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

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Thesis to obtain the Master of Science Degree in

Environmental Engineering

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Resumo

Lagoa dos Barros está localizada na bacia do Litoral Medio, na planície costeira do Rio Grande do Sul, no Sul do Brasil. No entanto, não é classificada como uma lagoa costeira porque a morfologia da região impede a ligação directa com o oceano, sendo a Lagoa dos Patos a saída da sua bacia hidrográfica. A lagoa cobre 92 km^2 de água doce e é extremamente importante para as atividades econômicas da região, principalmente a agricultura com culturas irrigadas de arroz que utilizam água da lagoa durante o verão. No entanto, no final de 2019, a eutrofização começa a ser visível na lagoa, atingindo seu pico em maio de 2020. Assim, a estação de tratamento de águas residuais, implantada em 2009, mas que iniciou sua operação no final de 2018, foi considerada a principal causa possível devido a descarga de seus efluentes sem tratamento terciário, que remova nutrientes, no corpo hídrico.

Assim, o foco deste trabalho foi identificar as fontes primárias de água para Lagoa dos Barros para então ser mais fácil identificar a causa mais provável de Eutrofização que ocorreu em 2020. Diferentes abordagens foram aplicadas para interpretar a dinâmica da complexa área. O modelo físico juntamente a diferentes abordagens como o balanço hídrico e estimativa de recarga de aquíferos são aplicados para avaliar as relações entre os sistemas aquífero e lacustre. Em seguida, verificasse que a contribuição das águas subterrâneas para a Lagoa dos Barros não é potencialmente uma fonte de nutrientes que poderiam ter sido envolvidos na causa da alta concentração de nutrientes que causa o florescimento das algas no período em que foi observado.

Este estudo corrobora a condição da lagoa como zona de recarga da bacia hidrográfica do Litoral Médio que desemboca na Lagoa dos Patos. A Lagoa dos Barros recebe água através dos canais tributários a partir da precipitação e escoamento das áreas Norte e Nordeste, onde atividades poluentes intensas são uma fonte potencial de alta carga de nutrientes que devem ser controladas. É importante notar que uma estrada BR-101 para o leste da Lagoa está historicamente localizada em altitudes mais elevadas do que o entorno e serve como uma barreira para o retorno das águas no lado nordeste do corpo de água. Por outro lado, a retirada de água deve-se à evaporação, ou após atingir um determinado nível, é drenada para fora da lagoa através dos canais de escoamento ou é retirada por bombagem para irrigar as terras agrícolas circundantes, e também pode ser considerado uma pequena porção perdida pelo escoamento subterrâneo contribuindo para a recarga do aquífero costeiro.

Então, em maio de 2020, com um baixo nível de água, a Lagoa dos Barros diminui seu nível uma vez que o lençol freático aumenta no mesmo período, o que significa que a água subterrânea não é relevante para o florescimento de algas observado no lago. No entanto, estudos de campo,

implantação de poços monitorando o nível piezométrico da região e canais detalhados devem ser feitos para que a conclusão sobre a perda de água da Lagoa para o aquífero abordado neste estudo seja confirmada.

Palavras-chave: Lagoa, água subterraneas, aquífero, interacções superfície-águas subterrâneas, modelagem, dinâmica de fluxo, balanço hídrico, planícies costeiras.

Abstract

Lagoa dos Barros is a water body located in the Litoral Medio basin, at the coastal plain area in South Brazil. However, it is not classified as a coastal lagoon because the region's geology prevents the direct connection with the ocean, bein Lagoa dos Patos the outlet of its watershed. The Lagoon covers 92 km2 of freshwater and is extremely important to the region's economic activities, mainly agriculture with irrigated crops that use water from the pond during summer. However, at the end of 2019, eutrophication starts to be visible in the water body, reaching its peak in May 2020. Thus, the wastewater treatment plant, implemented in 2009 but started its operation at the end of 2018, 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. The physical-based model, different water balance and aquifer recharge approaches are used 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 as a recharge zone of the Litoral Medio watershed that outflow 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. It is important to note that a road BR-101 to the East of the Lagoon is historically located at more elevated altitudes than the surroundings and serves as a barrier for returning the waters on the Northeast side of the water body. On the other hand, the withdrawal of water is due to evaporation, or after reaching a certain level, is drained out of the lagoon through the outflow channels or is withdrawn by pumping to irrigate the surrounding agricultural land, and can also be considered a small portion lost by underground runoff contributing to the recharge of coastal aquifer. Then, during May 2020, with a low water level, 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, field studies, implementing wells monitoring the piezometric level of the region and detailed channels must be done so that the conclusion on the loss of water from the Lagoon to the aquifer addressed in this study is confirmed.

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

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1. Introduction

Lagoa dos Barros is a vital water body found in the Coastal South of Brazil placed between the cities Santo Antonio da Patrulha and Osório. Because it covers a large extension with fresh water, 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 emergence of algae blooms which had its peak in May 2020 at some places within Lagoa dos Barros. Thus, 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, which processed data is implemented in a physically-based model to support the region's decision-making related to this 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 some practices.

1.1. Background and Problem

1.1.1. Importance of Lagoa dos Barros

The area that contemplates Lagoa dos Barros is very rich in ecological terms, for being relatively young in geological terms (5,000 years old), the ecosystems there are rare and vulnerable. Thus, the importance of maintaining the ecosystem sustainability is directly related to the water body conservation, which is described as a protected zone as the surroundings lagoons, and should be protected by national law, which in theory are prohibited from receiving any water discharge, even after treatment.

Besides the importance of maintaining a healthy environment, Lagoa dos Barros was not inserted in any conservationist plan until 2008. Thus the lagoon was not described to be protected by any legislation. Only after the beginning of the construction of WWTP did the population start to organise the watershed committee with 30 members (Decree 45.460, January 2008) to define and restrict uses of water from Lagoa dos Barros (Herms, Análise do Termo de Licitação da CORSAN., 2015). Hence, it is relevant to mention that just around the lagoon, in Santo Antonio da Patrulha, the Conservation unity Parque Manuel de Barros Pereira is a protected area of Atlantic forest covering around 24.61 ha. The state of Rio Grande do Sul recognises this area as a conservation area and was created under the law of Santo Antonio da Patrulha number 2549/1992.

Santo Antonio da Patrulha is interested in preserving the Lake ecosystem because shortly, the city predicts not being able to supply fresh water for the population, and the option is to use the water from Lagoa dos Barros. Which has consistently been recognised as clean and of good quality for human uses; thus, it was an attractive source to supply the city. This information can be checked through many news and history of the region. (RDI, 2009)

Also, many cities in the surroundings have Lagoa dos Barros as a source of economic income (fishery, livestock, irrigation, tourism), seen as cultural interest due to old relation of the local community with nature, especially water bodies, and uses with recreational purposes to do kitesurf and windsurf as some examples. If the WWTP operates, the negative impacts are beyond the environmental aspects, once the Lake provides many services that can be destroyed with water pollution.

1.2. Current Situation

1.2.1. Waste Water Treatment Plant

March 2007, the Sanitation Company of Rio Grande do Sul (CORSAN), the public statal institution responsible for the sanitary sector in the state together with Osorio city presented a project where they planned to implement a Waste Water Treatment Plant (WWTP) for treating the defects of its inhabitants and dispose these effluents at Lagoa dos Barros afterwards. One month later, the previous license LP.221/2007-DL was emitted by the environmental agency responsible for state issues FEPAM. In December 2007, the operation license was issued. This document provided authorisation to CORSAN to start to construct the WWTP. (Borges, Bordignon, & Sossela, 2009)

The project contemplates a UASB reactor followed by a biologic filter and wetlands, which send the effluent to a mixed emissary, leading to the lagoon by seven pumping stations, increasing the cost of construction and operation. The discharge structure is constituted by a terrestrial emissary that transports the effluent to the equilibrium chimney, responsible for maintaining the treated effluent's constant and continuous pumping flux. After that, the subaquatic emissary is supported or buried in the pond bed, transporting the effluents to the diffuser pipe containing several orifices where the effluent is released into the water body. (UFRGS II, 2015)

Local people organised with the neighbouring city of Santo Antonio da Patrulha presented a repudiation statement in January 2009. The population of Santo Antonio da Patrulha have a strong habit of appreciating Lagoa dos Barros. In December 2008, local people were surprised with the beginning of the construction of WWTP in the Osorio. Citizens from Santo Antonio da Patrulha claim none were consulted about opinion on the project, or any public hearing happened, even though the entire community around the lagoon is directly affected by the station's construction and the discharge of effluents in the lagoon.

At the end of 2008, Santo Antonio da Patrulha presented a document to Osorio’s Major requesting an explanation about the project without answering his questions. Additionally, Professor Dr Freiderich Herms from UERJ (State University of Rio de Janeiro) was reached by the municipality of Santo Antonio da Patrulha to support technical studies about the environmental damages for the water body related to the project. Because, in January 2009, it was discovered that the WWTP did not present the mandatory study of the structure’s environmental impacts, and also that the WWTP does not present the tertiary treatment, which has the function of removing Nitrogen and

Phosphorus from the water. These two nutrients are essential nutrients that influence most reactions within a water body and are related to an organic matter within the complex. If the concentration of the nutrients is elevated, algae phytoplankton, naturally living in equilibrium before, can grow more than usual and cause Eutrophication problems in the lagoon. Consequently, the system's health depends on control when discharging effluents is crucial for maintaining life there (RDI, 2009).

In 2015, CORSAN hired UFGRS (the Federal University of Rio Grande do Sul) to develop a study about the lagoon's physical, chemical and biological characteristics to identify the potential of the water body to receive the effluent. This study has two volumes and supports this research as a source of information; however, critical analysis shows some irregularities in developing some measurements. Thus every information acquired from it is carefully considered. Additionally, it is essential to mention that this study established a value for support capacity of the lagoon of 4 kg per day of Phosphorus. Also, in 2015, FEPAM emitted the operation license Nº 3451/2015-DL, which authorised the actual discharge of 8,684 m^3/day (100.5L.s-^{1}) and a future of 11,577 m^3/day (134.13L.s^{-1}) without tertiary treatment to remove nutrients.

Until the end of 2018, CORSAN insisted on authorising the operation license once the structure was built and ready to operate, even though the WWTP still did not meet the environmental requirements necessary to start functioning.

On December 19 of 2018, the official launch of the WWTP occurred with affirmations of CORSAN that the complete infrastructure could beneficiate around 30 thousand people with the capacity of treating 30% of the total sewage generated by the city of Osorio with an average flow of 100 litres per second of discharge of treated water into the lagoon (CORSAN, Companhia Rio Grandense de Saneamento, 2018). Although the discharge of total Phosphorus in the lagoon was inside the threshold described by the study made by UFRGS in 2015, in March 2020, eutrophication started to grow and be visible on the surface of Lagoa dos Barros (Figure 2), leading to doubts related to the reliability of that study and about the effluents load from the station. Additionally, professor Dr Herms also made a rigorous analysis of the mentioned document. They verified some irregularities with measurements and calculations made by UFRGS in 2015, such as the

Bathymetry of the water body, which can compromise the quality of results since modelling needs accurate data to simulate the real scenario properly. Another point was the permanence time of the lagoon, which is underestimated and not well applied.

Figure 1 Sludge with bloom of cyanobacteria removed from the surface of Lagoa dos Barros in May 2020

During inspection realised by PMSAP (Municipal prefecture of Santo Antonio da Patrulha) in March 2020 at Lagoa dos Barros, after complaints from the local community about the quality of water, there are registries of the security guard Mr Diego Correa, which works in the camping site just around the lagoon, saying that since December 2019 he noticed a visible increase on algae concentration (Figures 1, 2 and 3)

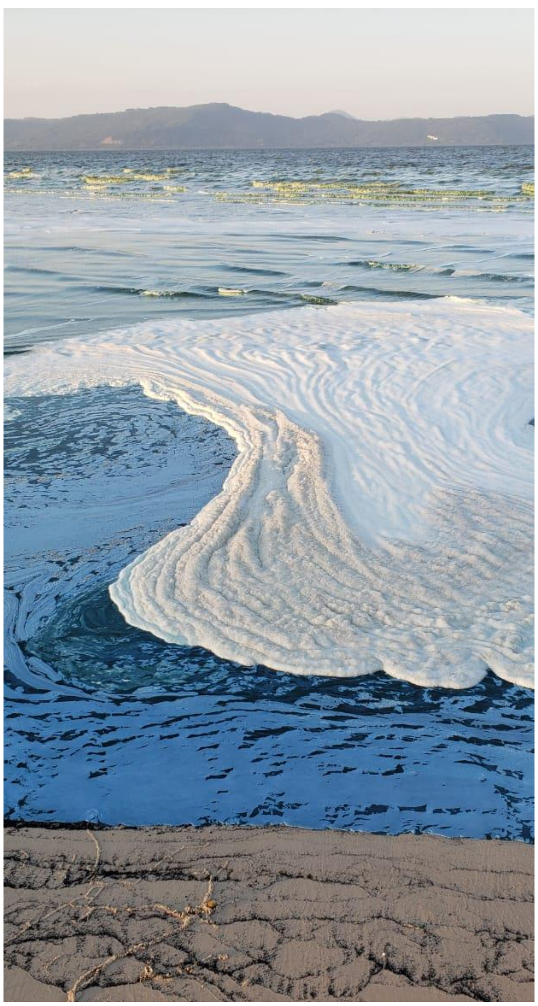


Figure 3 May 2020 at west border of Lagoa dos Barros

Thus, in September 2020, FEPAM suspended the operation license until the adequacy of the effluent nutrients concentration. Then, in December 2020, they emitted another document to CORSAN listing all the necessary changes of the treatment plant and further studies of the lagoon's capacity on receiving the discharge with the deadline of 4 months for those implementations to be made. Otherwise, the process

Figure 2 Cyanobacteria's bloom at Lagoa dos Barros, March 2020

would be archived, as it again happened in April 2021.

Table 1 summarises the central moments during the implementation process of the WWTP in Osorio since its beginning of elaboration in 2007, until the last decision in April 2021 when the license continues temporarily cease.

Table 1 - Timeline of WWTP implementation process

Timeline implementation of WWTP	
2007	Project and studies elaboration by CORSAN and Osorio city
	Previous licence LP.221/2007-DL
	Installation licence LIN.1073/2007-DL
2009	Note of rejection from Santo Antonio da Patrulha city
	Technical Report from UERJ
	Civil Action to cease the project
	Final report installation WWTP
	Construction continues
	Civil Action to cease the project
2011	Civil Court
2013	Court agreement term
2015	Operation license LO 3451/2015-DL
	Final report UFRGS I and II
2016	Technical Report Rio Grande do Sul Public ministry MPRS 823/2016
2019	Official launch operation of WWTP
2020	Eutrophication starts to appear at Lagoa dos Barros
	Operation license LO 3451/2015-DL suspended
	Further studies requested to restart the operation

1.2.2. Eutrophication and groundwater influence on Algal Bloom

Eutrophication has its roots in Greek words: *eu* meaning "well" and *trope,* which means "nourishment". It occurs when a change in natural nutritional status occurs, caused by a high load of nutrients (Nitrogen and Phosphorus) discharged into a water body, increasing its concentration causing Eutrophication (Richardson & Jørgensen, 1996).

In lakes and lagoons containing freshwater, this adverse environmental effect is mainly caused by an overload of Phosphorus. This situation leads to a rapid increase in the algae community, which can cause, in extreme cases, algal bloom (EEA, European Environment Agency, 2016). The consequences of Eutrophication can be severe when the blooms are toxic. There is not a common understanding of how these planktons' toxicity happens and the trigger for it. However, the emergence of bloom brings concerns due to the toxicity risk for animals that use water from these systems, including humans.

Additionally, when algae decompose after it is dead, it consumes oxygen within the water to biodegrade the organic matter, leading to depletion of dissolved oxygen, causing hypoxia and threatening the life of organisms and animals present there (Richardson & Jørgensen, 1996). Also, the vegetation of the lagoon changes to adapt to the new circumstances. This ecological disequilibrium caused by changes in chemical composition also affects the quality of water for recreational and other uses by humans.

The European Water Directive has been controlling the concentration of nutrients in water bodies. With the effective implementation of the law, it was possible to reach a noticeable increase in water quality, especially related to phosphorus concentrations, decreasing over the last few years. The main focus to control phosphorus loads has been improving the efficiency of wastewater treatments plant, including removing this nutrient. Through investments in improving infrastructure and technology, most countries around Europe upgraded the WWTP, adding the Tertiary treatment, which removes nutrients, to comply with the Urban Waste Water Directive and improve water quality around Europe. (EEA, European Environment Agency, 2016)

The difference in residence time of groundwater and surface water leads to distinct waters characteristics. Algal Bloom depends on watershed hydrodynamics, geomorphological, biogeochemical, food-web and climate dynamics related to in-stream pathways. Furthermore, groundwater can play a role in nutrient budget and food-web due to this difference in residence time, resulting in geochemical and physical properties to vary from surface water. And finally, groundwater is the major contributor to benthic and in-stream algae stability, for being a path control for biochemistry, which is described by the hyporheic zone dynamics, which is the mixing area of groundwater and surface water. (Brookfield, et al., 2021)

The recent study from Brookfield et al. (2021) brought novel insights on the relation of Eutrophication with groundwater recharge in a water body. The vertical exchange between shallow and deep groundwater is a high source of input of nutrients in the system, containing high amounts of microbial matter and solutes. Some minerals are essential in maintaining the ecosystem balance, which can exceed or limit the growth of algae and are essential nutrients to algae maintenance. Thus, if the model demonstrates that groundwater plays a vital role in the recharge of the lagoon, these components need to be analysed, aiming not to discard any hypothesis of a source of Eutrophication.

1.3. Hypothesis

Eutrophication started to be visible in the lagoon and was pointed out to be originated from the operation of the wastewater treatment plant. Once the short period after its operation began, the lagoon phenomenon was noticed and reported around one year later. The loads were reported as being within the threshold determined by Universidade Federal do Rio Grande do Sul (UFRGS) in 2015. However, nutrient load analysis of the effluent of the wastewater treatment plant discharging into the lagoon showed higher amounts of Nitrogen and Phosphorus, which may cause disturbance in the system's equilibrium and have contributed to the 'bloom' of cyanobacteria. Consequently, some discussion recommences to appear again around the WWTP in 2020, by the municipality of Santo Antonio da Patrulha, the neighbour of Osorio where the plant is installed.

Moreover, in Lagoa dos Barros, the more robust hypothesis is that the source of nutrients originated from the WWTP. However, attempts to prove that were insufficient to convince authorities to understand the dimension of the problem and its consequences. Thus, the purpose is to gather as much information as possible to elucidate the water body dynamics since 2009. MOHID Land is applied to describe the system dynamics from another perspective, supported by the technical approach used in defence of the equilibrium and maintenance of the ecosystem.

1.4. 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.

Each goal originates a big task that can be individually implemented because it needs different data that can be developed independently, although field information could complement each other.

1.4.1. Specific Goals

Identify the role of groundwater contribution to the system. To achieve the objectives is necessary to divide the task into steps that support and complement each other:

- 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 in Lagoa dos Barros basin;
  - Determination of groundwater recharge and its role in the behaviour of the lake.

2. Study Area

2.1. Location

Lagoa dos Barros is situated in Brazil's southern state of Brazil, Rio Grande do Sul (Figure 5), within the "Litoral Medio" Basin (Figure 4), and is part of the Coastal Plain of Rio Grande do Sul ("Planície Costeira do Rio Grande do Sul", called PCRS).

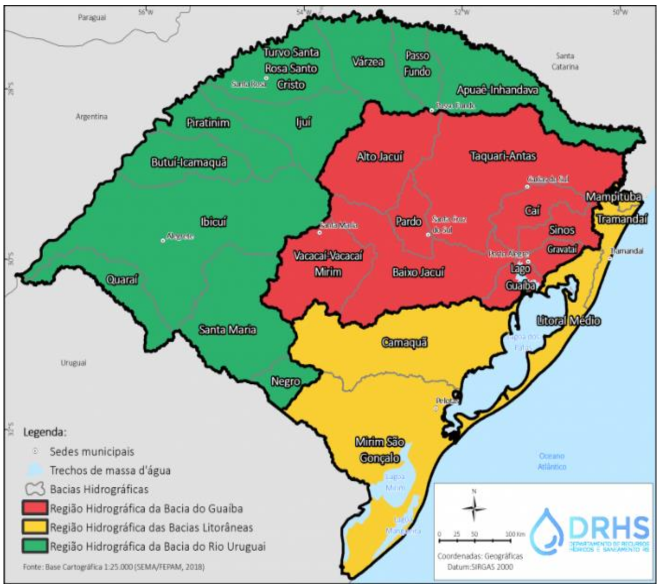


Figure 4 Main Hydrographic wateersheds at Rio Grande do Sul (DRHS, 2020)

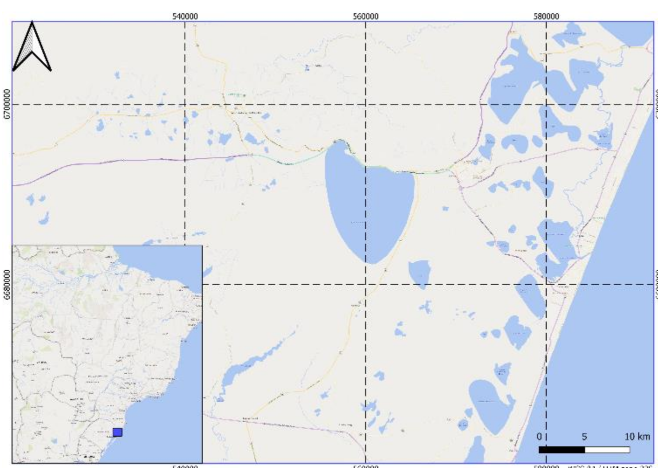


Figure 5 Lagoa dos Barros location

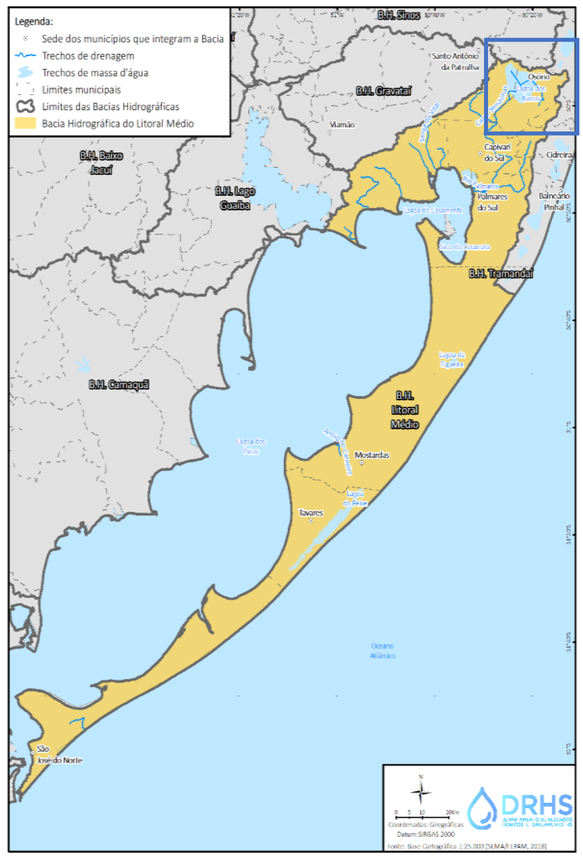


Figure 6 Litoral Medio Watershed delineation, where Lagoa dos Barros is located (DRHS, 2020)

The basin drains water to the ocean through the important Coastal Lagoa dos Patos (Figure 6). Litoral Medio basin is located between WSG84 Geographic coordinates of 29°51′ to 32°11′ South and 50°15′ to 52°05 West.

Litoral Medio watershed compromise an area of 6,113 km^2 where Lagoa dos Barros (92km^2), at Southeast Lagoa Mirim (3,770 km^2) and Lagoa dos Patos (10,000km^2) are found, and municipalities such as Balneário Pinhal, Capivari do Sul, Cidreira, Mostardas e São José do Norte are located (Figure 6) (DRHS, 2020).

Lagoa dos Barros water body appears in the Northeast zone of the Litoral Medio basin, is located between the WSG84 Geographic coordinates of 29°51′ to 30°00′ of South latitude and 50°19′ to 50°25 West longitude (Figure 5). It 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).

Table 2 presents the main characteristics of the Lagoa dos Barros water body, presenting an average area of 92 km^2 and water level that varies of minimum from 7.8 in April 2000 to the peak of 11.86 m.a.s.l. (meters above sea level) in November 2015, with an average of 9.8 m.a.s.l. since 1999 (STIL, 2021).

Lagoa dos Barros is located between the cities of Osório, at East, where Lagoa dos Indios and the Eolic park of Osório can be found. At west, the municipality of Santo Antônio da Patrulha (SAP), where the surface runoff flows through Capivari river later reaching Lagoa dos Patos to the South. In the North of Lagoa dos Barros, the roads RS-30 and BR-290 cross (incorporated in 1933 and 1970 respectively), and around the roads to the Northward direction, the lagoon is delineated by "Serra do Mar", reaching altitudes of more than 800 meters.

Table 2 – Morphological characteristics of Lagoa dos Barros (Source: adapted from (Marchett, 2017)and (UFRGS I, 2015)

Area (km^2)	Perimeter (km)	Length (km)	Largura (km)	Average depth (m)	Maximum depth (m)	Relative depth (%)	Volume (10^6 m^3)
91.78	39.5	14.54	10.13	6.1	4.7	0.06	432

2.2. Climate

The region is characterised by presenting a humid subtropical climate with warm summers, an average of 1775 mm of accumulated precipitation yearly (STIL, 2021) with an annual average Temperature of 17.6 º C, with the summer season happening from December to March, varying around 22ºC on January, and winter months from June to September, presenting a range of temperatures from 3 to 18 ºC in July. The precipitation accumulated monthly is calculated from 2011 to 2020 based on information from the STIL (Sociedade Técnica de Irrigação) station located West of the water body, ceded regularly (Figure 7)

The coastal region of Rio Grande do Sul is a vast plain area, and where Lagoa dos Barros is located, it suffers from strong winds that influence the mixing within the water body. The annual average wind speed in Osório is 6 meters per second (22 km/h), with a minimum of 4.9 (18km/h) and a maximum of 7 m/s (25 km/h), which is characterised as a moderate breeze by Beaufort scale. (INMET, 2021)

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 balance and the movement within the system. Therefore, they are crucial elements to carefully consider during the system's data, processes, and simulation. The air masses in the region are usually associated with anticyclones responsible for the meteorological instability that influence Lagoa dos Barros, which is also affected by rainfall produced by the water condensation when the air masses reaches the Serra Geral hillside.

The climate conditions such as precipitation, radiation and wind are fundamental parameters necessary to understand the system's dynamics we are analysing. These factors are drivers of the physical and biological processes in the water body, controlling recharge, evaporation, and therefore the water balance. By obtaining this sort of information is possible to estimate the rates and fluxes of the system to identify contributions or withdrawals of lagoon water, which also is necessary to implement in the model to approximate the most to the actual scenario.

Figure 7 depicted below makes it possible to visualize the temperature and rainfall evolution in the last 10 years.

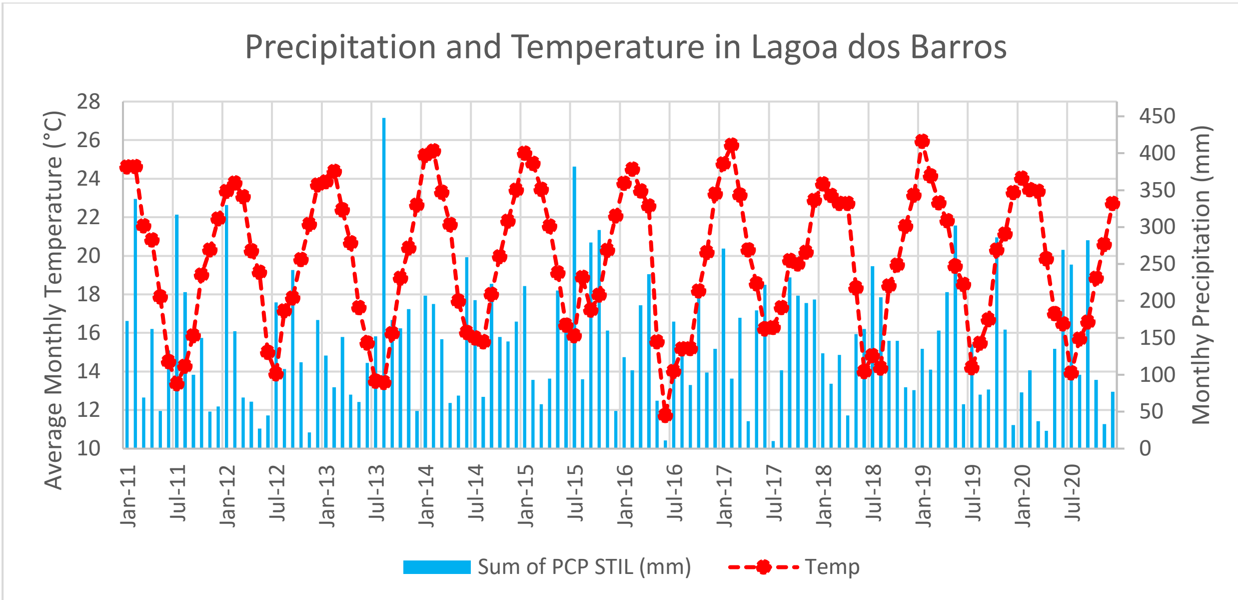


Figure 7 Precipitation accumulated monthly (STIL) and average temperature (climatic reanalyses model ERA5 (ECMWF, European Centre for Medium-Range Weather Forecasts, 2021))

2.3. Topography

It is relevant to notice the configuration of the terrain to infer the hydrogeology of the area and infer regional and local groundwater flows that can happen in the region.

It is visible from Figure 8 that Northwards Lagoa dos Barros there is a highly mountainous zone, where Mesozoic sedimentary and volcanic rocks from the Parana watershed exist. 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. Additionally, in the plain area, sandy sediments maintain an unconfined aquifer recharged mainly by precipitation and runoff from the volcanic areas. The deposits found in the plains region of Lagoa

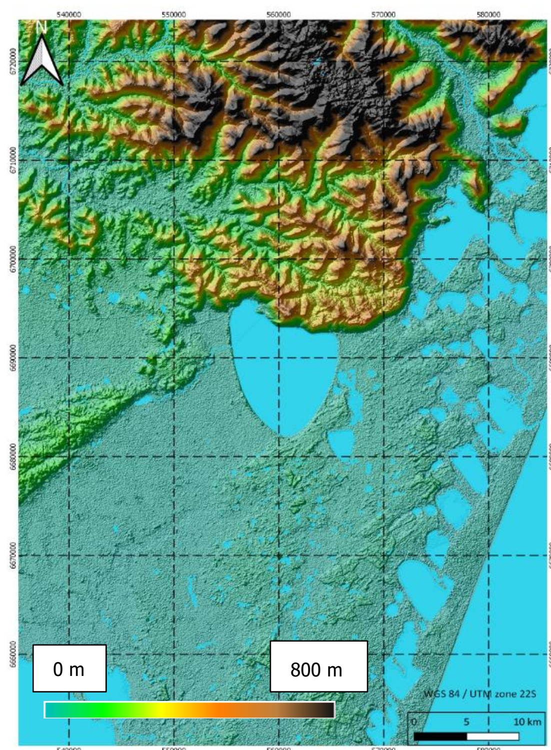


Figure 8 Map of Digital Elevation Model (NASA - EARTH DATA, National Aeronautics and Space Administration, 2000)

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).

