Water Dynamics and Role of Groundwater in the 'Lagoa dos Barros', South of Brazil

Priscila Kayani Ghellere Vanzella[1], Ana Oliveira[1], Friedrich Herms[2], Teresa Melo[1], Ramiro Neves[1].
[1]IST, Instituto Superior Técnico,. Lisboa, Portugal.
[2] UERJ, Universidade do Estado do Rio de Janeiro. Rio de Janeiro-RJ, Brasil

Abstract

Lagoa dos Barros is a water body located in the Litoral Medio basin, at the coastal plain area in South Brazil divided by Santo Antonio da Patrulha (SAP) at West and Osório at East. Still, it is not classified as a coastal lagoon because the region's morphology prevents the direct discharge into the ocean, bein Lagoa dos Patos the outlet of its watershed. The lagoon covers 92 km^2 of freshwater and is extremely important to the region's economic activities, mainly agriculture with irrigated crops that pumps water from the Lake during summer. However, a wastewater treatment plant (WWTP) was implemented in 2009 by CORSAN (Companhia Rio Grandense de Saneamento) and Osório, which started its operation at the end of 2018. However, at the end of 2019, Eutrophication started to be visible in the water body, reaching its peak in May 2020, and the WWTP was considered the leading possible cause for discharging its effluents without tertiary treatment in the Lake. Thus, the focus of this work was to identify the primary water sources to Lagoa dos Barros for then be easier to identify the most probable cause of Eutrophication that happened in 2020.

Different approaches were applied to interpret the dynamics of the complex area. A physical-based model and a simplified water balance are applied to evaluate the relations between the aquifer and lake systems. Then, estimate whether groundwater contribution to Lagoa dos Barros is potentially a source of nutrients that could have been involved in the cause of the high nutrient concentration that originated the algae bloom.

This study corroborates the condition of the lagoon placed at a higher altitude than the rest of the area, acting as a recharge zone of the Litoral Medio watershed that outflow South to Lagoa dos Patos. Lagoa dos Barros receives water through the tributary channels from the Precipitation and runoff of the North and Northeast areas, where intense pollutant activities are a potential source of high nutrient load. On the other hand, the water withdrawal is due to evaporation or is poured out of the pond through the canals when a certain level is reached, or, during summer, it is pumped out to irrigate the surrounding farmland and may lose a parcel contributing to recharge the coastal aquifer placed below the lagoon. Because, during May 2020, during a dry period, Lagoa dos Barros decrease its level once the groundwater table increases in the same period, meaning groundwater is not relevant for the algae bloom observed in the Lake. However, a constant and adequately distributed piezometric level monitoring and further studies of the Northern and Southern region should be implemented to define the aquifer flow with detailed channel info is essential to draw a final concrete conclusion on the suggestions addressed in this study.

Keywords: Lagoon, groundwater, aquifer, surface-groundwater interactions, modelling, flow dynamics, water balance, coastal plains.

Introduction

Lagoa dos Barros is a vital water body in the Coastal South of Brazil found between Santo Antonio da Patrulha and Osório. Because it covers a large extension with freshwater, the water body sustains many essential activities in the region. The interest in Lagoa dos Barros has been increasing since 2009 by Santo Antonio da Patrulha (SAP) municipality when the Companhia Rio Grandense de Saneamento (CORSAN) started implementing a Waste Water Treatment Plant (WWTP) in its neighbour Osorio. Since then, SAP has aimed to cease the WWTP implementation, affirming that the operation and effluent disposal threaten the region's ecological equilibrium. Nevertheless, CORSAN had the WWTP operation license emitted at the end of 2018, which allowed the functioning for more than one year. However, in June 2020, the environmental agency Fundação Estadual de Proteção Ambiental Henrique Luiz Roessler (FEPAM) revoked the licence because of the association with the emergence of algae blooms which had its peak in May 2020 at some places within the water body. Therefore, SAP requested the support of different specialists to investigate the lagoon behaviour that may support its position. This work further analyses the lagoon and aquifer relationship, aiming to identify sources and sinks of water to the system, where water balance and a physically-based model is applied to support the region's decision-making about the infrastructure. The simulation tries to reproduce the environment for then compare simulated results with actual measurements in specific conditions. In a physically-based model, gathering the most information is necessary to achieve a good representation of reality. However, it is essential to be critical about information and parameters inserted as input. This analysis is made through a literature review of the area aligned with communication with local people accompanying the problem since 2009. The focus of this scientific work does not justify an interest; the fundamental importance of technical development is to see a real problem, develop a hypothesis, test them, find explanations, causes, and origins for situations that negatively impact the environment and human lives. Understanding the issue root for then propose solutions and adequate technical procedures for each circumstance. With technologies, such as modelling, novel discoveries, and evolution on understanding natural processes, society can play a role with scientific groups to plan efficiently, focusing on decreasing negative impacts associated with practices like the WWTP.

Objectives

The uncertainty of water sources to the water body bring questions that this work aims to verify by applying a physically-based model and different approaches to assess the aquifer contribution to Lagoa dos Barros. This work aims to identify if Lagoa dos Barros depends on the aquifer to maintain the water volume within itself or if it is a system that loses water by the subsoil constantly recharging the aquifer, where groundwater interaction is a critical player on the water levels control.
The main objective is to identify the role of groundwater contribution to the system. Each goal originates a big task that can be individually implemented because it needs different independently information. The specific goals are:

- Assess groundwater and surface contribution to Lagoa dos Barros;
- Identify possible sources and sinks of water to the water body;
    - Water balance support characterisation of the hydrogeological cycle and estimate recharge and discharge rates from the lagoon to the aquifer;
- Evaluate groundwater influence on Lagoa dos Barros during the period of visible Eutrophication;
    - Simulation flow direction at Lagoa dos Barros basin;
    - Determination of groundwater recharge and its role in the behaviour of the Lake.

Study Area

Location

Lagoa dos Barros is situated in Brazil's southern state Brazil, the Rio Grande do Sul, between Santo Antonio da Patrulha and Osório. Being part of the "Litoral Medio" Basin draining water Southwards to the important Lagoa dos Patos (Figure 1 and Figure 2) and is part of the Coastal Plain of Rio Grande do Sul ("Planície Costeira do Rio Grande do Sul", called PCRS), where the shallow granular unconfined aquifer is found in connection with the water body. Lagoa dos Barros covers an area of 92km^2 of freshwater and is characterised by presenting an average low altitude of around 10 meters above sea level, and the area is marked for the presence of plains of marine barriers and fluvial sediments. (Marchett, 2017).

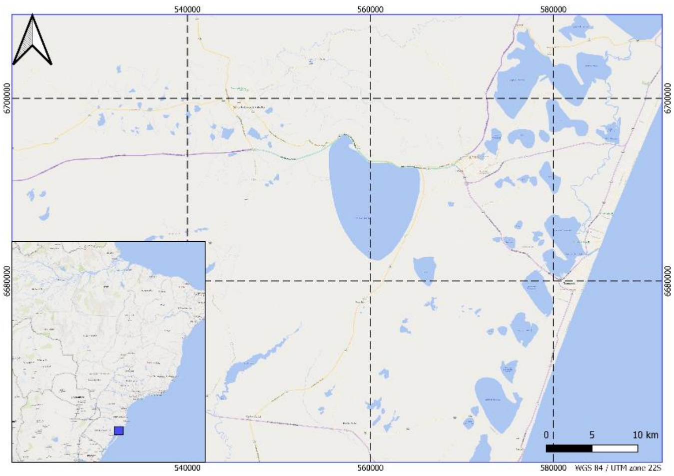

Figure 1 Lagoa dos Barros location

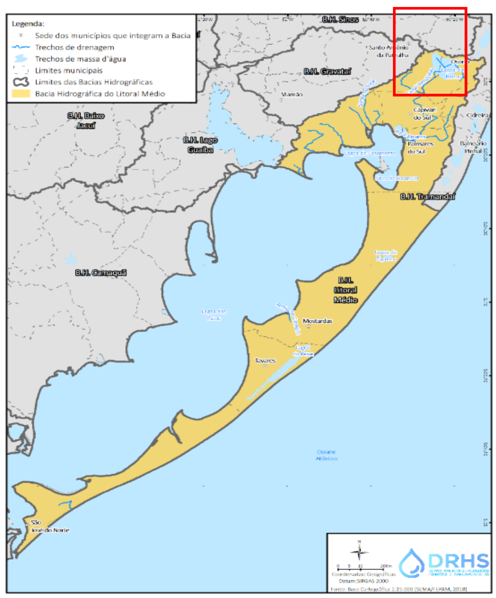

Figure 2 Location of Lagoa dos Barros at Litoral Medio Watershed **(DRHS, 2020)**

Climate

The region presents a humid subtropical climate with warm summers and wet winters with an average of 1775 mm of accumulated Precipitation distributed yearly (STIL, 2021) with an average temperature of 17.6°C, and the summer season happening from December to March, and winter months from June to September.

