Watershed Management under Climate Change Scenarios.

Case study: Maranhão watershed, Portugal

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Master Thesis

August 2022

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Master of Science Thesis
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This thesis is submitted in partial fulfilment of the requirements for the academic degree of

Master of Science in Water Science and Engineering
UNESCO-IHE Institute for Water Education, Delft, the Netherlands

Master of Science in Environmental Engineering
Instituto Superior Técnico, Universidade de Lisboa, Portugal

Master of Science in Hydro Science and Engineering
Technische Universität Dresden, Germany

MSc research host institution
Instituto Superior Técnico, Universidade de Lisboa, Portugal

Lisbon

August 2022

Resumo

A gestão de bacias hidrográficas enfrenta um considerável desafio perante as alterações climáticas. As projeções climáticas indicam um clima mais seco e quente na bacia do Maranhão, no leste de Portugal. Este estudo utilizou o modelo MOHID Land para quantificar o impacto das alterações climáticas no balanço de água, na quantidade de água superficial e subterrânea na bacia do Maranhão e a contribuição da barragem do Maranhão para a rega sustentável do Vale do Sorraia, tendo em conta os cenários de alterações climáticas RCP4.5 e RCP8.5 para um futuro próximo (2024-2039) e longínquo (2075-2090). O presente estudo avalia, também, o impacto na quantidade de água que aflui à albufeira do Maranhão como consequência da construção de uma nova barragem, considerada aqui uma medida de adaptação às alterações climáticas, na zona Norte da bacia, tendo em conta o cenário RCP8.5. Em comparação com o cenário de referência (2001-2008), os resultados indicam um aumento de 16% no caudal do rio considerando o cenário RCP4.5, uma diminuição do mesmo em 32% para o cenário RCP8.5 e uma diminuição média de 0.02 a 0.77% (0.1 a 2 m) nos níveis da água subterrânea ao longo do tempo. Espacialmente, as alterações no nível da água subterrânea variam entre -0.82 a 0.89%, com a zona Nordeste da bacia experienciando o decréscimo mais acentuado. A diminuição do nível da água subterrânea é principalmente justificada por aquela zona da bacia ser ocupada por solo de textura franco-argilosa. Os minerais de argila tendem a ter uma estrutura laminar e depositam-se em aluviões, promovendo o fluxo lateral em vez de vertical, levando a uma diminuição subsequente recarga. O erro médio do balanço de água na bacia é de 15%, indicando que o MOHID Land apresenta uma boa capacidade de simular o balanço de água. O impacto das alterações climáticas no balanço de água foi quantificado tendo em conta o rácio entre a evapotranspiração e a precipitação (ETP:P) e o volume de água que aflui à barragem do Maranhão e a precipitação (Q:P). A evapotranspiração é o processo dominante na extração de água do sistema. Para os RCP4.5 e RCP8.5, o rácio ETP:P aumenta, em média, 5% nos próximos anos e 8% no longo termo devido à previsão de diminuição da precipitação e aumento da evapotranspiração. O rácio Q:P diminui em média 6% no futuro próximo e 8% no longo termo, principalmente devido à rápida diminuição do volume de água afluente ao Maranhão por comparação à diminuição da precipitação. A simulação das necessidades de rega à escala da parcela agrícola aumentam ligeiramente devido ao aumento da transpiração da cultura, exceto no caso do olival, considerando os próximos anos. A diminuição em 0.2% na rega desta cultura nos próximos anos pode ser devida à metodologia adotada no modelo, que considera o crescimento da planta segundo as unidades de calor, sendo que cada grau contribui para o crescimento da planta. Com a previsão do aumento da temperatura a planta crescerá mais depressa e o período de crescimento diminui, levando à da biomassa e das necessidades de água. Com uma diminuição de 19% no curto termo e 7% no longo termo na contribuição da barragem do Maranhão para a rega no Vale do Sorraia, a agricultura desta zona poderá tornar-se insustentável. Considerando a construção da barragem sob o efeito das alterações climáticas, o caudal afluente à barragem do Maranhão diminuirá cerca de 50%. Contudo, é necessária uma análise mais exata do impacto da construção de uma nova barragem na zona montante da bacia hidrográfica tendo em conta um melhor conhecimento das características da barragem e sua operação.

Palavras-chave: MOHID Land; Maranhão; alterações climáticas; água subterrânea; balanço de água; reservatório.

Abstract

Watershed management faces a big challenge considering climate change. Climate projections point to a dryer and hotter Maranhão watershed in Eastern Portugal. This study used the MOHID Land model to quantify climate change's impact on the surface water, groundwaters, water balance, and Maranhão reservoir's contribution to sustainable irrigation farming in Sorraia valley, under RCPs 4.5 and 8.5 emission scenarios for the near (2024-2039) and far (2075-2090) future. The study also assessed the impact of upstream reservoir construction on watershed water balance under climate change scenarios. Compared with the reference scenario (2001-2008), results indicated a 16% increase in streamflow under RCP4.5, a 32% decrease under RCP8.5 in stream discharge, and a 0.02 to 0.77% (0.1 to 2m) mean decrease in groundwater levels at the temporal scale due to less precipitation hence recharge compared to discharge (uptake by trees and flow to surface water). Spatially, groundwater change ranged from -0.82 to 0.89% (-3.1 to 3.4m), with the Northeastern part of the watershed experiencing the most groundwater level decrease. The decrease in water levels could be attributable to most of Northeastern Maranhão being occupied by clay loams. Clay minerals tend to have a platy crystalline habit and lie flat in alluvial deposits, thus promoting lateral instead of vertical flow and subsequent recharge. The mean water balance error was 0.7%, indicating good MOHID Land capabilities at watershed scale water balance. The impact of climate change on water balance was quantified using evapotranspiration and outlet flow volume to precipitation (ETP:P and Q:P) ratios. Evapotranspiration was the dominant process concerning water extraction from the system. For RCPs4.5 and 8.5, ETP:P ratio averagely increased by 5% in near years and 8% in long term due to a predicted decrease in precipitation and high ETP. Q:P ratio averagely decreased by 6% in the near years and 8% in the long term future for both scenarios most likely due to faster decrease in outlet flow volume than precipitation. Plot scale irrigation needs predictions slightly increased due to increased transpiration requirements except for olive trees in the near years. The 0.2% decrease in olive irrigation needs in the near years could most likely be due to the methodology to which plant development considers heat units, meaning each degree increase in temperature contributes to plant growth. With the predicted increase in temperature, plants grow faster, and hence a decreased growth period or season, leading to less biomass and water requirements. With a climate change (RCP8.5) related 19% decrease in Maranhão reservoir`s contribution to irrigation needs in the near years and a further 7% decrease in the long term, irrigation agriculture in Sorraia valley could be rendered unsustainable. For reservoir construction under the climate change scenario, the more than 50% decrease in downstream Maranhão's outlet flow volume could be due to the combined impact of climate change, decreasing water availability, and new upstream reservoir intercepting and storing runoff. At the same time, the overestimation could be related to inaccurate reservoir data. However, using accurate reservoir and operation parameter values, an accurate impact assessment of upstream reservoir construction on Maranhão water balance is necessary.

