obtained from previous studies.

Due the required time for that the biogeochemical cycles be completed, the modelling of ecological processes needs a long simulation time (about one year) to be stabilized and in fact represent the environment.. As the proposed duration of the study was the year 2006, both simulations were made consecutively. The first one enabled ecological parameters to be inserted in the water column and had a chance to interact, i.e. time enough for the stabilization of phytoplankton and zooplankton variations in biogeochemical cycles. The second one was for the period of interest and had as initial condition the results from the first.

In both simulations, the domain was divided into compartments called integration boxes. Each box is the averaging concentration of the properties of all cells inserted therein, resulting in flows (defined as the mean velocity multiplied by the mean concentration of border cells) that allow to infer the areas which are producers or carriers, an important aspect for assessing the total ecological balance. Furthermore, the integration boxes enable instantaneous variation of these properties to be monitored over time.

3 HYDRODYNAMIC ANALYSIS

3.1 Hydrodynamic Model Validation

Model validation was made on comparisons of actual data on rising sea levels obtained from ANA, and results were calculated by the model at the stations of Ponta Grossa, São Lourenço, Laranjal, and Rio Grande. The results showed that the model simulates the actual data as it tracks the changes in sea level, but cannot keep up with the maximum and minimum elevation. For assessing the quality of results thereof, the Relative Mean Absolute Error statistical method was applied according to Walstra classification [13]. In this classification, errors below 0.2 are considered ‘excellent’; 0.2 to 0.4 ’good’; 0.4 to 0.7 ’reasonable’; and 0.7 to 1 ’poor’. Ponta Grossa station showed an error of 0.183, classified as ‘excellent’, while the reproduction model was rated as ‘good’ for the stations of São Lourenço, Laranjal, and Rio Grande, with errors of 0.397, 0.295, and 0.338, respectively.

3.2 Hydrodynamic Assessment

From the hydrodynamic perspective, the Patos Lagoon is governed by a system of bidirectional winds, parallel to the coast, as well as by river discharge. The effect of the tide is negligible because the estuary is of hyposynchronic type, i.e. the effect of friction is greater than that of the channel convergence, causing the tidal wave to be attenuated inside the channel [14]. Guaíba is the main river flowing into the lagoon, where the Jacuí-Taquari system is responsible for 85% of total freshwater average input [7] (Figure 2). The seasonal movement of air masses implies a system of NE-SW winds acting along the lagoon. SE/SW winds of greater intensity occur more frequently between between March and August (autumn and winter). When operating on a scale of 3-15 days associated with a low discharge, they force the water inlet from the ocean into the lagoon, causing salinity to increase. Moreover, N/NE winds of greater intensity occur more frequently between September and February (spring and summer), forcing the output of fresh water from the lagoon to the ocean. The sum of the local and remote wind effects generate gaps of 0.3-0.4 m along the lagoon [15, 16], which together with the river discharge effect interfere with salinity and variation in sea level. The river discharge behaviors differently throughout the year, showing high discharge in late winter and early spring, and low to moderate discharge during summer and autumn (Figure 2).

The results of the model indicate that the discharge strongly influences the salt water inlet so that salinity decreases exponentially with increasing the river discharge. Since the stations of Ponta Grossa, E1, and E3 are far from the region where the saline intrusion occurs and close to the discharge from Guaíba, they have the lowest salinity values compared to the stations of E6, Laranjal, Rio Grande, and Molhes (Figure 3). From the results it is also possible