2.4. Formation and Geology

It is essential to start presenting the formation of the Northern mountainous area, the oldest formation located at the end of the coastal plain of the Lagoa dos Barros area. Sedimentary rocks of Botucatu formation from the Jurassic period were covered by the volcanic igneous rocks of the Serra Geral from processes that originated around 130 and 133 million years ago in the Cretaceous period when the rupture of Gondwana happened (separation of South America and Africa). This formation thickness varies from 5 to 50 meters with an average of 30, and are composed of basalts and andesites with dark grey and brown colour. In the North region of Lagoa dos Barros, Serra Geral formation is represented by the Gramado facies, basalts and andesites that present dark grey, brown to brown colouring, with fine phaneritic texture to aphanitic textures. (Tomazelli, Dillenburg, & Villwock, 2000)

These volcanic rock spills present different structures from the base to the top of a spill and may occur: vitreous or partially glazed mass area, may present volcanic gaps; zone of horizontal diaclases; vertical diaclases zone; and Amygdales and Vesicles at the top of the spill (Figure 9). Amygdales may be filled with minerals such as zeolites, aptolites, amethyst, chalcedony, agate, opal, calcite, selenite, among other minerals. These volcanic rocks are mineralised, exploited and employed in diverse civil construction materials (UCS, 2017).

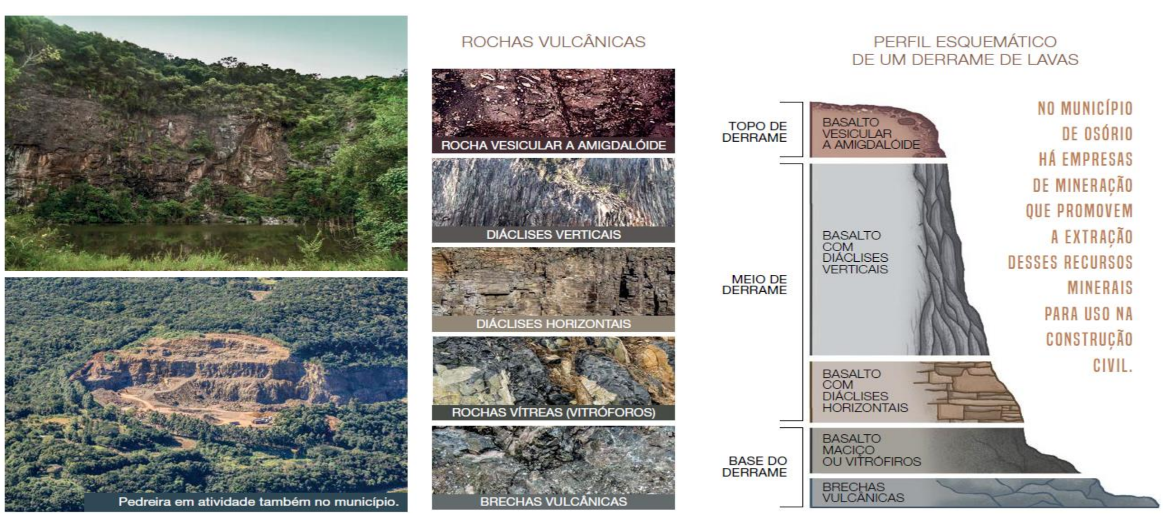


Figure 9 Representation of Geology at North of Lagoa dos Barros (UCS, 2017)

Afterwards, the coastal lagoon's complex formation in the Rio Grande do Sul (RS) state started in the Quarternary period around 400 thousand years ago with many variations of the sea level where transgression and regression periods occurred. Until current times, the formation of different alluvial fan systems happened, creating unique geomorphology found in the region. The four generations of barriers were responsible for creating the large lagoon water bodies typical in the coastal region where Lagoa dos Barros and Lagoa dos Patos are located (Figure 12) (UCS, 2017).

As already mentioned, the coastal plain of RS was formed during the Quarternary glacio-eustatic period by the fluctuations in sea level, when the four Barrier-lagoon systems developed from the oldest to the newest: I, II, III Pleistocene Barrier-Lagoon Systems, and IV Holocene Barrier-Lagoon System comprehending the extreme coastal land (Figure 12). Lagoa dos Barros is located between the three first formations, as visible in Figure 10.

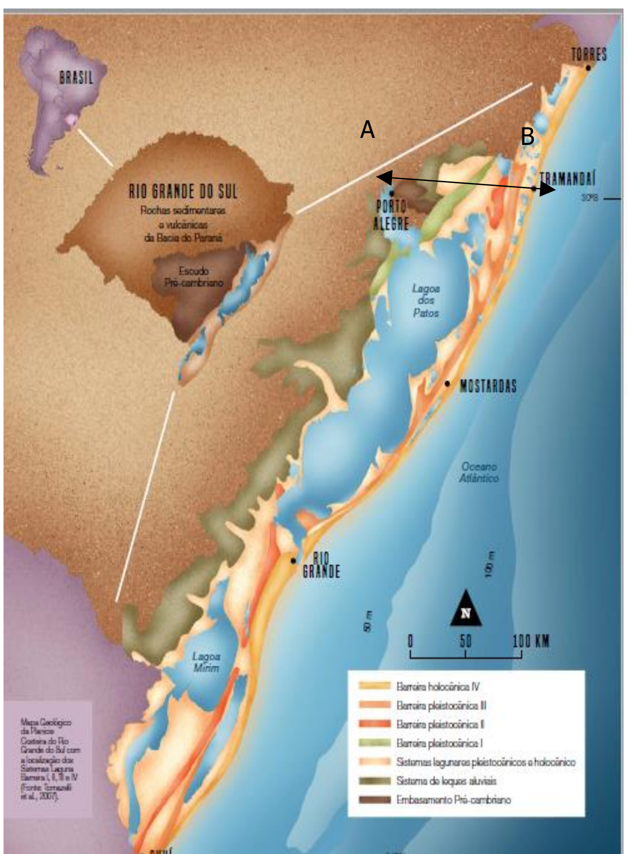


Figure 10 Geological Barriers in the coast of Rio Grande do Sul (Source: UCS, 2017)

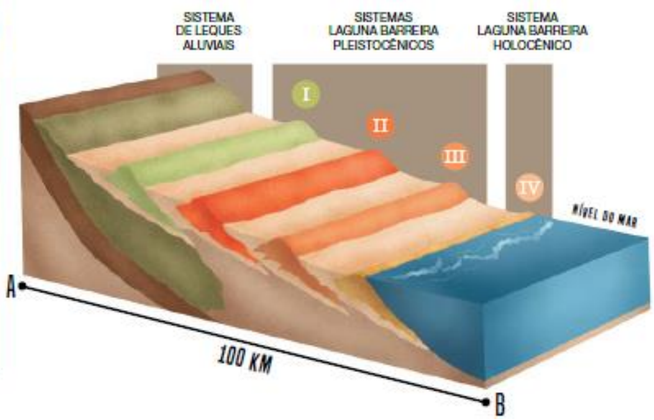


Figure 12 Profile and representative scheme of the Barrier-Lagoon deposits (UCS, 2017) and (Tomazelli, Dillenburg, & Villwock, 2000)

Figure 11 Representation of Barrier-Lagoon deposits III where Lagoa dos Barros is located (UCS, 2017)

During the heighten and subsequent fall in sea level, the barriers progressed seaward. This dominant regressive phase is apparent in the vertical facies' succession of Barrier III and along coastal bights in the Holocene Barrier IV. Hence, Lagoa dos Barros is enclosed amongst the systems I, II and III, as is possible to observe from Figure 12 and Figure 11, which represents the system scheme in which this water body is enclosed, differing from the other lagoons located in this region mainly within the III and IV systems.

The I Lagoon-Barrier System was created in the Pleistocene period around 400 thousand years ago, being the first to be established. This first formation was responsible for creating the isolation of the Guaíba Gravataí lagoon system in the Northwest of Lagoa dos Patos, where today is the region of Porto Alegre, the capital of Rio Grande do Sul (UCS, 2017). It appears as a NE-SW stripe of fine windy sands with higher elevations, around 250 km long and 5 to 10 km wide, creating a profile varying from 14 to 80 meters altitudes, formed mainly by aeolian sands and onlapping basement highs. (Tomazelli, Dillenburg, & Villwock, 2000).

The II Barrier-Lagoon System presents an estimated age of 325 thousand years and isolated Lagoa Mirim in the Rio Grande do Sul state (Figure 10). The II Barrier-Lagoon deposits are composed of lagoon plain sediments and eolic beach deposits. However, in the II Barrier, the plain lagoon sediments present mainly clayey, silty sands, cream colour, unequal distribution with flat-parallel lamination incipient and presence of concretions. The first two barriers formed are composed mainly of well-rounded, fine to medium gained, reddish-yellow, semi-consolidated quartzose sands with up to 15% silt-clayey matrix, from the chemical breakdown of feldspars and other minerals followed by clay illuviation. (Tomazelli, Dillenburg, & Villwock, 2000).

Around 120 thousand years ago, the ocean transgression formed the III Barrier-Lagoon System, the most preserved system, when the sea level reached around 6 to 8 meters above current sea level. At that time, Serra Geral was the coastline and suffered from erosion, creating holes in the arenites called Furnas. Still, the third system of lagoons was settled and responsible for the final formation of Lagoa dos Patos, the biggest of the region (Figure 10) (UCS, 2017). After this period of transgression that formed the III Barrier system, sea-level presented another regression reaching 120 to 130 meters below current sea level, bare land was uncovered, and a vast fluvial plain area was created (which is hidden by the ocean nowadays). In the North, the fluvial systems originated in the scarps of Serra Geral flow to this plain, eroding the newly III Barrier-Lagoon deposits.

In the III Barrier-Lagoon, mainly deposits are lagoon plain sediments, marine deposits and eolic deposits. The lagoon plain sediments ("Depósitos de planície lagunar") are fine sands, silty clayey and clayey silt with variable organic matter content, and clays with moderate to high plasticity. These sediments present cream, grey, lead grey, greenish-grey and black colours. Also, it consists mainly of well-sorted, white, quartzose fine sand, with well-developed stratification representing the different processes in the beach environment in that period (Tomazelli, Dillenburg, & Villwock, 2000), also, the sediment structures are flat-parallel lamination, and there is the occurrence of ferruginous and carbonate levels. Meanwhile, the marine deposits ("Depósitos praiais") are characterized by very fine quartz-sands with low silt and clay contents, greenish-yellow colour, and crossed stratification. And finally, the eolic deposits ("Depósitos eólicos") are characterized by fine sands of reddish-brown colouration that may be massif or present a stratification marked by horizontal to sub-horizontal layers (Figure 13) (UCS, 2017).

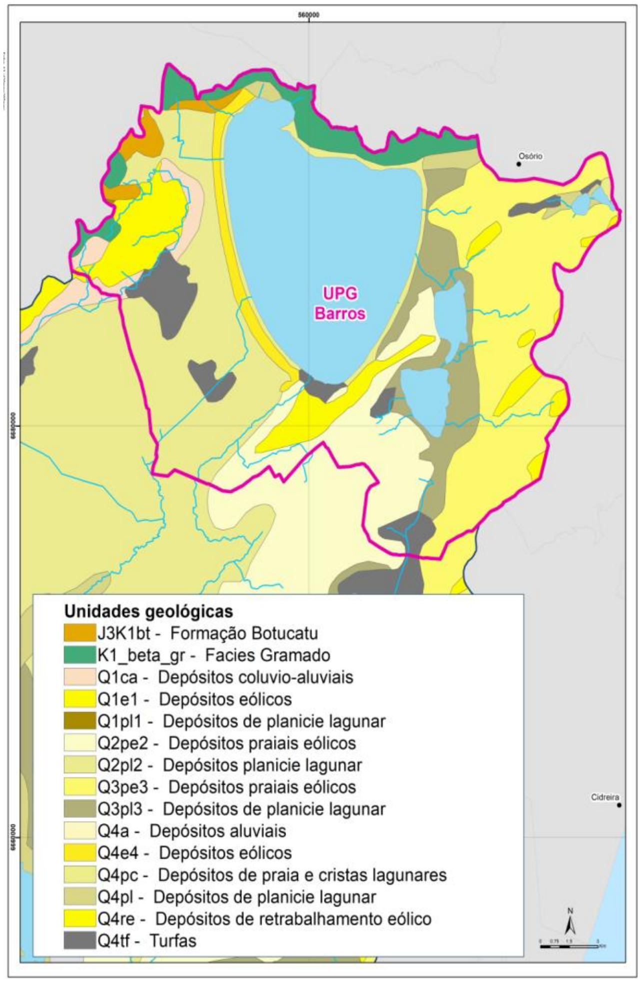


Figure 13 Geological units of the Basin delineated by CBHLM (CBHLM, Comitê da Bacia Hidrográfica do Litoral Médio, 2018)

After the latest regression period, between 5 to 6 thousand years ago, the sea level rose again, reaching around 4 meters above sea level to stabilise the current sea level. These processes of variation of sea level created the newest Holocene Barrier-Lagoon system (Barrier-Lagoon IV) (UCS, 2017). The regressive sandy strands and the lagoon system exist in the whole coast of the Rio Grande do Sul from North to South, as observed in Figure 10.

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).

2.5. Soil classification

Two databases were consulted to obtain information about the soil in the region, the Harmonized World Soil Databse (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009) and from Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA, 2010) (Figure 14 and Figure 15). It is possible to notice the differences in the distribution of the soil in the area, where the first does not reproduce the details closely as the Brazilian database. However, the data from EMBRAPA present a problem related to the coordinate system since the coastline of the database is dislocated compared with other maps like Google Maps (see Figure 14).

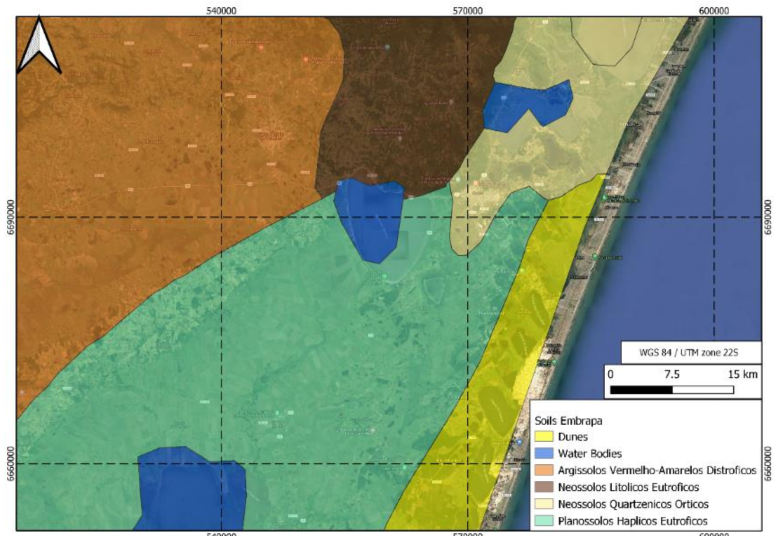


Figure 14 Predominant soil classes at Lagoa dos Barros basin (EMBRAPA, 2021)

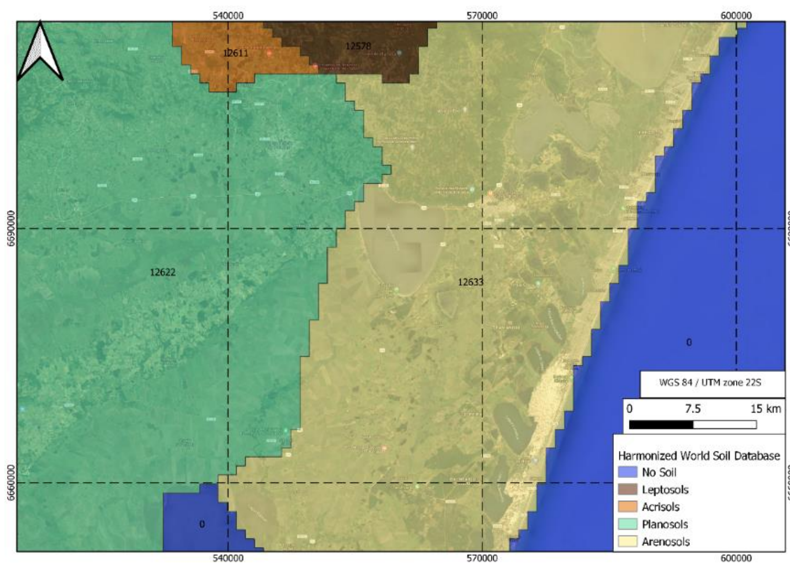


Figure 15 Predominant soils at Lagoa dos Barros basin (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009)

The soil arrangement along the zone from EMBRAPA, present the dominance of Planosols at South of Lagoa dos Barros, at West Acrisols (Argissolos) and in the other zones, Neosols, which comprehend Arenosols and Leptosols (presented as Neossolos Quartzarênicos and Neossolos

Litólicos). However, the HWSD present the area as arenosols throughout the coast and at West planosols.

The Neosols are shallow or deep and are found in the most diverse relief conditions. At North, the Neosol Leptosols are predominant; they are very shallow soil over hard rocks or deeper soil that are extremely gravelly and stony. (UFRGS I, 2015). While the Arenosols are deep soils where the surface horizon above the sediments is composed of sandy sediments with quartz. (EMBRAPA, 2021). The World Reference Base for Soil Resources (WRB) describes Planosols as soils with a light-coloured, coarse-textured surface horizon showing signs of intermittent water stagnation. It abruptly overlies a dense, slowly permeable subsoil with a dense, slowly permeable subsoil significantly more clay than the surface horizon. And Acrisols present a clay-rich subsoil and is associated with humid, tropical climates, typical of Brazil, and often supports forested areas (World Reference Base for Soil Resources (WRB) , s.f.).

2.6. Hydrogeology

Groundwater is the existing water underground, filling the empty spaces (pores) existing in sediments or rocks of the soil. In sediments and sedimentary rocks, pores are the spaces between the grains that form these geological materials. In igneous (volcanic and intrusive) and metamorphic rocks, the empty spaces represent the fractures. The saturated rock and sediment, which are all pores filled with water, is called an aquifer, and this water can be exploited through drilling. Depending on the pores that sediments and rocks present, we can classify the aquifers as granular or sedimentary, fractured or fissural and karst. The pores formed between mineral grains and rocks are the aquifers in soils formed by sediments and sedimentary rocks. The fractured porosity is the fractures, and these aquifers are located in intrusive igneous rocks (granites) and volcanic (basalts) also in metamorphic rocks (gneisses, schist, etc.). Finally, the Karst aquifers manifest porosity as voids and ducts generated through the dissolution of limestone rocks (UCS, 2017).

Additionally, aquifers can be classified as confined or unconfined depending on the pressure that groundwater is subjected. Confined aquifers are limited by an impermeable layer at the top exerting higher pressure than the atmospheric. When drilled, the water table (static level) in the well increases in function of the pressure, potentially reaching the surface. Thus, the static level is observed to describe the flow direction in confined aquifers. While unconfined aquifers present the water table near the surface, atmospheric pressure influences water; thus, topography dictates the flow.

Water present in the aquifers originates from precipitation, which infiltrates the recharge zones. As water is part of the hydrological cycle, it moves to points where it returns to the surface, called groundwater discharge zones. In coastal regions, the discharge zones include the ocean, lagoons, wetlands and springs. As Lagoa dos Barros present an intriguing morphology, besides receiving recharge from precipitation and runoff, there is the suspicion that the water body could be a discharge zone of an aquifer. The *water bodies that depend on the water originating from the aquifers are called groundwater-dependent ecosystems (GDE)* because the system requires water from the aquifer on a permanent or intermittent basis to meet all or some of the water needs to maintain the ecosystem on it (Queensland, 2017).

According 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 16 facilitates understanding of the region´s hydrogeology.

- SAQC: The Quaternary Coastal Aquifer System is the main groundwater supply to the municipality of Osório, and it is divided into two aquifers, SAQC I and II. The layers of sand have different colourations (yellow, grey, green, brown), different thicknesses, occur at various depths and may be interspersed with layers or lenses of thinner sediments (clayey, clayey-sandy and silica-clayey). The aquifers are granular, unconfined and confined, in sandy sediments composed mainly of fine to medium sand granulometry and clayey sand. In general, in the shallow layers of sand, in depths less than 25 m, there is the occurrence of free granular aquifers, while in the deeper layers, between 25 to 75 meters depth, which is interlarded with an impermeable layer of fine sediments such as clay, there is the occurrence of confined granular aquifers.
- SASG: The Serra Geral Aquifer System is characterized by fractured aquifers associated with tectonic (fractures) and cooling (diaclases) structures present in the volcanic rocks of the Serra Geral Formation. The occurrence, formation of aquifers and groundwater circulation depend on rock structuring (for example, quantity and orientation of the structures). SASG's fractured

aquifers generally sustain low production capacity (low flow rates, usually below 5m^3/h) good quality water with low salt concentration. It is possible to visualize in Figure 17 that hydrogeology shapefiles containing information from Serviço Geológico do Brasil (CPRM) does not classify the hydraulic conductivity because of its low water production capacity. Moreover, free granular aquifers that excavated wells can capture are possible in the soils formed above the volcanic rocks. In this case, the aquifers are of a small extent with low production capacity, presenting greater vulnerability to contamination.

- SAG: The Guarani Aquifer System is characterized by aquifers associated with sedimentary rocks (sandstones) belonging to different geological formations (Botucatu Formation, Piramboia, among others). There are granular and free aquifers in the upwelling areas of sedimentary rocks, while in the regions where these rocks are covered by the volcanic rocks of the Serra Geral Formation, the aquifers are granular and confined. In general, they are aquifers that present a good production capacity and good quality waters. In the region of Osório, the sedimentary rocks of the Botucatu Formation occur below the volcanic rocks of the Serra Geral Formation.

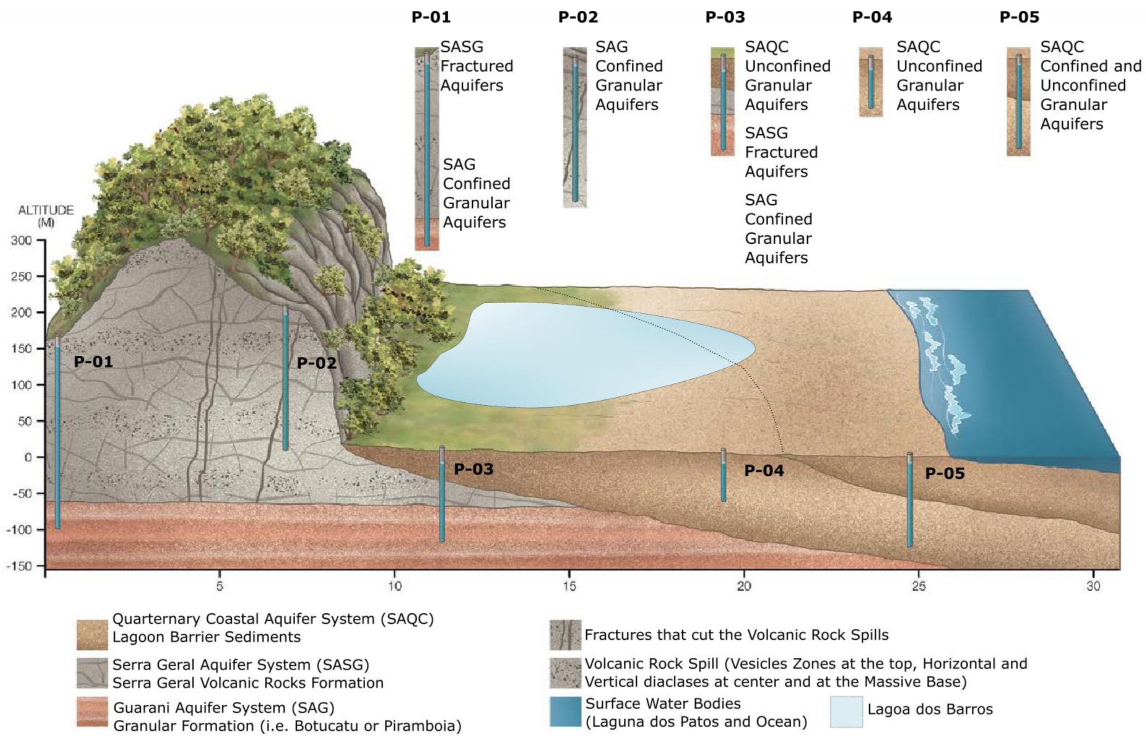


Figure 16 Simplified Lagoa dos Barros hydrogeology system (Adapted from (UCS, 2017))

Groundwater flow system analysis requires knowledge of the piezometric level of the area, where the movement of water occurs from the highest water level table to the lowest, i.e., the recharge from other areas to the lagoon occurs if the groundwater level in a specific area is higher than the surface level in the water body, so the hydraulic gradient present decrease to this direction. Additionally, the contrary is also relevant. If the aquifer presents a lower water table, the lagoon loses water to the aquifer, recharging it to maintain the hydrostatic pressures.

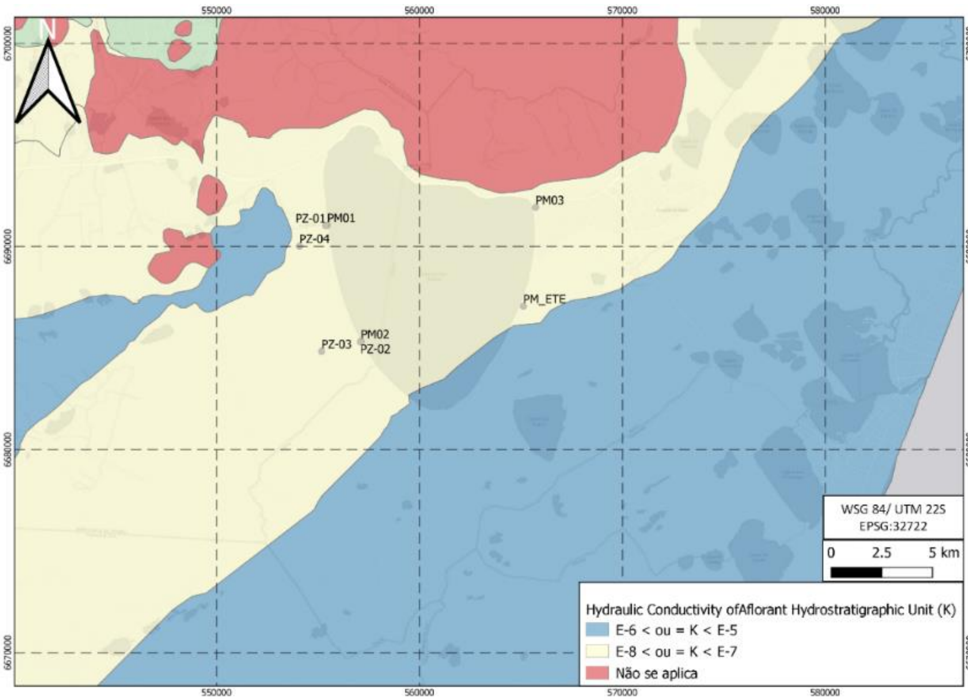


Figure 17 Hydrogeology of Lagoa dos Barros region and piezometers installed in the area (CPRM) and (UFRGS I, 2015)

The lack of a piezometric monitoring network in the region is a challenge. The map of the Geological Service of Brazil website (CPRM, SIAGAS, 2021) was found only one monitoring well in the interest region within a radius of 24 km. The well is adjacent to the Waste Water Treatment Plant of Osório (ETE), named PM_ETE monitors the unconfined aquifer placed over 30 shallow meters. The piezometer is located at an altitude of 12.481 meters and records groundwater table depth from August 2012 till September 2020 is presented in Figure 18 with lagoon level variation recorded at STIL (see locations in Figure 17 and STIL at Figure 19). The present work relied on these groundwater records, which supports the analysis of simulation results and as validation data, aiming to investigate the interaction and influence of the aquifer at Lagoa dos Barros.

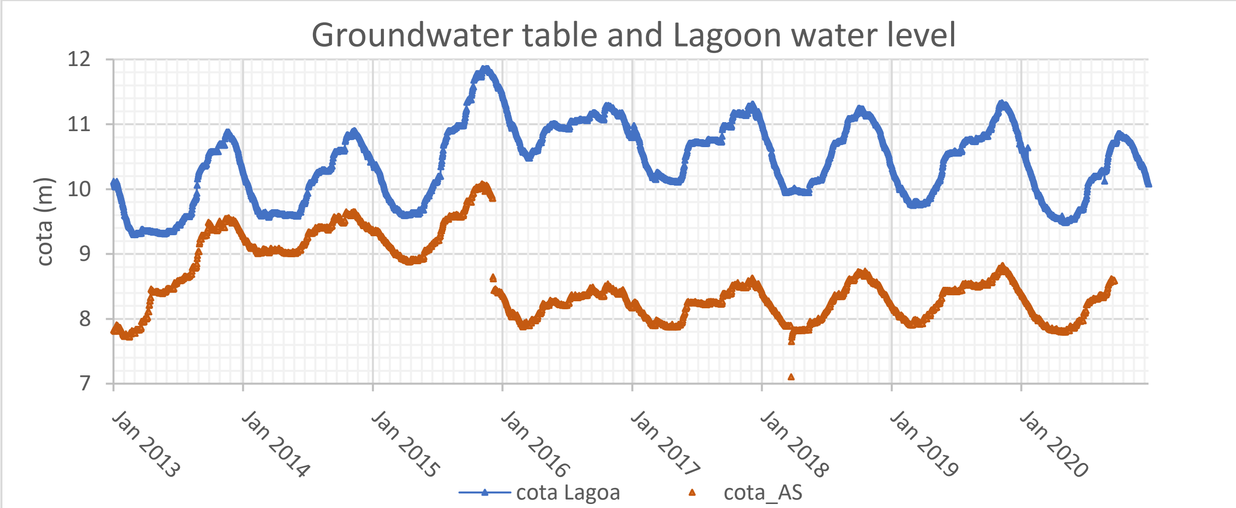


Figure 18 Groundwater observations at PM_ETE and in blue Lagoa dos Barros monotoring level at STIL (CPRM, SIAGAS, 2021) (STIL, 2021)

The area's configuration brings questions about the potential contribution of aquifers discharging into the Lagoa dos Barros. Once prominent elevations found at Serra Geral formations placed at North of the Lake is still not well studied neither considered in any study about the Lagoa dos Barros. Thus, the need for studies about piezometric information in this region is reinforced. The contribution of groundwater recharge dynamics was planned to be analysed in the Universidade Federal do Rio Grande do Sul (UFRGS I, 2015) study. Piezometers were implemented to obtain groundwater level data and predict the flux within the basin. In the mentioned study, it was impossible to record the groundwater table and consequently estimate the flow arriving from the North of the basin due to the lack of consistent data in this region because of the high variation on piezometric level (needing deep wells in order of 120 meters).