Topography and Geology

The coastal region of Rio Grande do Sul is a vast plain area where Lagoa dos Barros is located. It suffers from strong winds that influence the mixing within the water body. Additionally, due to the shallowness of the lagoon, the radiation impacts the movement inside it, by increasing rapidly its temperature influence the density of water and consequently circulation. Wind and radiation significantly affect the water cycle and the movement within the system.

Northwards Lagoa dos Barros is a mountainous zone (Figure 3) where Mesozoic sedimentary covers volcanic rocks from the Parana watershed over a confined granular aquifer. There is suspicion of an aquifer that recharges the Lagoa dos Barros once a regional flow of groundwater could explain the freshwater at the lagoon and its maintenance as a freshwater body. Thus this hypothesis should be further investigated in the field.

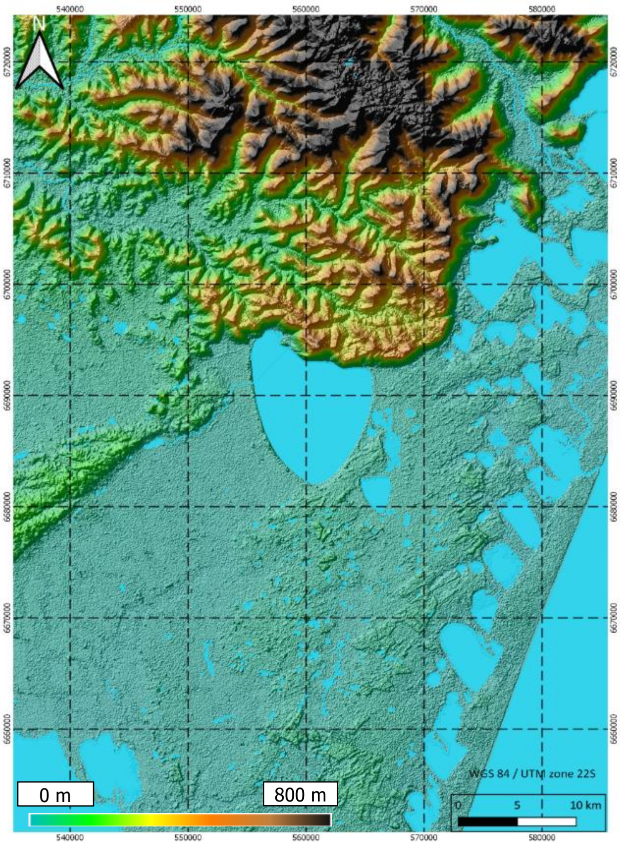

Figure 3 Map of Digital Elevation Model **(NASA - EARTH DATA, National Aeronautics and Space Administration,**

From several sources consulted and based on the topography, there are different interpretations about the delineation of the LB watershed. The CBLM suggests one with a drainage area of 377 km^2, while the study by UFRGS, 2015 presents a drainage area of 242 km^2 (Figure 4), and finally two studies, one of Gomes da Silva & Selistre (2016) and Villena (2020) estimate the watershed delineation with an area of 152 km^2 which is closest to the one presented by this author as Result.

Hydrogeology

In the plain area, sandy sediments maintain an unconfined aquifer recharged mainly by Precipitation

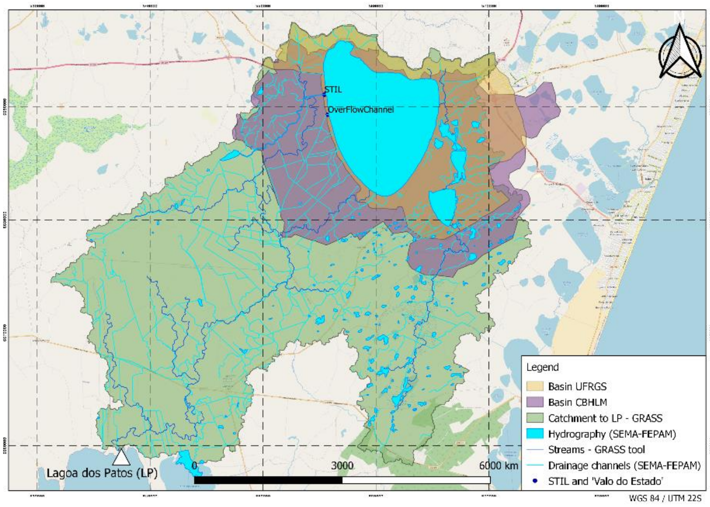

Figure 4 Watershed Delineations, drainage channels **(FEPAM - SEMA, 2005)**, streams constructed with GRASS tool in QGIS Software **(NASA - EARTH DATA, National Aeronautics and Space Administration, 2000) (STIL, 2021) (Gomes da Silva & Selistre, 2016)**

and runoff from the volcanic areas. The deposits found in the plains region of Lagoa dos Barros are originated from eroded higher lands, which through time remained trapped in the coastal lagoons and other barriers environments (Tomazelli, Dillenburg, & Villwock, 2000). Summary, the plain area where Lagoa dos Barros is found, presents mainly deposits characterised by sand and eolian origins from the Quaternary period, trapped within the barriers systems, with altitudes reaching a maximum of around 25 meters above sea level. Despite the North, the Serra Geral scarp, where the altitudes reach more than 300 meters with high steepness of around 45% in some parts (Marchett, 2017).

Accordingly to the book "*Atlas do município de Osório*" (UCS, 2017) groundwater in the region is associated with different types of aquifers that are part of three large systems: Quaternary Coastal Aquifer System (Sistema Aquífero Quaternário Costeiro, SAQC), Serra Geral Aquifer System (Sistema Aquífero Serra Geral, SASG) and Guarani Aquifer System (Sistema Aquífero Guarani, SAG). The systems are described next, and a schematic view is presented as a conceptual site model in Figure 5 to ease the region's hydrogeology understanding.