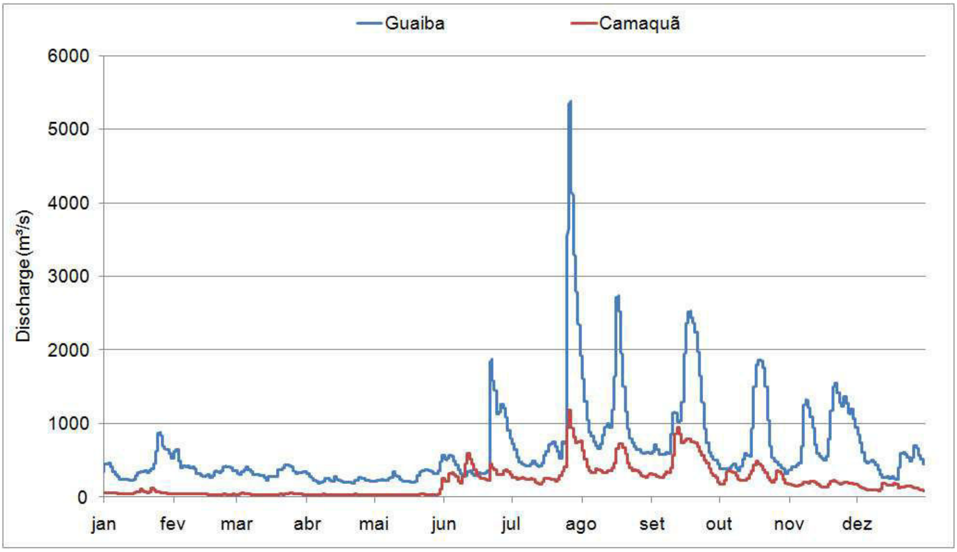


Figure 2. *River discharge from Camaquã and Guaíba Rivers.*

to observe the strong influence of the performance of bidirectional winds parallel to the coast, forcing the entry of saline water (Figure 4) and forcing the output of fresh water (Figure 5), which confirms the findings of previous studies.

4 FLOWS QUANTIFICATION AND VARIATION OF ECOLOGICAL PARAMETERS

4.1 Water Quality Model Validation

Assessment of results from the water quality module was based on a comparison of salinity, chlorophyll-a, ammonia, nitrate and phosphate, all of which refer to Barra station and were calculated by the model with field data. The salinity data were provided by the Laboratory of Estuarine and Coastal Oceanography at FURG. It is possible to see that the model follows the variation of salinity given by actual data, but does not reach the maximum and minimum values, showing sometimes a difference of up to 12 psu. The same behavior was also observed for sea level elevation.

In order to verify that the correlation between the measured and calculated values of salinity was significant, the correlation coefficient (R^2) and the hypothesis test (P) were calculated. Results showed R^2 = 0.73 and P = 0. Correlation coefficients greater than 0.70 are considered to have strong correlation: so the correlation of salinity data is significant. The Relative Mean Absolute Error calculation for salinity data indicated a value of 0.29, which describes the model result as 'good'. The next step was to evaluate the behavior of solar radiation, which showed that low values of solar radiation are found between June and September, corresponding to winter, with peaks between December and March for the summer, a situation that is consistent with the expected to temperate regions of the Southern Hemisphere. Other properties were validated using data from the Laboratory of Phytoplankton at FURG, which held monthly cruises to collect physical and chemical parameters and nutrients. The Relative Mean Absolute Error method for chlorophyll-a, nitrate, ammonia and phosphate provided RMAE values of 0.43, 0.60, 0.20, and 0.43, respectively. These values indicate that the reproductive behavior of ammonia was classified as excellent, while for others it was reasonable.

4.2 Water Quality

The water quality module outputs indicate that changes in phytoplankton concentration and hence the primary production is associated with changes in concentration of inorganic nutrients dissolved in water, namely: ammonia, nitrite and phosphate. In general larger variations and concentrations are found during spring and summer, probably due to uptake by primary producers, salinity and the interaction with sediment.