Keywords: MOHID Land; Maranhão; climate change; groundwater; water balance; reservoir.

Acknowledgements

My sincere thanks to the European Commission through the Erasmus+ EM Partner country scholarship award for allowing me to pursue my dream master's programme, the Erasmus Mundus Joint Master Degree (EM JMD) Groundwater and Global Change. I express my deepest thanks to Judith van Eeden for her support at the start of the programme and during the tricky COVID-19 travel arrangements. Also, to the coordinators at programme institutions, namely Prof. Tibor Stigter, Prof. Maria Teresa Condesso de Melo, Prof. Rodrigo Proença de Oliveira, and Dr. Judith Pöschmann, for the endless support I received from them throughout the programme.

I extend my deepest gratitude to my thesis supervisor, professor Ramiro Joaquim De Jesus Neves, and mentor, Ana Isabel Baião Ramos de Oliveira, for constant guidance, calibrating, and validating the MOHID Land model, organising a field visit, and endless support during this research. The time dedicated to discussing my research has been valuable and furthered my understanding of the subject.

Special thanks to the entire IST-MARETEC team, especially the MOHID Land model team, for hosting me during the research period, notably Tiago B. Ramos for aiding the field visit and sharing data, and Lucian Simionesei for sharing an already validated plot scale irrigation model.

I must thank Dr. Kenneth Nyombi, Dr. Kenneth Balikoowa, and professor John R.S. Tabuti from Makerere University, Uganda, for recommending me to further studies. Finally, I thank my parents, siblings, and friends for their constant prayers, love, and support. Thanks be to God.

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Nomenclature

Abbreviations

APA	:	Agência Portuguesa Do Ambiente
ARBVS	:	Associação de Regantes e Benefeciários do Vale do Sorraia
C2011	:	population census 2011
C2021	:	population census 2021
C20th	:	Twentieth-century
C3S	:	Copernicus Climate Change Service
CC	:	Crop coefficient
CDS	:	Copernicus Climate Change Service Climate Data Store
CMIP	:	Coupled Model Intercomparison Project
CO2	:	Carbon dioxide
DPSIR	:	Drivers, Pressure, State, Impact, and Response
DTM	:	Digital Terrain Model
E	:	Evaporation
ERA5	:	Fifth Generation of ECMWF Atmospheric Reanalyses of the Global Climate
ETP	:	Evapotranspiration
EU	:	European Union
fh	:	factor horizontal
GHG	:	Greenhouse gases
GW	:	Groundwater
IISD	:	International Institute for Sustainable Development
INE	:	Instituto Nacional de Estatística Portugal
IPCC	:	Intergovernmental Panel on Climate Change
LULC	:	Land use and land cover
NASA	:	National Aeronautics and Space Administration
RCP	:	Representative Concentration Pathway
RH	:	Relative Humidity
SDGs	:	Sustainable development goals
SNIRH	:	Sistema Nacional de Informação de Recursos Hídricos
SSP	:	Shared Socioeconomic Pathway
UNFCCC	:	United Nations Framework Convention on Climate Change
WFD	:	Water Framework directive
WRM	:	Water Resources Management

Units

km^2	:	Squared kilometers
%	:	Percentage
mm	:	millimeter
^oC	:	Celsius degrees
ha	:	Hectare
dam^3	:	Cubic decameter
ms^{-1}	:	meters per second
hm^3	:	Cubic hectometer

1: INTRODUCTION

1.1 Background

Global warming and extreme events are the two main features of climate change and a direct consequence of greenhouse gas (GHG) emissions, where carbon dioxide (CO_2) plays a significant role. Climate change is a global process with local impacts (Sheppard et al., 2011). Water is a critical nutrient partially exchanged between watersheds, and consequently, an adaptation of assessment of water use to climate change must be at the watershed scale.

Water resources along the watershed depend on rain intensity and distribution, flow, and evapotranspiration. Climate determines rain intensity (Ramke, 2018), and the latter is outside the control of the watershed manager. Distinctly, rain forces flow, while land use and land cover (LULC) modulate flow development due to water availability and management policies. Vegetation type and growth rates depend on water availability, solar radiation, air temperature, and CO2 availability. Increasing CO_2 in the atmosphere and air temperature would enhance vegetation growth (until photosynthetic capacity) if water is available (Lawlor & Mitchell, 1991).

Therefore, expectations include that climate change adaptation focusing on keeping soil fertility and water availability will be a central issue. The extreme events will increase (a) the intensity of rain events and surface runoff and (b) droughts intensity and duration, and consequently, water irrigation needs will be affected. Water retention in the watershed (though physically limited) reduces flood intensity (Collentine & Futter, 2018) and helps mitigate drought's consequences; thus, it is an expectedly essential aspect of climate change adaptation.

1.2 Problem statement and research justification

Globally, multiple issues confront decision-makers and water resource planners in ensuring efficient water allocation and water system performance amidst climatic variability and change (Jung et al., 2013; Manous & Stakhiv, 2021; Slootweg, 2010).

Regionally, Mediterranean areas experience water scarcity; hence, many economic activities in the region rely on water stored in reservoirs. The infrastructure construction in river valleys also leads to land-use changes that affect the watershed's overall water balance.

Locally, several reservoirs were constructed in Portugal around the middle of the twentieth century, primarily for agriculture (Almeida et al., 2019), whose production is heavily reliant on rainwater stored in reservoirs and the presence of hydraulic systems to distribute water during the dry season.

However, (i) reservoirs' cumulative storage may significantly decrease due to less precipitation, or (ii) reservoirs fill, but irrigated water does not contribute to crop water productivity due to higher water losses through evapotranspiration enhanced by global warming. So with a likely increase in evapotranspiration (as the increasing temperature may evaporate more reservoir waters), which management options can sustainably retain water in Maranhão? In addition to inadequate information about new management options, few predictions exist, constraining redesigning the existing ones. The schematic of the problem and justification compiled is as in Figure 1.