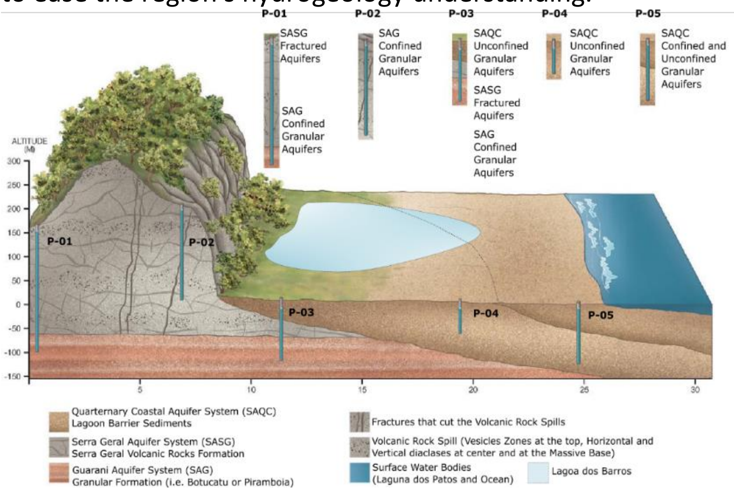

Figure 5 Lagoa dos Barros hydrogeology system **(CPRM, SIAGAS, 2021)** Adapted from **(UCS, 2017)**

The lack of a piezometric monitoring network in the region is a challenge. The Geological Service of Brazil website Map (CPRM, SIAGAS, 2021) presents only one monitoring well in the interest region within a radius of 24 km. The well is adjacent to the Lagoa dos Barros border and to the Waste Water Treatment Plant of Osório (WWTP), where the well is named PM_ETE and monitors the unconfined aquifer of 30 meters thick. The piezometer is located at an altitude of 12.481 meters and records groundwater depth from August 2012 till September 2020. The present work relied on these records to support the simulation results analysis and validate data to investigate the aquifer interaction and influence on Lagoa dos Barros water level.

Spillway Channels

To maintain an adequate water level in Lagoa dos Barros and control the floods adverse effects, as damaging of the surroundings with consequently economic losses, in 1984, the Watershed Committee (Comitê da Bacia Hidrográfica do Litoral Médio-CBHLM) dimensioned and implemented at West of Lagoa dos Barros border the "Valo do Estado" spillway. This spillway is installed at an altitude of 10.6 meters, discharging the excess of water by gravity. Then, in 2016, the need for a reassessment of the channel conditions appeared, given that in 2015 LB reached levels of 11.8 meters (Gomes da Silva & Selistre, 2016). Also, the report from Gomes da Silva & Selistre (2016) evaluated that the farmer's cooperatives pumping water out the Lake to irrigate the downstream land during rainfall summer, from November to March yearly, is a critical measure for the protection of the basin vicinity against floods and it is responsible for the diminishing of 80% on the LB water level each period. Thus, Figure 7 shows the main channels around the Lake, the cooperatives (Sincol and STIL) and the drainage systems connecting the water body to the crops used as irrigation channels.

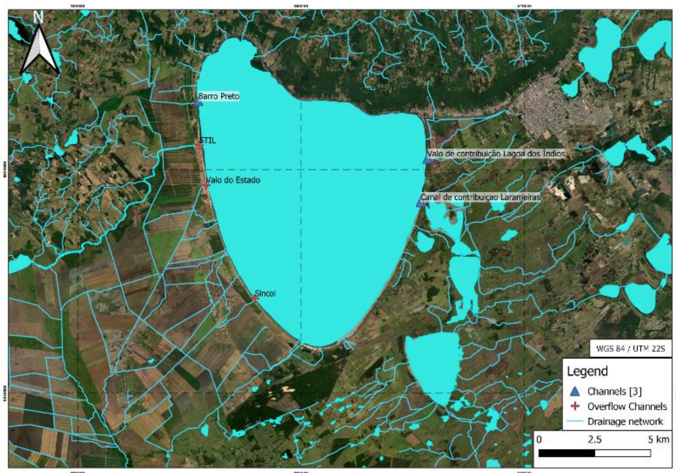

Figure 6 Location of main channels that drains water out and in Lagoa dos Barros **(FEPAM - SEMA, 2005)**

Land Use

The area is covered mainly by agriculture and livestock, native land, forest, anthropised area (roads, urban zone, industrial), water bodies (lakes and coastal lakes). From the agricultural activities, rice may be considered the primary potential source of pollutants to the Lake due to applying pesticides and fertilisers with high amounts of nutrients. Furthermore, farmers drain water from Lagoa dos Barros to irrigate their rice crops during the summer when periods of low Precipitation are frequent, going from October/November until February/March (IRGA - DATER, Instituto Rio Grandense de Arroz - Divisão de Assistência Técnica e Extensão Rural, 2019).

Model Description

MOHID is a three-dimensional water modelling system developed by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Técnico (IST), and it is an open-source hydrological model, which its code can be accessed online. MOHID model permits the use of the model in any dimension (one, two or three-dimensional). The integration of MOHID several tools (MOHID Water, MOHID Land and MOHID Soil) allows water cycle studies in an integrated approach. The present research applies MOHID Land to understand the dynamics of the complex system of the Lagoa dos Barros basin. The simulation domain can be discretised by a regular grid, quadrangular or rectangular horizontal plane, and by a cartesian coordinate system in the vertical direction. Thus, a 2D horizontal grid describes surface land, and the 3D domain represents the porous media that includes the same horizontal Grid as the surface complemented with a vertical grid with variable layer thickness. The modules used in this work were Atmosphere, Porous Media, Runoff, Vegetation, and the detailed model description were obtained from Oliveira et al. (2020).

Infiltration

The MOHID-Land model calculates soil water infiltration rate (i, LT^{-1}) accordingly to Darcy's law (Equation 1) and the Green and Ampt method(Equation 2) (Green & Ampt, 1911).

$$i = -K_{sat}\left(\frac{\partial h}{\partial t} + 1\right)$$

Equation 1

$$i = \Delta\theta \left(\frac{D_0}{2t}\right)^{1/2}$$

Equation 2

Wherefrom Equation 1 K_{sat} is the saturated soil hydraulic conductivity (LT^{-1}), *h* is the soil pressure head (L), z is the vertical space coordinate (L).

In Equation 2, *t* is the time (T), D_0 is the soil water diffusivity (L^2T^{-1}), $\Delta\theta$ is the difference between the volumetric water content in the wetted region (θ_0) and soil initial conditions (θ_i) ($\Delta\theta = \theta_0 - \theta_i$, L^3L^{-3}), where the soil water diffusivity (D_0) can be calculated as:

$$D_0 = \frac{K_0 \Delta h}{\Delta\theta}$$

Equation 3

Where K_0 is the hydraulic conductivity of the wetted region (LT^{-1}), Δh is the difference between the matric head in the wetted region (h_0) and at the moving front (h_F) ($\Delta h = h_0 - h_F$).

Surface flow

The surface flow is computed by solving the Saint-Venant equation's conservative form, accounting for advection, pressure, and friction forces as Equation 4.

$$\frac{\partial Q_u}{\partial t} + v_v \frac{\partial Q_u}{\partial x_v} = -gA\left(\frac{\partial H}{\partial x_i} + \frac{|Q|Q_i n^2}{A_v^2 R_h^{4/3}}\right)$$

Equation 4

Where *Q* is the water flow in the river (L^3T^{-1}), *A* is the cross-sectional flow area (L^2), *g* is the gravitational acceleration (LT^{-2}), *v* is the flow velocity (LT^{-1}), H_{is} the hydraulic head (L), *n* is the Manning coefficient ($TL^{-1/3}$), R_h is the hydraulic radius (L), and the subscripts *u* and *v* denote flow to *x* and *y* directions.

Porous Media

Richard's equation (Equation 5) calculates the water movement of infiltrated water within the porous media as follows:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x_i}\left(K(\theta)\left(\frac{\partial h}{\partial x_i} + \frac{\partial}{\partial x_i}\right)\right) - S(h)$$

Equation 5

Where ϑ is the volumetric water content (L^3L^{-3}), x_i represents the xyz directions (-), *K* is the hydraulic conductivity (LT^{-1}), *S* is the sink term representing root water uptake ($L^3L^{-3}T^{-1}$).