Moreover, in the same study from UFRGS (2015), values of a single water table record are presented on day 23 October 2014, in 7 wells in the vicinity of Lagoa dos Barros. This information does not allow the analysis in time (monitoring) or further system insights because it presents insufficient measures. However, this information is analysed and explored further in the Methodology section.

Furthermore, it could be a probability that the mountainous area at North infiltrates rain falling through the basalt cracks and recharges the granular Guarani aquifer found in deep depths, which could, in the future, discharge towards a surface water body area with decreasing hydraulic pressure. However, this needs further research.

It is essential to mention that because the terrain is characterised by being a flat area (excluding the Northern part belonging to the Serra Geral), groundwater flow may move slowly in the region due to minor differences in hydraulic gradient. Thus, mand made overflows channels were built to control the Lagoa dos Barros water level, increase the flow in the area and irrigate the croplands around it. These features are elaborated further in the next section (Spillway channel), such as the system configuration and dynamics uncertainties of the interconnection between the water storages (lagoon and aquifer) are further discussed in the Results (Watershed Delineation and Surface Runoff).

2.7. Spillway channels

In the year 2016, a hydrological study made by Gomes da Silva & Selistre (2016) reviewed historical data, together with a hydrological analysis about the Lagoa dos Barros situation, where they established a comparison between the water level behaviour and the volume required to overflow to control flood damages in periods of anomalous high precipitation amounts, which occurs in El Niño periods. The document presents information on the altitudes defined by reports made by the "Rio Grande do Sul Water Resources Advice" (CRH – Conselho de Recursos Hídricos do RS) in 1984. It refers to two earlier processes from the Government of Rio Grande do Sul in 1958 and 1965, where there was the fixation of the maximum water level of Lagoa dos Barros to be 11.45 meters and a minimum of 7 meters the water body borders safe limits to protect its structures. The critical period for the water level and its neighbourhood was when the *El Niño* phenomena happened intensely, mainly affecting the region on two occasions where the level was higher than 11.5 meters, in 1984 (11.84 m) and 2015 (11.86 m). When the lake's level exceeds the critical level of 11 meters, damages start to happen and consequently affect infrastructures installed at a lower position than the water level. The adverse effect is preponderant on the west border because of the northeast winds common during spring and summer. However, if the lake's level does not reach more than 11 meters, the adverse effects may go unnoticed.

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. The 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, given that in 2015 the lake reached levels of 11.8 meters (Gomes da Silva & Selistre, 2016).

Thus, the period of hydraulic analysis was divided into four cycles of critical water level at Lagoa dos Barros, and it was concluded that by observing data from April each year and the intensity of precipitation is possible to predict if the lake may surpass the critical level, occurring during winter of the following periods:

- DEPRC Cycle, maximum of 11.48 meters in 1959 (1957-1961);
- Committee of the Stranded Basin Cycle, maximum of 11.74 meters in 1984 (1983-1986)
- The Road Cycle, maximum of 11.2 meters in 1998 (1995-1999)
- Constructions Cycle, maximum of 11.86 meters in 2015 (2011-2016)

Additionally, the report from Gomes da Silva & Selistre (2016) evaluated that the pumping of water out the lake to irrigate the downstream land during the summer, from November to March yearly, is a critical measure for the protection of the basin vicinity against floods in the next year, and it is responsible for the diminishing of 80% on the water level Lagoa dos Barros each period.

Thus, Figure 19 shows the main channels around the Lake and the delineation of the drainage systems used as irrigation channels. Where is possible to visualize the Valo do Estado as the overflow channel placed at 10.6 meters, STIL and Sincol are from irrigation groups, where water removal occurs by pumping, and the remaining are contribution channels to Lagoa dos Barros driving the water that descends from the hills around the lagoon.

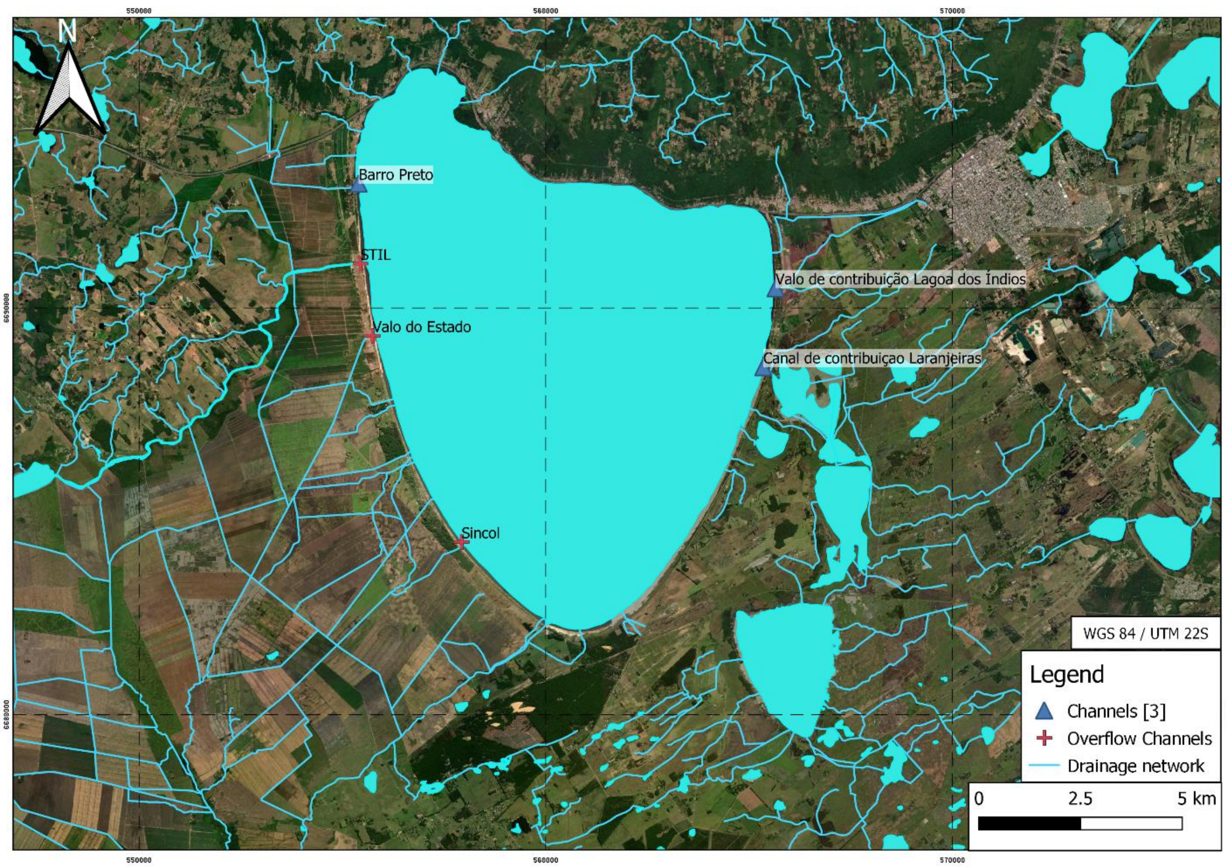


Figure 19 Location of main channels that drains water out and in Lagoa dos Barros (FEPAM - SEMA, 2005)

To estimate the overflow required for moments of high precipitation intensity and to verify the efficiency of the installed weirs, a Water Balance was calculated adapted from Tucci (1993). The calculation presents information on the surface area of Lagoa dos Barros of 92.4 km^2, with the watershed area contributing with runoff to the water body was estimated to have 152 km^2. Gomes da Silva & Selistre (2016) study results corroborate the result presented in 1984 with a maximum flow capacity of 4.08m^3/s extravasate by the channels installed in the area, which is not sufficient to impact the surface water level of the water body. In this sense, predominantly, the pumping to remove a constant flow of 16.14 m^3/s of water to irrigate crops in the summer is the principal regulator of the water level in the Lake. Accordingly to Gomes da Silva & Selistre (2016), between 2010 to 2016, the average area of irrigated crops using water from Lagoa dos Barros was around 10,757 ha of rice with a flow rate of 1.5 l/s/ha.

2.8. Conceptual Model

After looking at the topography, hydrogeology and the channels around Lagoa dos Barros, it is plausible to estimate the groundwater flow in the area, characterizing even further the zone for a more accessible analysis of results and interpretation. The cross-section used in Figure 20 was created at QGIS Software using the raster of the topography to visualize the elevations with a vertical exaggeration of 10. Then the main features of water transport are added to the map, representing the possible main directions around the water body. Additionally, in the figure is possible to visualize the area marked with a question mark where the three aquifer systems can be found (see Figure 16 and the profile of the well in the annexe section: Wells located in the North of the Lagoa dos Barros) in a complex transition of soil and aquifer type. Thus, further investigation in this zone may clarify whether a connection between the lagoon and the confined aquifer system discharging from the North exists and could act as a recharge source to the water body.

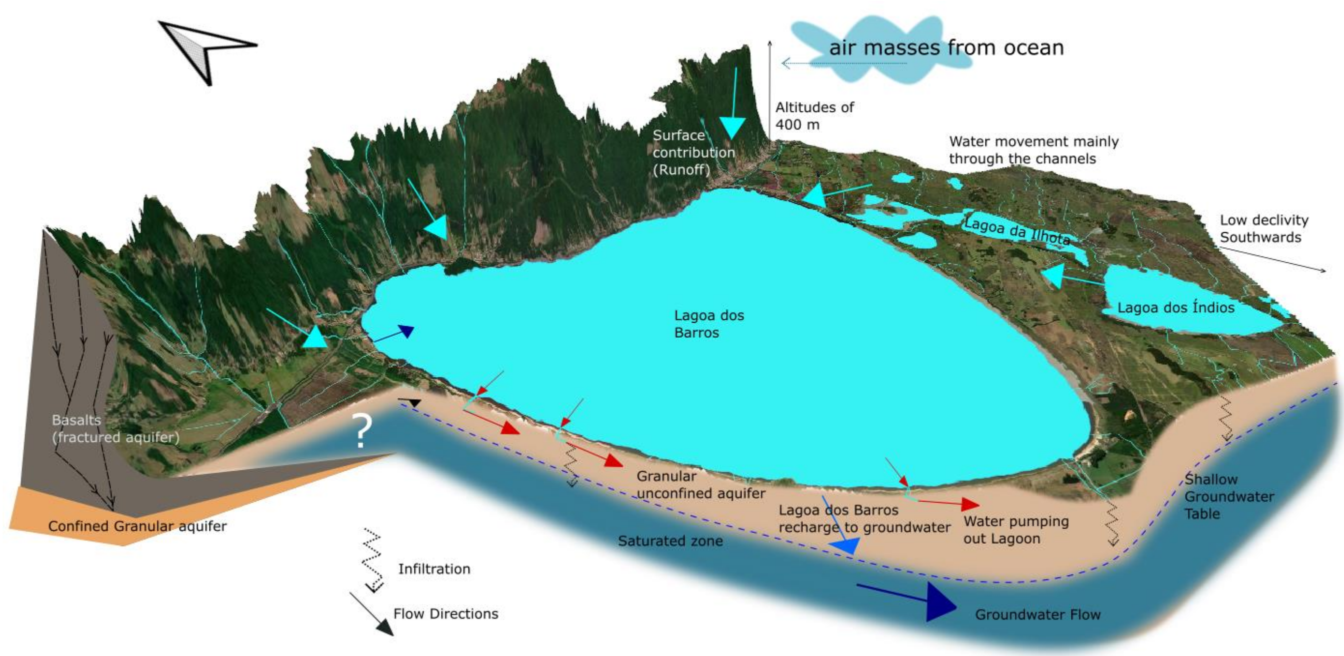


Figure 20 Conceptual Model of Lagoa dos Barros and its vicinity

2.9. Land Use

Lagoa dos Barros region is famous for being a solid agriculture area, which is the region's main economic activity. The distribution of the land use accordingly to Empresa de Assistência Técnica e Extensão Rural (Emater) presented in Figure 21.

The area is covered mainly by agriculture and livestock, native land, forest, anthropized area (roads, urban zone, industrial), water bodies (lakes and coastal lakes). From the agricultural activities, rice is considered the primary potential source of pollutants to the Lake due to the application of pesticides and fertilisers containing high amounts of nutrients. However, it is crucial to remember that the return of removed water from the lake needs further analysis, but it is a hypothesis that needs to be verified. Furthermore, farmers drain water from Lagoa dos Barros to irrigate their rice crops during periods of low precipitation, usually between the summer and drier periods in October/November until February/March of each year. (IRGA - DATER, Instituto Rio Grandense de Arroz - Divisão de Assistência Técnica e Extensão Rural, 2019). The rice culture is made without pre-germinated rice, bringing many nutrients with the runoff generated in the zone. Thus, conventionally the farmers utilise the rest of the cultivation dried to feed beef cattle. Some farmers are applying crop rotation using soybeans to intercalate with rice aiming to eliminate intrusive herbs. The native field is used for breeding beef cattle with no intensive production, with a low number of animals per area. And the grassland areas are where originally was native forest from Serra Geral scarps, but they were deforested and nowadays present bush cover used to breed animals. (UFRGS I, 2015).

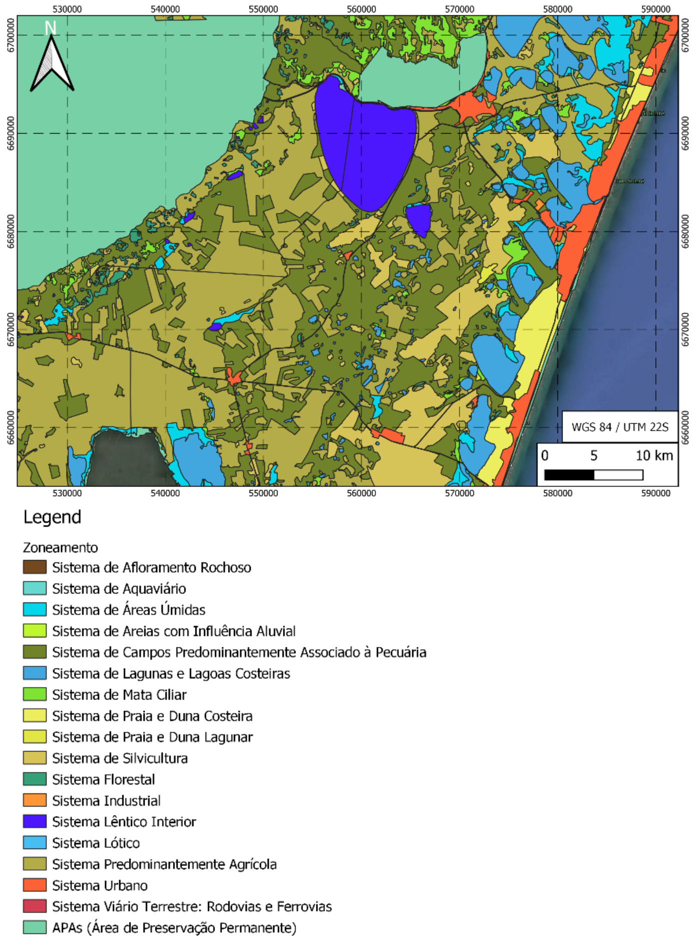


Figure 21 Land Use (FEPAM - SEMA, 2005)

3. Model Description

MOHID is a three-dimensional water modelling system developed by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Técnico (IST), which belongs to the Universidade de Lisboa in Portugal. Bentley is responsible for the development and the availability of the model interface, which Neves firstly developed in 1985 and has been updating since then.

MOHID model permits the use of the model in any dimension (one, two or three-dimensional). The model is programmed in ANSI FORTRAN 95, using the objected-oriented philosophy. The integration of MOHID several tools (MOHID Water, MOHID Land and MOHID Soil) allows water cycle studies in an integrated approach. Once these tools are based on the same framework, the coupling of them is easily achieved. MOHID has been applied to different study cases, as coastal and estuarine areas, oceanic processes and reservoirs, and it has shown its ability to simulate complex flows' features. The present research applies MOHID Land to understand the dynamics of the complex system of the Lagoa dos Barros basin.

MOHID Land is an open-source hydrological model, which its code can be accessed online (github.com/Mohid-Water-Modelling-System/Mohid). MOHID Land is an integrated model with four compartments or mediums (atmosphere, porous media, soil surface, and river network) (Figure 22). The atmosphere is not explicitly simulated but provides data necessary for imposing surface boundary conditions to the model, such as precipitation, solar radiation, wind, relative humidity, which are space and time-variant. Water moves through the mediums based on mass and momentum conservation equations using a finite volume approach. The model is a physically-based, fully distributed model, using an explicit algorithm with a variable time step, maximum during the dry season when fluxes are reduced and minimum when fluxes increase during rain events that could destabilise the simulation. (MARETEC , 2020; Oliveira et al, 2020).

The simulation domain can be discretized 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 river network is a 1D domain defined from the digital terrain model (DTM), with ranges connecting surface cell centres. Fluxes are computed over the faces of the finite volumes, and state variables are computed at the centre to assure conservation of transported properties.

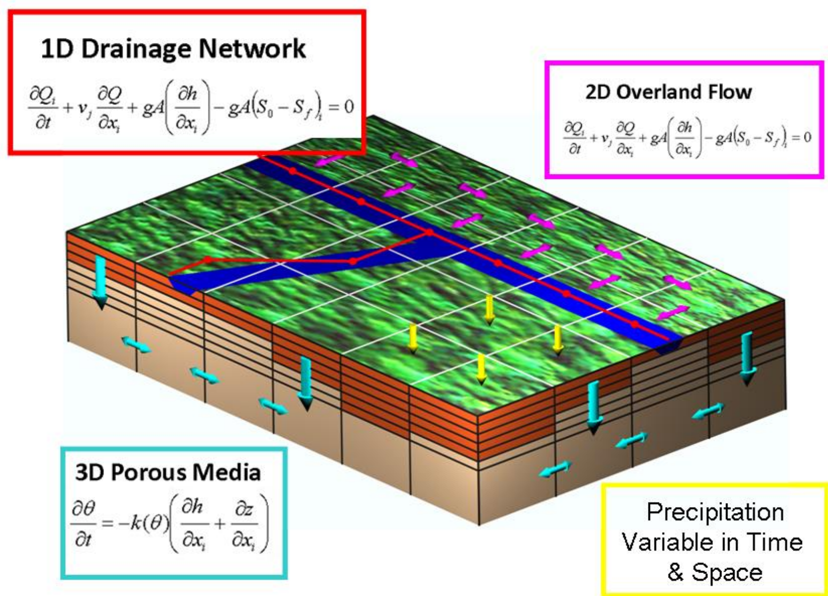


Figure 22 Main medium and equations of MOHID Land model (MARETEC , 2020)

A detailed description of the MOHIDLand processes were taken from Oliveira et al. (2020) and is presented in the following sections.

3.1. Infiltration

The MOHID-Land model includes three options to calculate soil water infiltration. The infiltration rate (i, LT^{-1}) can be estimated accordingly to Darcy's law, as presented below:

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

Equation 1

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

The infiltration rate can also be calculated according to the Green and Ampt method (Green & Ampt, 1911):

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

Equation 2

Where:
- 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}).

The soil water diffusivity can then be calculated as:

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

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) ($\Delta h = h_0 - h_F$).

3.2. Surface Flow

Surface flow is computed by solving the Saint-Venant equation in its conservative form, accounting for advection, pressure, and friction forces as follows:

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

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),
- The subscripts u and v denote flow directions.

In the drainage network, surface flow is solved for one direction (1D domain) considering the water lines obtained from the DTM. Outside the drainage network, surface flow results from the amount of water that does not infiltrate or ascends by capillarity and is solved on a 2D domain considering the directions of the horizontal grid. Water exchanges between the soil surface and the drainage network are computed according to a kinematic approach, neglecting bottom friction and using an implicit algorithm to avoid instabilities.

3.3. Porous Media

Richard's equation calculates the water movement of infiltrated water within the porous media:

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

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 ($L^3L^{-3}T^{-1}$).

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

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

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(-).

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.

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. This procedure eases the implementation of the model and simplifies its use at an annual scale. The consequence is that the time step during the wetting period must be shorter to guarantee stability. The constraint is minimized using parallel computing. The water fluxes between the porous media and the drainage network are also driven by the pressure gradient in the interface of these two mediums.

3.4. Root Water Uptake

Root water uptake 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 a single crop coefficient (K_c).

The K_c is imposed, with the model either assuming a constant value representing the average characteristics of each vegetation type over the entire growing season and average effects of evaporation from the soil (Canuto et al., 2019)or a crop stage-dependent value as used in (Allen et al., 1988).

The advantages and limitations of these approaches are discussed in Canuto et al. (2019). The ET_c values are 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)

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

Equation 8

$$E_p = ET_c - T_p$$

Equation 9

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)

Root water uptake reductions, i.e., Tp reductions, are finally computed using the macroscopic approach proposed by Feddes et al. (1978) as follows:

$$T_a = \alpha(h)T_p(z)$$

Equation 10

Where:

- T_a is the actual transpiration rate (T_a, LT^{-1})
- α is a prescribed dimensionless function of h ($0 \leq \alpha \leq 1$) limiting T_p over the root zone in the presence of depth-varying stressors, such as water stress (Šimunek & Hopmans, 2009) (Skaggs, van Genuchten, Shouse, & Poss, 2006)

Accordingly to the linear model proposed by Feddes et al. (1978), the root water uptake is maximum when the pressure head is between h_2 and h_3, has a linear reduction when $h > h_2$ or $h < h_3$, and becomes zero when $h < h_4$ and $h > h_1$ (subscripts 1-4 denote different threshold pressure heads).

Finally, the actual soil evaporation (E_a, LT^{-1}) is calculated from E_p values by imposing a pressure head threshold (American Society of Civil Engineers (ASCE), 1996).

4. Methodology

4.1. Topography analysis

The terrain elevation is highly relevant for the simulation and for clarifying the dynamics of the zone. In the first steps, the model runs, containing only information on the topography, which is used as the basis of the flow direction definition. The surface runoff results describe the superficial flow on the area, presenting a preliminary understanding of how water is distributed throughout the basin. Elevation information was downloaded at *NASA's Earth Observing System Data and Information System* (EOSDIS), which archives and distributes data from multiple missions throughout the *Land Process Distributed Active Archive Centers* (LP DAACs) and supports the delineation of the watershed presented in the results.

Within LP DAAC, it is possible to obtain the *NASA Making Earth System Data Records for Use in Research Environments* (MEaSUREs) *Digital Elevation Model* (DEM) version 1 (NASADEM_HGT) dataset, which provides global elevation data at 1 arc-second spacing, with a resolution of 30 meters. The NASADEM products derived from telemetry data from the *Shuttle Radar Topography Mission* (SRTM), a collaboration between NASA, the *National Geospatial-Intelligence Agency* (NGA) and participation of Italian and German agencies, which uses radar interferometry to generate a near-global DEM of the Earth, improving the accuracy of the elevation terrain compared to previous missions.

Two DEM tiles need to be downloaded from the coordinates of Lagoa dos Barros. Thus, NASADEM_HGT_s30w051 and NASADEM_HGT_s31w051 files were downloaded, corresponding to 30 and 31 in South and at 51 West in WGS 1984 coordinates system. Figure 23 presents the result of two DEM tiles merged and clipped to the area of interest.

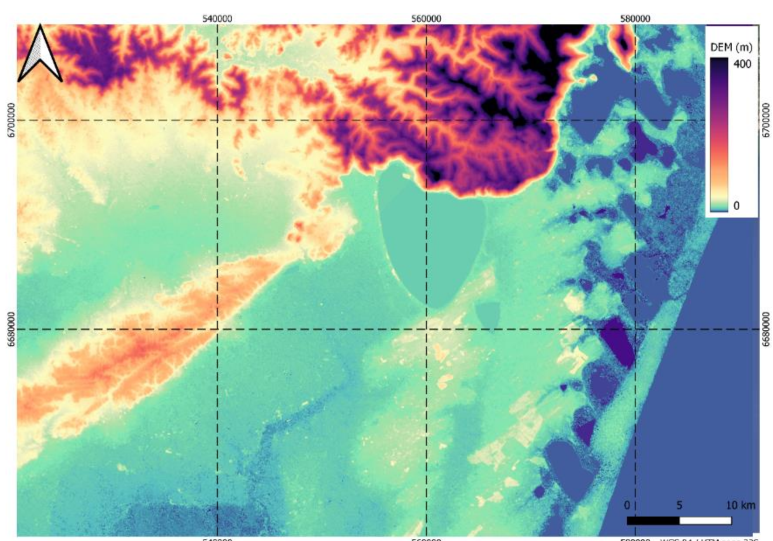


Figure 23 Map of Digital Elevation Model (NASA).

4.1.1. Watershed Delineation

From the 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}, and the study by UFRGS, 2015 presents a drainage area of 242 km^{2} (see Figure 24) 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}. The latest information is the closest to the one presented by this author in the Watershed Delineation and Surface Runoff Results.

It is visible that the North region presents a similar delineation in the division of the basin. However, the divergences are visible when looking in other directions. At West, the zones diverge the most. However, in both directions, CBLM considers the area that drains water to the channels that could contribute to Lagoa dos Barros in the period of high precipitation. This variation is because the southern zone is a vast plain area, where the correct delimitation needs to be further analysed with field marks to estimate an accurate demarcation. This condition suggests that the surface flow contributing to discharge at Lagoa dos Barros is still dubious due to the lack of detailed information on the plain area topography that influences the runoff.

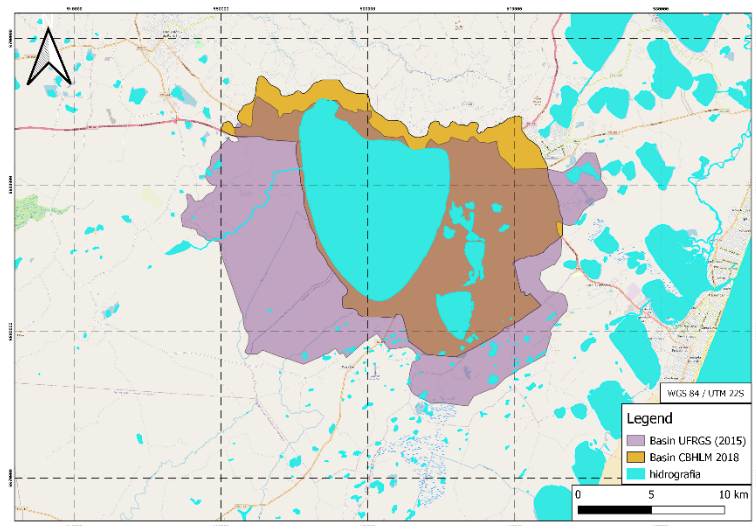


Figure 24 Delineation of basin contributing to Lagoa dos Barros Runoff by UFRGS (2015) and (CBHLM, Comitê da Bacia Hidrográfica do Litoral Médio, 2018)

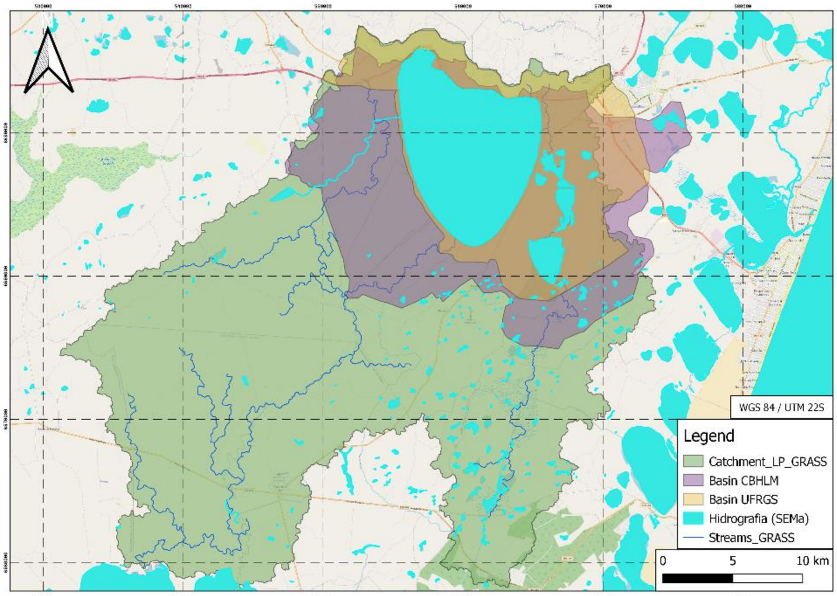


Figure 26 Watershed Delineation and streams constructed with GRASS tool in QGIS Software, (NASA - EARTH DATA, National Aeronautics and Space Administration, 2000) (STIL, 2021) (Gomes da Silva & Selistre, 2016)

Because of these divergences, different approaches were applied to understand the surface contribution to Lagoa dos Barros and the Basin. Thus, the Digital Elevation Model (NASA - EARTH DATA, National Aeronautics and Space Administration, 2000) was used to delineate the watershed and the streams. It was constructed with GRASS tools in QGiS Software, where the outlet of the Basin is the Lagoa dos Patos margin (See delineations at Figure 26). Nevertheless, it is relevant to notice that the Lagoa dos Barros is located in the upper part of the delineated Basin, i.e. the flow goes to the delineated streams and towards the outlet in the South direction.