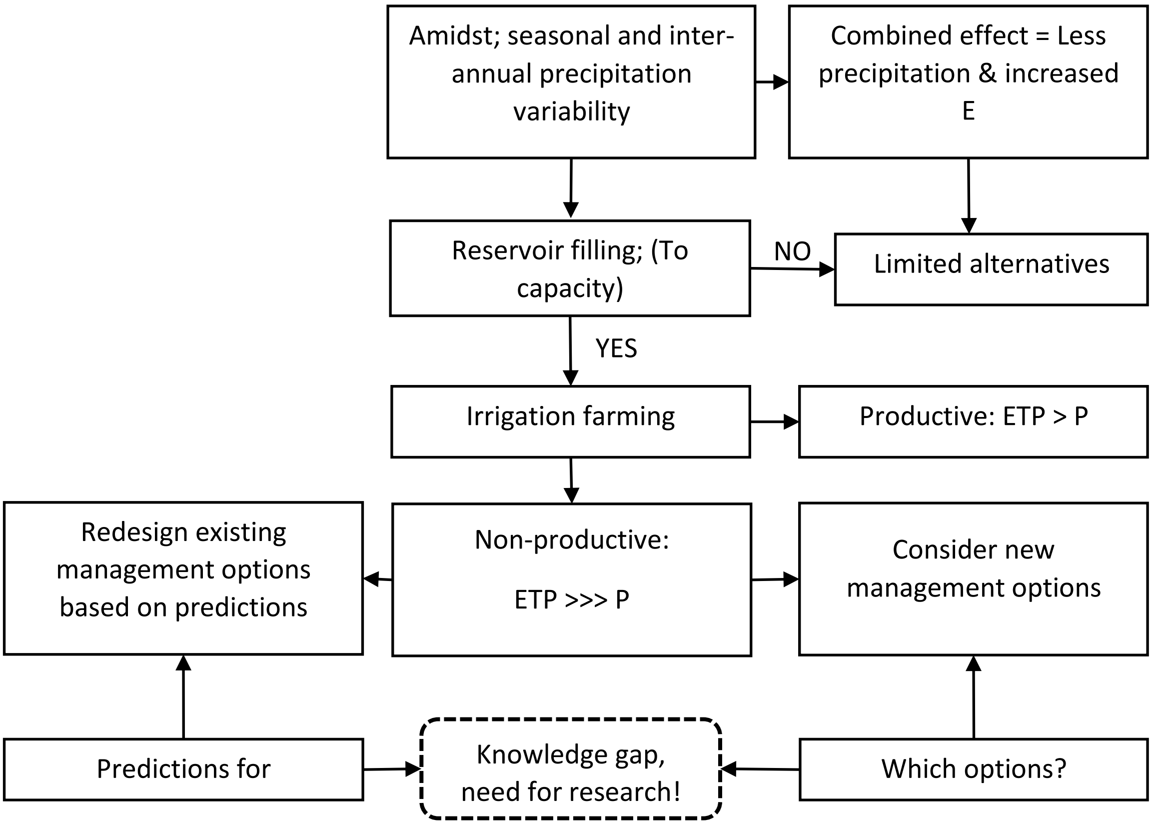

Figure 1. Schematic representation of the problem statement and research justification

1.3 Research goal and specific objectives

The goal is to assess the impact of climate change on watershed management. Research further evaluates reservoir construction as an adaptation measure at the Maranhão watershed towards social, economic (agriculture), and environmental sustainability amidst climate change and its related impacts on the watershed's water balance. Specific objectives of the study include:

(i) To perform a water budget in a catchment under present conditions.

(ii) To quantify the impact of climate change on surface water and groundwater levels in the watershed.

(iii) To assess the impact of climate change on the Maranhão reservoir's contribution to sustainable irrigation farming in Sorraia valley.

(i) To assess the impact of upstream reservoir construction on watershed water balance under climate change scenarios.

1.4 Study hypotheses

Considering climate change scenarios, will farmers have enough water to irrigate their crops or not in Portugal's Sorraia valley? Will it be essential to change the crop in the valley, or will reservoir usage offset the climate change-related irrigation needs? Other specific hypotheses include:

(i) Maranhão watershed could experience evapotranspiration enhanced by climate change; this could impact surface water flow regimes and the groundwater levels.

(ii) Forecasting the evolution of river runoff under different rain intensity scenarios is critical for adaptation to climate change. On the other hand, areas with a high surface water retention are at different river trenches relative to regions with irrigation water needs. So the hypothesis is that climate change could increase irrigation water needs more than available water to meet them.

(iii) Climate change affects the hydro-reactivity of the watershed. Under the same climate change scenario, specific areas within the watershed could (in the short term) experience an increase in groundwater levels while a decrease in others.

1.5 Research significance; link to Sustainable Development Goals.

Amidst increased seasonal and intra-annual variability of water resources due to climate change, what information do managers require to: diversify water retention options in the watershed, redesign existing management options such as reservoirs or consider different crops more suitable for different climates? This research seeks to provide a significant portion of that information. Combining findings from this study with an understanding of the adaptation priorities specified in a (2019-2030) Portuguese National Adaptation Plan for climate change (Climate-ADAPT, 2019) and the national budgeting process, the watershed management authorities will strategically foresee opportunities and eventually prioritise action towards watershed sustainability.

The MOHID Land model and the Maranhão watershed case study will help to identify the potential for mitigating climate change impacts. Table 1 shows the link between study goals and SDGs. This link clarifies the relationship of research goals with society's challenges.

Table 1: The link between study goals and SDGs.

SDG number	**SDG**	**The link between SDGs and study goal**
1	No poverty	Reduce the exposure and vulnerability of the community to climate-related extreme events such as drought
7	Affordable and clean energy	Less energy used in pumping irrigation water; improvement in energy efficiency
11	Sustainable cities and communities	Reduce the direct financial losses caused by disasters, notably water-related disasters, by a significant amount.
13	Climate Action	Increase resilience and adaptability to climate-related risks.
15	Life on land	By promoting the long-term use of terrestrial habitats and the services they provide

2: LITERATURE REVIEW

2.1 Findings from previous inline studies

In the foreseeable future, the Sorraia River basin will likely have a significant (between 25% and 50%) decrease in precipitation (Almeida et al., 2018). This decline may increase irrigation and fertilisation needs (Almeida et al., 2019). Adapting to climate change in agriculture entails modifying agricultural management techniques in response to climatic changes, for example, through drought-resistant crop types, crop diversity, adjustments to the cropping schedule and tillage practices, increased irrigation effectiveness, afforestation, and agroforestry (Akinnagbe & Irohibe, 2014). Reservoir construction is an adaptation mechanism implemented in the past years in the Sorraia irrigation district. However, adaptation by constructing reservoirs has some adverse impacts; for example, reservoirs are significant landforms influencing surface runoff in basins (Dantas et al., 2020).

On the other hand, climate change significantly impacts the reservoir's water availability (Molina-Navarro et al., 2016). Therefore reservoir operations modelling provides a valuable opportunity for minimising hydrologic reactions to climate change, which might reduce the negative impact on water availability (Almeida et al., 2019). Reservoir modelling also allows us to understand if the construction of these structures is sustainable in terms of water availability and quality.

Model climate forecasts and IPCC scenarios can aid in creating plausible climate scenarios for hydrological projections (Fuso et al., 2021). Water resources' temporal stationarity cannot be a working hypothesis for water management in watersheds with changing land cover (Gallart & Llorens, 2003). Despite the growing connection between land use and climate change (Kaushal et al., 2017), this study will only focus on climate change to arrive at relevant findings for future water security decisions.