Moreover, the soil hydraulic properties are described using the van Genuchten Mualem functional relationships (Mualem, 1976) (Van Genuchten, 1980) as follows:

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha h|^{\eta})^m}$$

Equation 6

$$K(h) = K_{sat} S_e^l (1 - \left(1 - S_e^{l/m}\right)^m)^2$$

Equation 7

Where S_e is the effective saturation (L^3L^{-3}), ϑ_r and θ_s are the residual and saturated water contents, respectively (L^3L^{-3}), K_{sat} is the saturated hydraulic conductivity (LT^{-1}), (L^{-1}), η (-) are empirical shape parameters, *m* is calculated as (1-1/ η), *l* is a pore connectivity/tortuosity parameter(-). The model applies the Richards equation in the whole subsurface domain and simulates saturated and unsaturated flow using the same Grid. A cell is considered saturated when moisture is above a threshold value (e.g., 98%) defined by the user. When a cell reaches saturation, the model uses the saturated conductivity to compute flow, and the pressure becomes hydrostatic, corrected by friction.

In MOHID-Land, the relation between the horizontal and vertical hydraulic conductivities is defined by a factor ($f_h = K_{hor}/K_{ver}$) that the user can adjust. In this model, the factor is 10.

Root water uptake

It considers the weather conditions and soil water contents. The reference evapotranspiration rates (ET_o, LT^{-1}) are first computed according to the FAO Penman-Monteith method (Allen, Pereira, Raes, & Smith, 1988), where crop evapotranspiration rates (ET_c, LT^{-1}) are then obtained from the product of ET_o and the single crop coefficient (K_c) as follows:

$$ET_c = K_c * ET_o$$

Equation 8

In this study, K_c is imposed, with the model assuming a constant value representing the average characteristics of each vegetation type over the entire growing season and the average effects of evaporation from the soil (Canuto et al., 2019). The resulted ET_c is partitioned into potential soil evaporation (E_p, LT^{-1}) and crop transpiration (T_p, LT^{-1}) as a function of the simulated leaf area index (LAI, L^2 L^{-2}) (Ritchie, 1972)

$$T_p = ET_c(1 - e^{(-\lambda LAI)})$$

Equation 9

$$E_p = ET_c - T_p$$

Equation 10

Where λ is the extinction coefficient of radiation attenuation within the canopy (-), LAI values are simulated using a modified version of the EPICmodel (Neitsch et al. 2011) (Williams et al. 1989), considering the heat units for the plant to reach maturity, the crop development stages, and crop stress (Ramos et al. 2017). Finally, the actual soil evaporation (E_a, LT^{-1}) is calculated from E_p values by imposing a pressure head threshold of -150 as default (American Society of Civil Engineers (ASCE), 1996).

Methodology

Data

The STIL (Sociedade Técnica de Irrigação) station measures daily Precipitation in mm, and water level in meters, used as a data reference (see location in Figure 4). The values are being recorded since 1999. The Lagoa dos Barros' water level varies between 9 and 11.5 meters, with an average of 10.4 meters above sea level. Furthermore, the groundwater monitoring data was obtained from CPRM from the well PM_ETE located at LB Eastside. Additionally, data from an automatic meteorological station from INMET-BMPE (Instituto Nacional de Meteorologia – Banco de Dados Meteorológicos) in Tramandai, located 30 km from Lagoa dos Barros, was downloaded on an hourly basis from 2010 to 2020. It is essential to mention that the records from this station present significant gaps of information for all variables, leading to high uncertainty about its correspondence to reality. Due to these gaps, reanalysed climate data were obtained from ERA5 (ECMWF , European Centre for Medium-Range Weather Forecasts, 2021) from January 2017 to December 2020. ERA5 is the acronym of ECMWF Atmospheric Reanalyses of Global Climate 5th Generation and estimates hourly a large number of atmospheric, land and oceanic climate variables.

Data Analysis

Different goodness-of-fit tests were considered for assessing climatic model performance. A statistical approach was used to compare data from meteorological stations and data from climatic reanalysed models to confirm whether the modelled information is consistent with the observed data for the parameters of Temperature and Precipitation. It was necessary to exclude several lines from the Tramandai station (INMET) due to a high period of empty cells. Thus, periods without data on the observed stations were not considered in the analysis because of the high error resultant. Additionally, it is relevant to remember that this analysis is made to check the validation of the climatic model data to verify whether their implementation on the simulation is coherent. The statistical approaches used in this work were based on Oliveira et al. (2020), which describes the root mean square error (RMSE), the RMSE-observation standard deviation ratio (RSR), Nash and Sutcliffe model efficiency (NSE), the per cent bias (PBIAS) and the coefficient of determination (R^2). According to Moriasi et al. (2007), the model performance can be classified as satisfactory when NSE>0.50, PBIAS±25%, $R^2 > 0.5$, RSR≤0.70.

Temperature Tramandai (station observed) vs Tramandai (modelled)

The parameters present NSE of 0.94, PBIAS of 0.45, RSR of 0.25 and R^2 with 94% correlation between the two analysed data, meaning an appropriate fit between modelled values and the recorded in Tramandai station. Thus, the temperature data from ERA5 is used as atmospheric conditions input to substitute Tramandai records data due to significant gaps in the meteorological station.

Precipitation: STIL (station observed) vs STIL (modelled)

The parameters present NSE of -0.06, PBIAS of 21.07, RSR of 1.03 and R2 with a 5% correlation between the two analysed data. Thus, it is possible to say the modelled values for precipitation present a low correlation to the reality in the region recorded at STIL. This situation can be due to the specific characteristics of Lagoa dos Barros location, such as the proximity with the Serra Geral that acts as a barrier forcing the air masses to condensate and precipitate above Lagoa dos Barros producing localised conditions in the area. Furthermore, it is essential to notice that STIL writes the values just in the border of Lagoa dos Barros, being more accurate than the modelled, then the next step is to verify which precipitation records present stronger influences on the water levels found in the region.

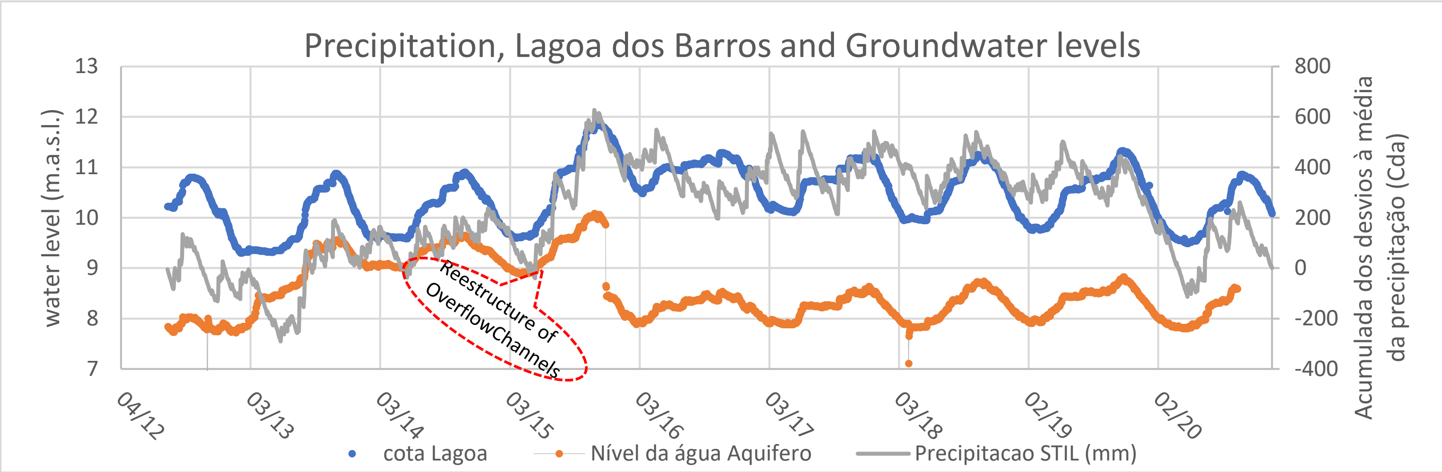

Figure 7 Precipitation, Lagoa dos Barros **(STIL, 2021)** and Groundwater **(CPRM, SIAGAS, 2021)** evolution**.**