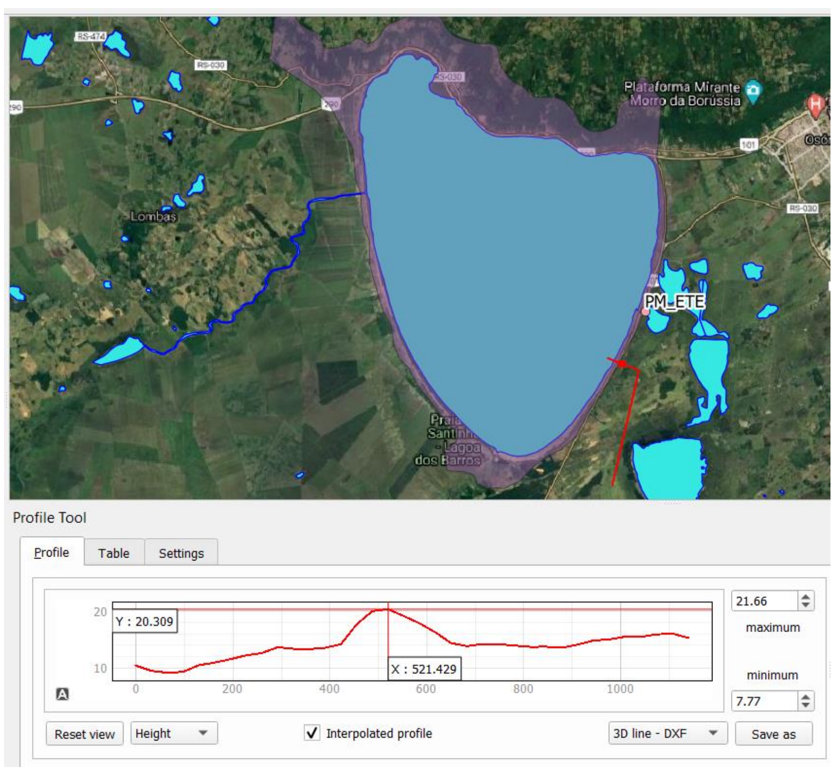


Figure 25 Profile tool visualization of QGis software applied around Lagoa dos Barros vicinity supporting basin delineation

Thus, as presented in Figure 25, a detailed analysis on the elevation using Google Earth Engine and the 'Terrain profile' tool in QGis through the DEM, Digital Elevation Model (NASA - EARTH DATA, National Aeronautics and Space Administration, 2000) 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. Following this, to define the micro basin that contributes solely to Lagoa dos Barros input, several cross-sections of Lagoa dos Barros were created perpendicular to its border to visualize the most probable division of the hydrographic basin that contributes to the lagoon presented in the results.

4.1.2. Bathymetry

In its study, UFRGS I (2015) presented the methodology applied to delineate the lake bottom, aiming to estimate the water body's volume. However, when analysed meticulously, the procedure used by the mentioned report presents several inconsistencies related to the bathymetry process. All issues related to the bathymetry defined by UFRGS is presented by Villena (2020), where the equipment and the operational methodology were reviewed and criticized.

When a bathymetry is developed, there are rules of the Maritime authorities to follow. In this case, the *Norma da Autoridade Marítima para Levantamentos Hidrográficos of Brasil* was not followed because one detail such as the WWTP submarine emissary should have been delineated, which was not. In Figure 27 (right) also it is possible to visualize the lines used during bathymetry in UFRGS (I, 2015), where the position of the lines should be parallel between them and should

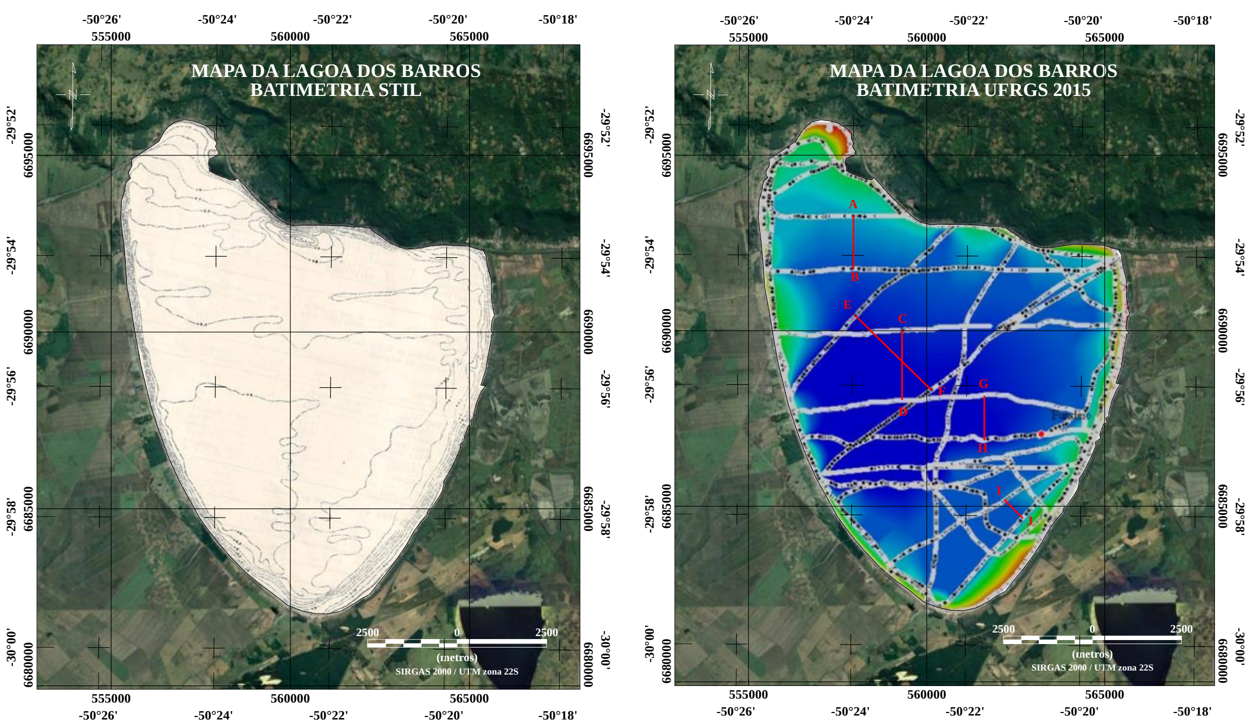


Figure 27 Bathymetries presented by STIL (1980) and UFRGS (2015)

be as close as possible to decrease the interpolation and the doubts, however, it is possible to see that they are too spaced, resulting in poor detailing of the bottom.

Additionally, during the operational method, the equipment used was not well described leading to questions about its reliability because it was pointed to be used to catch fish. The used apparatus is a sonar that identifies if there is a barrier and its distance, while the right equipment should identify even the soil formation if there are sediments or rocks. Thus, the bathymetry proposed by STIL in 1980 was chosen to be the most appropriate to implement on the model.

4.2. Meteorological information

The STIL station (Figure 28) measures daily precipitation in mm, and water level in meters, used as a data reference. The values are being recorded since 1999. The water level within the LB varies between 9 and 11.5 meters, with an average of 10.4 meters above sea level.

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 (Figure 28), 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.

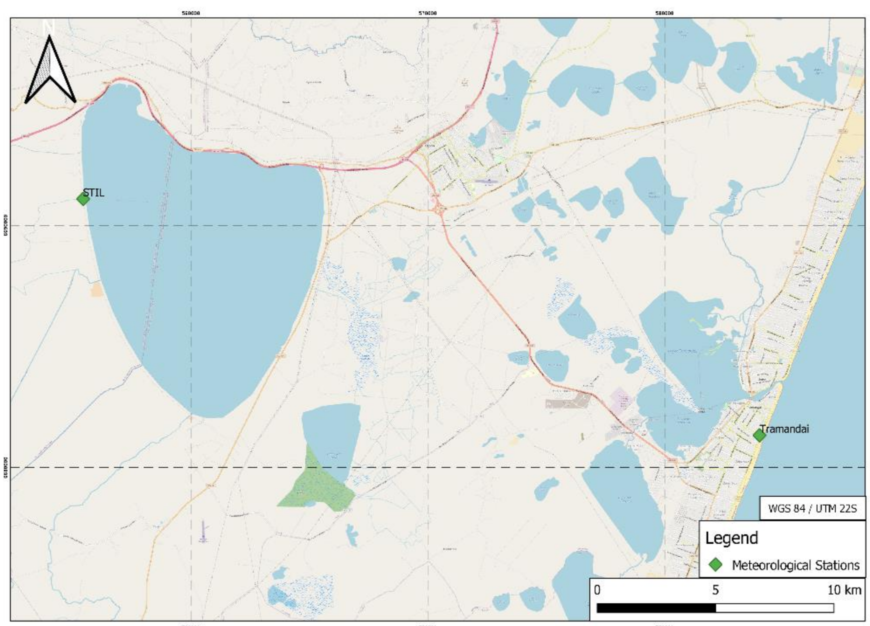


Figure 28 Tramandai Meteorological Station (INMET, 2021) and STIL (STIL, 2021)

The information acquired from INMET were:

- Precipitation (*Ppt* in accumulated mm);
- Pressure (*P* in hPa);

- Solar Global Radiation (*Sr* in KJ/m^2);
- Temperature (max, min, medium) (*Tmax*, *Tmin*, *Tmed* in Celsius degrees);
- Dew point (*Td* °C);
- Relative Humidity (*RH* in %);
- Wind speed and hourly direction (*ws*, *wd* in m/s and degrees)

The period of the records is for 10 years, varying from January 2010 to December 2020. However, the climatological data present several empty cells, mainly between January and February 2018, presenting two months of unfilled data in a row (1315 lines), which cause problems and uncertainties when inserting the time series in the simulation.

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.* ERA5 model uses a numerical description of the recent climate with 4-D data assimilation and forecasts produced by combining model with observations in CY41R2 of the ECMWF (European Centre for Medium-Range Weather Forecasts) Integrated Forecast System (IFS). The IFS atmospheric model is coupled to a land-surface model (HTESSEL), producing parameters such as 2m temperature and soil temperatures. The ERA5 dataset is composed of one high-resolution realisation (hourly, 31 km) referred to as "reanalysis" or "HRES" and by a reduced resolution ten-member ensemble, referred to as "ensemble" or "EDA". Most analysed parameters are available from the forecasts; however, several forecast parameters are not available from reanalyses, such as mean rates, fluxes and accumulations.

In this case, ERA5 modelled data were obtained at STIL, Tramandai and the four Grid borders points and were downloaded from 2017 to 2020. ERA5 values were found through the Climate Data Store (CDS) via the CDS web interface. The complete ERA5 dataset covers the period from 1979 forward nowadays and is updates of the dataset is available in nearly real-time.

The purpose is to evaluate the consistency of modelled values (ERA5, without gaps) with the data obtained from Tramandai station and STIL; where the following variables were downloaded from ERA5 on an hourly basis:

- Precipitation (Ppt in accumulated mm);
- The Temperature at 2 m height (T2 in °C);

- Wind Vector (composed by u and v components at 10 meters in m/s);
- Dew point (Td in °C);
- Solar Radiation (Sr in KJ/m^2);
- Cloud Cover (CC in %)

Relative Humidity is an essential factor to determine the development of clouds and precipitation. It is described by the water quantity transported by the air; however, the climate model ERA5 does not estimate values for relative humidity. Thus, using data of dew point and average Temperature is possible to estimate RH (Alduchov, 1996):

$$RH = 100 * E(Td) / E(T)$$

Equation 11

Where:
- RH = Relative humidity [%];
- E (Td) = Saturation Vapour Pressure at dew point Td (usually in g/m^3);
- E (T) = Saturation Vapour Pressure at real air temperature T (usually in g/m^3).

The following equation is the resultant of the displacement of Equation 4, and it is applied to ERA5 data:

$$RH = 100 * \left(\frac{EXP\left(\frac{17.625 * TD}{243.04 + TD}\right)}{EXP\left(\frac{17.625 * T}{243.04 + T}\right)} \right)$$

Equation 12

The parameters from the Tramandai station and the climate model were converted from hourly frequency values to a daily average, except precipitation that requires the sum of hourly values. Therefore, meteorological information from the climate model reanalysis is statistical compared with the observed values of the Tramandai station and at STIL to evaluate their correlation for application in the simulation.

4.2.1. Variables Statistical Analysis

There is available information from STIL recording precipitation and water level in the middle of the Lagoon. However, to implement the model, it is necessary to input several atmospheric values to predict the evolution of the simulation and estimate the system use of water, for example. Thus, the meteorological data collected at STIL and Tramandai were considered the observed values. However, as previously mentioned, the observed records of relative humidity, solar radiation, and dew point present many gaps that can influence the evapotranspiration estimation, causing an issue interrupting the climatic prediction. Therefore, it was necessary to validate the weather information from the model ERA5, where there are no gaps in the data, to confirm if the implementation of those values in the simulation is consistent. This validation was done in the location of the observed data (Tramandai and STIL), and the idea was that if the model described these variables well in this station, we could assume that it describes these same variables well in the centre of the water body and implement those at MOHID.

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, Ramos, Simionesei, Pinto, & Neves (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), which are presented below.
The first analysis is the root mean square error (RMSE), as follow:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2}$$

Equation 13

Where:
- O_i are the observed values (from meteorological stations),
- S_i are the simulated values (from the climatic model),
- n is the number of daily records analysed,

The RMSE-observation standard deviation ratio (RSR) incorporates the benefits of error index statistics and includes a scaling/normalization factor. RSR equals 0.0 when RMSE is 0.0, indicating that the residual variation and the model is perfect. Thus, low RSR values correspond to low RMSE values and a good model simulation performance.

$$RSR = \frac{RMSE}{STDEV_{obs}}$$

The Nash and Sutcliffe model efficiency (NSE) is used to assess the relative magnitude of residual variance compared to the measured data variance. It ranges between -∞ and 1.0, with 1.0 being the optimal value. Values between 0.0 and 1.0 are classified as acceptable performance levels, and values ≤0.0 indicate that the mean observed value is a better predictor than the simulated value. The NSE is estimated as:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right]$$

Equation 14

Where:
- O_i are the observed values (from meteorological stations),
- S_i are the simulated values (from the climatic model),
- n is the number of daily records analysed,
- $\bar{O}$ is the observations averaged values.

The percent bias (PBIAS) is a statistical parameter that measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, and low-magnitude values indicate accurate model simulation. Positive values demonstrate model underestimation, while negative values represent model overestimation. It is computed as follows:

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(\Upsilon_i^{obs} - \Upsilon_i^{sim}\right) * 100}{\sum_{i=1}^{n}(\Upsilon_i^{obs})}\right]$$

The coefficient of determination R^2 describes the degree of collinearity between simulated and measured data and ranges from 0 to 1, with higher values indicating minor error variance.

This statistical parameter is computed as follows:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2}}} \right)^2$$

Equation 15

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.

<u>Temperature:</u>

<u>Tramandai (station observed) vs Tramandai (modelled)</u>

Firstly, the Regression method compares the data from ERA5 at the Tramanadai location and uses the average of hourly to daily information, presented in the y-axis, and then it is then compared with observed records for the Tramandai station (INMET) represented in the x-axis as observed data (Figure 29).

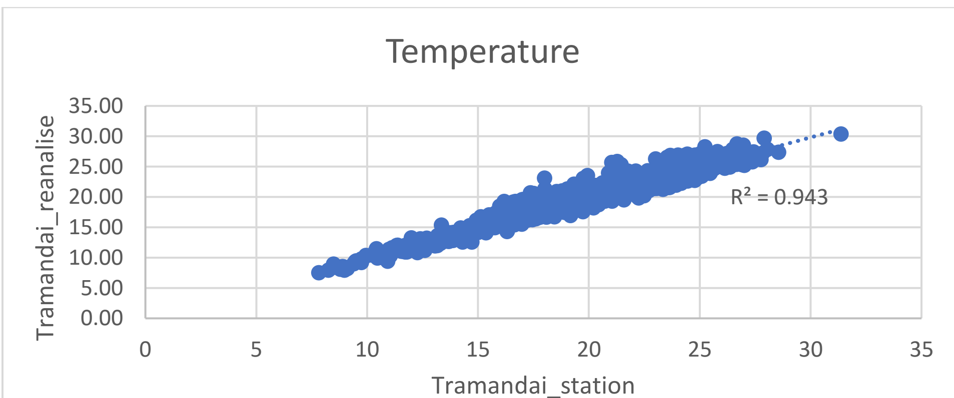


Figure 29 Temperature for Tramandai station (observed) x STIL reanalyse (modelled).

Table 3 Statistics Temperature: Tramandai station (observed) x STIL reanalyze (modelled).

	NSE	PBIAS	R^2	RMSE	STDEVobs	RSR
Calibração	0.94	0.45	0.94	1	4.03	0.25
Validação	0.86	0.45	0.94	1	4.03	0.25

Table 3 presents the results for the temperature analysis, where the parameters a good model performance, where the efficiency of the curve fitting is R2*100%, resulting in a 94% correlation between the two analysed data, meaning an appropriate fit between modelled values and the recorded in Tramandai station (Table 3). 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:

The daily average value for precipitation modelled is averaged daily. The mentioned statistical approaches were made to estimate the correlation between the modelled precipitation and record from STIL and Tramandai stations.

Tramandai (station) vs Tramandai (modelled)

The first analysis is considering the ERA5 precipitation inputs at Tramandai with the observed in the referred station.

Table 4 Statistics of Precipitation at Tramandai station (observed) and reanalyses (modelled ERA5)

	NSE	PBIAS	R2	RMSE	STDEVobs	RSR
Calibração	0.41	4.16	0.41	8.64	11.23	0.77
Validação	0.41	4.16	0.41	8.64	11.23	0.77

Table 4 shows a good but inadequate fitting, meaning the precipitation presents a characteristic not described in the climatic model.

STIL (station) vs STIL (modelled)

Then, the analysis is made between the information model for precipitation in the location of the STIL station and the actual observed values for Precipitation at the STIL station. Precipitation recorded at STIL presents no gaps in the data. Thus, no value needed to be excluded from the analysis period (Figure 30).

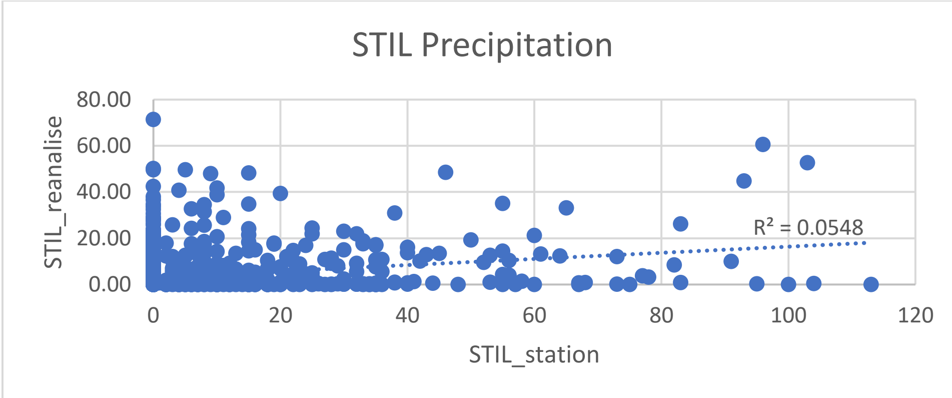


Figure 30 Precipitation for STIL station (observed) x STIL reanalyzes (modelled).

Table 5 Statistics Precipitation: STIL station (observed) x STIL reanalyze (modelled).

	NSE	PBIAS	R2	RMSE	STDEVobs	RSR
Calibração	-0.06	21.07	0.05	13.93	13.52	1.03
Validação	-0.06	21.07	0.05	13.93	13.52	1.03

It is possible to say that by the statistical analysis in Table 5, the relationship between precipitation values of the model is very low correlated with the records at STIL.

Thus, it is possible to say the modelled values for precipitation present a low correlation to the reality in the region. 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 localized 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.

4.3. Lagoa dos Barros, aquifer and precipitation analysis

Figure 31 presents the monitoring data of water level and precipitation. The data were obtained from a local monitoring system implemented in the area since 1992 by STIL (Technical Irrigation System from Santo Antonio da Patrulha) to control the recall of water from the Lake and its level, once the irrigation of the crops around the lagoon is made by the water pumped and drained from Lagoa dos Barros.

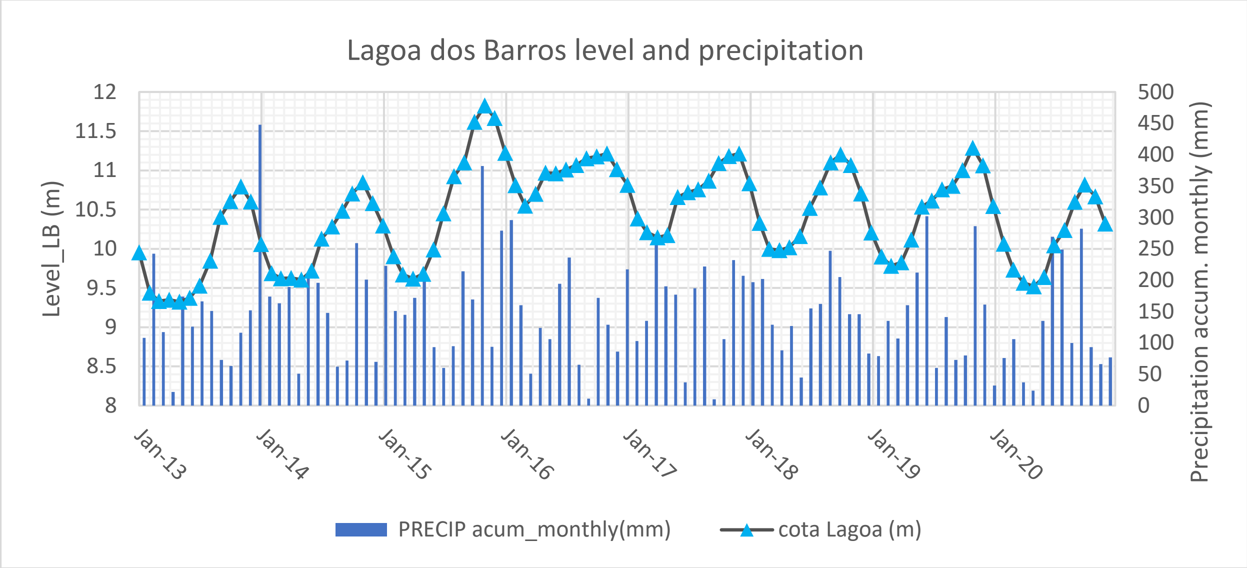


Figure 31 Precipitation and Lagoa dos Barros surface water level (Source: STIL, 2021)

4.3.1. Precipitation and water levels

Cumulative deviations from average precipitation (Cda) were computed and then plotted with the water level and the groundwater evolution through time to verify if the precipitation evolution behaviour of STIL records is appropriate to the water level variations (Figure 32).

$$Cda_n = (P_n - \bar{P} + Cda_{n-1})$$

Equation 16

It is possible to suggest an association between the variation in water storage with precipitation. Based on Figure 32, the aquifer system and the water body present similar behaviour in response to precipitation recorded at STIL. Thus, the precipitation recorded at 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.

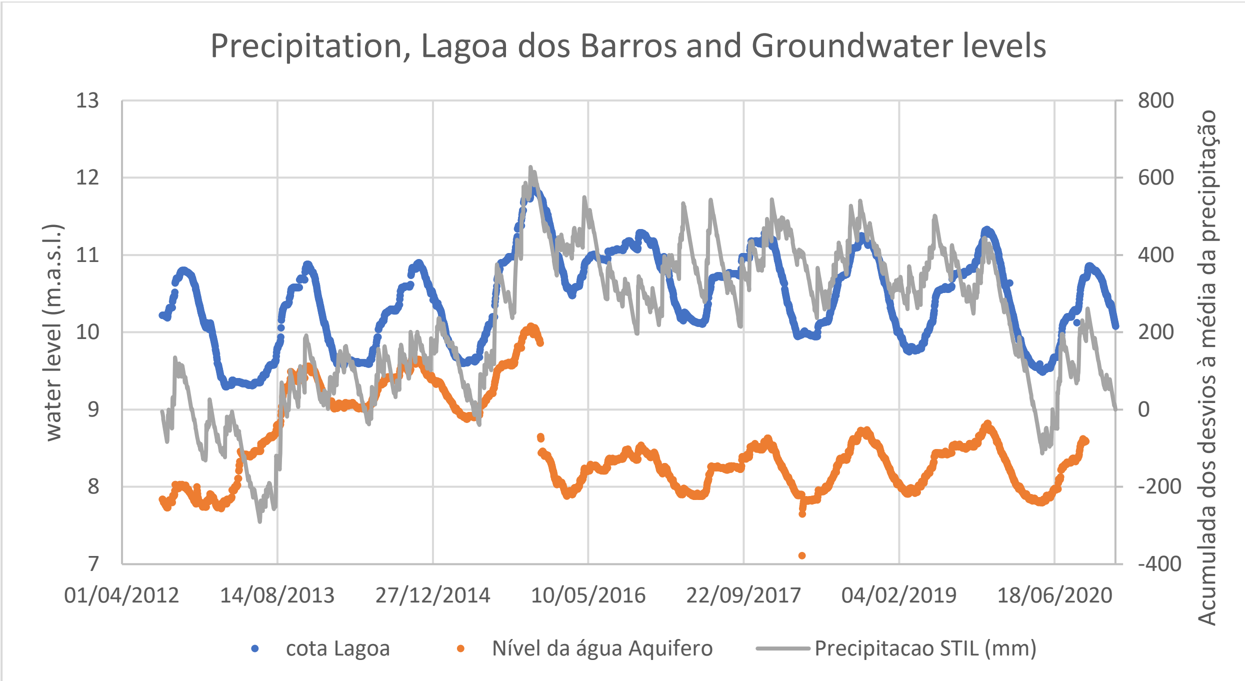


Figure 32 Precipitation, Lagoa dos Barros (STIL, 2021) and Groundwater (CPRM, SIAGAS, 2021).

By analysing the water levels from the area, it is possible to visualize a correlation between the Lagoon's surface water level and groundwater table variation. The relationship is way more significant after 2017 than the whole analysis period since 2012 (Figure 33).

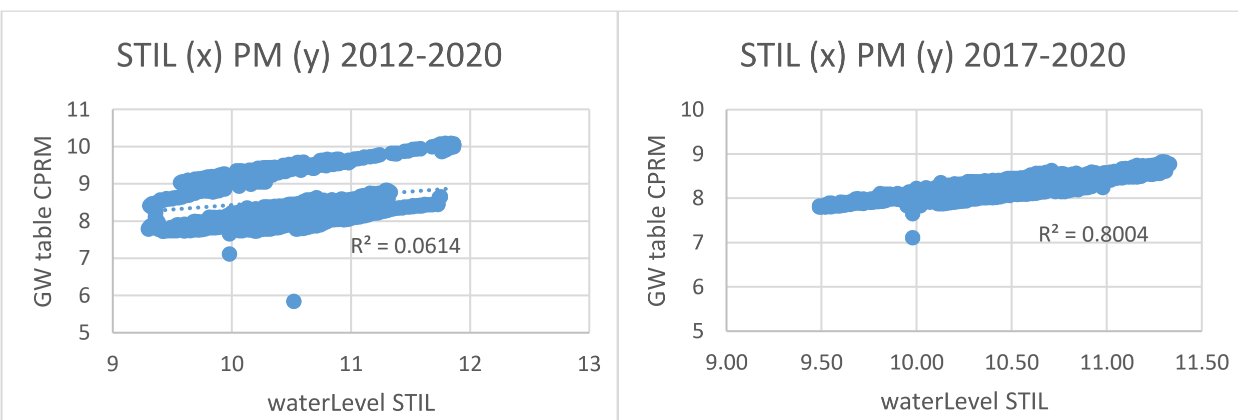


Figure 33 Correlation between Lagoon's water level and groundwater table from 8th August 2012 until 29th September 2020 (left) and from 1st January 2017 until 29th September 2020 (right) (STIL, 2021) (CPRM, SIAGAS, 2021)

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 balance. It indicates the relationship between those water bodies. The focus is to identify if the Lake responds to the aquifer or if the aquifer receives water from Lagoa dos Barros leading a similar evolution through time.

4.4. 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. In this sense, information and data from the literature review support the characterisation of the area. The water balance comprises three main factors: the input, the output water contents in the Lake, and the volume variation based on the surface area and the water body level.

$$\Delta V = IN - OUT \pm GW$$

$$\Delta V - (IN - OUT) = \pm GW$$

$$\boldsymbol{\Delta V - P - WWTP + ETP + I = \pm GW}$$

Equation 17

Where:

- ΔV= Volume variation;
- P = Precipitation;
- WWTP = Waste Water Treatment Plant;
- ETP = Evapotranspiration;
- I = Irrigation;
- GW =Groundwater contribution.

The Lagoon's water balance needs to know the surface water area to estimate its volume variation, total precipitation volume, and open water evaporation. Thus, this parameter is estimated through satellite imagery, explained in the Lagoa dos Barros imagery section. Furthermore, this information is analysed together with the Lagoon's surface water level recorded by STIL meteorological station.

The method used rainfall as input described further in Input: Precipitation, the evaporation is explained in Output: Evapotranspiration, the calculations to estimate the volume of water for irrigation at Output: Irrigation and discharge into Lagoa dos Barros from the WWTP (Input: Waste Water Treatment Plant Effluent) are all described in the following sections.

Hence, after calculating the parcels, it can be induced that what is absent may be the groundwater input or output and the spillways that discharge water out the lake when the lagoon reaches the altitude of the channels, happening every summer, as Figure 34 shows. As already mentioned, it is unfeasible to estimate an accurate flow rate within these channels once it is variable and dependent on the system conditions, such as the lake's water height and soil conditions. Likewise, the flow is not constant in the drainage network neither presents a pattern that allows flow estimation in these channels. Thus, to confirm if the constructed spillway flow is irrelevant to decreasing Lagoa dos Barros's water level, as Gomes da Silva & Selistre (2016) mentioned, an analysis considering every channel should be done in a subsequent study to quantify the outflow correctly.

Based on this, it is correct to affirm that the resultant volume of this equation may consider the contribution of groundwater and the discharge of the lake's channels that behave as affluents.

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.

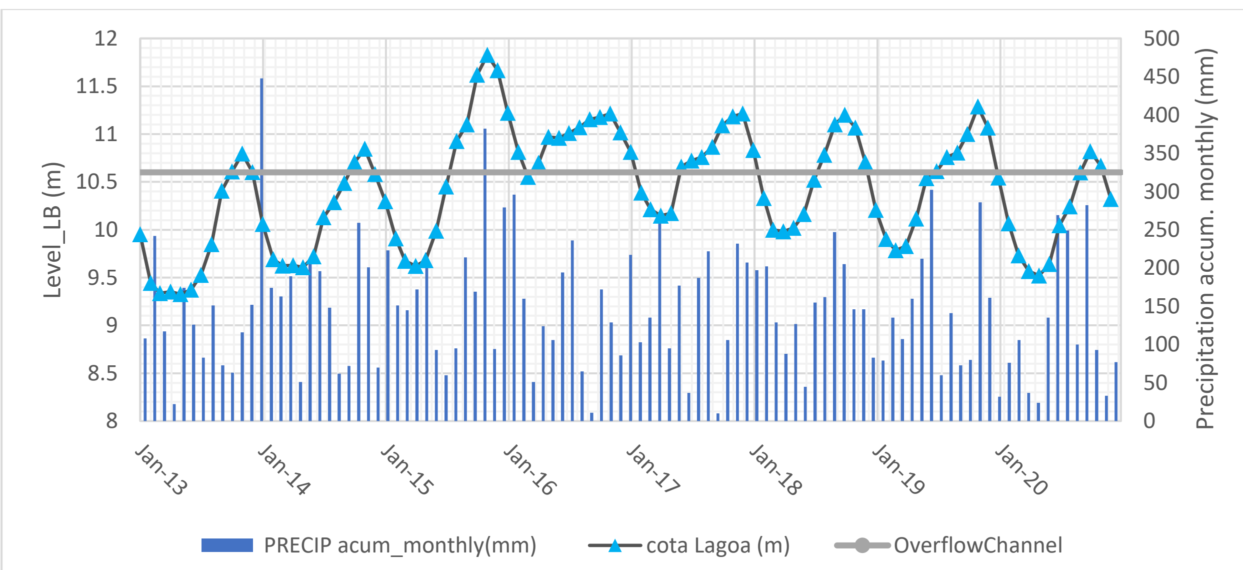


Figure 34 Lagoa dos Barros surface water level with the base quota of the known overflow channel.