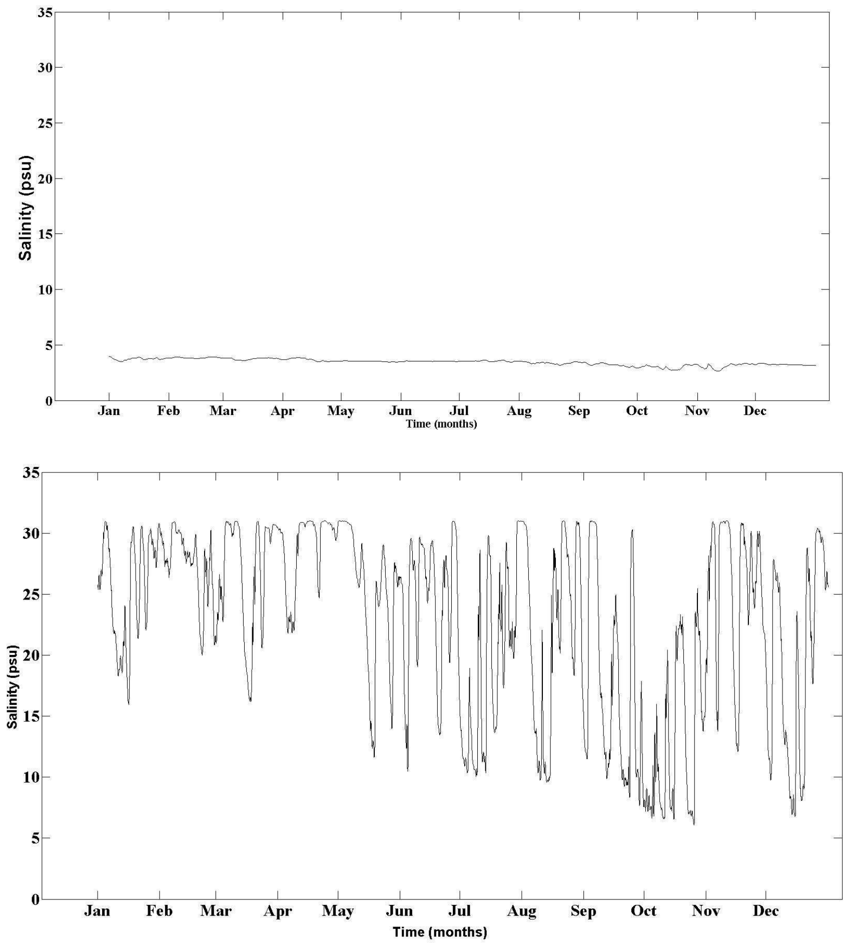


Figure 3. *Time series of salinity: (A) E1; (B) Rio Grande.*

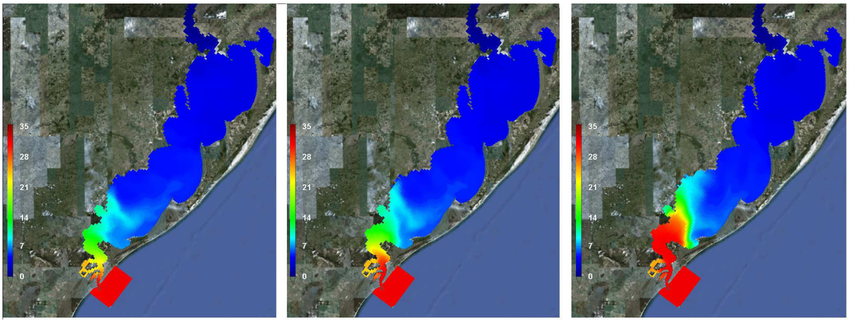


Figure 4. *Salinity variation with SW winds with low river discharge (April).*

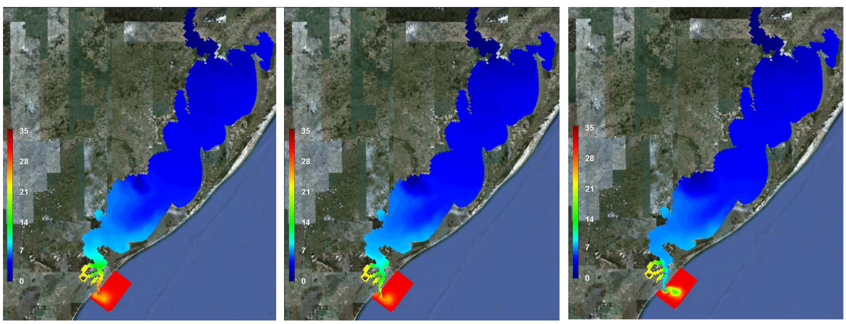


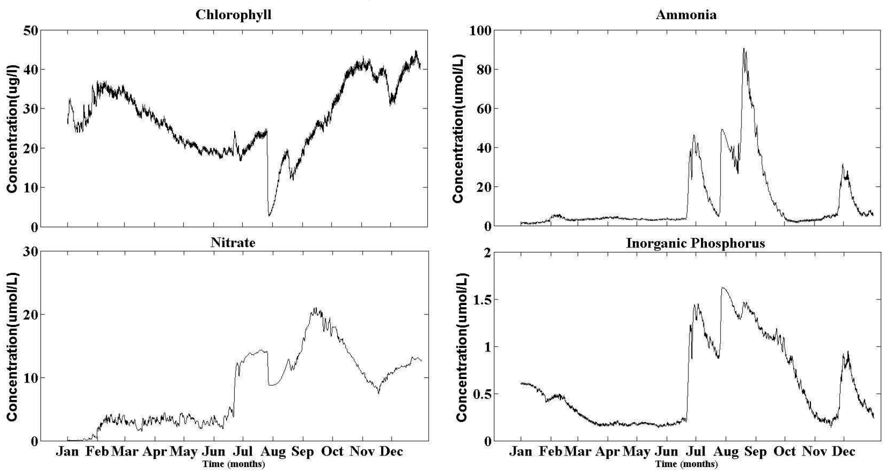
Figure 5. *Salinity variation with NE winds with high discharge rates (September)*

These inorganic forms are produced from organic matter remineralization. According to [17], there are several factors leading to changes in concentration of phytoplankton in the Patos Lagoon, such as: precipitation - which transports more dissolved inorganic nutrients by the continental discharge and changes salinity and ionic strength, influencing the flocculation of particles; saline wedge input - which causes the elevation of dissolved inorganic nutrients which may be caused by return of estuarine water still containing high levels of nutrients; wind action - at low hydrodynamic an potential gradient redox in the sediment is formed. This makes that reductive conditions occurs over the sediment, facilitating the production and retention of dissolved inorganic nutrients near the bottom. With the action of the winds, there is an increase of the local hydrodynamic and redox gradient is disrupted, causing the release of dissolved inorganic nutrients to the water column; and human activities - which are responsible for the main sources of phosphate and the main cause of eutrophication in the estuary.