Precipitation and water levels relationship

Cumulative deviations from average Precipitation (Cda) were computed and then plotted with the water level and the groundwater evolution over time to verify if the precipitation evolution behaviour of STIL records is appropriate to the water level variations (Figure 7). It is possible to suggest an association between the variation in the aquifer water storage with Precipitation, where the aquifer system and the water body present similar behaviour in response to rainfall recorded at STIL. Thus, the Precipitation from STIL is the most appropriate to consider as representative of the region-specific characteristics. The question is whether the aquifer responds to the lagoon's behaviour, vice versa or acts in both directions depending on the system conditions. As a result, the gathered information from the water bodies variation and the topography analysis supports the proposal of the flow dynamics within the area. At the end of 2015, it is visible that a modification in the area impacted the groundwater level directly in the vicinity of the Lake, which can be the implementation and restoration of the capacity of the overflow channels around Lagoa dos Barros. Thus, the groundwater table is impeded to increase higher altitudes than the channels, which is perceptible after 2016, because when the level is reached, it flows throughout these networks channels by gravity. Moreover, the relationship between the lagoon's surface water level and groundwater table variation is way more significant after 2017 (R^2 0.8) than the whole analysis period since 2012 (R^2 0.06). This variation on the determination coefficient (R^2) can be due to the reform of the spillway channel in 2015/2016, where the system readjusted to achieve a new equilibrium.

Watershed Delineation

Because of divergences, different approaches were applied to comprehend the surface dynamics around LB and within the Basin. So, the Digital Elevation Model, DEM (NASA - EARTH DATA, National Aeronautics and Space Administration, 2000), was used to delineate the streams and the watershed. It was constructed in QGiS Software with GRASS tool, resulting in the outlet of the Basin as the Lagoa dos Patos margin (Figure 4).
Hence, as presented in Figure 8, a detailed analysis on the elevation using Google Earth Engine and the 'Terrain profile' tool in QGis through the DEM, together with the channels delineation and interviews with local people, supports the understanding of the area hydrodynamics and the final definition of the Lagoa dos Barros contributing basin. The micro Basin contributing solely to Lagoa dos Barros, mainly at East, was investigated through several cross-sections of Lagoa dos Barros created perpendicular to its border to visualise the relief, and the most probable division of the hydrographic Basin contributing to the lagoon is presented in the Results. Nevertheless, the analysis confirmed that Lagoa dos Barros is located in an upper part of the Basin, i.e. the flow goes through the delineated streams towards the outlet to the South.

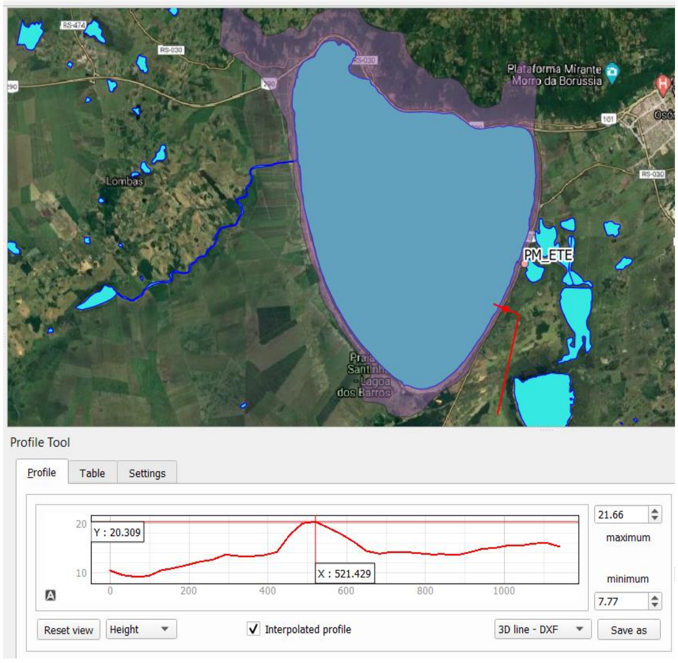

Figure 8 Profile tool visualization of QGis software applied around Lagoa dos Barros vicinity and micro basin delineation in purple.

Water Balance

The water balance of Lagoa dos Barros supports identifying possible contributions as recharge or discharge to the water body and understanding the dynamics of the LB system. The water balance comprises three main factors: the input, the output water contents in the Lake, the volume variation based on the surface area and the water body level, and the groundwater can be added as a resultant positive or negative (donating or receiving water from the Lake).

The method considers rainfall as input, the evaporation from Penman equation (Linacre, 1977), to estimate the volume of water for irrigation estimated from users in the region (STIL, 2020 and IRGA, 2020) and discharge into Lagoa dos Barros from the WWTP (CORSAN, 2020) are all described in the following sections. The limitation of this approach is that the balance only considers the Lake's surface area without contemplating the Basin that contributes to runoff. Thus the input of water can be underestimated and need to be carefully analysed.

Based on the water balance theory, Precipitation is compared with the variation of the water level in the lagoon. To isolate variables and notice the effect of precipitation input only at the surface area of Lagoa dos Barros, the months where there is no discharge to irrigation were considered because of the strong impact on the lagoon water level. The variables are being considered separately to visualise the impacts of each factor and infer specific conclusions by decreasing the variables then the probability of errors. Thus, if necessary, knowing the maximum possible increase by Precipitation, the remaining variables can be considered. The objective is to see if the Precipitation falling within the water body can influence the observable variations and identify if excluding the surface runoff contribution or another source is significantly relevant to the system behaviour.

Simulations

Two main simulations were analysed. The catchment area was delineated to simulate the runoff containing only information on the land use (using manning coefficient) to perceive the flow within the Catchment considering Lagoa dos Patos. This Grid was created in the Geographic coordinates WSG84, presents 50x50 cells measuring 1x1 km and the origin at -50.6513 Longitude and -30.2942 Latitude.

The basin area's Grid was created in the Geographic coordinates WSG84, including 100 columns x 100 rows with a pixel measuring 0.003 with origin at-50.20174 in the x-axis and 0.002 degrees and -30.051177 in the y-axis, which corresponds to approximately 300x200 meter grid. At OpenfLowsFLOOD, the Lake's bottom is merged into the DTM to create the terrain in the more detailed Grid, considering the porous media and vegetation modules beyond the runoff.

The methodology compares the modelled results of water level with observed data from Lagoa dos Barros. Where different simulations are developed and the results compared with reality allowing inducement of hypothesis on the system behaviour. The methodology behind it is that several simulations are developed, and in each stage, a different property is added to the simulation.

The **initial conditions** are information on the water level at Lagoa dos Barros, selected from STIL records. It is necessary to find the level on 1st January 2018, when the simulation begins, 11.08 meters at this date. This day was chosen because of the warming period the model needs to stabilise the system and provide accurate results for 2020.

Land Use was downloaded from the GlobCover Portal, an ESA initiative in partnership with JRC, EEA, FAO, UNEP, GOFC-GOLD and IGBP. The GlobCover 2009 (ESA, European Space Agency; UCLouvain, Université Catholique de Louvain, 2009). The shapefile of the land use is selected together with the final Grid. Then, land use features are presented in the Shapefile Value, where each specific value represents a different land use and needs to be assigned a specific manning coefficient. Associations and comparisons were made based on Van der Sande, de Jong, & de Roo (2003) and Pestana et al. (2013) to estimate coherent values of terrain roughness to insert in the model.