2.2 Regulatory aspects.

Maranhão reservoir has several purposes: energy production, industrial and agricultural supply, and is responsible for the irrigation of 21 878 ha (APA, 2022). National and regional regulations guide the management of the reservoir toward meeting its purposes. Regulations include:

(i) Law No. 58/2005 of December 29: The "Water Law" establishes the framework for long-term water management. Water use for irrigation and food production constitutes consumption in agriculture (Mimoso, 2018).

(ii) The water framework directive: Directive 2000/60/C.E., the Water Framework Directive (WFD), entered into force in December 2000, following the conclusion of the Portuguese Presidency of the European Union in June of that year. The WFD's acceptance signaled a significant shift in Portugal's water policies, implied response to the country's continued urbanization, the entry of a private sector into water resource management, and heightened environmental concerns (Costa, 2018).

(iii) Climate change relating to water resources and adaptation strategies: Portugal produced the National Strategy for Adaptation to Climate Change (NSACC; Resolution of the Council of Ministers No. 24/2010), highlighting water resources as a critical sector with global concerns and European policy. The NSACC on Water Resources (NSACC-WR) focuses on three primary lines of debate, namely, to reduce the vulnerability of systems and activities to climatic phenomena, to increase robustness and resilience of climate-exposed sectors, and to increase understanding of climate change impact evaluation and the viability of potential adaptation strategies (Costa, 2018).

2.3 IPCC findings

According to IPCC`s Masson-Delmotte et al. (2021), Portugal lies in the Mediterranean region. Increased ecological, agricultural, and hydrological droughts are among the observation. Predictions show an increase in fire weather and aridity at two degrees centigrade and above global warming (Masson-Delmotte et al., 2021).

According to (Gutiérrez, 2021) Coupled Model Intercomparison Project six (CMIP6) Tagus river basin datasets, Figure 2 represents a statistical summary of IPCC (SSP5-8.5) predictions of mean temperature and total precipitation for near-term, medium-term, and long-term periods on an annual scale. Considered statistical parameters are median and percentiles (P5, P10, P25, P75, P90, and P95). Datasets are only available for larger basins such as the Tagus to which Maranhão belongs. Figure 2 indicates that daily mean temperature increases and daily total precipitation decrease with the transition from near through medium to long term of the Tagus basin.

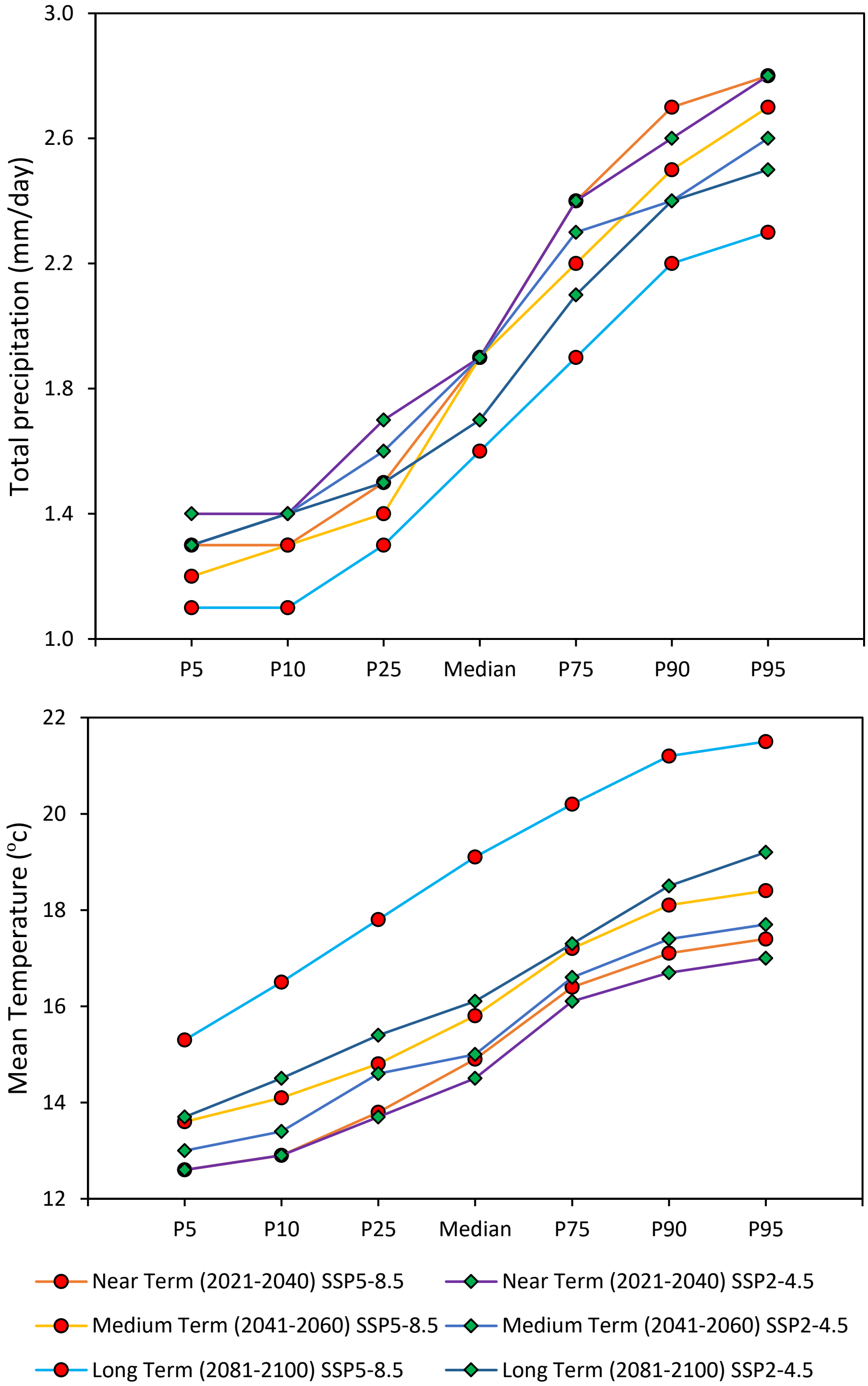

Figure 2. A statistical representation of daily mean temperature and total precipitation projections for the Tagus basin under RCPs 4.5 and 8.5_CMIP6

2.4 Maranhão management issues

Maranhão belongs to the 7730 km^2 Sorraia basin in central Portugal, whose length is 155km (Chrzanowski & Buijse, 2017). Sorraia basin's major river is Sorraia, a tributary of the Tagus River;

therefore, holistic watershed management is discussable at Sorraia, not Maranhão scale. Since 1959, the Association of Irrigators and Beneficiaries of Vale do Sorraia (ARBVS) administers, conserves, and operates the Vale do Sorraia Irrigation System. However, construction works of the Maranhão and Montargil dams started in 1955 (ARBVS, 2022). Figure 3 shows the evolution of the total cultivated area for various crops (rice, tomatoes, olive, corn, and fodder) and complete irrigation systems coverage in Sorraia Valley. Irrigated area coverage gradually increases with the cultivated area, partially indicating increased water use for irrigation over the years.