4.4.1. Precipitation and surface-level monthly variation

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 visualize the impacts of each factor and infer specific conclusions by decreasing the variables then the probability of errors. Thus, knowing the maximum possible increase by precipitation, the remaining variables can be considered, if necessary, to the Water Balance (Equation 18). 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.

$$\boldsymbol{IN} = \boldsymbol{\Delta hL} + \boldsymbol{OUT} + \boldsymbol{\Delta hGW}$$

Equation 18

4.4.2. Evaporation

To estimate the evaporation rate from the surface area of Lagoa dos Barros, the simplified Penman equation (Equation 19) is applied to estimate evaporation from the surface manually. Over the potential evaporation, the available water is considered as the maximum actual evaporation because it cannot evaporate more than that. Also, it is applied by the model MOHIDLand during the simulation process (see Output: Evapotranspiration).

$$E_0 = \frac{700\, T_m/(100 - A) + 15\,(T - T_d)}{(80 - T)}$$

Equation 19

Where:

- E_0 = Evaporation rate (mm/day);
- T_m = T (°C) + 0.006h, h is the elevation (metres),
- T = Mean temperature (°C);
- A = Latitude (degrees);
- T_d = Mean dew-point (°C);

Values resulting from this formula typically differ from measured values by about 1.7 mm/day for a day (Linacre, 1977). In this case, the evaporation was estimated daily. Figure 35 presents the evapotranspiration plotted with precipitation and temperature to visualize its behaviour in the last 5 years.

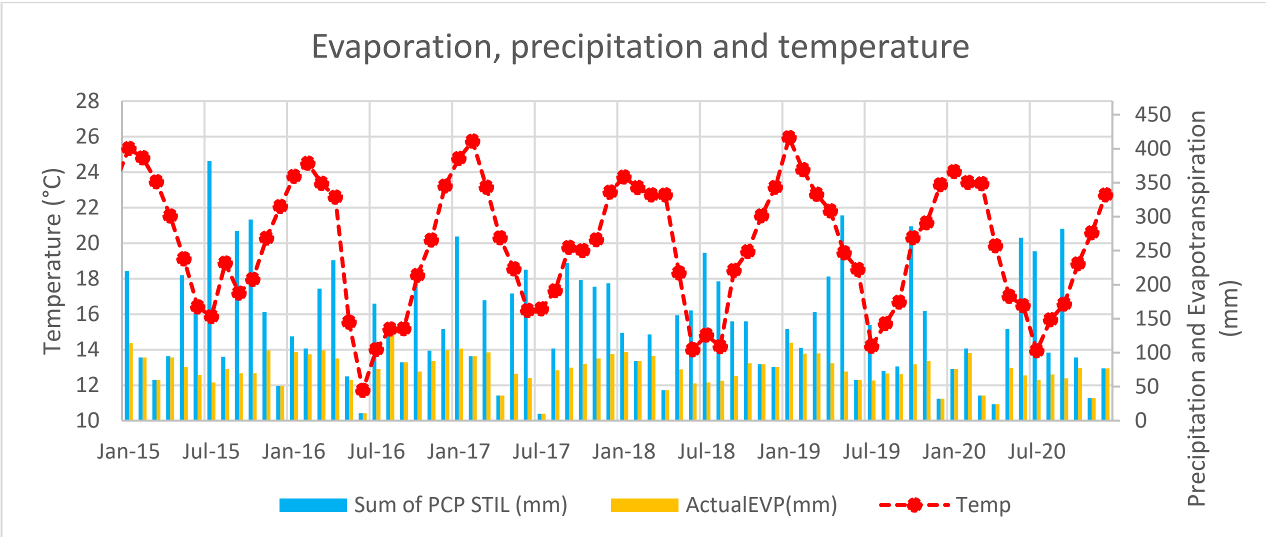


Figure 35 Monthly average Temperatures (ERA5) sum of Precipitation (STIL) and Evapotranspiration (estimated by Penman eq and available water)

4.5. Lagoa dos Barros imagery from Sentinel-2 Satellite

Satellite images downloaded from Copernicus are called tiles. Sentinel-2 tiles present usually 110x110km^{2}, varying the total area based on the longitude of the interest zone.

The satellites identify the Earth's reflectance based on different wavelengths and save the images of each band separately. All the imageries contain information of Earth surface described in 13 bands defined by the resolution spectra of the tile, which can be 10, 20 and 30 meters in pixel size (NASA, 2021).

From Sentinel-2, it is possible to obtain two types of tiles, Top-Of- Atmosphere Level 1C and Bottom-Of-Atmosphere Level 2A. They differ on the organisation of the files within the folder downloaded. Sen2Cor, downloaded from European Space Agency (ESA), was applied in the transformation. It is a processor of Sentinel-2 products that perform atmospheric, terrain and cirrus correction to the archives 1C transforming into 2A format. Moreover, the correction transforms the information from 1C to 2A, dividing them into 3 folders corresponding to the spatial resolution (10, 20 and 60 meters).

Furthermore, the size of each pixel from the analysed image is calculated to calculate the total area of water in the Lagoa dos Barros. Knowing the UTM (Universal Transverse Mercator) specific zone location is possible to know the pixel size in the y and x-axis. Lagoa dos Barros is located around the latitude 30 Degrees South. The size of each tile based on its location is 110,852.42 meters (Latitude) and 96,486.25 meters (Longitude), for a tile presenting 11,780 pixels in the x-axis (lat) and 10,219 pixels in the y-axis (long), resulting in an area of 89 m^2 per pixel.

Using scripts written in Python, at least 20 images from different dates with less than 10% of cloud cover were downloaded since 2016 when the Satellite Sentinel-2 was launched. The NDWI area is calculated and associated with the Lagoa dos Barros surface water level each day from those images. This process resulted in a curve and an equation supporting the area's finding through the water level measured daily. Through satellite images of the area, it is possible to estimate the variation of water area to use on the hydrological balance of the lagoon, based on the NDWI (Normalized Difference Water Index). To obtain the variation of volume of water in the lagoon, which is necessary on the water balance, the area of water obtained from satellite image analysis is used to construct Figure 36 to facilitate the association of level with the area and consequently the estimation of volumes.

With the area calculate from python codes, we get the superficial area covered by water. After, it is necessary to construct, in QGis, a model where together with the lake bathymetry, we get the volume of water.

From the Copernicus webpage, it is possible to access and download images of the interest area from Sentinel satellites (NASA's EOSDIS, Earth Observing System Data and Information System., 2021). This step focuses on obtaining information about surface water coverage area to identify the changes through time. In this case, the most indicated analysis uses images from Sentinel-2, which allows to download bands and process them to identify the NDWI (Normalized Difference Water Index). The NDWI is applied to monitor water content variations of water bodies.

NDWI uses the reflected green light (GREEN: Band 03) and near-infrared radiation (NIR: Band 08) bands to highlight water bodies; once the water strongly absorbs light from the visible to the infrared electromagnetic spectrum. Following this, it was applied the NDWI index proposed by McFeeters to the downloaded imageries (McFeeters, 2007):

$$NDWI = (GREEN - NIR) / (GREEN + NIR)$$

Equation 20

When Equation 20 is applied to process multispectral satellite images, water features present positive values, while vegetation and terrestrial features have negative values. The NDWI processed files count the pixels and estimate the total area covered by water within a polygon around Lagoa dos Barros. Then, the surface of the area is associated with the lagoon's water level observed on the same day Figure 36 was constructed with a curve to estimate the area based on the water level using these correlations. This equation is applied to the water balance to estimate the input value within a certain period. However, it is relevant to mention that the variation in the area is insignificant. This is due to the lake's shape, practically rectangular in the boundaries, resulting in a slight variation of the area between 9.5 and 11.3 meters.

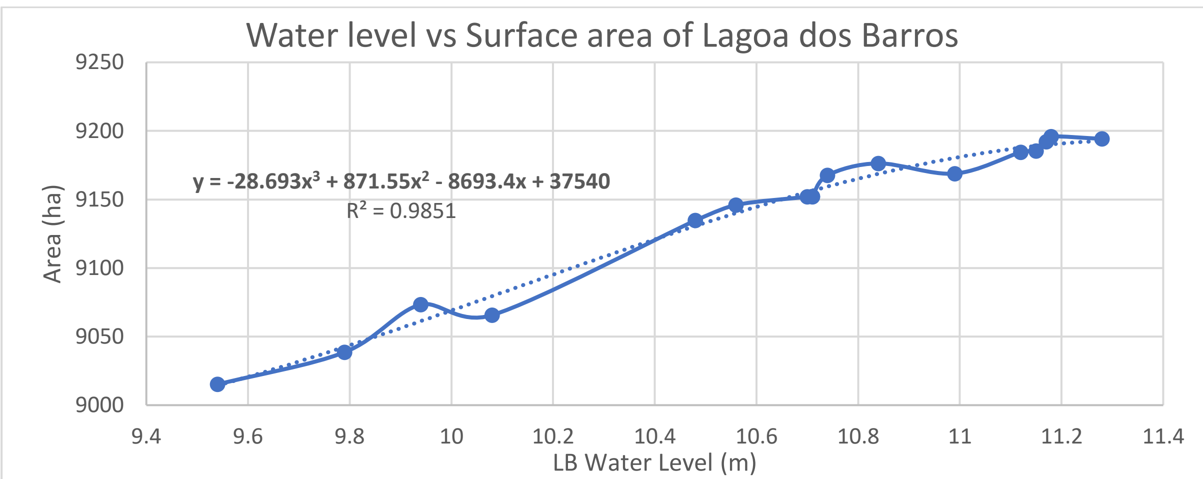


Figure 36 Curve Water Level versus Area of Lagoa dos Barros

4.6. Simulations

The methodology compares the modelled results of water level with observed data from Lagoa dos Barros. Different simulations were developed, and the results compared with reality allowing inducement of hypothesis about water system behaviour. The methodology behind it is that several simulations are developed, and, in each stage, a different characteristic is added or altered in the simulation to identify its influence.

The first simulation runs considering only the DEM (Digital Elevation Model), the atmospheric conditions (already described in the statistical analysis section) and the manning coefficient (reliant on the land cover and use). Within this first simulation, two scenarios were created. One scenario considers all the data acquired from the climatic model reanalysis, and the other scenario considers the same values for almost all meteorological variables unless the precipitation is recorded at the STIL station. However, as described earlier, the best result was with precipitation from STIL, thus this data was chosen as input to all simulations.

4.6.1. Implementation of the study area

The catchment area was delineated to simulate the runoff and see 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 (Figure 37).

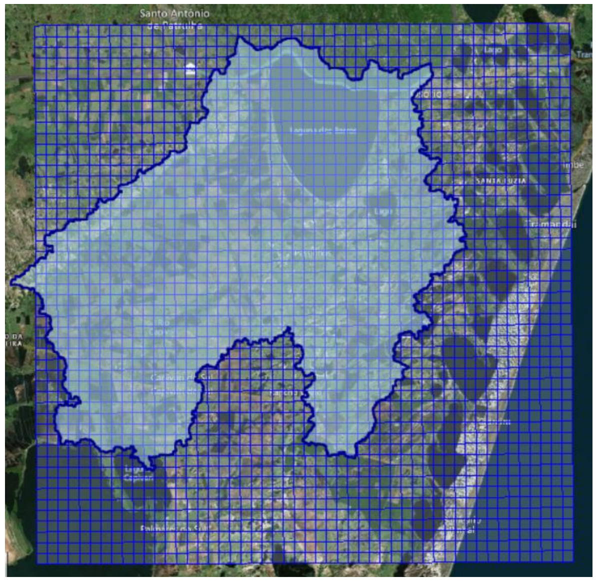


Figure 37 Grid used including the Lagoa dos Patos

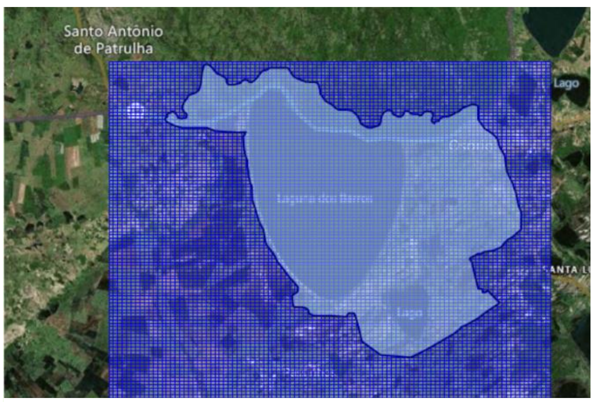


Figure 38 Grid used to simulate the micro basin of Lagoa dos Barros

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, as presented in Figure 38. Then, it is necessary to create the grid data from the raster that contain information from DEM within the Grid just created. The DEM raster was obtained from NASA and Geographic coordinates as described earlier, and it is added to OpenFlows with the Grid.

4.6.2. Basin and Lagoa dos Barros

At OpenfLowsFLOOD, the lake's bottom is merged into the DTM to create the terrain in the more detailed grid. Thenceforth, it is possible to apply the tool "Create Grid Data", which results in a file containing the DTM information inside the Grid. This Grid Data presents the same information for the whole area of the water body. Thus, it is necessary to replace this zone for its bottom, which is the Bathymetry.

Figure 40 Grid Data without information of Lagoa dos Barros surface

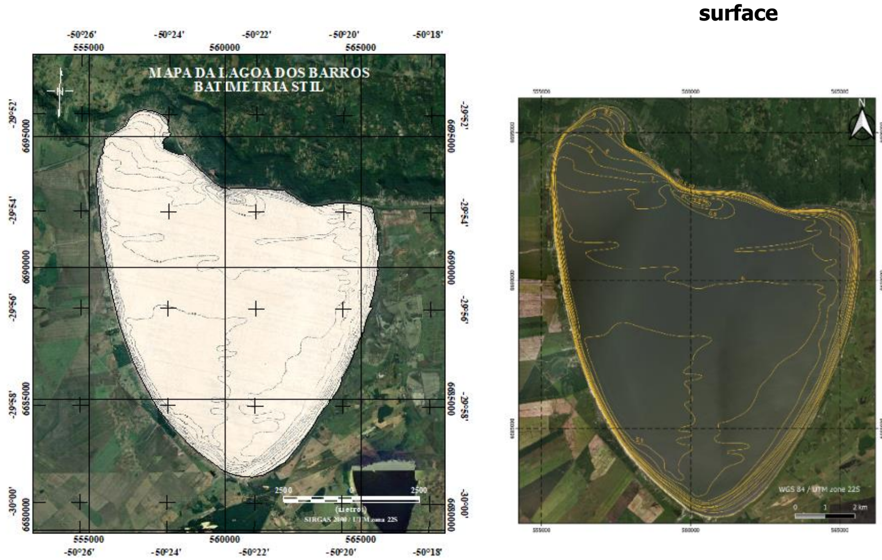


Figure 39 STIL Bathymetry (left) (1970) and shapefile containing the bottom altitude of Lagoa dos Barros (right)

In QGIS, using the tool "Difference", the polygon of the surface contour area of Lagoa dos Barros has removed information from the Grid Data through this process, resulting in the Grid presented in Figure 40. This Grid Data resultant of the difference is used in MOHID to interpolate the bathymetry lines within this area and unify them with the topography. The Bathymetry produced by STIL in 1970 is presented in Figure 39. It was inserted in QGIS and georeferenced. Then, the author created the contour lines corresponding to each specific altitude relative to the bottom Lake as visible below in the same image.

Then, in QGIS with the feature “points along geometry”, these lines are used to originate points with an output of a file of points equally distancing above the original vector line. Then, this shapefile was inserted in OpenFlows FLOOD and within the Tool “File conversion” transformed into .xyz format. The Bathymetry points containing altitude information relative to sea level need to be extrapolated and transformed into a shapefile of the bottom area, and it substitutes the Grid throughout the Lake surface area. At OpenFlows, the tool “Create Grid Data” uses the Grid without information in the Lake and the Bathymetry points in .xyz to interpolate the points values within the “Polygons Representing Non-Computed Areas” (NCA). The software asks which interpolation method to use. In this case, the “Average Z within grid cell” method with the Triangulation: Extrapolation method interpolates the Bathymetry using the initial Grid as a reference. The resultant interpolated bottom of the Lake is presented in Figure 42. Then, the two grids with information need to be merged, the bottom of Lagoa dos Barros. This process results in a final grid representing the topography containing DTM and the Bathymetry information in the same file presented in Figure 41.

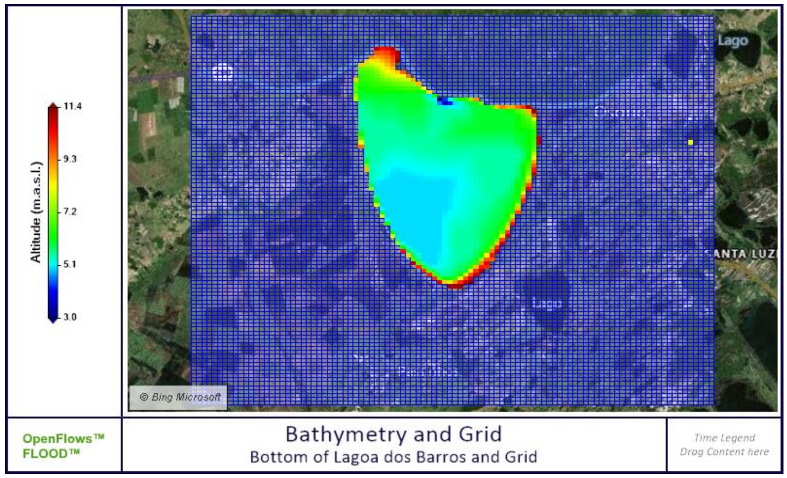


Figure 42 Bottom of Lagoa dos Barros interpolated from STIL

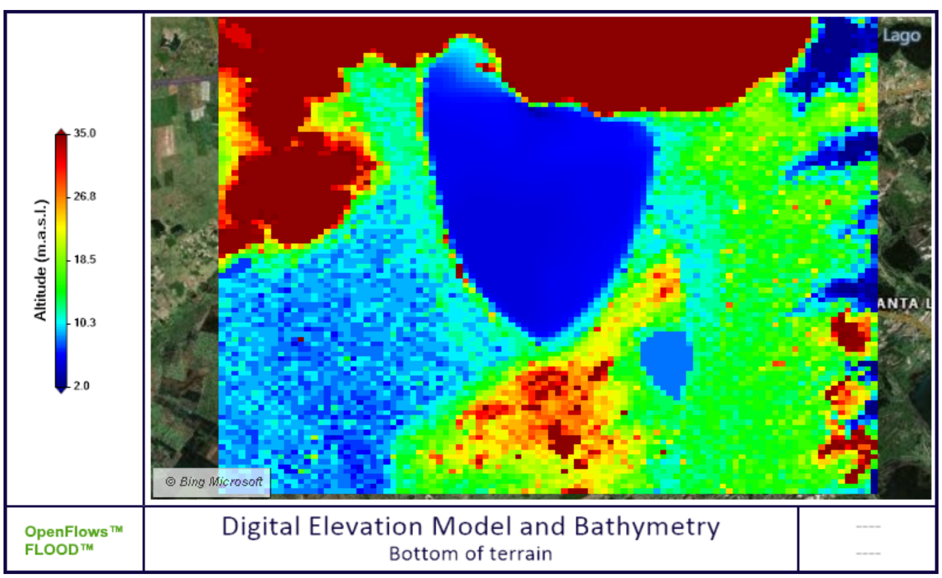


Figure 41 DEM and Bathymetry in the Grid region around Lagoa dos Barros.

4.6.3. Initial conditions

Still, at the runoff parameter, the initial water column needs to be settled. It is created from the final topography with the Lake bottom merged into a single .dat file. The information on the water level at Lagoa dos Barros is selected from STIL records. It is necessary to find the information on January 1st 2018 when the simulation begins. The water level at Lagoa dos Barros at this date is measured at 11.08 meters. This day was chosen because of the warming period the model needs to stabilize the system and provide accurate results.

To create the initial water column at the Lake, the Bathymetry interpolated at OpenFlows FLOOD is opened at Excel, and the cells containing information are within the area of the Lake. Thus, from the water level of 11.08 meters, the bottom Lake needs to be subtracted to know the height of the water column on January 1st 2018. The file of the water column at Lagoa dos Barros is inserted in the "Initial conditions" as a Grid Data in the "Initial water depth [m]".

4.6.4. Land Use – Manning coefficient

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) was released on December 21 2010. The zip file contains a raster version of the GlobCover land cover map for 2009 (Figure 43). The map is in geographic coordinates in a Plate-Carrée projection (WGS84 ellipsoid). Explanatory documents are summarised in files within the zip, including the cover map's legend and description of the pixel's IDs values as presented in Table 6. The IDs stand for the land cover classes values and are linked with the corresponding land cover labels and RGB codes

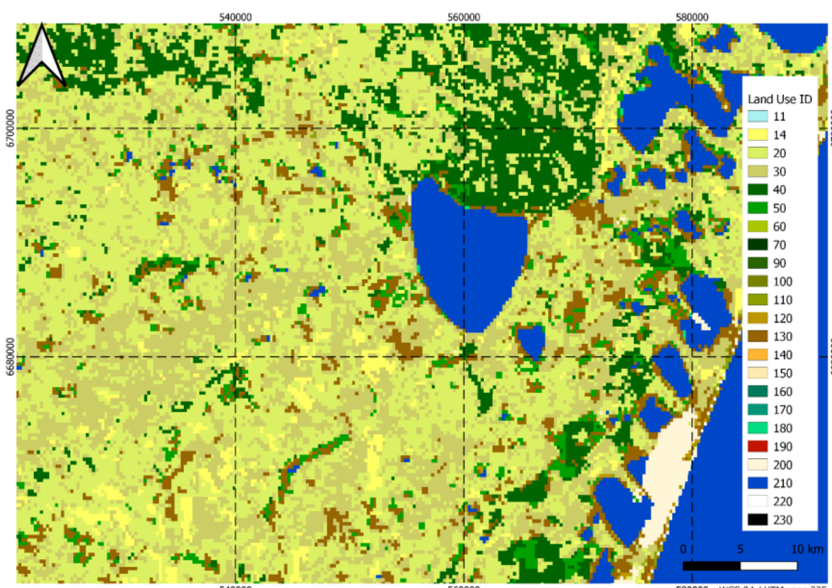


Figure 43 Map of Land Use (ESA, European Space Agency; UCLouvain, Université Catholique de Louvain, 2009)

(ESA 2010 and UCLouvain). Figure 43 presents the distribution of different soil uses in the Lagoa dos Barros area.

At OpenFlows, the land use shapefile was inserted to construct the Grid Data. 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 factor. 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 (Table 6). A grid data is then created based on the area grid because it is used as the bottom flow base when MOHIDLand calculates runoff isolated.

Table 6 Soil Use ID and respective associated manning value and description

ID ESA	ID MOHID	Manning	Description 1	Description 2
50	8	0.23	Broad-leaved forest	
40	6	0.23	Mixed forest	
30	15	0.058	Agriculture, w/significant natural vegetation	
210	18	0.035	Water bodies	
200	0	0.058	Exposed Soil	
20	1	0.093	Annual crops associated w/permanent crops	Natural grasslands
180	11	0.043	Permanently irrigated land	
150	12	0.104	Sparsely vegetated areas	
140	15	0.039	Natural grasslands	
14	33	0.033	Permanently irrigated land	Rice fields
130	7	0.23	Mixed forest	
120	16	0.045	Green Forest	
110	6	0.052	Transitional woodland-shrub	Natural grasslands

The output is Grid Data containing information about the Manning coefficient. This file created from the soil use needs to be associated with the Runoff properties in the "Grid Data" initialisation method at the "Manning coefficient" option.

4.6.5. Porous Media

The soil raster shapefile is downloaded from the FAO world soil database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009), where it is possible to find the viewer for the data in .mdb format to download the HWSD raster and implement as boundary conditions at OpenFlows. 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. Despite presenting the same configuration, they present different physical characteristics between them.

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) (Figure 44) described mainly concerning the horizons disposal and this the infiltration capacity and drainage of each soil. Additionally, the database provides information on the soil class, the bulk density and texture of each soil associated, as presented in Table 7.

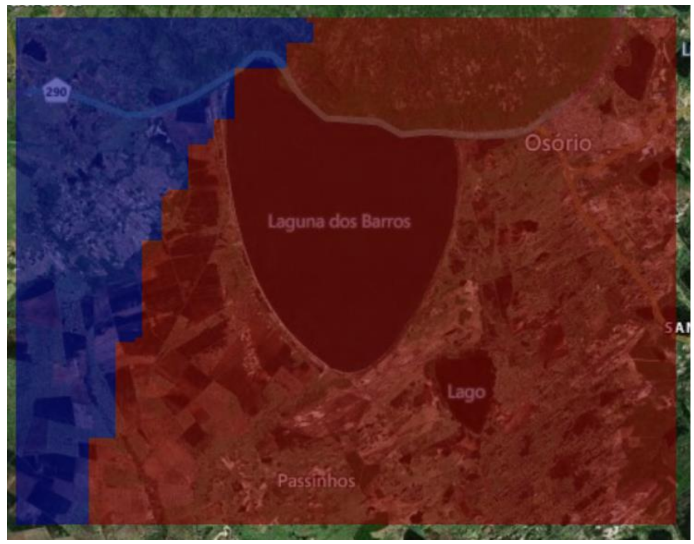


Figure 44 Sub and Top Soil distribution in the area, in Blue the Planosols and in Red the Arenosols (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009)

Table 7 Information obtained from Harmonized World Soil Database for the Region of Lagoa dos Barros

Characteristics obtained from HWSD	PL - Planosols	AR - Arenosols
	TOPSOIL (0 - 30 cm)	
Topsoil Sand Fraction (%)	46	89
Topsoil Silt Fraction (%)	36	5
Topsoil Clay Fraction (%)	18	6
Topsoil USDA Texture Classification	loam	sand
Topsoil Bulk Density (kg/dm3)	1.44	1.5
	SUBSOIL (30 - 100 cm)	
Subsoil Sand Fraction (%)	35	90
Subsoil Silt Fraction (%)	31	5
Subsoil Clay Fraction (%)	34	5
Subsoil USDA Texture Classification	clay loam	sand
Subsoil Bulk Density (kg/dm3)	1.49	1.53

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 shape parameters, which is from Equation 6 and is presented below (Van Genuchten, 1980)

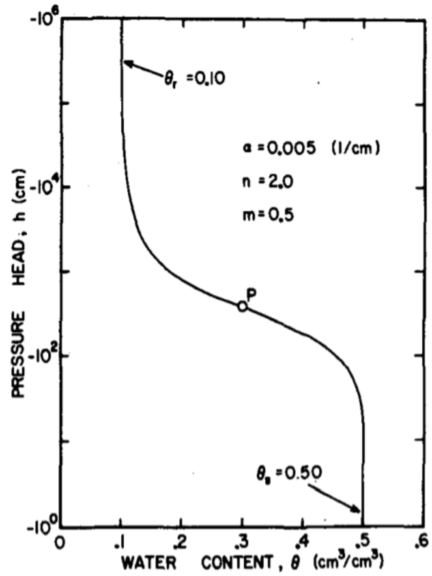


Figure 45 Example of soil-water retention curve (Van Genuchten, 1980)

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{1 + (\alpha h)^n]^m}$$

Equation 21

Where:
ϑ is the soil moisture content (m^3/m^3);
ϑ_r is the residual water content (cm^3/cm^3);
ϑ_s is the saturated water content (cm^3/cm^3);
α is related to the inverse of the air suction (cm^{-1});
h is the suction head (cm);
n is a measure of the pore-size distribution n>1 (dimensionless);
m 1–1/n (dimensionless);

Table 8 Van Genuchten water retention curve shape resulted from HYDRUS and inserted in MOHIDLand.

HWSD	θr [cm³/cm³]	θs [cm³/cm³]	α [1/cm]	n [-]	Ks [cm/day]	L [-]
PL top	0.0566	0.392	0.0122	1.498	15.71	0.5
PL sub	0.0798	0.4178	0.0137	1.3804	6.38	0.5
AR top	0.0523	0.392	0.033	2.4328	302.47	0.5
AR sub	0.0512	0.3815	0.0334	2.5884	336.59	0.5

The physical Properties described by UFRGS I (2015), such as texture and hydraulic conductivity of the vicinity of Lagoa dos Barros, are used to check the values obtained with the HWSD and through the Hydrus conversion software presented in Table 7. Also, on the porous media model, the horizontal hydraulic conductivity needs to be specified. If this value is inserted as the literature suggests, which is 10 times the vertical conductivity, the velocity within the soil becomes very small and is not well represented by the model. For example, the planosols present a saturated hydraulic conductivity of 7 cm/day, resulting in a movement of 25,6 meters per year, which even in the whole simulation period of 3 years can't be visualised in the model with cells of 300 meters width.

At MOHIDLand, 11 layers of soil with a total thickness of 10 meters were inserted to represent the Porous Media with a layer thickness of 0.15; 0.15; 0.3; 0.4; 0.5; 0.5; 1; 1; 2; 2; 2 meters respectively, starting from the topsoil. The layers are created to simulate the aquifer and the transport of water through the soil pores.

4.6.6. Vegetation

The vegetation was inserted as the same distribution as the soil cover (ESA, European Space Agency; UCLouvain, Université Catholique de Louvain, 2009). In VegetationParameters.dat, the identification of soil use is translated to a correspondent vegetation ID of MOHID as presented in Table 9 below. Additionally, it is necessary to impose the harvesting period for rice (represented as RICE number 33) and soybeans (represented as AGRL number 1) were analysed and inserted in the GrowthParameters of MOHID. Soy is represented as the other agricultural practice because it increases the planting area in the region. The planting day and the harvesting day is implemented as Julian day. Based on the STIL harvesting report, the rice planting day is around November 10 (Julian day 314), and the harvesting is around March 20 (Julian day 79), completing a cycle of around 130 days. For the soybeans' cultures, the planting day for the state of Rio Grande do Sul starts around the spring in Brazil and the harvesting in autumn. Thus, the days of December 10 (Julian day 344) was chosen to be the planting day and April 20 (Julian day 110) (Conab, Companhia Nacional de Abastecimento, 2021).