The **soil** raster shapefile is downloaded from the FAO world soil database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009). Accordingly to the database, the soil presents two main horizons, divided into the topsoil (0–30 cm) presenting thickness of 30 centimetres, and the subsoil (30–100 cm) measuring 70 centimetres thick. In the Harmonized World Soil Database map, it is possible to notice two main types of soils in the Basin: at West Planossolos (PL) are found and at East the Arenossolos (AR). Additionally, the database provides information on the soil class, the bulk density and texture of each soil associated. To from obtained information, the tool Rosetta from Hydrus software was applied to compute the soil hydraulic parameters based on the mentioned information, such as residual water content ϑr (L^3L^{-3}), saturated water content ϑs (L^3L^{-3}), saturated hydraulic conductivity Ks (LT^{-1}), and α (L^{-1}), n and l are Van Genuchten water retention curve parameters.

The **vegetation** was inserted as the same distribution as the soil cover (ESA, European Space Agency; UCLouvain, Université Catholique de Louvain, 2009). One averaged value was chosen to represent each vegetation type in the whole simulation period. The information was obtained from Allen, Pereira, Raes, & Smith (1988), which describes the parameters used by the model to estimate evapotranspiration in different soil uses.

In MOHIDLand, the **discharges** are estimated using the irrigation requirements based on information obtained from STIL and IRGA (STIL, 2021 and IRGA, 2020) and the WWTP effluents discharged from CORSAN's periodical reports (CORSAN, 2020) processed to insert the model correctly. For the simulation, an averaged flow of $16.14m^3/s$ for each irrigation period is removed from Lagoa dos Barros and was distributed into the three central farmers cooperatives, agreeing with Gomes da Silva & Selistre (2016).

Results

Water Balance

The behaviour of the aquifer is added to the graph to compare the precipitation input and lagoons' surface water level as the monthly difference in mm/month. It can be inferred, from Figure 9, that all the areas stay inundated just after the pumping stops, and the irrigation happens because of the rice crops. Thus, the infiltration also recharges the aquifer. Additionally, a decrease in the Lake's level and an increase in groundwater level without any imposed condition may mean the lagoon is losing water to the aquifer in these two ways baseflow and irrigation channels. And if we focused on May 2020, Lagoa dos Barros loses more, and the unconfined granular aquifer would increase its level and storage because of the remaining effect of the previous month, for in the next month, both water bodies increases at the same rate, meaning a correlation between them., which may be receiving from the lagoon. Nevertheless, it is relevant to mention that this month was when the algae blooms occurred at Lagoa dos Barros, then groundwater may not contribute to the water body but receiving from it, for in the next month.

Simulations

Figure 10 presents the MOHIDLand Runoff result for 1st May 2020 at left, which present a previous monthly accumulated rainfall of 25 mm in April, and at right is presented the runoff at 31st May 2020, after precipitates 135 mm in May 2020. The minimum visible water column is set as 0.01 m, and the minimum flow of 0.01 m^3/s was selected for visual purposes. The image shows variations evident, especially in the East direction, where the flow increases in Lagoa dos Barros after a wet period as of May 2020, meaning the surface flow at the end of this month could contribute to the water body.

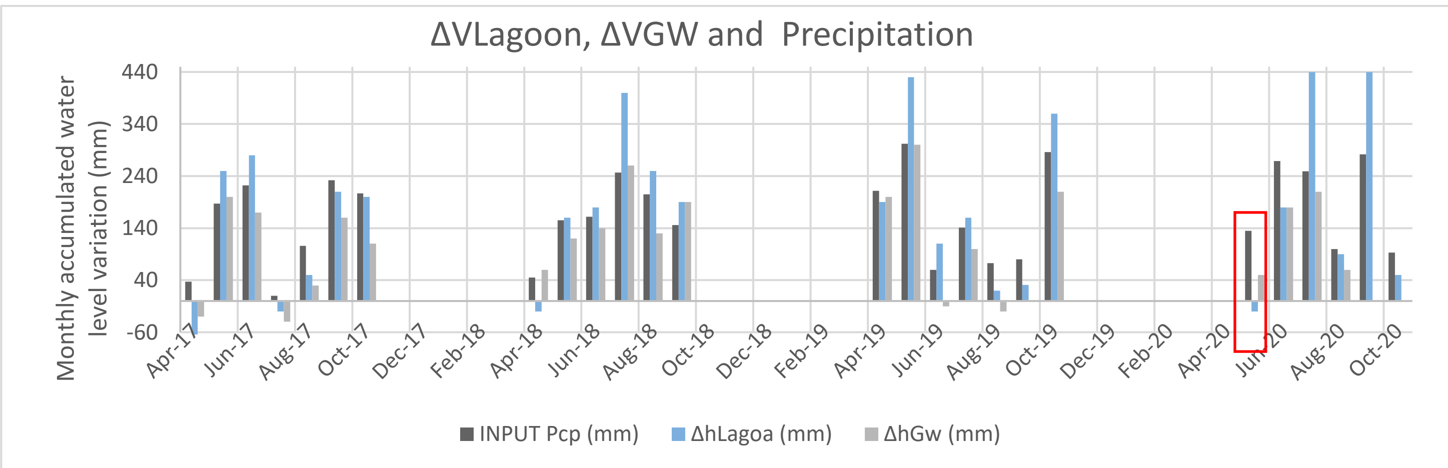

Figure 9 Monthly comparison of volume variation in Lagoa dos Barros, in the aquifer and the precipitation input in mm.

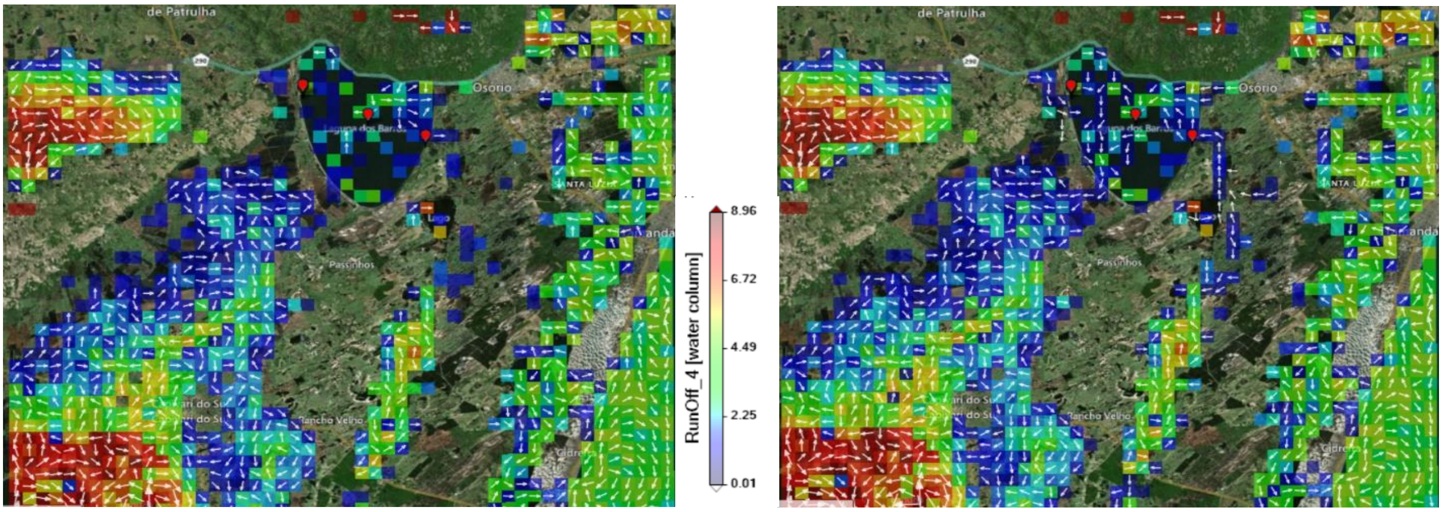

Figure 10 MOHIDLand Runoff simulation result for 1st May 2020 (left), and 30th May 2020 (right). Minimum water column of 0.01 meters and minimum flow of 0.01 m^3/s.