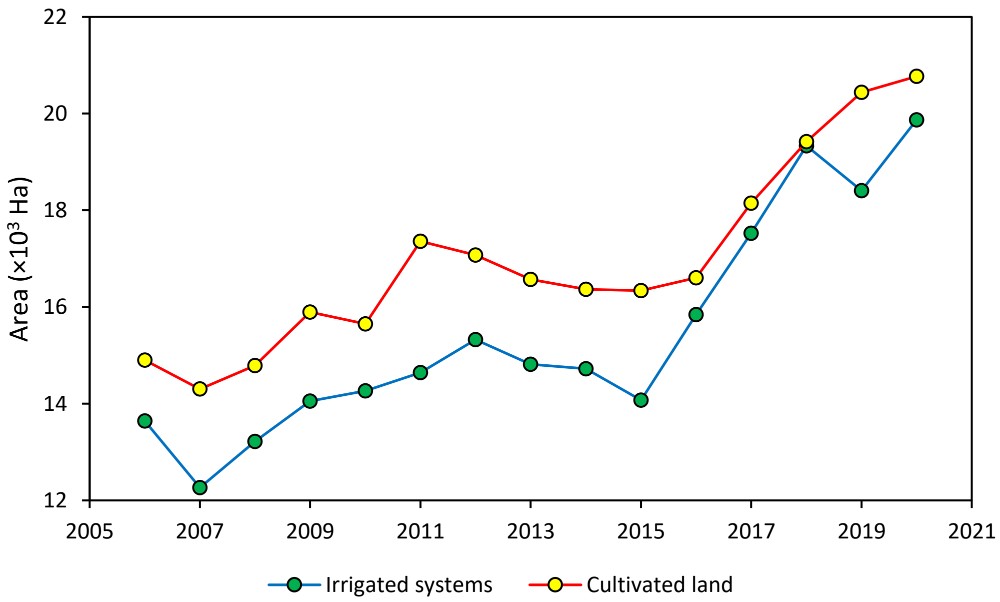

Figure 3. Evolution of cultivated area and irrigation systems coverage for Sorraia Valley.

In Europe, water resources management (WRM) includes four different activities: (1) The WFD's overarching framework is River Basin Management Planning, influenced by (2) assessment schemes for determining status, (3) risk assessment for characterising pressures and stresses, and (4) economic analysis for evaluating the costs and benefits of management activities (Hering et al., 2015). The planning phase requires adequate and relevant information.

2.5 Definition of keywords

In IPCC usage, climate change is a shift in the state of the climatic parameters whose detection (for example, using statistical tests) is by deviation in the mean and (or) variability of its attributes over time, generally decades or more. It considers any climatic change (over time) caused by natural variability or human activity (UNFCC, 2011). Watershed management is the process and procedure of coordinated planning, developing, distributing, and (or) redistributing water resources across all uses in quantity and quality to enhance overall efficiency while reducing damage and risks to humans and their environment. The concept is both interdisciplinary and integrated. This study will focus on water availability (quantity, not quality). The watershed is a natural, hydrologic unit appropriate for assessing, predicting, and managing water to achieve enhanced water quality, sufficient quantity, and improved access (Hub, 2017). In the study's context, a watershed scale will aid determining the extent of impacts of climate change on water availability and assess the suitability of an adaptation measure, the construction of a reservoir. Hydrologic mathematical modelling is a conceptualised and simplified version of reality, which establishes the relationship between the pressures and the state of a real-world system such as groundwater and surface water. Predicting impacts of watershed-based processes requires modelling because models aid the conversion of Drivers, Pressure, State, Impact, and Response (DPSIR) into numbers. Integrated Basin Modelling is a collection of empirical distributions and physical laws; this incorporates multiple processes to solve multiple-scale challenges.

3: CASE STUDY AREA

3.1 Location and digital elevation model

The investigated area is the Maranhão watershed. Located in Portalegre (a significant portion located here) and Évora districts, generally in eastern Portugal (Figure 4). It has an area of approximately 2291 km^2 (estimated by QGIS).

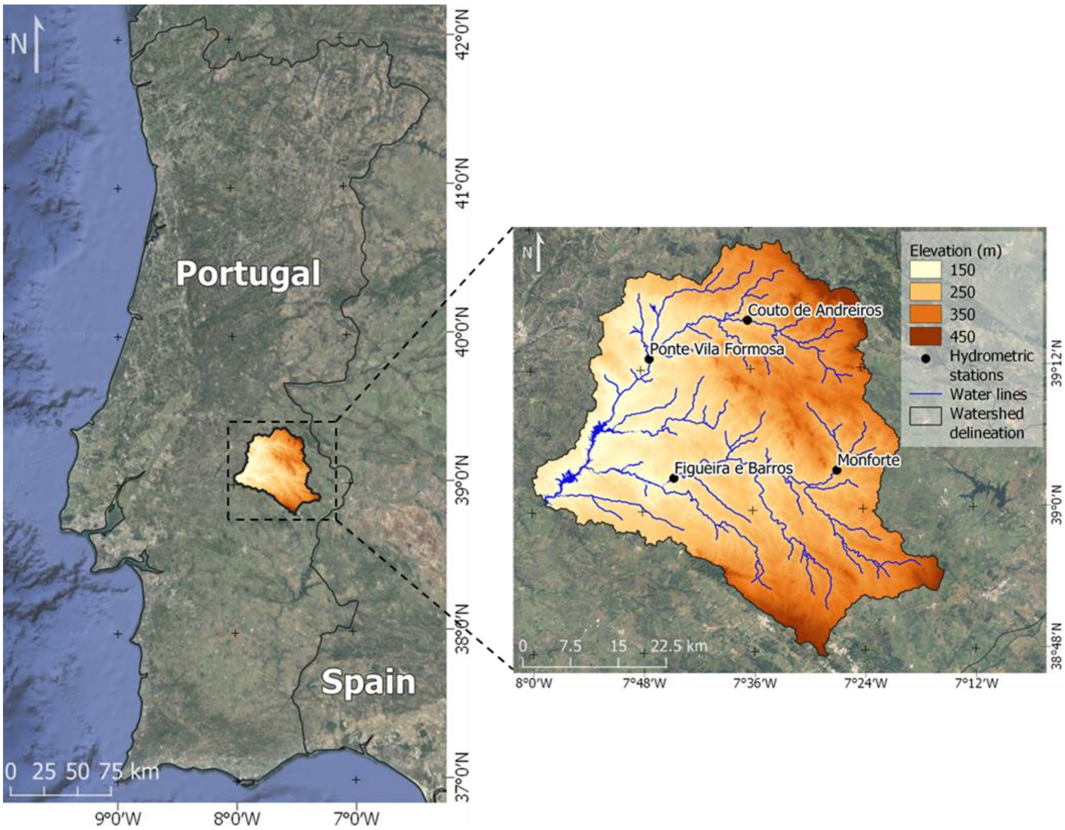

Figure 4. Location of the study area and digital terrain model

According to digital terrain model from Copernicus (2012), elevation ranges from 124 to 724 meters above mean sea level (m a.m.s.l). The topography is moderately steep (West of the watershed) to very steep (Northwest and southernmost part of the watershed). Some hills are in the middle of the watershed with rims extending up to 350m a.s.l (Figure 4). Each percentage area value in Table 2 is equal to or less than the corresponding elevation value. For example, 97.4% of the study area presents an elevation less or equal to 418 m a.m.s.l).