The calculation of crop evapotranspiration (ETc) is determined by the crop coefficient approach whereby the effect of the various weather conditions are incorporated into ETo (the evaporating power of the atmosphere) and the crop characteristics into the crop coefficient (Kc) as follows:

$$ET_c = K_c * ET_o$$

Equation 22

The vegetation IDs map respective for each type of soil cover is depicted in Figure 46.

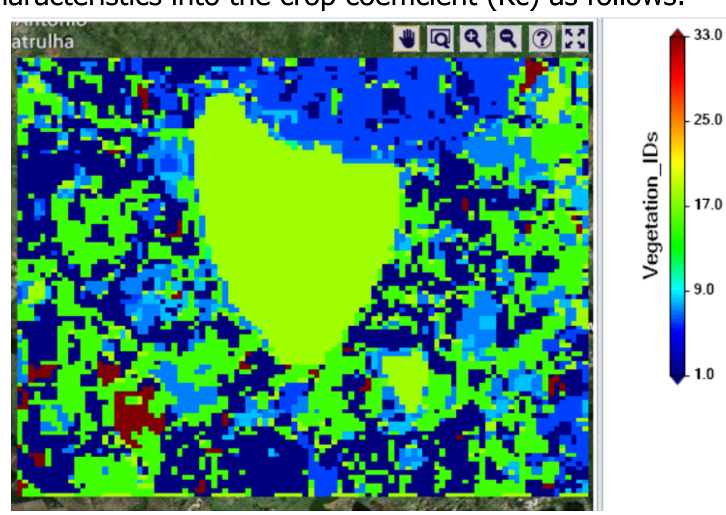


Figure 46 Vegetation IDs inserted in MOHIDLand

The database contains three different Kc values, one initial, mid and end, which are used to construct the evolution curve of the evapotranspiration and estimate the water removal from the soil (Figure 47).

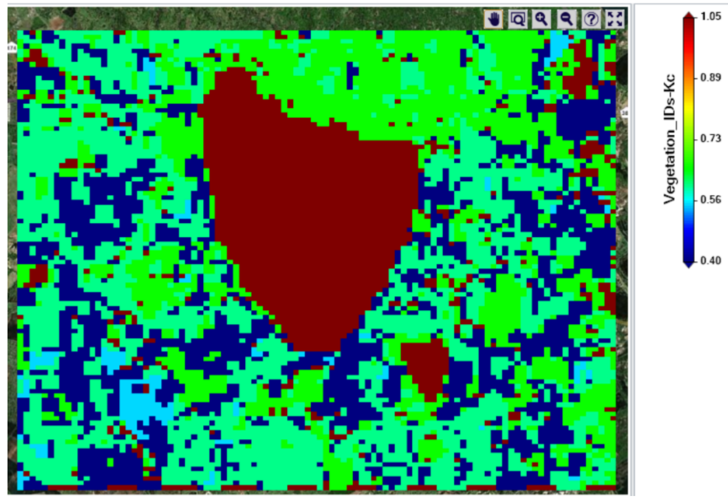


Figure 48 Crop Coefficient inserted in the model [Crop Coefficients (K_c)]

However, the vegetation was inserted as a constant Single Crop coefficient (Kc) due to

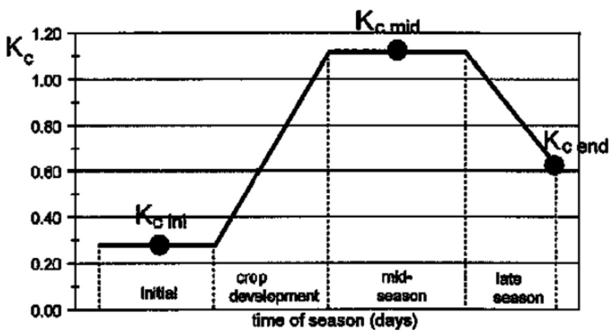


Figure 47 Crop Coefficient curve

issues. 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 (Table 9), while Figure 48 presents the crop coefficients distribution along the area.

Table 9 ID value and description from GlobCover and its correspondent in MOHID and the Kc applied.

Value Label	Sigla	Vegetation_MOHID_ID		K_c
50	BroadFor	8	FRSE	0.65
40	MixFor	6	FRST	0.65
30	GrShrFor	15	RNGE	0.4
210	Wat	18	WATR	1.05
200	BaAr	0	NoVeg	0.15
20	CrGrShr	1	AGRL	0.6
180	GrWooFloo	11	WETN	1.05
140	GrSav	15	RNGE	0.4
14	RaCr	33	RICE	0.55
130	BroNee	7	FRSD	0.65
120	GrFor	16	RNGB	0.4
110	ForShrGr	6	FRST	0.65

4.7. Atmospheric data

After climatic analysis, the data from the model was processed and organised to insert into the software. Two files containing atmospheric information were created and originated the two first simulations. The first file contains STIL precipitation and since 2012 in daily records. The second contains the variables from the ERA5 climatic model except for precipitation on an hourly basis. Thus, the data is inserted daily because of the impossibility of dismembering the daily precipitation data into hourly information. The variables used were already described and analysed in the Meteorological section.

4.7.1. Input: Precipitation

The input of water in the Lagoa dos Barros is mainly from precipitation. Thus, after the climactic analysis of the gathered data presented, precipitation recorded at STIL was visible the most appropriated to insert on the model. The calculation uses the daily accumulated values to calculate the total volume inputted in the surface area of Lagoa dos Barros.

4.7.2. Output: Evapotranspiration

Evapotranspiration is the sum of water evaporated from soil, canopy storage, surface water column, and plant transpiration. MOHIDLand applies the Penman-Monteith equation (already presented in Evaporation) and uses the water availability in soil.

4.8. Discharges

The next step is to add the discharges in the Runoff section. In this sense, the information of water used for irrigation and effluents discharges from WWTP were processed to insert in the model correctly.

4.8.1. Output: Irrigation

During summer, water is pumped out from Lagoa dos Barros to maintain a constant flow and enough volume for irrigation. Then, it flows by gravity throughout the natural and constructed channels to irrigate the crops in the plain area downstream.

To estimate the total volume supplied from Lagoa dos Barros to irrigate the flooded rice crops during the harvest period, information from IRGA reports for the latest years is used as a reference for approximating the total rice farming area. According to the harvesting bulletins for 2018/19 and 2019/20 and water balance studies made by Gomes da Silva & Selistre (2016), the average extent of irrigated rice using water discharged from Lagoa dos Barros has been around 10,757 hectares since 2015. STIL represents around 30% of the total irrigated area, which by providing information, supports the estimation of the total volume within summer. Data provided from STIL are the beginning and end of the harvesting period, the number of motors working, which is 4 with a constant flow of 1200l/sec during the pumping, and the total pumping hours facilitating the estimation of the total volume removed within a certain period. Then, by knowing the total volume per area is possible to apply the same flow to the other irrigated zones.

The average flow rate per area is then used to estimate the total volume of water withdrawn from the water body during high precipitation and biomass growth in the crops, which usually varies between November to March, as presented in Table 10.

Table 10 Information from STIL about the irrigation pumping period

Safra	Irrigação (dias)	Horas de recalque (vazão de 1200 L/sec)	Horas recalque/dia por motor (h/day)	Volume por bomba L/day	/azao por bomba L/sec	Àrea irrigada STIL qq.	ha	m3/ha	TOTAL AREA IRRIGADA (ha) IRGA	Total Volume por safra (m3)	Flow m3/s
2010/2011	120	4,960	10.3	44,640,000	1,200	1,819.00	3,169.43	6760.59	**9800**	66,253,822.14	14.84
2011/2012	126	5,625	11.2	48,214,286	1,200	1,812.00	3,157.23	7696.62	**9800**	75,426,906.03	14.90
2012/2013	108	5,942	13.8	59,420,000	1,200	1,794.00	3,125.87	8211.95	**9800**	80,477,072.33	15.05
2013/2014	114	5,666	12.4	53,677,895	1,200	1,831.00	3,190.33	7672.27	**9900**	75,955,513.63	14.89
2014/2015	125	4,699	9.4	40,599,360	1,200	1,838.00	3,202.53	6338.64	**10757**	68,184,708.95	16.12
2015/2016	137	5,697	10.4	44,910,657	1,200	1,982.00	3,453.44	7126.54	**10757**	76,660,142.52	14.95
2016/2017	122	4,817	9.9	42,642,295	1,200	1,694.00	2,951.63	7050.16	**10757**	75,838,597.58	17.49
2017/2018	125	5,244	10.5	45,308,160	1,200	1,707.00	2,974.28	7616.67	**10757**	81,932,501.56	17.36
2018/2019	161	5,237	8.1	35,130,186	1,200	1,579.00	2,751.25	8223.11	**10757**	88,456,040.80	18.77
2019/2020	142	5,281	9.3	40,165,352	1,200	1,434.00	2,498.60	9130.68	**10757**	98,218,674.57	20.66

The total volume of water used to irrigate the area per period was divided into the days and the pumping hours of the harvesting, which goes from November until March of each year, usually containing 130 days and a 10h/day of averaged pumping, resulting in the volume per hectare presented in the column "m^3/ha". Then, this volume rate was applied in the total irrigated area and resulted in the presented flow in m^3/s for each specific time.

For the simulation, an averaged flow of 16.14m^3/s for each irrigation period was distributed into the three central farmers cooperatives, agreeing with Gomes da Silva & Selistre (2016). However, it is crucial to notice the underestimation, especially for the 2019/2020 period, resulting in an omission of around 4m^3/s (closely to the overflow channel capacity).

The total volume of water was estimated in the Output: Irrigation section, then it was distributed between STIL and Santa Teresinha, which are the largest ones, and for each was assigned 2/5 of flow, and for the other less expressive it was estimated 1/5 of the total volume. These values were distributed into the days of harvesting in m^3/sec on an hourly basis. Additionally, the irrigation flow needs to assign a negative value representing volume removal from the water body. The locations of the discharge point were estimated roughly within the lagoon's surface area and far from the borders to not cause instability on the removal of flow from the water column.

4.8.2. Input: Waste Water Treatment Plant Effluent

The discharge flow from the WWTP was obtained from monthly reports of CORSAN (CORSAN - Companhia RioGrandense de Saneamento, 2018-2020), presenting the flow in L/sec per day during the period of operation from November 2018 to May 2020, with a daily average of 11.7 Litres per second. These records were transformed into m3/sec on an hourly basis to insert into the model. The WWTP effluent is inserted as a positive value because it is an input of water volume. Although this discharge is insufficient to influence the water level, its concentration of nutrients can highly influence water quality.

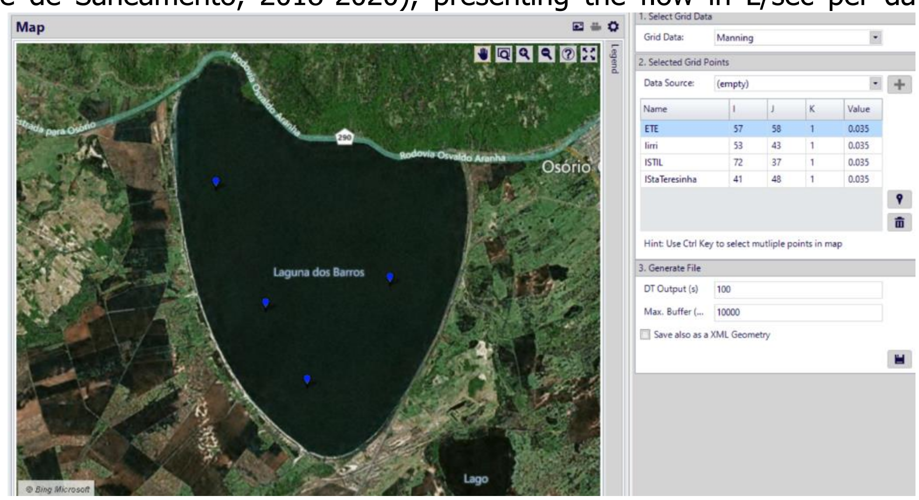


Figure 49 Discharge's location

The location of the discharges was chosen based on the best option to maintain the model stable during the simulation. Consequently, the points were settled considerably far from the border of the Lagoon for not having the risk to destabilise the calculus in the cell and cause an error during the simulation process. Figure 49 presents the location of the discharges.

4.9. Time series location

The time series location is selected from the final grid data to say to the model where we want to see the simulation outputs of each module such as runoff, porous media and vegetation. Thus, three main points were selected, one at STIL, one in the centre of Lagoa dos Barros, and one where the piezometer of CPRM is located. The location of the point is presented in Figure 50. These points were chosen for then, be possible to compare the simulated with observed values.

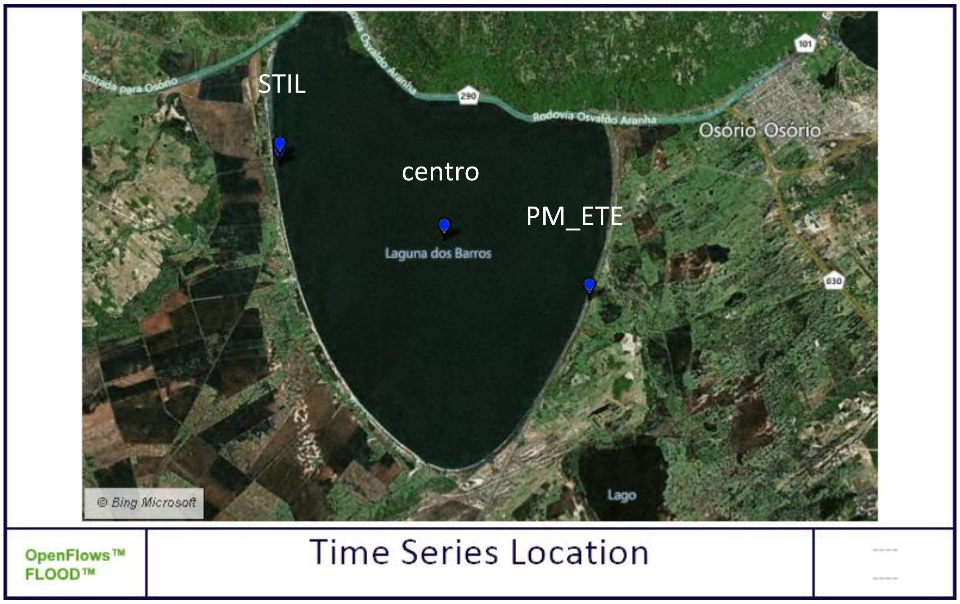


Figure 50 Time Series location

4.10. Runoff Simulation

Firstly, MOHIDLand runs without soil, vegetation and drainage network to understand only the runoff dynamics based on topography. Then, more components are added to increment the reliability and reality of the simulation.

4.11. Hydrogeology

The Brazilian Geological Service (CPRM, SIAGAS, 2021) monitors almost 400 wells across the country. Fortunately, a Piezometer is installed close to the Waste Water Treatment Plant (PZ-ETE) in the coordinate system of UTM in the 22South zone with latitude 6687060 and longitude 565115, monitoring the depth of water in the aquifer from August 2012 until November 2020. The altitude of the terrain in the point is 12.48 m.a.s.l. (CPRM, SIAGAS, 2021), thus the depth needs to be subtracted from altitude to obtain a quota in meters above sea level. As already mentioned, the piezometric level from one day, on 23/10/2014, was recorded in 4 points in the West of LB and one in the East (UFRGS I, 2015).

When inserting the initial water level in the basin soil, the groundwater level was set as the same level as the lagoon (11.08 meters) to the whole area, unless the lake bottom presents the groundwater level saturated. Thus the level is the same as the bathymetry. This condition is accepted as a simulation warming condition because it gives time to the model run and may reach a balance.

As already mentioned, the information provided by UFRGS in 2015 presents a single value for the day of 23/10/2014 for seven piezometers placed around the Lake. The data is presented in Table 11; the wells placed at East are marked in blue, and the rest are placed at West of the water body. The difference in the depth of water found in the wells from UFRGS I (2015) and the one from CPRM (SIAGAS, 2021) is visible.

Table 11 Piezometric information obtained on 23/10/2014 when Lagoa dos Barros is at 10.8 m.a.s.l.

Ponto	UTM-E (m)	UTM-N (m)	Cota terreno (m)	Profundidade perfuração (m)	Profundidade NE (m)	Cota NE (m)
PM01	555449.40	6691055.27	12.04	3.0	**0.70**	11.34
PM02	557114.02	6685328.08	11.72	3.0	**0.50**	11.42
PM03	565722.81	6691926.23	12.99	3.0	**1.30**	11.69
PZ-01	555373.97	6691037.44	13.59	1.2	**1.40**	12.19
PZ-02	557085.75	6685309.38	13.32	2.1	**1.93**	11.39
PZ-03	555173.00	6684837.4	9.20	1.1	**0.40**	8.80
PZ-04	554083.00	6690018.30	10.80	1.0	**0.70**	10.10
PZ_ETE	565115	6687060	12.481	88	**2.86**	9.621

If the data is analysed deeply, it is possible to find incongruencies in the information from UFRGS. For example, PM01 and PZ01, distancing 77 meters between them and increasing 2 times its depth from one to another. The same occurs with PM02 and PZ02, which are virtually in the same place distancing 34 meters between them, and present a variation on water depth of three times, which may be unrealistic. Another interesting observation is that at West, the three wells record present differences that are problematic to be explained, such as the increase from 11.34 to 12.19 in 77 meters and then a decrease from 12.19 to 10.1 meters, as is visible in Figure 51.

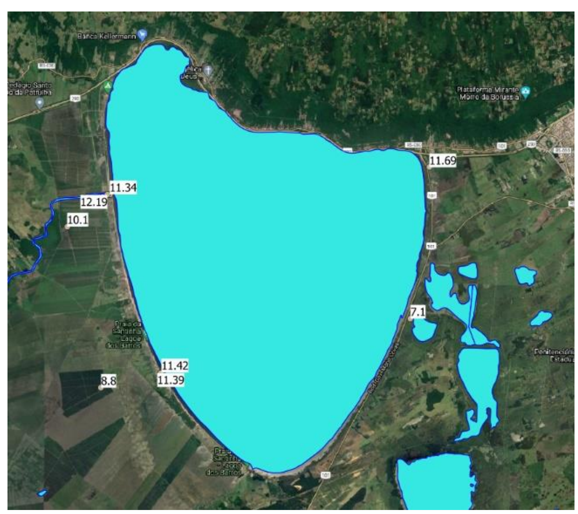


Figure 51 Groundwater Level recorded in wells around the lake in m.a.s.l. at 23/10/2014.

Thus, because of these doubts, the only information about the groundwater table in the zone data from CPRM (SIAGAS, 2021) was solely considered.

4.12. Water Table Fluctuation Method

The water-table fluctuation method (WTF) may be the most widely used technique for estimating aquifer recharge; it requires knowledge of specific yield (S_y) and changes in water levels over time. Advantages of this approach include its simplicity and insensitivity to the mechanism by which water moves through the unsaturated zone. Uncertainty in estimates generated by this method relates to the limited accuracy with which specific yield can be determined and to the extent to which assumptions inherent in the method is valid. The water table fluctuation method is applied to estimate the annual recharge of the analysed aquifer. The examination is based on the water behaviour over many years, where the WTF method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table (Healy & Cook, 2002).

Firstly, it is necessary to consider the groundwater budget within a basin, where variations in water storage can be related to recharge and groundwater flows into the basin minus the water discharging into water bodies (baseflow) evapotranspiration from groundwater and the flow out the basin. Where the groundwater budget can be estimated in mm/year as follow:

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + Q^{gw}_{off} - Q^{gw}_{on}$$

Equation 23

Where:
- R is recharge in mm ,
- ΔS_{gw} is the change in subsurface storage(L),
- Q_{bf} is baseflow,
- ET_{gw} is evapotranspiration from groundwater
- $Q^{gw}_{off} - Q^{gw}_{on}$ is net subsurface flow from the study area, including pumping

Then, recharge is calculated as:

$$R = \frac{S_y dh}{dt} = \frac{S_y \Delta h}{\Delta t}$$

Equation 24

Where:
- S_y is the specific yield(-)
- h is the water-table height (L)
- t is time (T)

The WTF method to produce a value for total or "gross" recharge requires an application for each water-level rise. In this study Equation 23 is applied over longer time intervals (annual) to estimate the change in subsurface storage, ΔS_{gw}. This value is sometimes referred to as "net" recharge. To calculate the total recharge, Δh is set equal to the difference between the peak of the last rise and the low point of the extrapolated antecedent recession curve at the peak time. The antecedent recession curve is the trace that the well hydrograph would have followed without the rise produced by precipitation (Figure 52). However, drawing the extrapolated line is a subjective matter. If long-term hydrograph records are available, many recession curves should exist from which a trace can be patterned. Particularly difficult is when a water-level rise begins during the steepest part of the previous peak's recession.

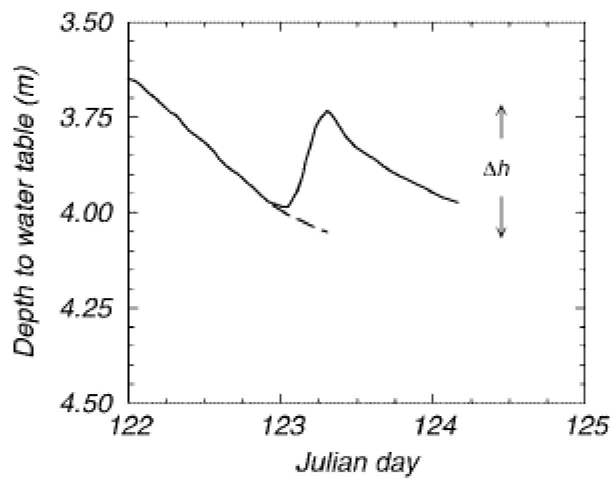


Figure 52 Hypothetical water level rise, Δh is the difference between the peak of the rishe and low point of the extrapolated antecedent recession curve (dashed line) (Healy & Cook, 2002)

For an estimate of the net recharge (ΔS_{gw}.), Δh is the difference in head between the second and first times of water-level measurement. The difference between total (R) and net recharge equals the sum of evapotranspiration from groundwater, baseflow, and net subsurface flow from the site (see Equation 23). The WTF method can estimate these parameters when making few assumptions (Healy & Cook, 2002).

Thus, the implementation of the WTF is adequate to analyse recharge at the Lagoa dos Barros aquifer system because it corresponds to the conditions of the method as being an unconfined shallow aquifer with high precipitation rates and low declivities terrain.

Data on water levels variation were obtained from the monitoring well from RIMAS (CPRM, 2017) with data periods between 2012 to 2020. As the daily data did not present a significant percentage variation, it was decided to adopt the monthly average to evaluate the recharge for a more extended series. Therefore, for each of the monitoring months, the arithmetic mean was calculated. To obtain Δh, the monthly means of level were plotted in a graph, and the acquisition of the adjustment line was performed through extrapolation with linear adjustment for each recessive curve of the hydrographer (Figures 2 and 6). The specific yield (Sy) of soil (or rock) can be defined as the proportion of the volume of water that, after saturation, is drained by gravity concerning its volume (MAZIERO & WENDLAND, 2017). For this study, reference values were sought in geophysical profiles performed in nearby wells belonging to CRPRM (RIMAS), which indicate an average value of 30% of total porosity for the superficial layers. Thus, specific yield Sy was estimated for the three most typical values for sandy soil type, 0.3 0.27 and 0.2 of the area was based on Troian et al. (2017) analysis. The sum of all water level variations, individually multiplied by the chosen Sy, resulted in the total recharge for the monitoring well during the period considered for analysis. By dividing this recharge value (mm) by the precipitation (mm) in the same period, we obtained the percentage of precipitation that can be considered recharge for the well that we consider the aquifer system adjacent to the lagoon.

A combination of the explained approach supports the characterization of the Lagoa dos Barros system.

5. Results and Discussion

5.1. Watershed Delineation and Surface Runoff

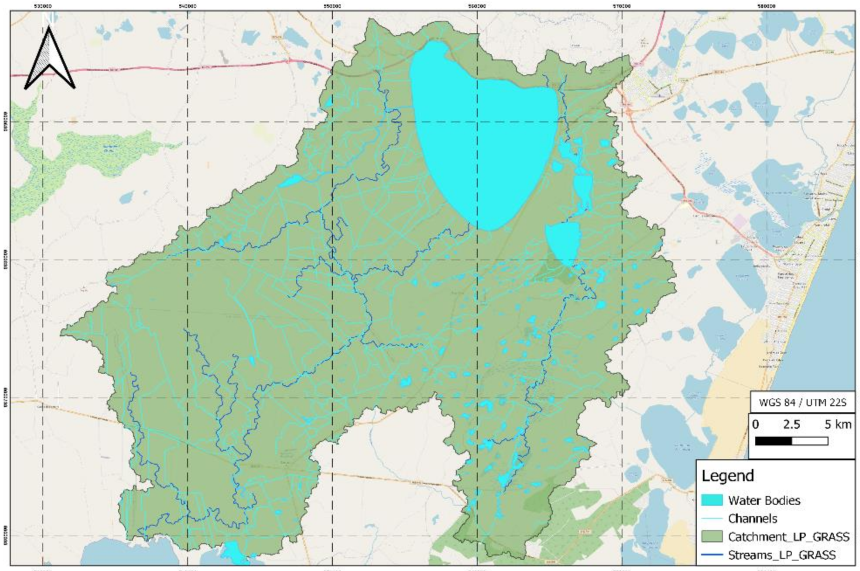


Figure 53 Drainage channels (FEPAM - SEMA, 2005) and streams delineated with QGIS Software using DTM (NASA - EARTH DATA, 2000)

After delineating the catchment of Lagoa dos Barros, the channels were added to the map because these channels are not considered in any terrain elevation model for presenting dimensions in the order of 5 to 10 meters width. This meticulous terrain analysis around the Lagoon defines essential details on the water drainage channels within the basin and supports the idea that the Lagoon is located in an upper area compared to the surroundings (Figure 53). The input of runoff happens mainly by the three affluent channels at North of Lagoa dos Barros.

Furthermore, crucial information is detectable from the terrain analysis, such as the importance of the spillway and pumping to maintain the flow towards the South when a critical level is reached, avoiding the return of runoff to this water body and be used by the crops through evapotranspiration or recharging the aquifer.

Figure 54 presents the MOHIDLand Runoff result for the 1st of 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.

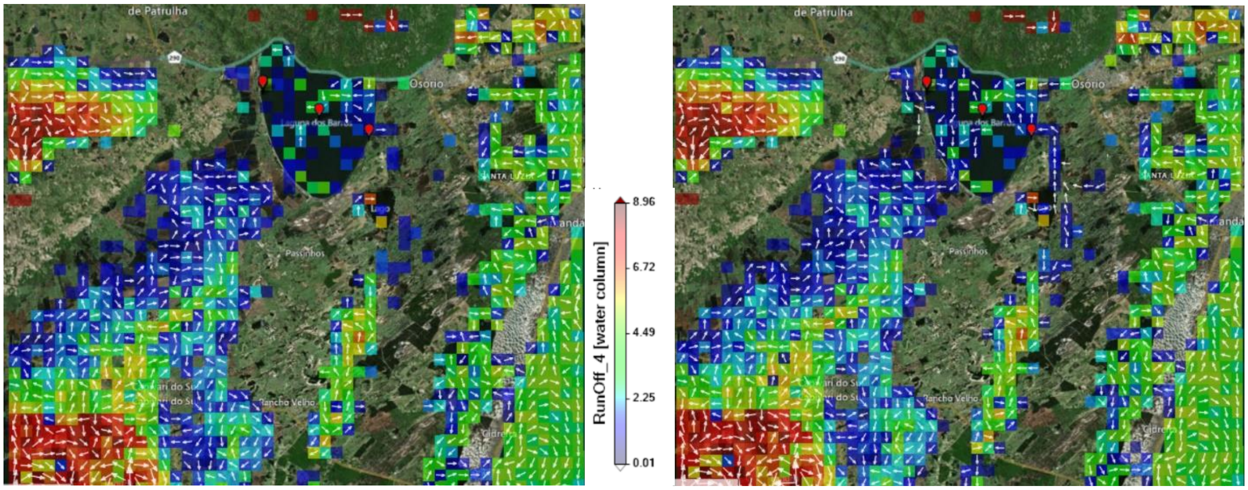


Figure 54 MOHIDLand Runoff simulation result for 1st May 2020 (left), and 30th May 2020 (right). Minimum water column of 0.01 meters and minimum flow of 0.01 m^3/s.

The variations are visible, especially in the East direction, where the flow increases in direction to Lagoa dos Barros after a wet period as may 2020, meaning the surface flow at the end of this month could contribute to the water body. However, after the extensive terrain analysis and local interviews, it is essential to mention that the 'Rodovia Gov. Mario Covas' (BR-101, Figure 55) 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). 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 characterized 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 54 shows.

Figure 55 Location of the Road BR 101 at Lagoa dos Barros Eastern direction connecting South to North (Google Earth)

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.

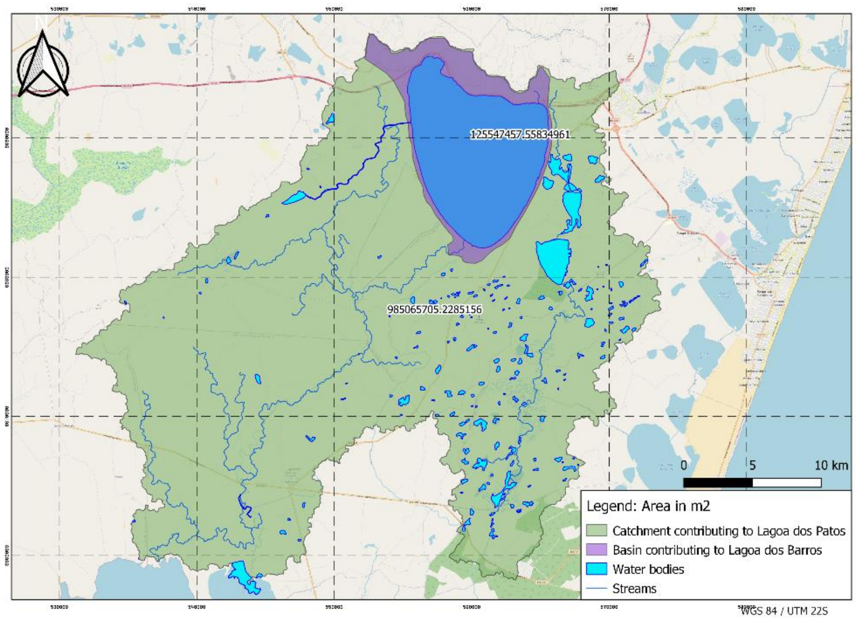


Figure 56 Catchment delineation (Lagoa dos Patos outlet) MicroBasin Lagoa dos Barros and respective areas in m^2.

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 56). 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.

5.2. Water Balance

5.2.1. Output: Irrigation

The estimated water removed from Lagoa dos Barros can control the water levels during critical periods. Thus, Table 12 presents the total removed volume for each period, and the estimated water level diminishes due to pumping to irrigate croplands.