However, after the extensive terrain analysis and local interviews, it is essential to mention that the 'Rodovia Gov. Mario Covas' (BR-101, Figure 11) act as a higher elevation plateau, passing through the eastern border of Lagoa dos Barros. This road has existed since the beginning of the XX century, which is used to connect and trade towards the country North direction, aiming to develop the transportation and economy of Brazil (Nunes, 2008).

Figure 11 Location of the Road BR 101 at Lagoa dos Barros Eastern direction connecting South to North **(Google Earth)**

Since the start of the century, the migration with horse troops followed this path, which naturally presented higher altitudes than the rest of the coastal region characterised by a vast flat area. Thus, it is essential to consider this characteristic to infer that the road acts as a topographical barrier at East, avoiding the water return to Lagoa dos Barros as presented in the MOHID results as Figure 10 shows.

The simulation of the area containing Lagoa dos Patos is analysed to confirm the area surface flow dynamics present the flow direction as arrows. At the West of Lagoa dos Barros is possible to see the small strip that point to Lagoa dos Barros direction, then runoff leaving the water body flowing to the South and reaching Lagoa dos Patos in the Southwest of the Grid. The small area contributing to the lagoon is noticeable from the North, where the arrows point to the South. Then, in the East, many cells drain the flow to Lagoa dos Barros. However, it is essential to mention that the detailing of the Grid cannot identify the drainage network that highly influences the flow in the plain area.

Based on the gathered information through the different approaches, it was possible to estimate the runoff contribution area around Lagoa dos Barros with around 126 km^2 compared to the watershed of 985km^2 (Figure 12). Remembering this delineation does not consider the area that drains the West's channels from Lagoa dos Índios and its surroundings, which drains to the channels and contributes to the volume of lagoons in high rainfall periods.

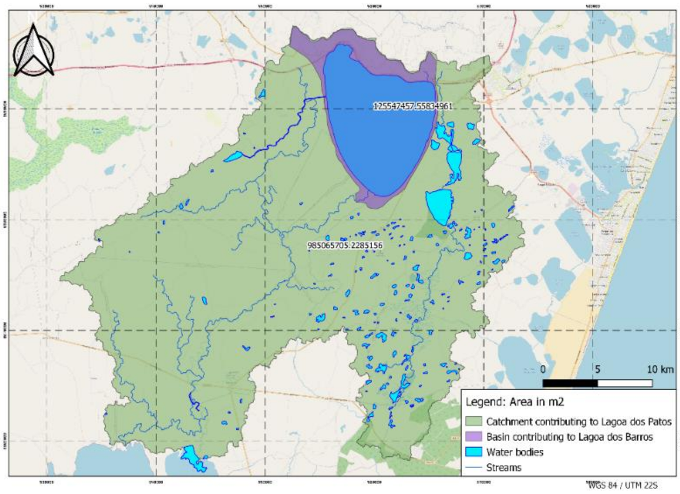

Figure 12 Catchment delineation (Lagoa dos Patos outlet) MicroBasin Lagoa dos Barros and respective areas in m^2

The two simulations were then finally analysed. The Result from MOHID considering the total soil thickness of

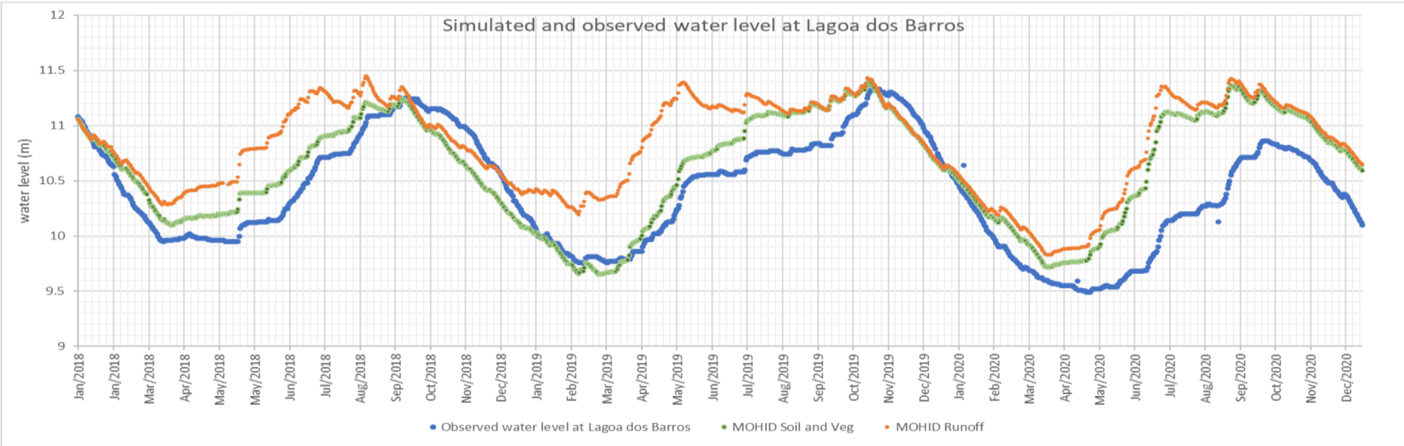

Figure 13 Simulated MOHID Results and Observed values at Lagoa dos Barros

10 meters, the vegetations with their respective crop coefficients and a different simulation considering only the terrain and the manning controlling runoff, evapotranspiration and discharges active during the simulation are plotted with the observed water level in Figure 13. The model's output results of the simulated water levels placed at the centre of Lagoa dos Barros is plotted with the observed values for Lagoa dos Barros recorded at STIL. Despite assumptions, the modelled curves present an appropriate behaviour compared to reality. This overestimation behaviour of the simulated values can be due to the estimates applied to a few factors such as approximations and assumptions applied during area characterisation to model. Firstly, the irrigation pumped during the period may have been underestimated in estimating 16.14m^3/sec. Also, the simulation doesn't recognise the limit of 10.6 meters of water level as the Valo do Estado spillway, which should not be considered but should diminish the level from the modelled Result. Also, the area presents many groundwater users who are not identified. However, they present active pumping wells for domestic and agricultural use, which is not being considered and can influence the hydraulic gradient of the region, increasing it and imposing a different condition.
Additionally, few barriers as roads and dikes built in the vicinity of Lagoa dos Barros aren't defined in the simulation, while they highly influence the flow dynamics due to the flatness of the area. The uncertainties and errors from the model are attributed to the estimations made for soil parameters as homogeneous layers and constant characterisation when in reality, the area is highly complex. Also, vegetation estimations and disregarding its seasonality influence the behaviour because of the evapotranspiration extracting water from the soil and affecting the hydraulic gradient in the area and between the water storage systems. And finally, channels discretisation is not considered in the model and highly influence the flow dynamics.

Conclusions and Recommendations

After temporal and physical features analysis through different approaches, the objective of characterising this complex area and the different water relationships and dynamics resulted in a few conclusions and suggestions.
The hydrogeological water balance of the Lake with information from Satellite Sentinel-2 and the lagoon's water level from STIL was used to derive the volume of water and quantity of the variation in a specific time. When computing the water balance, the discharges for irrigation flow is estimated based on information shared by the irrigation cooperatives and applied in the calculations. Then, groundwater recharge is estimated from water table variation obtained from the piezometer records (CPRM, SIAGAS, 2021). Additionally, because of the uncertainty of water sources to the water body, the work applied MOHIDLand to assess the contribution of Lagoa dos Barros to the aquifer, especially the relation to Eutrophication.
The extensive investigation of the surface and soil flow suggests that the Northern area acts as a barrier where the humid air masses from the ocean shock and condensate, producing a specific localised effect with a high amount of rain falling over Lagoa dos Barros and Serra do Mar. This high volume of water percolates through runoff and infiltration at the mountainous fractured aquifer until it reaches the plain area and the channels that outflow at Lagoa dos Barros. The surface flows from the North, directs to the "Barro Preto" channel at the Northwest of its border. The Northern area is an essential contributor of water to Lagoa dos Barros. Moreover, it is relevant to notice that this area presents highly human interference. Activities such as mining (basalt extraction), agricultural practices, and

roads where high traffic intensity occurs are potential detritus sources, and pollution brings them as input to Lake flowing during rainfall events. Thus, it is crucial to preserve this area as a contributor to the interest Lagoon.