Table 2: Hypsometric table of Maranhão watershed.

Area (%)	Elevation (m)
9.3	168
33.1	218
54.5	268
78.6	318
93.8	368
97.4	418
99.2	468
99.7	518
99.8	568
99.9	618
100.0	768

3.2 Climate

Classifying the Maranhão watershed's climate involved using datasets from (NASA, 2022) and SNIRH (2022) meteorological stations: Maranhão dam (19J/04C)) for 1989- 2021. According to the Köppen-Geiger climate classification, the climate is a CSa corresponding to the Mediterranean climate subgroup, with winters being rainier than the summers. The area experiences warm temperatures with an annual average temperature of roughly 16.5 °C. The average yearly rainfall is approximately 570 mm. Concerning average monthly precipitation, the watershed receives a minimum of about 4.8 mm (in the June-July-August quarter) and a maximum of 87.2 mm (in the October-November-December quarter), as represented in Figure 5. The area's average hottest temperature (in August) and lowest (in January) are roughly 24.7 °C and 8.6 °C, respectively. The region has an average maximum relative humidity of 84.1 % in December-January and a minimum relative humidity of 52.5 % in August.

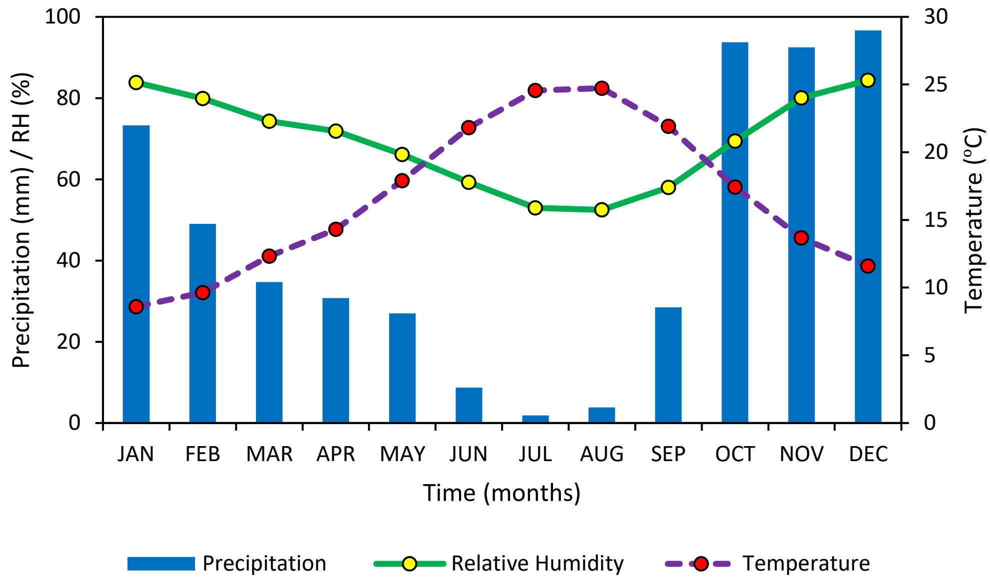

Figure 5. Monthly average precipitation, relative humidity, and temperature of Maranhão (32 years average).

3.3 Land use and land cover

Using the land use and land cover (LULC) map (Copernicus, 2019), with a resolution of 100 m), dominant LULC types of the Maranhão watershed include; herbaceous vegetation (41%), open forest (34%), and cultivated and managed vegetation/agriculture (14%). According to Figure 6, other LULC types, chiefly shrubs, account for 5% of the watershed, as statistically shown in Figure 7. Vegetation of the herbaceous taxa is representative of the surface-dwelling groundwater-dependent species in the area.

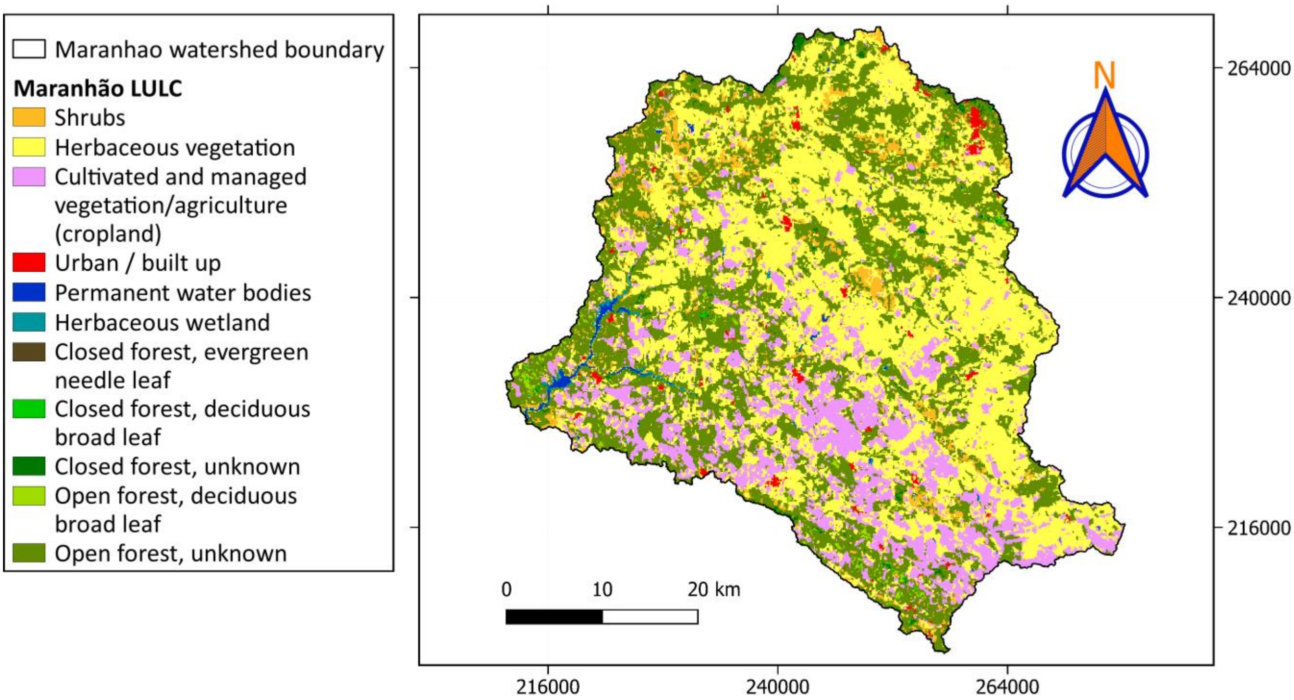

Figure 6. Maranhão's land use and land cover.