Table 12 Volume of water pumped out Lagoa dos Barros to irrigate rice crops and the influence on the water level of Lagoa dos Barros

IrrigationPeriod	Days	Início	Término	Total volume per period (m3)	WL (avg period)	Area (ha)	A (m2)	WL removed (m)
2010/2011	120	08/11/2010	08/03/2011	167,339,520	10.3	9104	91040593	1.84
2011/2012	126	14/11/2011	19/03/2012	175,706,496	10.5	9131	91311424	1.92
2012/2013	108	10/11/2012	26/02/2013	150,605,568	10.0	9071	90710023	1.66
2013/2014	114	06/11/2013	28/02/2014	158,972,544	10.3	9106	91064119	1.75
2014/2015	125	14/11/2014	19/03/2015	174,312,000	10.3	9104	91041349	1.91
2015/2016	137	03/11/2015	19/03/2016	191,045,952	11.3	9192	91918423	2.08
2016/2017	122	08/11/2016	10/03/2017	170,128,512	10.8	9165	91648989	1.86
2017/2018	125	15/11/2017	20/03/2018	174,312,000	10.7	9159	91592164	1.90
2018/2019	161	10/10/2018	20/03/2019	224,513,856	10.5	9132	91322604	2.46
2019/2020	142	14/11/2019	04/04/2020	198,018,432	10.4	9126	91262362	2.17

5.2.2. WWTP Effluent discharges

Figure 57 presents the total volume discharged into Lagoa dos Barros monthly. It is interesting to notice the increase in the discharge volume during summer, which is coherent in seeing the natural increase in tourism on the coast during the summer holidays. Additionally, the increase in the effluent amount coincides with the pumping from irrigation, which puts the Lagoon in a critical situation once the decrease of water volume and the increase in the discharge with high nutrients concentration from the WWTP at the same time interval.

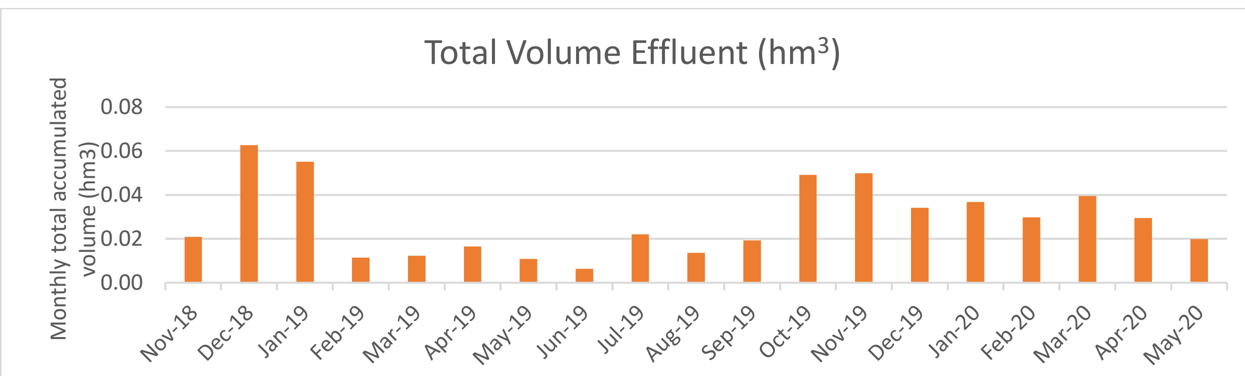


Figure 57 Accumulated monthly volume of WWTP effluent discharging into Lagoa dos Barros

5.2.3. Water level variation

Figure 58 presents the levels at Lagoa dos Barros from STIL (2021) and the groundwater table measured at PM_ETE (CPRM, SIAGAS, 2021). 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.

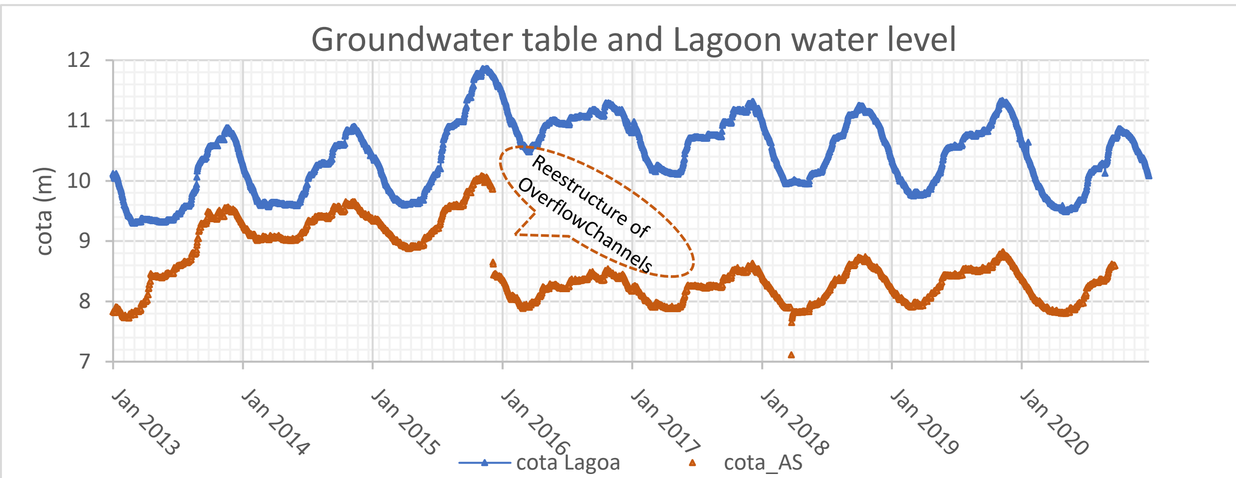


Figure 58 Daily Groundwater level (CPRM) and Lagoa dos Barros water level (STIL) in m.a.s.l.

While Figure 59 below presents the monthly values of the groundwater table, the lake's surface water level variations and accumulated precipitation amount. It is possible to perceive that these records present similar behaviour through time. When after the irrigation period, the lagoon takes time to recover its level to rise again. Also, it is essential to notice that the low rainfall period from November 2019 until May 2020 requires more water to irrigate the crops, exactly when the algae bloom became visible.

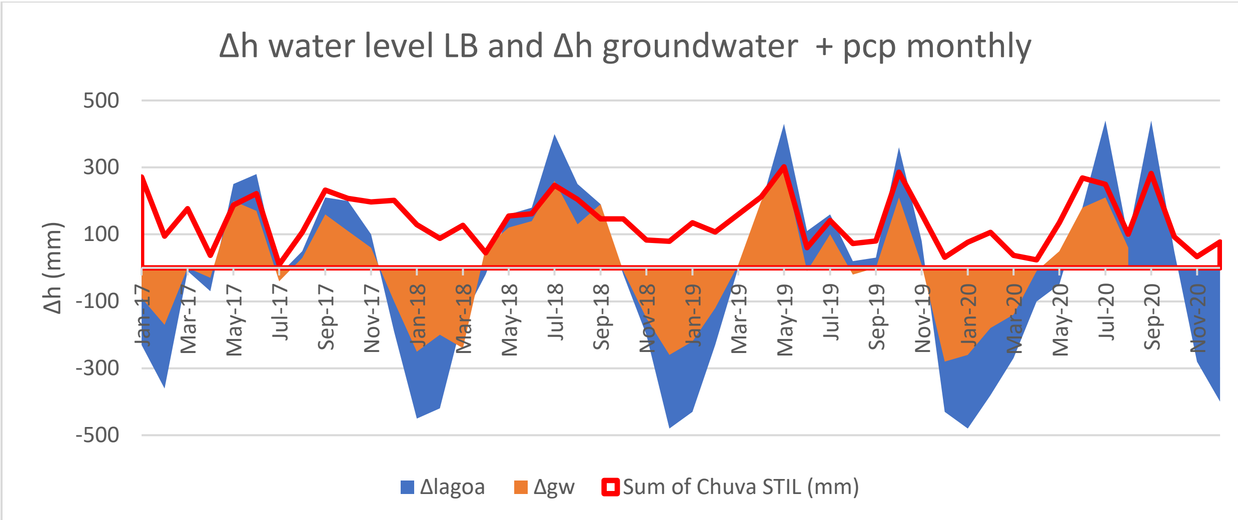


Figure 59 Monthly variation in mm of Lagoa dos Barros water level and groundwater table at PM_ETE

5.2.4. Precipitation and surface-level monthly variation

Then, precipitation is compared with the variation of the water level in the Lagoon. To notice the effect of precipitation input, the months where there is no irrigation discharge were considered because of the activity's substantial impact on the lagoon water level. The variables are being separately considered to visualize the impacts of each factor and infer conclusions by decreasing the variables, which probability of errors also decreases.

Thus, knowing the maximum possible increase by precipitation compared to the variation in water level characteristics, the possible inputs and outputs can be drawn from an adaptation of the water balance (Equation 17) as follows:

$$\Delta hL = IN - OUT \pm GW$$

Equation 25

Therefore, monthly precipitation is compared with the lake water level variation (Figure 60). Based on this, it is possible to perceive if the precipitation falling within the water body can influence the observable variation.

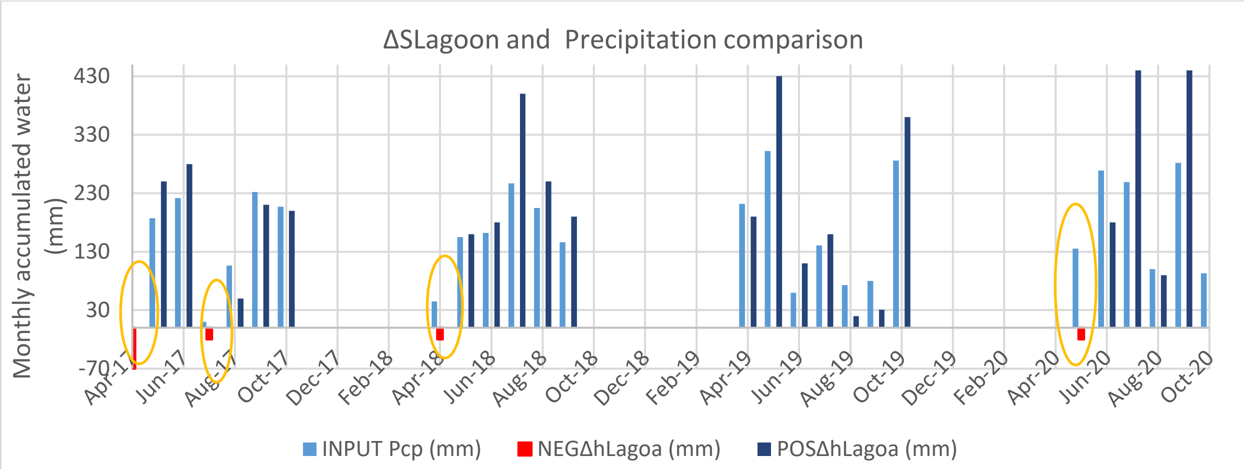


Figure 60 Monthly accumulated precipitation and recorded a variation of Lagoa dos Barros (STIL, 2021)

When there is water removal from the Lake to discharge through the crops, the level in the water body decreases to reach an equilibrium of a situation imposed artificially, and if it rains less than the needed volume, the water body cannot recover. From Figure 60, it is perceptible that the water body still faces a decrease in the water level even after the pumping stops in the first months after the irrigation period. Possible due to conditions after the water subtraction and low precipitation in the area, which cannot cause the elevation on the lake’s level

The Lagoon shows a decrease in its level in April and July 2017, and April 2018 and May 2020, presented as red bars in Figure 60. During this period, the water level in the lake is lower than 10 meters. Thus, there is no spillway from Valo do Estado. The negative variation means the deficits (evaporation and lagoon’s base flow contribution to groundwater recharge) are higher than the water input (precipitation in the lagoon's surface and the runoff contribution) to the lake in this period. The input of precipitation and runoff are smaller than the losses that can be by evaporation and discharge to groundwater. It is relevant to mention that the algae blooms were massive during May 2020, when it is visible that even accumulated precipitation of 135 mm was not sufficient to increase the water volume in the period, but it is detectable the decrease of 20 mm at Lagoa dos Barros.

Furthermore, during the remaining months where there is an increase in the water level, the water input is sufficient to produce an increase on the lagoon’s surface.

However, when the Lagoon's variation is higher, the water level variation is higher than the precipitation input, meaning a contribution beyond water falling on its surface. For example, this volume may be generated by runoff from the Northern Zone and the three main affluent channels arriving at the lagoon from these areas.

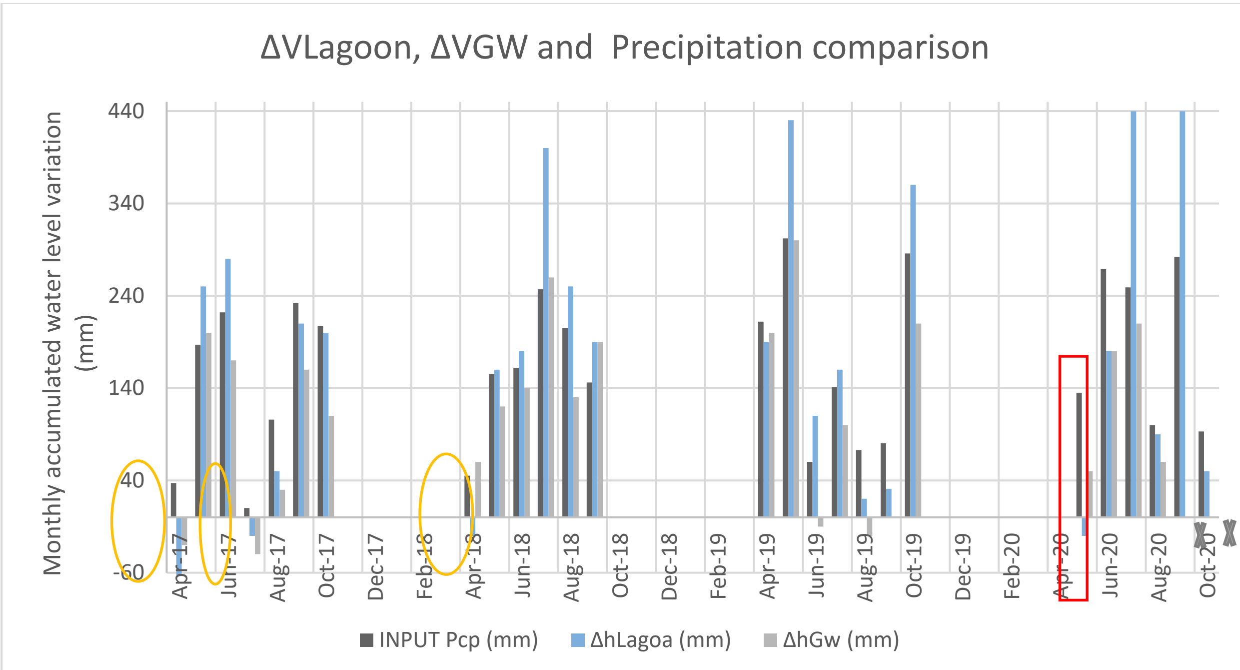


Figure 61 Monthly comparison of volume variation in Lagoa dos Barros, in the aquifer and the precipitation input in mm.

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. Looking closely at the periods in Figure 61, it can be inferred that just after the pumping stops and the irrigation happens, all the areas stay inundated 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

5.3. Simulations

Two simulations were then finally analysed. The result from MOHID considering the total soil thickness of 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. 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 in Figure 62. Despite assumptions, the modelled curves present an appropriate behaviour compared to reality.

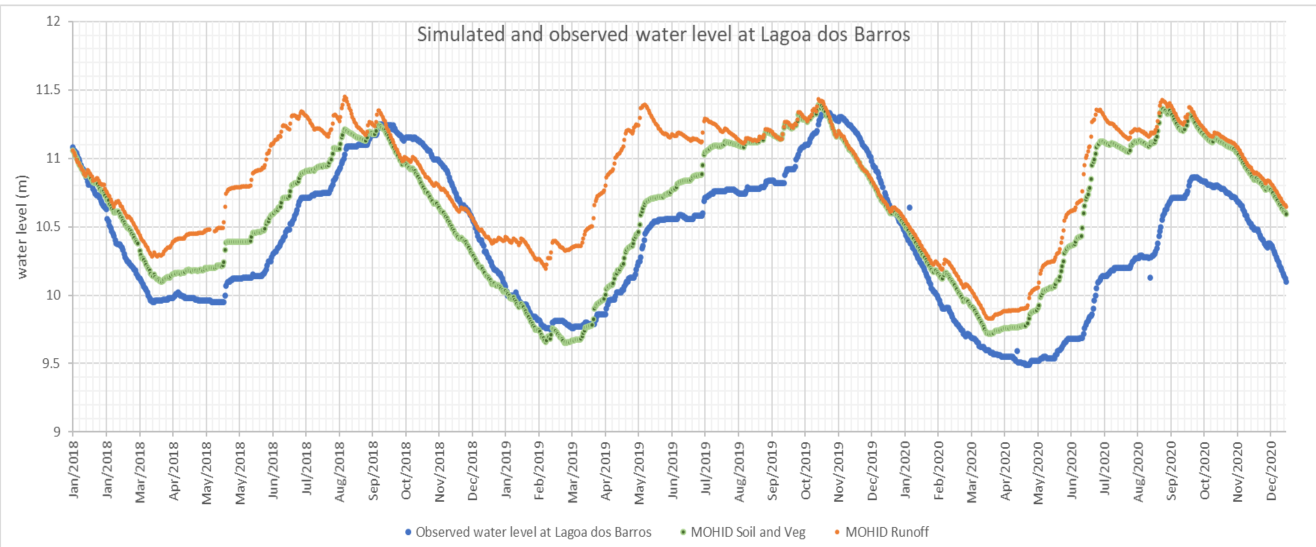


Figure 62 Simulated MOHID Results and Observed values at Lagoa dos Barros (STIL)

This overestimation behaviour of the simulated values can be due to the estimates applied to few factors such as approximations and assumptions applied during area characterisation to model. Firstly, the irrigation pumped during the period could be have been underestimated in this study. Also, the simulation doesn't recognise the limit of 10.6 meters of water level as the Valo do Estado spillway, which is not considered but should diminishing the level from the resulted 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 characterization 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.

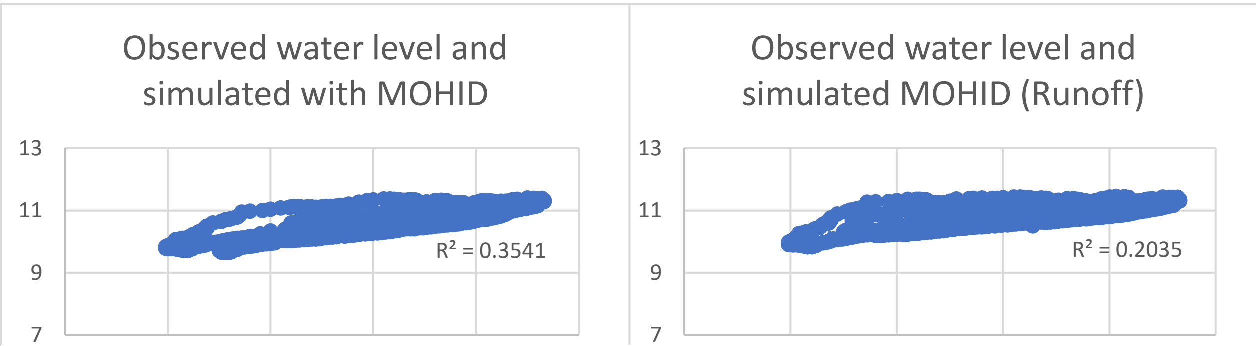


Figure 63 Observed water level values versus Simulated with soil and vegetation (left) runoff (right)

Simulated results are compared with the observed recorded by STIL. From the runoff output, the model present the water level in the time locations inserted. Thus, the time output of the point placed at PM_ETE is analysed to identify the groundwater behaviour compared to observations. Only the simulation with soil present this output because runoff does not consider the porous media.

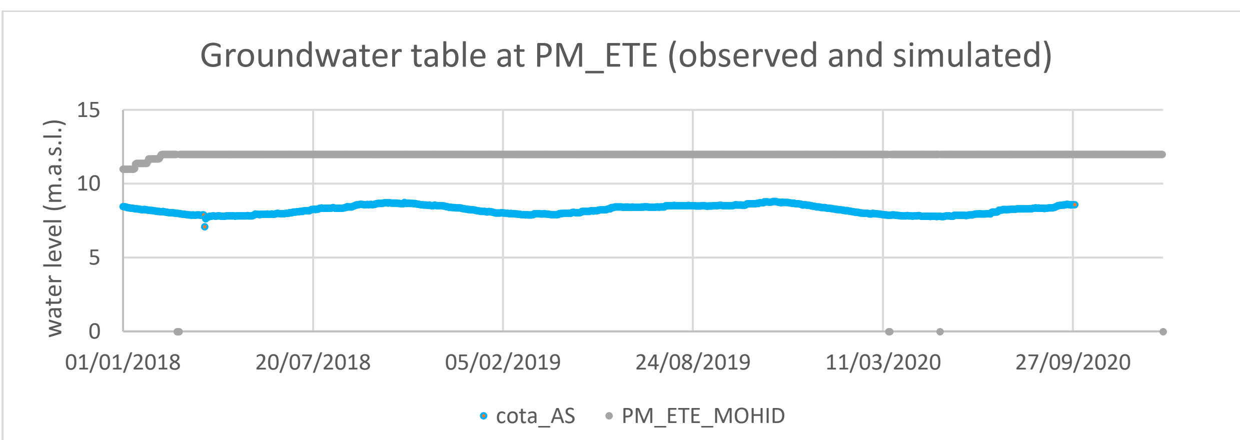


Figure 64 Groundwater level observed and simulated at PM_ETE (CPRM,SIAGAS) location

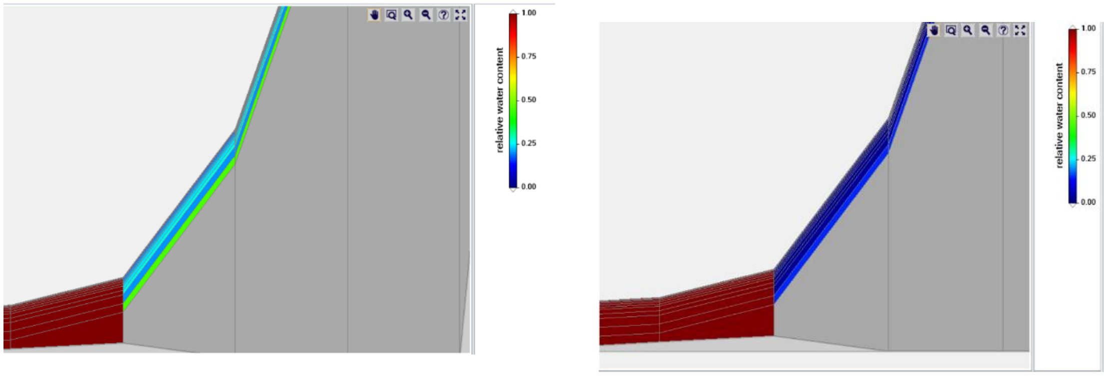


Figure 65 Crossection at Lagoa dos Barros N-S direction, left 5 July 2018, and 3rd May 2019 at right.

From Figure 64, it is visible that the simulation shows saturated soil during the whole simulation period, and Figure 65 present the cross-section where it is visible that the soils stay red during the whole simulation, meaning they are saturated even in dry periods. Also, the low gradient hydraulic represented by the flat area may influence the slow movement of water in the zone in the model. The water table doesn't vary, which may be because of all the factors already mentioned that may affect the water flow within the soil. From Figure 65, on 5 July 2018 in a wet period, thus the steep barrier with water, and interesting to notice even in the 3rd May 2019 during a dry period the figure shows the mountainous dry and the plain area saturated.

5.4. Water Table Fluctuations

The data are plotted relative to sea level, and the peaks are used to estimate the recharge of the unconfined aquifer (Troian et al., 2017). The observations show clearly the intervention made in 2015 that impacts the groundwater levels. Finally, the results of the WTF method are presented in Table 13 and Figure 66, where depending on the specific yield, the aquifer recharges from 30 to 50 cm annually. Which are plausible values compare with the mentioned study of Troian et al. (2017).

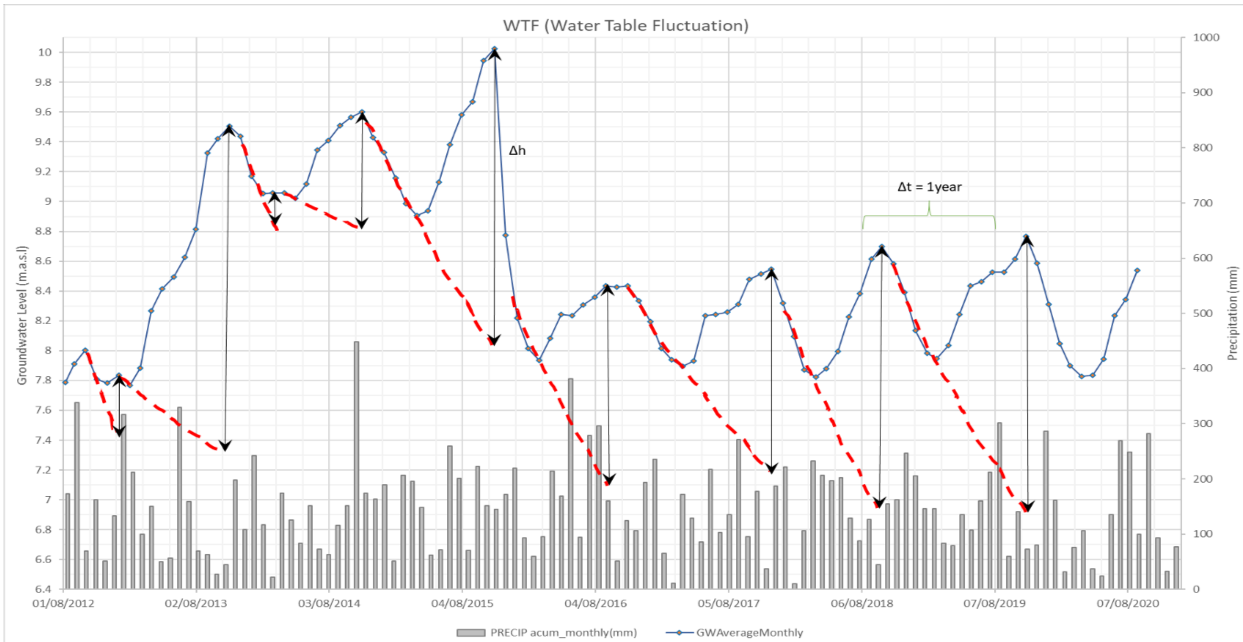


Figure 66 Groundwater table and recession curves of well PM_ETE (CPRM, SIAGAS, 2021)

Table 13 Recharge estimated with WTF for 10 years and the average annually

Δh	m	cm	mm
1	0.42	42	420
2	2.2	220	2200
3	0.27	27	270
4	0.8	80	800
5	2	200	2000
6	1.15	115	1150
7	1.39	139	1390
8	1.73	173	1730
9	1.85	185	1850
10	1.3	130	1300
Total Δh (m)	**13.110**	**1,311**	**13,110**
Δtime(years)			**8**
TotalPcp (mm)			**14,349**
AvgPcpMonthly (mm/year)			**1,794**
AvgPcpMonthly (cm/year)			**179**

Table 14 Recharge for different specific yields

Recharge (mm/year)			**% of Pcp is Precharge**		
Sy (30%)	**Sy (25%)**	**Sy (20%)**	**Sy (30%)**	**Sy (25%)**	**Sy (20%)**
492	410	328	27%	23%	18%
Recharge (cm/year)			**% of Pcp is Precharge**		
Sy (30%)	**Sy (25%)**	**Sy (20%)**	**Sy (30%)**	**Sy (25%)**	**Sy (20%)**
49	41	33	27%	23%	18%

Additionally, it is relevant to perceive the patterns of the lines drawn in the graph. However, interpretations of the data presented here should consider the limitations and uncertainties of the method. The results were found to give an idea of the order of magnitude of the values and represent only the region studied and should not be extrapolated to the entire area of the aquifer. A more careful determination of Sy values is essential, as slight variations may represent significant differences in recharge values. A better understanding of the behaviour of this aquifer and its recharge is essential for the knowledge of its governing storage, helping in the area groundwater management.

6. Conclusions and Recommendations

After temporal and physical features analysis through different approaches, the objective of characterising this complex area and the different relationships 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, which uses the piezometer records from CPRM (CPRM, SIAGAS, 2021). Additionally, because of the uncertainty of water sources to the water body, the work applied MOHIDLand to assess the contribution of the aquifer to Lagoa dos Barros or identify the significant basin flow.

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 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. However, 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 flow 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 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 water could flow from the East region to Lagoa dos Barros during wet periods, 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.

When the water levels are high at the end of winter (October), the pumping starts from the two channels placed at 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 above sea level.

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 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 adequate bathymetry of the Lagoa dos Barros should be made to characterize 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, the soil characterization 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 characterization 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

Bibliography

Alduchov, O. A., & Eskridge, R. E. (1996). Improved Magnus' form approximation of saturation vapor pressure. *J. Appl. Meteor.*, 601-609.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1988). Chapter 6 - ETc - Single crop coefficient (Kc). In *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56.* Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

American Society of Civil Engineers (ASCE). (1996). Hydrology Handbook Task Committee on Hydrology Handbook;. *II Series, GB 661.2. H93;* , pp. 96–104.

Borges, P., Bordignon, D., & Sossela, G. (2009). *Relatório Final do Processo de instalação da Estação de Tratamento de Esgoto da cidade de Osório.* Osório, RS - Brazil: RDI Nº 18/2009 - Processo nº 20174.01.00/09-3.

Brookfield, A. E., Hanse, A. T., Sullivan, P. L., Czuba, J. A., Kirk, M. F., Li, L., . . . Wilkinson, G. (2021). Predicting algal blooms: Are we overlooking groundwater? *Science of the Total Environment*, 15.

Buckingham, E. (1907). *Studies on the movement of soil moisture.* Washington, United Satates of America: Washington, Govt. Print. Off.

Canuto, N., Ramos, T. B., Oliveira, A. R., Simionesei, L., Basso, M., & Neves, R. (2019). Influence of reservoir management on Guadiana streamflow regime. *Hydrology Reg. Stud.*, 25.

CBHLM, Comitê da Bacia Hidrográfica do Litoral Médio. (2008). *COMITÊ DA BACIA HIDROGRÁFICA LITORAL MÉDIO*. Retrieved from https://comitelitoralmedio.com.br/quem-somos

CBHLM, Comitê da Bacia Hidrográfica do Litoral Médio. (2018). *Levantamento de informações para o Plano de Recursos Hídricos do Litoral Médio.* Governo do Estado do Rio Grande do Sul - Secretaria do Ambiente e Desenvolvimento Sustentável.