Still contributing to Lagoa dos Barros inflow, at Northeast, two channels dictate the main flow from and to Lagoa dos Indios and Lagoa da Ilhota flat area. In this region, surface contribution appears represented as the Laranjeiras and Ilhota channels contributing to Lagoa dos Barros. This plain area travels from Osório until Lagoa dos Barros, where the eolic park and the Waste Water Treatment Plant are located. It is relevant to mention the importance of further analysis on the effluent discharge of the WWTP, which was planned to be injected into the aquifer as the tertiary treatment. At the same time, this area acts as a wetland, not recommended injection of high loads of nutrients because of the low probability of biodegradation due to low aeration processes. Also, the surface flow simulation analysis shows that during wet periods, water could flow from the East region to Lagoa dos Barros, then the importance on the water quality maintenance, even though Road BR-101 is the topographical barrier avoiding the water return to LB. Moreover, the area and groundwater table should be better investigated and studied to delineate a correct groundwater flow, which needs further field data and increased monitoring networks and records. The conceptual model created by the author after the presented study depicts the main water dynamics within Lagoa dos Barros and is presented in Figure 14 below.

When the water levels are high at the end of winter (October), the pumping starts from the two channels placed at the Southwest of Lagoa dos Barros (STIL and Sincol), keeping a constant flow to maintain the irrigation at satisfactory levels since the begging of the planting season. Also, during the high water levels, the water level spillway from Valo do Estado when water reaches 10.6 meters. During the irrigation period (summer), Precipitation is low, and the aquifer is maintained saturated because of the inundated croplands (main rice). Then when the irrigation and the harvesting finish, the pumping stops. Then, water still in the soil naturally infiltrates and recharges the aquifer. However, the lagoon presents a low level, so there is no spillway nor pumping. It takes longer to recover its level because its free surface is more vulnerable than the aquifer. During this period, the lagoon may be losing water to the aquifer because groundwater presents an increase while the Lake decreases its levels, remaining only evaporation and losses to the aquifer be considered.

Their relationship is visible when looking the similar behaviour on the water levels. This study suggests that the aquifer responds to the water body behaviour, mainly receiving from the water body. This similar behaviour can be because of the canals that overflow water in a period of high Precipitation and then recharge groundwater beyond Lagoa dos Barros bottom area and from the area of the channels, serving as an extension of the contribution capacity from the Lake to the aquifer.

It is essential to mention that during the analysis of the borders of the Lake to place the Discharges points, it was

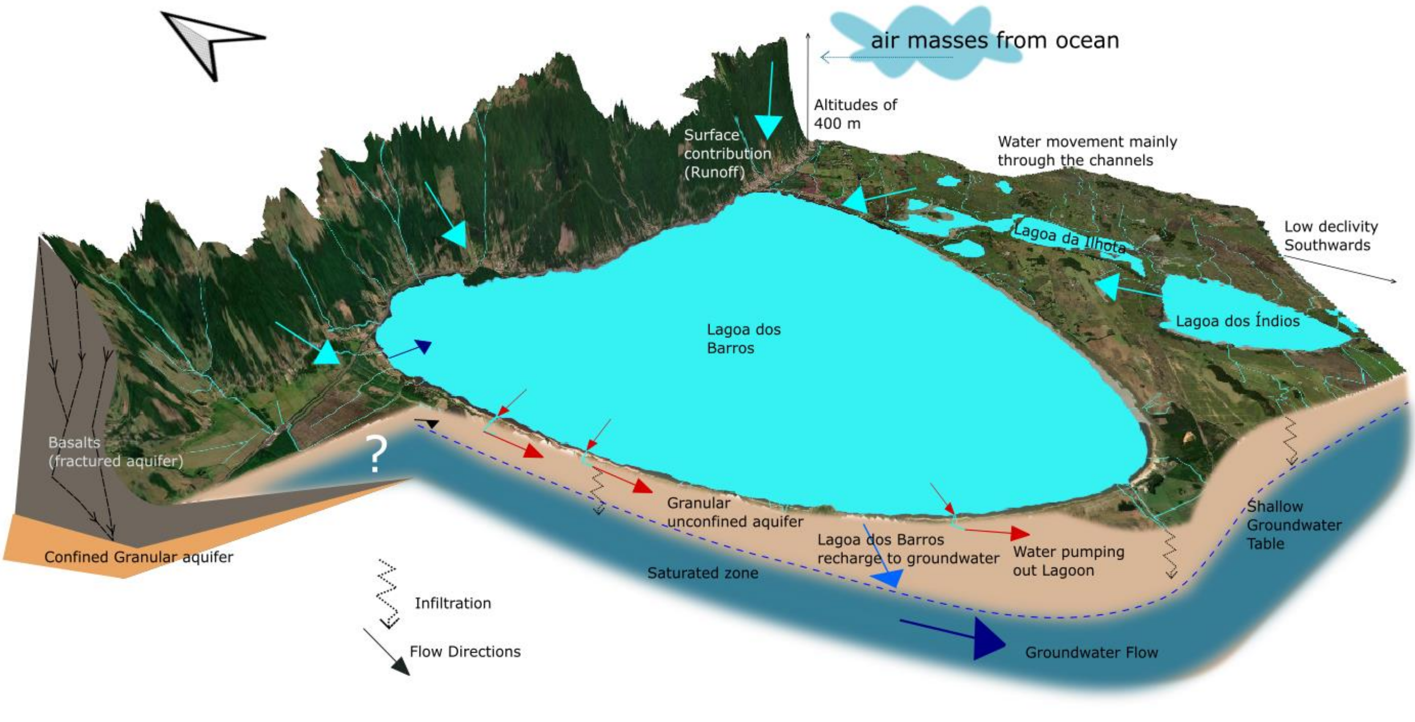

Figure 14 Conceptual Model of Lagoa dos Barros and its vicinity.

noticed the existence of more channels that drain water in or out of Lagoa dos Barros and should be described in detail to comprehend the interactions fully.

It is possible to estimate the flow within the system to understand the dynamics that govern water movement being from the Northern to the Southern zones. Also, the goal was to identify the groundwater flow systems, which was lower than the Lake after 2016, suggesting an interference at this time, which can be the spillway channels implementation that resulted in a new balance on the groundwater table. However, the aquifer still presented a shallow water table in the plain area resulting in a slow movement that discharges into the canals to drain downstream by gravity.

Furthermore, an adequated bathymetry of the Lagoa dos Barros should be made to characterise its bottom formations and geology to identify possible recharge zones, which should be made through field investigation. Aligned with the water body description, field measurements that quantify the contribution or discharge of groundwater on the lake bottom should be applied. It is essential to mention that, due to the high residence time of groundwater during the flow through the soil, it suffers different processes controlled by soil characteristics. Thus, the physical and geochemical properties of the area are critical information to predict and describe the behaviour of nutrients and minerals through groundwater paths within the soil.

Finally, soil characterisation and groundwater table monitoring should be implemented in the area. For being a strict flat area, the dynamics are influenced by slight differences in the hydraulic gradient, where surface and groundwater constantly move through these storage systems. Thus, with better field data, a better characterisation should also be made on the model where the identification and detailing of soil layers as the Grid's refinement decreases the size of the cells and implements the spillway channels dimensioning its flows as the affluents.

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