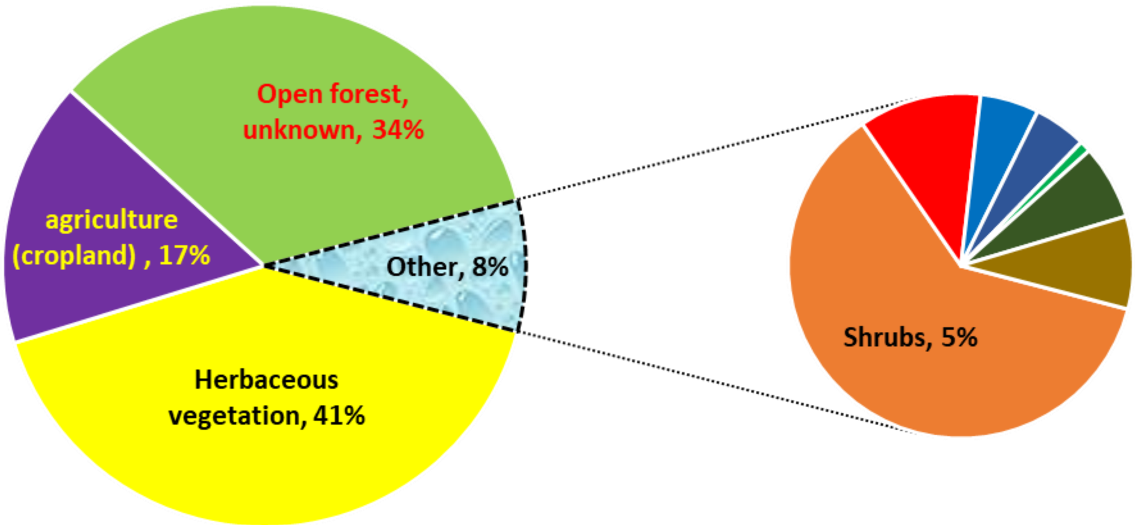

Figure 7. Maranhão's land use and land cover statistics

Agriculture occupies a significant portion of the Maranhão watershed (Figure 7); therefore, it was adequately represented under this study's third objective, which compares Sorraia valley's irrigation needs with irrigation water availability in Maranhão reservoir (under climate change scenarios).

3.4 Soils

In terms of soils, the study area mainly consists of Luvisols (ferric, gleyic, and orthic), dystric cambisols, orthic podzols, and a tiny percentage of lithosols (FAO, 2007).

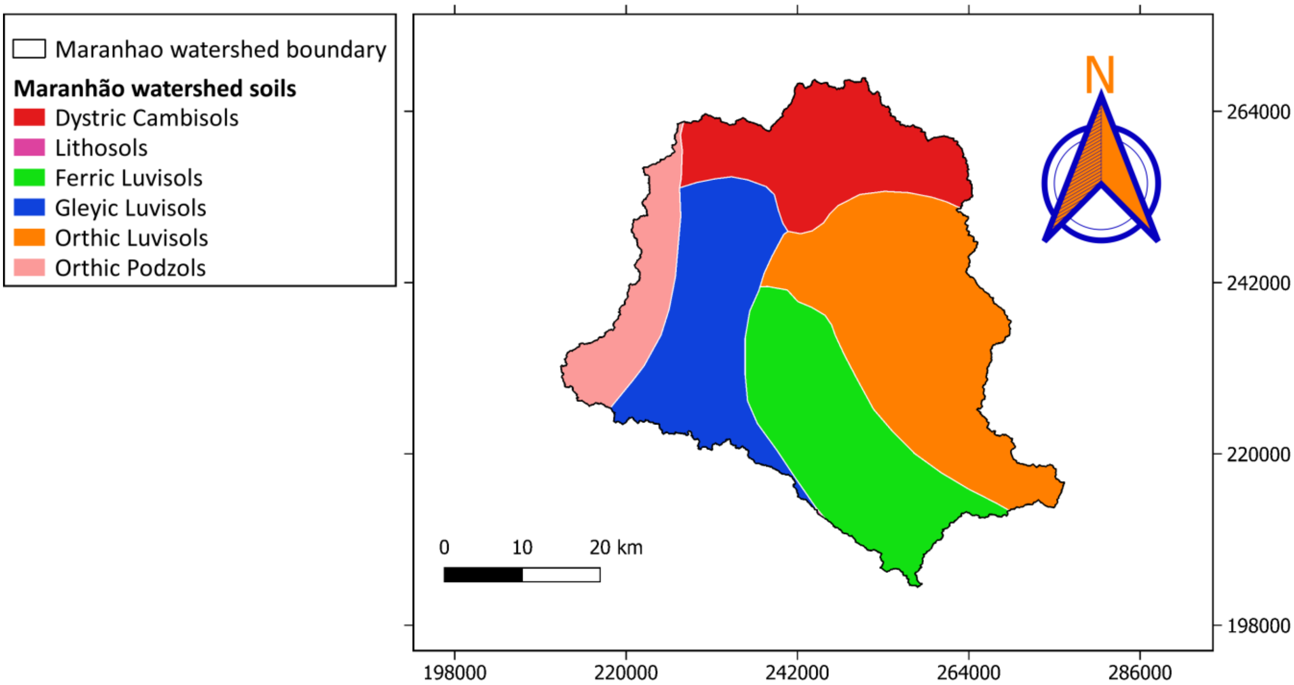

Figure 8. Soil types of Maranhão Watershed

Based on Figure 8, Cambisols occupy the North of the watershed, Luvisols in the central to the East, while Podzols occupy the Western part of the watershed. Based on the understanding that organic matter increases a soil's ability to hold water, an increase in bulk density is associated with reducing total pore volume, consequently reducing available water holding capacity. Therefore, Cambisols hold more water than Podzols, which have more water than Luvisols.

3.5 Geology

Regarding the geologic time scale, regarding rock materials, the study area mainly consists of sedimentary rock units of the Paleogene, Neogene, and Cambrian periods. Paleozoic intrusive rocks, Paleozoic metamorphic rocks, and volcanic rock formations are also inclusive. In Figure 9 (Pawlewicz et al., 2003), a map extracted from an existing data set shows the distribution of rocks formed under different geological times. Geology, among other factors, affects watershed hydrology (Tomer & Schilling, 2009). Watershed geology affects soil properties (Djodjic et al., 2021) and thus water retention capacity.