A representation of the behavior of environmental parameters is shown in Figure 6. The maximum values of chlorophyll-a were found in the northern portion of the lagoon (Ponta Grossa: 44.9 μg L^{-1}) and the minimum at E1 (1.56 μg L^{-1}). The largest variations in chlorophyll-a followed the saline intrusion; thus above the maximum reach of salt in the lagoon (stations E1 and E3) the variation in chlorophyll-a is minimal. As an exception to this situation, the station of Ponta Grossa even without any interference of salt has large variations in chlorophyll-a, related to continental discharge. The mean concentration of the lagoon was approximately 9.0 μg L^{-1}, which is equivalent to a primary production of 0.45 mgC L^{-1}.

The maximum and minimum concentrations of nitrate were found at Ponta Grossa (21.09 μmol L^{-1} and 0.007 μmol L^{-1}). The mean values for the lagoon as a whole was 2.14 μmol L^{-1}. Ponta Grossa station also had the maximum and minimum concentrations of ammonia (90.4 μmol L^{-1} and 0.74 μmol L^{-1}). The mean concentration of ammonia for the entire lagoon was 3 μmol L^{-1}. At all stations the increase in chlorophyll-a was find to cause a decrease in ammonia. At Ponta Grossa station the maximum and minimum concentrations of phosphate were found (1.6 μmol L^{-1} and 0.137 μmol L^{-1}). The mean value for the lagoon was 0.9 μmol L^{-1}.