CBHLM, Comitê da Bacia Hidrográfica do Litoral Médio. (n.d.). Levantamento de informações para o Plano de r.

Cherry, J. A., Nwankwor, G. I., & Gillham, R. W. (1985). A Comparative Study of Specific Yield Determinations for a Shallow Sand Aquifer. *Groundwater, 22*, 9.

Conab, Companhia Nacional de Abastecimento. (2021). *Calendário Agrícola (plantio e colheita).* Retrieved from Conab, Companhia Nacional de Abastecimento: https://www.conab.gov.br/institucional/publicacoes/outras-publicacoes

CORSAN - Companhia RioGrandense de Saneamento. (2018-2020). *Resultados Analíticos de Controle de Qualidade de Efluentes .* Osório - RS: SUTRA/DECE/MAN.

CORSAN, Companhia Rio Grandense de Saneamento. (2018, 12 19). *Estação de tratamento de esgoto em Osório é inaugurada e beneficia 30 mil pessoas*. Retrieved from CORSAN: https://www.corsan.com.br/estacao-de-tratamento-de-esgoto-em-osorio-e-inaugurada-e-beneficia-30-mil-pessoas

CPRM. (n.d.). *Layer: Hidrogeologia .* Retrieved from Mapa Hidrogeológico do Brasil ao Milionésimo: http://www.cprm.gov.br/publique/Hidrologia/Estudos-Hidrologicos-e-Hidrogeologicos/Mapa-Hidrogeologico-do-Brasil-ao-Milionesimo-756.html

CPRM, SIAGAS. (2021). *Serviço Geológico Brasileiro*. Retrieved from Serviço Geológico Brasileiro: http://siagasweb.cprm.gov.br/layout/visualizar_mapa.php

Domínguez-Niño, J. M., Arbat, G., Raij-Hoffman, I., Kisekka, I., Girona , J., & Casadesús, J. (2020). Parameterization of Soil Hydraulic Parameters for HYDRUS-3D Simulation of Soil Water Dynamics in a Drip-Irrigated Orchard. *Water*, 25.

DRHS. (2020). *Bacias Hidrográficas do Rio Grande do Sul*. (D. d. Saneamento, Editor, D. d. Saneamento, Producer, & Departamento de Gestão de Recursos Hídricos e Saneamento) Retrieved 2021, from SEMA- Secretaria do Meio Ambiente e Infraestrutura: https://www.sema.rs.gov.br/bacias-hidrograficas

ECMW , European Centre for Medium-Range Weather Forecast. (2021). Retrieved from Advancing global NWP through international collaboration: www.ecmwf.int

ECMWF , European Centre for Medium-Range Weather Forecasts. (2021). *Climate reanalysis.* Retrieved from Climate - Copernicus: https://climate.copernicus.eu/climate-reanalysis?q=products/climate-reanalysis

EEA, European Environment Agency. (2016). Chapter 13- Eutrophication. In E. E. Agency, *Environmental signals 2000.* Copenhagen: European Environment Agency.

EMBRAPA. (2010). *Index of /amb_data/Shapefiles.* Retrieved from Divisão de Processamento de Imagens (DPI) : http://www.dpi.inpe.br/amb_data/Shapefiles/soloEmbrapa.zip

EMBRAPA. (2021). *Correspondência entre classes do SiBCS, WRB/FAO e Soil Taxonomy.* Retrieved from Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA Solos : https://www.embrapa.br/solos/sibcs/correlacao-com-wrb-fao-e-soil-taxonomy

ESA, European Space Agency; UCLouvain, Université Catholique de Louvain. (2009). *Global Land Cover Map for 2009 ©.* Retrieved from ESA-DUE Data User Element: http://due.esrin.esa.int/page_globcover.php

Fante, K. P., & Sant'Anna Neto, J. L. (2016). TÉCNICAS ESTATÍSTICAS PARA A HOMOGENEIZAÇÃO DE DADOS DE TEMPERATURA EM SÉRIES TEMPORAIS CLIMATOLÓGICAS. *Revista Brasileira de Climatologia*, 14.

FAO/IIASA/ISRIC/ISS-CAS/JRC. (2009, IIASA, Laxenburg, Austria and FAO,. Rome, Italy). *Harmonized World Soil Database (version 1.1).* Rome: FAO. Retrieved from FAO/IIASA/ISRIC/ISS-CAS/JRC,. Harmonized World Soil Database (version 1.1). FAO, Rome, .

Feddes, R., Kowalik, P., & Zaradny, H. (1978). *Simulation of Field Water Use and Crop Yield.* NJ, USA: Wiley: Hoboken.

FEPAM - SEMA. (2005). *Biblioteca Digital FEPAM*. (Secretaria do Meio Ambiente e infraestrutura) Retrieved from Fundação Estadual de Proteção Ambiental Henrique Luiz Roessler - RS: http://www.fepam.rs.gov.br/biblioteca/geo/bases_geo.asp

Gomes da Silva, A., & Selistre, F. (2016). *Estudo sobre o comportamento hidrológico na Subacia da Lagoa dos Barros e os efeitos do sistema aliviador de cheias e a a atividade de irrigação sobre a redução do nível da Lagoa nos períodos de cheia.* Santo Antonio da Patrulha / RS: ECOFIELD - Engenharia e Meio Ambiente.

Green, W. H., & Ampt, G. A. (1911). Studies on Soil Physics, Part 1, the Flow of Air andWater through Soils. *Agriculture science*, 11-24.

Healy, R., & Cook, P. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal*, 19.

Herms, F. (2009). *Relatório Técnico de Situação da Lagoa dos Barros, RS.* Rio de Janeiro - RJ, Brazil: Universidade do Estado do Rio de Janeiro - UERJ.

Herms, F. (2015). *Análise do Termo de Licitação da CORSAN.* Rio de Janeiro - RJ, Brazil: Universidade do Estado do Rio de Janeiro, UERJ.

INMET. (2021). *Banco de Dados Meteorológicos do INMET, Instituto Nacional de Meteorologia Brasil.* Retrieved from BDMEP: https://bdmep.inmet.gov.br/

INMET, Instituto Nacional de Meteorologia Brasil. (2021). *Mapa Estações.* Retrieved from https://mapas.inmet.gov.br/

IRGA - DATER, Instituto Rio Grandense de Arroz - Divisão de Assistência Técnica e Extensão Rural. (2019). *BOLETIM DE RESULTADOS DA LAVOURA - SAFRA 2018/19 - Arroz Irrigado e Soja em Rotação*. Retrieved from https://irga.rs.gov.br/upload/arquivos/201909/05171808-relatorio-da-safra-2018-19-31-agosto-2019.pdf

IRGA - DATER, Instituto Rio Grandense de Arroz - Divisão de Assistência Técnica e Extensão Rural. (2020). *BOLETIM DE RESULTADOS DA LAVOURA – SAFRA 2019/2020 Condições meteorológicas e seus impactos sobre as lavouras de arroz.* Retrieved from https://irga.rs.gov.br/upload/arquivos/202008/19144808-boletim-de-resultados-da-lavoura-safra-2019-2020-irga.pdf

Jacomine, P. K., Santos, H. G., Anjos, L. H., de Oliveira, V. Á., Lumbreras, J. F., Coelho, M. R., . . . Cunha, T. J. (2018). *Sistema Brasileiro de Classificação de Solos.* Rio de Janeiro - RJ, Brazil: Embrapa Solos.

Linacre, E. T. (1977). A simple formula for estimating evaporation rates in various climates, using temperature data alone. *Elsevier Scientific Publishing Company, Agricultural Meteorology, 18*, 409-424.

Marchett, C. A. (2017). *Caracterização morfológica das Lagoas de Osório, Norte da Planície Costeira do rio Grande do Sul, Brasil.* Caxias do Sul - RS, Brazil: UCS - Universidade de Caxias do Sul.

MARETEC . (2020). *What is MOHID?* Retrieved from MOHID Water Modelling System: http://www.mohid.com/

MAZIERO, T. A., & WENDLAND, E. (2017). Avaliação da recarga subterrânea de bacias urbanas no município de São Carlos, SP. In: XIV Encontro Nacional de Perfuradores de Poços, II Simpósio de Hidrogeologia do Sudeste 2005. *Aguas Subterraneas ABAS*. Retrieved from https://aguassubterraneas.abas.org/asubterraneas/article/view/23197

McFeeters, S. K. (2007). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 8.

Moriasi, D., Arnold, J., van Liew, M., Bingner, R., Harmel, R., & Veith, T. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. Am. Soc. Agric. Biol. Eng.*, 885–900.

Mualem, Y. A. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources*, 513-522.

NASA - EARTH DATA, National Aeronautics and Space Administration. (2000, February). *NASADEM_HGT Merged DEM Global 1 arc second.* Retrieved from LP DAAC - Land Processes Distributed Active Archive Center: https://lpdaac.usgs.gov/products/nasadem_hgtv001/

NASA - ESDS, Earth Science Data Systems Program. (2021). *Making Earth System Data Records for Use in Research Environments (MEaSUREs) Program.* Retrieved from EARTH DATA - Open Access for Open Science: https://earthdata.nasa.gov/esds/competitive-programs/measures

NASA. (2021). *Harmonized Landsat Sentinel-2*. Retrieved from NASA: https://hls.gsfc.nasa.gov/products-description/tiling-system/

NASA's EOSDIS, Earth Observing System Data and Information System. (2021). *Earth Data Search.* Retrieved from LP DAACs, Land Processes Distributed Active Archive Centers: https://search.earthdata.nasa.gov/search?m=-0.140625!0!2!1!0!0%2C2

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). *Soil and Water Assessment Tool, Theoretical Documentation,Version 2009.* Texas A&M University System: College Station. TX, USA: Texas Water Resources Institute. Technical Report No. 406;.

Oliveira, A. R., Ramos, T. B., Simionesei, L., Pinto, L., & Neves, R. (2020). Sensitivity Analysis of the MOHID-Land Hydrological Model: A Case Study of the Ulla River Basin. *Water*, 25.

Pestana, R., Matias, M., Canelas, R., Araújo, A., Roque, D., Van Zeller, E., . . . Heleno, S. (2013, December). Calibration of 2D Hydraulic Inundation Models in the Foodplain Region of the Lower Tagus River. *ESA Living Planet Symposium*.

Queensland. (2017). *Groundwater dependent ecosystems*. (Q. Government, Editor) Retrieved August 2021, from WetlandInfo website: https://wetlandinfo.des.qld.gov.au/wetlands/ecology/aquatic-ecosystems-natural/groundwater-dependent/

Ramos, T., Simionesei, L., Jauch, E., Almeida, C., & Neves, R. (2017). Modelling soil water and maize growth dynamics influenced by shallow groundwater conditions in the Sorraia Valley region, Portugal. *Agric. Water Manag.*, 27-42.

Richardson, K., & Jørgensen, B. B. (1996). Eutrophication in a coastal marine ecosystem. *Coastal and estuarine studies, 1*, pp. 1-9.

Ritchie, J. T. (1972). Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Res.*, 1204-1213.

Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, 18-39.

SEMAM, Secretaria Municipal da Agricultura e Meio Ambiente. (2020, April 22). *Lagoa dos Barros: Município busca a suspensão integral do funcionamento da ETE de Osório*. Retrieved 2021, from Prefeitura Municipal de Santo Antônio da Patrulha: http://www.santoantoniodapatrulha.rs.gov.br/pmsap/noticias/Lagoa-dos-Barros-Municipio-busca-a-suspensao-integral-do-funcionamento-da-ETE-de-Osorio-5531

Šimunek, J., & Hopmans, J. (2009). Modeling compensated root water and nutrient uptake. *Ecol. Model.*, 505-521.

Skaggs, T., van Genuchten, M., Shouse, P., & Poss, J. (2006). Macroscopic approaches to root water uptake as a function of water and salinity stress. *Agric. Water Manag.*, 140-149.

STIL. (2021). *Monitoramento Nível Lagoa dos Barros.* Santo Antônio ad Patrulha - RS, Brazil: Sociedade Técnica de Irrigação.

Tomazelli, L. J., Dillenburg, S. R., & Villwock, J. A. (2000). Late Quaternary Geological History of Rio Grande do Sul Coastal Plain, Southern Brazil. *Revista Brasileira de Geociências, 30*(3), 474-476.

Troian, G. C., Reginato, P. A., Senhorinho, E. M., Marcuzzo, F. F., Kirchheim, R. E., & Kuhn, I. A. (2017, December 01). ESTIMATIVA DE RECARGA PELO MÉTODO WATER TABLE FLUCTUATION (WTF) NA PORÇÃO NORTE DO AQUIFERO COSTEIRO DO ESTADO DO RIO GRANDE DO SUL. *XXII SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICOS* (p. 9). Florianópolis-SC: Associação Brasileira de Recursos Hídricos.

UCS. (2017). *Atlas Socioambiental do município de Osório.* Caxias do Sul - RS, Brazil: EDUCS · Editora da Universidade de Caxias do Sul (UCS).

UFRGS I. (2015). *Avaliação da Capacidade de Recepção de Efluentes Domésticos Tratados pela ETE de Osório na Lagoa dos Barros Relatório Final Volume I Diagnóstico Ambiental da Lagoa dos Barros.* Porto Alegre- RS, Brazil: Fundação Luiz Englert & Universidade Federal do Rio Grande do Sul.

UFRGS II. (2015). *Avaliação da Capacidade de Recepção de Efluentes Domésticos Tratados pela ETE de Osório na Lagoa dos Barros Relatório Final Volume II Modelagem Hidrodinâmica e da Qualidade da Água da Lagoa dos Barros.* Porto Alegre: Universidade Federal do Rio Grande do Sul and Fundação Luiz Englert.

van der Sande, C., de Jong, S., & de Roo, A. (2003). A segmentation and classification approach of IKONOS-2 imagery for land cover mapping to assist flood risk and flood damage assessment. *International Journal of Applied Earth Observation and Geoinformation*, 217-229.

Van Genuchten, M. T. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*, 7.

Villena, H. H. (2020). *Parecer Técnico sobre levantamento batimétrico usado na modelagem dinâmica da Lagoa dos Barros-RS.* Rio de Janeiro: UERJ - Universidade do Estado do Rio de Janeiro.

Williams, J., Jones, C., Kiniry, J., & Spanel, D. (1989). The EPIC crop growth model. *Trans. Am. Soc. Agric. Biol. Eng.*, 497-511.

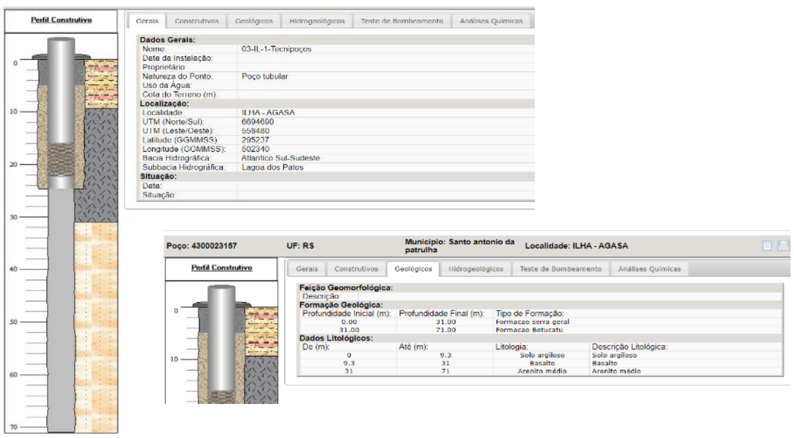
World Reference Base for Soil Resources (WRB) . (n.d.). Retrieved from http://www.fao.org/nr/land/soils/soil/en/

Annex

6.2. Wells located in the North of the Lagoa dos Barros (CPRM, SIAGAS, 2021)

<u>**Used to define the terrain cross-sections**</u>

P-01



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	03-IL-1-Tecnipoços
Data da Instalação:	
Proprietário:	
Natureza do Ponto:	Poço tubular
Uso da Água:	
Cota do Terreno (m):	
Localização:	
Localidade:	ILHA - AGASA
UTM (Norte/Sul):	6694690
UTM (Leste/Oeste):	558480
Latitude (GGMMSS):	295237
Longitude (GGMMSS):	502340
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	
Situação:	

Poço: 4300023167 | **UF: RS** | **Municipio: Santo antonio da patrulha** | **Localidade: ILHA - AGASA**

Perfil Construtivo

Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Feição Geomorfológica:
Descrição:

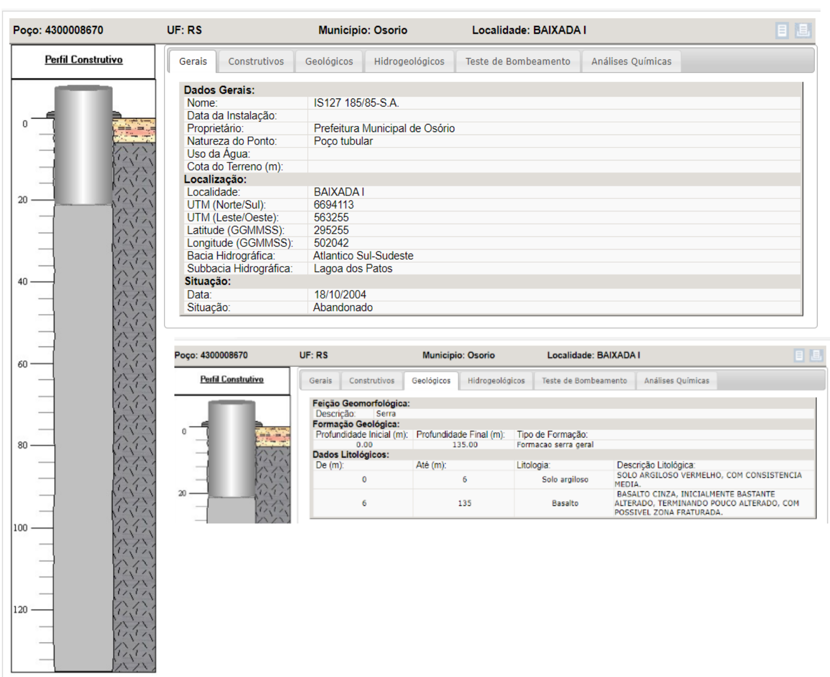
Formação Geológica:

Profundidade Inicial (m):	Profundidade Final (m):	Tipo de Formação:
0.00	31.00	Formacao serra geral
31.00	71.00	Formacao Botucatu

Dados Litológicos:

De (m):	Até (m):	Litologia:	Descrição Litológica:
0	9.3	Solo argiloso	Solo argiloso
9.3	31	Basalto	Basalto
31	71	Arenito médio	Arenito médio

P-02



Poço: 4300008670 | **UF: RS** | **Municipio: Osorio** | **Localidade: BAIXADA I**

Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	IS127 185/85-S.A.
Data da Instalação:	
Proprietário:	Prefeitura Municipal de Osório
Natureza do Ponto:	Poço tubular
Uso da Água:	
Cota do Terreno (m):	
Localização:	
Localidade:	BAIXADA I
UTM (Norte/Sul):	6694113
UTM (Leste/Oeste):	563255
Latitude (GGMMSS):	295255
Longitude (GGMMSS):	502042
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	18/10/2004
Situação:	Abandonado

Poço: 4300008670 | **UF: RS** | **Municipio: Osorio** | **Localidade: BAIXADA I**

Perfil Construtivo

Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Feição Geomorfológica:
Descrição: Serra

Formação Geológica:

Profundidade Inicial (m):	Profundidade Final (m):	Tipo de Formação:
0.00	135.00	Formacao serra geral

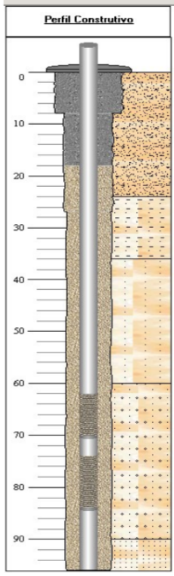
Dados Litológicos:

De (m):	Até (m):	Litologia:	Descrição Litológica:
0	6	Solo argiloso	SOLO ARGILOSO VERMELHO, COM CONSISTENCIA MEDIA.
6	135	Basalto	BASALTO CINZA, INICIALMENTE BASTANTE ALTERADO, TERMINANDO POUCO ALTERADO, COM POSSIVEL ZONA FRATURADA.

P-03

Poço: 4300027598 | UF: RS | Município: Santo antonio da patrulha | Localidade: RODOVIA BR 290 , KM 19

Perfil Construtivo

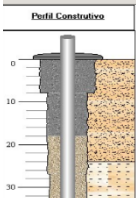


Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	006870-05.67/09-6
Data da Instalação:	
Proprietário:	
Natureza do Ponto:	Poço tubular
Uso da Água:	Outros (lazer,etc.)
Cota do Terreno (m):	15.00
Localização:	
Localidade:	RODOVIA BR 290 , KM 19
UTM (Norte/Sul):	6693827
UTM (Leste/Oeste):	553298
Latitude (GGMMSS):	295306
Longitude (GGMMSS):	502653
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	28/05/2009
Situação:	Bombeando

Poço: 4300027598 | UF: RS | Município: Santo antonio da patrulha | Localidade: RODOVIA BR 290 , KM 19

Perfil Construtivo



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Feição Geomorfológica:
Descrição: Planicie fluvio-lagunar

Formação Geológica:

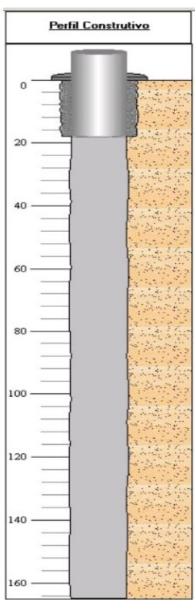
Profundidade Inicial (m):	Profundidade Final (m):	Tipo de Formação:
0.00	24.00	Depositos litoraneos
24.00	60.00	Formacao Botucatu
60.00	96.00	Formacao Piramboia

Dados Litológicos:

De (m):	Até (m):	Litologia:	Descrição Litológica:
0	24	Areia siltosa	Sedimentos síltico- argilosos com areno -argiloso de cor cinza
24	36	Arenito argiloso	Arenito argiloso cinza esverdeado
36	60	Arenito médio	Arenito médio a grosso róseo, matriz argilosa
60	90	Arenito grosso	Arenito grosso a médio avermelhado
90	96	Arenito fino	Arenito fino a médio marrom

P-04a

Perfil Construtivo



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	IS200
Data da Instalação:	
Proprietário:	Prefeitura Municipal de Osório
Natureza do Ponto:	Poço tubular
Uso da Água:	Abastecimento doméstico
Cota do Terreno (m):	91.00
Localização:	
Localidade:	TOMBADOR-BELA VISTA PROPRIEDADE DE MANOEL BARBOSA
UTM (Norte/Sul):	6693585
UTM (Leste/Oeste):	561674
Latitude (GGMMSS):	295312
Longitude (GGMMSS):	502141
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	28/10/2004
Situação:	Bombeando

Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Feição Geomorfológica:
Descrição: Encosta

Formação Geológica:

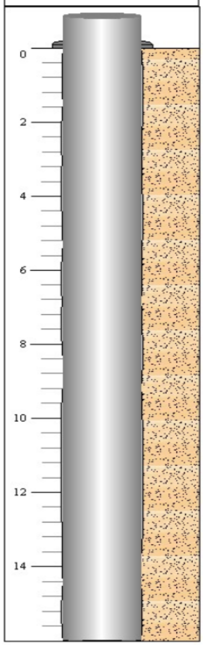
Profundidade Inicial (m):	Profundidade Final (m):	Tipo de Formação:
0.00	165.00	Depositos fluvio-marinhos

Dados Litológicos:

De (m):	Até (m):	Litologia:	Descrição Litológica:
0	165	Areia média	Areia média

Poço: 4300025789 | **UF: RS** | **Município: Osorio** | **Localidade: RST 101 km 8**

Perfil Construtivo

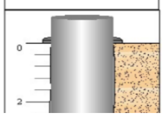


Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	PP02
Data da Instalação:	27/11/2014
Proprietário:	
Natureza do Ponto:	Poço ponteira
Uso da Água:	Abastecimento doméstico
Cota do Terreno (m):	
Localização:	
Localidade:	RST 101 km 8
UTM (Norte/Sul):	6678950
UTM (Leste/Oeste):	560484
Latitude (GGMMSS):	300108
Longitude (GGMMSS):	502222
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	27/11/2014
Situação:	Bombeando

Poço: 4300025789 | **UF: RS** | **Municipio: Osorio** | **Localidade: RST 101 km 8**

Perfil Construtivo



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Feição Geomorfológica:

Descrição: Planicie fluvio-marinha

Formação Geológica:

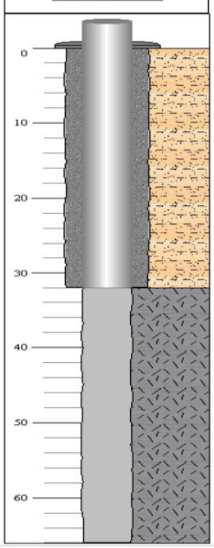
Profundidade Inicial (m):	Profundidade Final (m):	Tipo de Formação:
0.00	16.00	Depositos litoraneos

Dados Litológicos:

De (m):	Até (m):	Litologia:	Descrição Litológica:
0	16	Areia fina	Areia fina amarela

P-04b

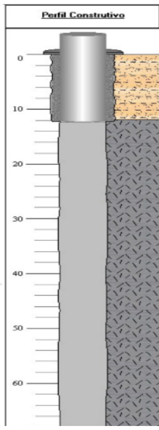
Perfil Construtivo



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	IS126
Data da Instalação:	14/09/2000
Proprietário:	
Natureza do Ponto:	Poço tubular
Uso da Água:	Abastecimento doméstico
Cota do Terreno (m):	202.00
Localização:	
Localidade:	BAIXADA CURUA
UTM (Norte/Sul):	6693875
UTM (Leste/Oeste):	562819
Latitude (GGMMSS):	295303
Longitude (GGMMSS):	502058
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	18/10/2004
Situação:	Bombeando

Perfil Construtivo



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	IS144
Data da Instalação:	
Proprietário:	
Natureza do Ponto:	Poço tubular
Uso da Água:	Abastecimento doméstico
Cota do Terreno (m):	243.00
Localização:	
Localidade:	ARROIO GRANDE - ESCOLINHA
UTM (Norte/Sul):	6695199
UTM (Leste/Oeste):	562129
Latitude (GGMMSS):	295220
Longitude (GGMMSS):	502124
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	19/10/2004
Situação:	Bombeando

Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Feição Geomorfológica:

Descrição: Serra

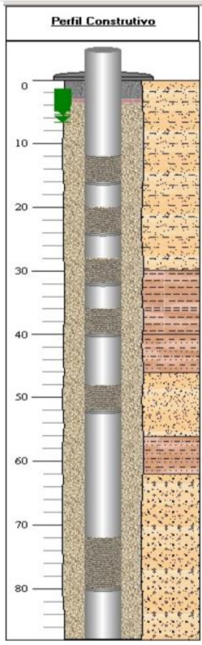
Formação Geológica:

Profundidade Inicial (m):	Profundidade Final (m):	Tipo de Formação:
0.00	68.00	Formacao serra geral

Dados Litológicos:

De (m):	Até (m):	Litologia:	Descrição Litológica:
0	12	Areia argilosa	Areia argilosa marrom
12	68	Basalto	BASALTO PRETO A VERMELHO, COM MUITA INCLUSOES E AMIGDALAS QUARTZO, COM PORCOES ALTERADAS E FRATURADAS.

P-05ª.



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	ETE Osório / JP822
Data da Instalação:	15/09/2011
Proprietário:	Companhia de Pesquisa de Recursos Minerais
Natureza do Ponto:	Poço de monitoramento
Uso da Água:	Sem uso
Cota do Terreno (m):	7.48
Localização:	
Localidade:	ETE OSORIO
UTM (Norte/Sul):	6687060
UTM (Leste/Oeste):	565115
Latitude (GGMMSS):	295643
Longitude (GGMMSS):	501931
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	16/02/2017
Situação:	Poço RIMAS equipado c medidor automático de nível

Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Feição Geomorfológica:

Descrição: Planicie fluvio-lagunar

Formação Geológica:

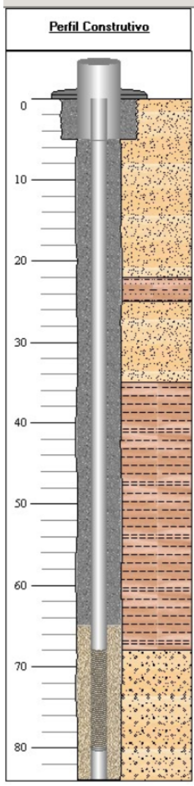
Profundidade Inicial (m):	Profundidade Final (m):	Tipo de Formação:
0.00	88.00	Depositos litoraneos

Dados Litológicos:

De (m):	Até (m):	Litologia:	Descrição Litológica:
0	30	Areia argilosa	Areia argilosa
30	40	Argila	Argila cinza amarronzado com conchas.
40	46	Argila arenosa	Argila arenosa cinza amarronzado
46	56	Areia fina	Areia fina cinza amarronzado
56	62	Argila arenosa	Argila arenosa cinza amarronzado
62	88	Areia grossa	Areia grossa cinza amarronzado

P-05b

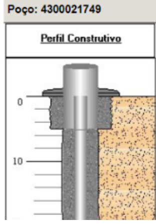
Poço: 4300021749 **UF: RS** **Municipio: Osorio** **Localidade: PARQUE EOLICO DE OSORIO**



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Dados Gerais:	
Nome:	2086 - hidrogeo
Data da Instalação:	
Proprietário:	
Natureza do Ponto:	Poço tubular
Uso da Água:	
Cota do Terreno (m):	
Localização:	
Localidade:	PARQUE EOLICO DE OSORIO
UTM (Norte/Sul):	6685265
UTM (Leste/Oeste):	568051
Latitude (GGMMSS):	295741
Longitude (GGMMSS):	501741
Bacia Hidrográfica:	Atlantico Sul-Sudeste
Subbacia Hidrográfica:	Lagoa dos Patos
Situação:	
Data:	
Situação:	

Poço: 4300021749 **UF: RS** **Municipio: Osorio** **Localidade: PARQUE EOLICO DE OSORIO**



Gerais | Construtivos | Geológicos | Hidrogeológicos | Teste de Bombeamento | Análises Químicas

Feição Geomorfológica:

Descrição:

Formação Geológica:

Profundidade Inicial (m):	Profundidade Final (m):	Tipo de Formação:
0.00	84.00	Depositos litoraneos

Dados Litológicos:

De (m):	Até (m):	Litologia:	Descrição Litológica:
0	22	Areia fina	Areia fina
22	25	Argila arenosa	Argila arenosa
25	35	Areia fina	Areia fina
35	68	Argila	Argila
68	84	Areia grossa	Areia grossa