a) Ponta Grossa



b) E3

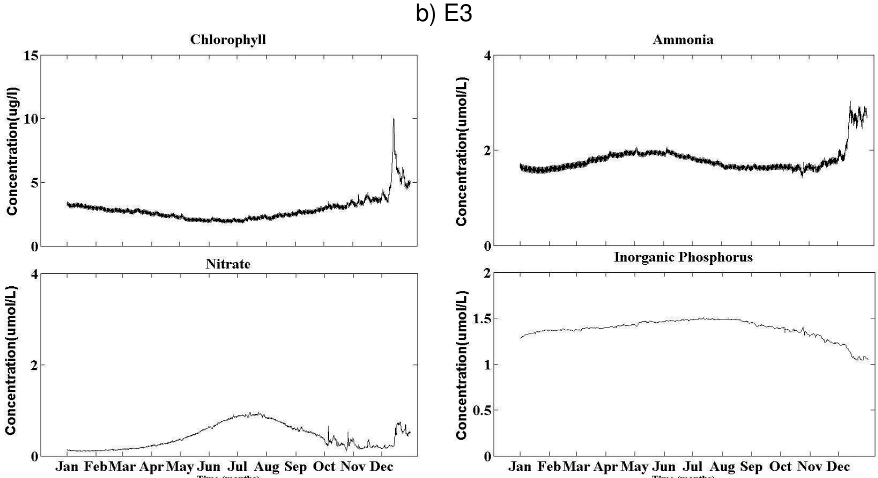


Fig 6. *Cont.*

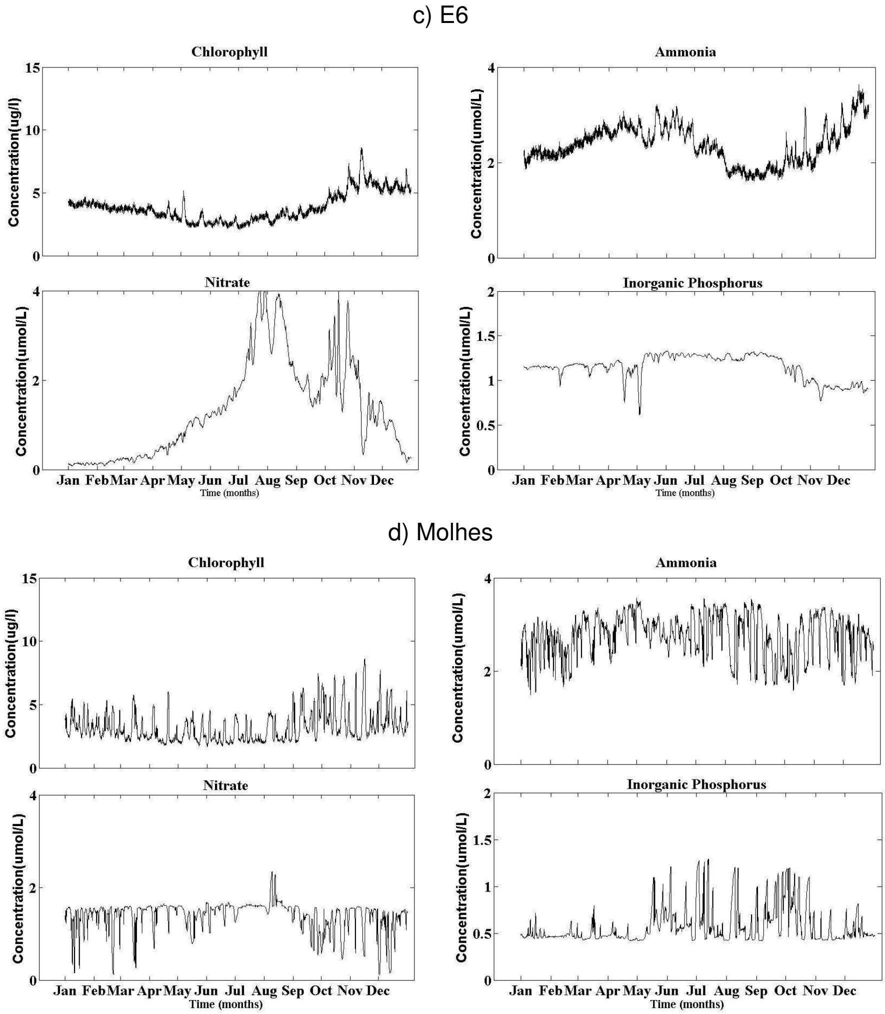


Figure 6. *Variation in ecological parameters for the stations of: a) Ponta Grossa; b)E3 ; c)E6 e d) Molhes.*

Low concentrations of phosphate and ammonia are related to long-stay fresh water within the lagoon, which leads to lower nutrient release from sediments [17]. This behavior was verified for all stations in November. The high values of dissolved inorganic nutrients in the north of the lagoon are related to land supply as transported by rivers to the lagoon. These high values are also observed near the discharge of Camaquã River.

There is a tendency for higher values of nitrite, nitrate and phosphate as the water goes fresher in the low estuary [17], and this can be verified by comparing the behavior of the stations E6 and Molhes. Flocculation and uptake by primary producers are the two reasons which may lead dissolved inorganic nutrients to removal from the water column in areas of salinity level lower than 5 psu. In the limnic region of Patos Lagoon phytoplankton depletes nutrients in the water when they form large biomass, making this nutrient-poor water to reach the estuarine portion [17]. Such behavior was verified at Ponta Grossa, which though being close to the river discharge shows low nutrient levels during summer and spring, when there is high rate of phytoplankton growth.

Large variations of dissolved inorganic nutrients and chlorophyll-a in the estuary may be related to wind action and the entry of saline water. The action of winds and the entry of saline water disrupt the redox gradient and release great amounts of nutrients into the water column [17]. The interference of salinity was observed at E6, Laranjal, Rio Grande, and Molhes, where salinity variations occurred in a short time, causing a large change in ecological parameters over the year. This behavior was not standard for the entire lagoon and may be related to the proximity of some stations to the river discharge (Ponta Grossa and E1, for example), which consequently causes the nutrient concentration in the water column to increase and thus prevents the sediment from spreading.

Studies [17] indicate that periods of high river discharge and precipitation turn light into the major limitation of phytoplankton growth, since the high river discharge increases the concentration of suspended matter in water and reduces the penetration of light. As observed for Ponta Grossa in August the decreased chlorophyll-a concentration may have been caused by high river discharge. Previous studies on the evolution of chlorophyll-a and dissolved inorganic nutrients in the Patos Lagoon found that in the limnic region, north of the lagoon, there is a high mean chlorophyll-a concentration; as for the oligohalina region (salinity from 0.5 to 5 psu) a biomass phytoplankton was found controlled not only by light but by nitrogen as well. Over the year E3 and E4 stations showed low values of nutrients when compared to other stations, agreeing thus with the study. This still indicates that relatively high values of phosphate, greater than 1 μmol L^{-1}, prevail along the lagoon and virtually throughout the year. Such behavior was also found in the model results.

Analyzing the flow of properties among the boxes along the lagoon (Figure 7) the estuary was found to receive yearly approximately 13,240 tons of chlorophyll-a (in terms of carbon), while 6,093 tones are exported to the coast. Thus there appears to be a significant death of phytoplankton in the lagoon. In general there is an annual flow of ammonia, nitrate, chlorophyll-a and phosphate from inside the lagoon to the coast. However the highest flows were observed in the estuarine portion. This behavior can be explained by the intrusion of sea water, which carries a portion of the estuarine water previously discharged on the coast containing large amounts of dissolved inorganic nutrients.

The flow of sediment nutrients meets the needs of primary production by phosphorus, whereas only 25% of the nitrogen needs are met [17]. This statement may justify the behavior of ammonia and nitrate between boxes 6 and 7. The low concentration of these in box 6 induces the phytoplankton to import them from an area of high concentration. As the area of box 7 includes the Camaquã River discharge it has higher concentrations of nitrogen than box 6 and generates the observed flow.

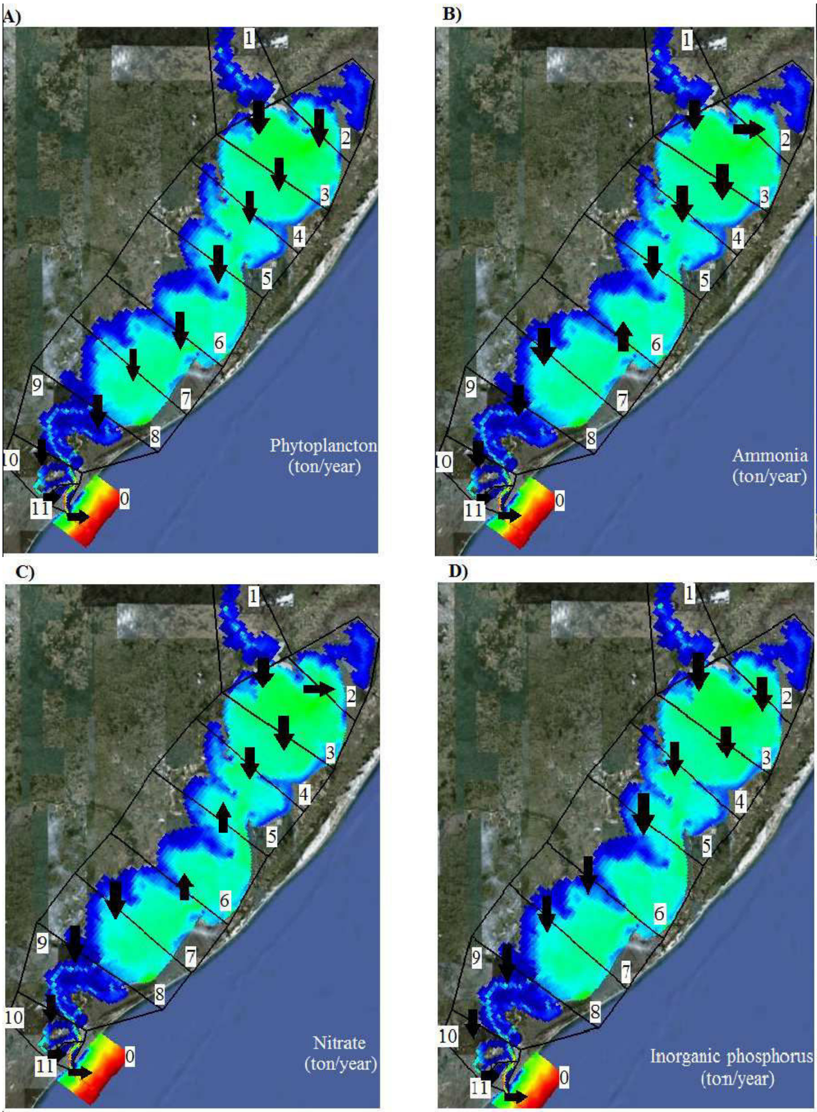


Figure 7. *Flow of properties among the boxes along the lagoon: Phytoplancton (A); Ammonia (B); Nitrate (C), Inorganic Phosphorus*

5 CONCLUSION

Results represent a few more important steps in understanding the key processes controlling the water quality of the Patos Lagoon. Taking into account the time required for the stabilization of environmental parameters, the long numerical simulations (one year) were important in the reproduction of data measured in the field, whereas considering the new configuration of its access channel brought model results closer to the environment reality.

However, the reproduction of data measured in the field was not perfect due to a series of approximations and limitations of numerical models. This was evidenced by the failure of the model to reproduce the maximum and minimum peaks of the calculated parameters. The model used was two dimensional, i.e. the result calculated by the model represents the integration of the parameter along the water column, regardless of stratification, and this was one of the factors that contributed to this behavior. Furthermore, there is a great need for water quality data on temporal and spatial scale suitable for the model.

There is a great lack of water quality data in temporal and spatial scale adequate to feed the model. As phytoplankton activity fluctuations occur on a small scale (hours or days) and with non-standard behavior and the field data used for validation has a monthly time scale, the comparison between simulated results (hourly time scale) and the field data is limited. Thus, the fact that the model does not follow the peak of dissolved inorganic nutrients and chlorophyll-a, as was observed in field datas, may not be an error of the model.

Even within this context, the model validation exercises have resulted in ratings ranging from 'excellent' to 'good', which indicates it is suitable for the proposed study. Moreover, the results also indicate that the variation of ecological parameters is complex and directly linked to climatic variations, mainly river discharge, wind action and salinity. Therefore, a similar ecological behavior across the lagoon was not observed: some parts of the lagoon are strongly influenced by river discharge, while others are strongly influenced by seawater intrusion. Furthermore, the results indicate that the main limiting factors for primary productivity are the shortage of nutrients and/or light.

Analyzing the results of ecological properties flow, it was noted that even though these are more intense in estuarine portion what is exported from the lagoon to the coast is less than that entering it via river discharge, i.e. there is an indication of loss of phytoplankton biomass and nutrients along the lagoon. The hypotheses that could explain such a behavior is that the phytoplankton was used as food, and hydrodynamic events which makes the lagoon water almost entirely fresh intensify the flocculation processes, thus eliminating the dissolved inorganic nutrients from the water column. In this same analysis it was also observed that in the region of the lagoon between the boxes 5 and 6 there was intense sediment deposition, which reduced the concentration of sediment and environmental parameters in this area, so that such may be characterized as areas low productivity.

Overall this work contributed to an assessment of the key ecological parameters controlling the water quality of the Patos Lagoon, considering its short time scale (time variation). Based on the evaluation of transport and production of biomass, it is possible that studies related to other economic activities such as aquaculture understand what period and region of the Patos Lagoon may have the best ecological conditions for the enterprise.

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