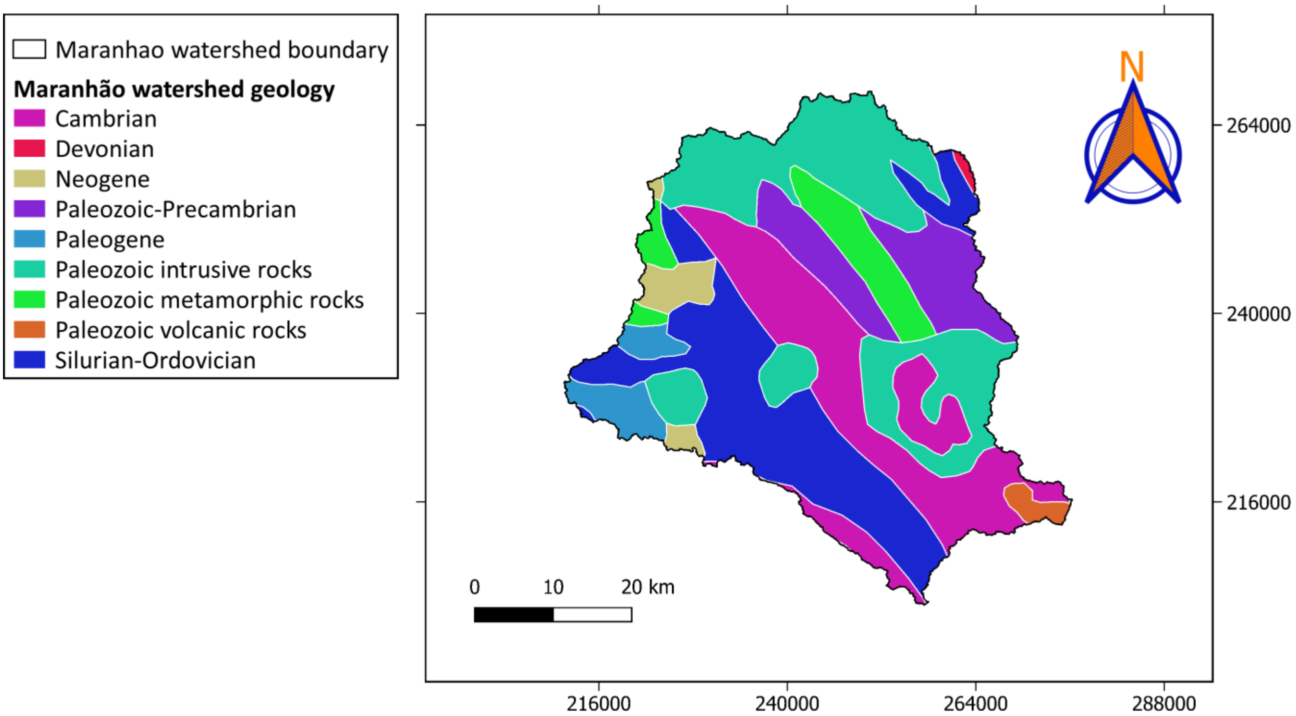

Figure 9. Geology of Maranhão watershed

Regarding geologic rocks, Figure 10 (BGR, 2019) confirms that conglomerates occupy a small part of the watershed. In contrast, the lithological class of phyllites, volcanic rocks, sandstones, shales, and gneisses occupy the most significant portion.

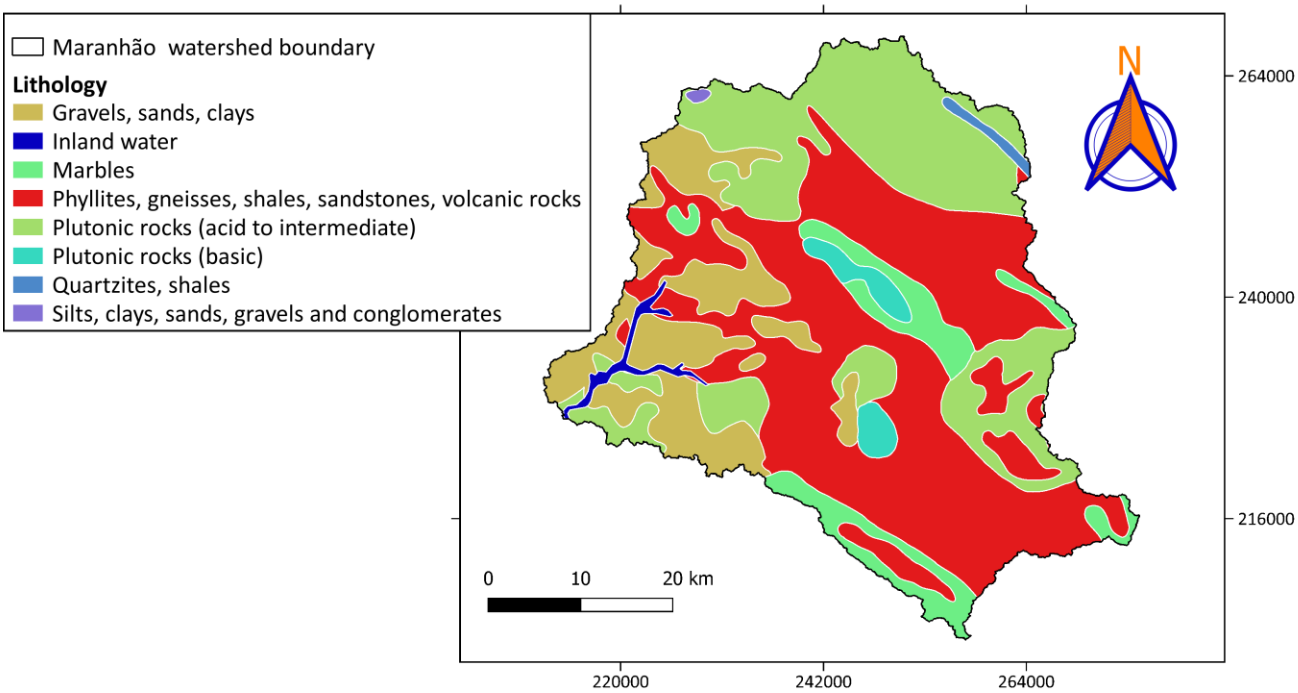

Figure 10. The lithology of Maranhão watershed.

3.6 Hydrology

Naturally, the watershed's main drainage channel is river Seda, a tributary of the Sorraia River (Sorraia also feeds into the Tagus River, whose basin boundary encompasses an area of up to 7730 km^2). A notable anthropogenic feature, the watershed includes the Maranhão reservoir, one of the largest Portuguese reservoirs in a dry place, with a total capacity, usable capacity, and dead capacity of 205.4, 180.9, and 24.5 hm^3, respectively. This reservoir, along with the Magos and Montargil reservoirs, is part of the Sorraia Valley watering system (Figure 11).

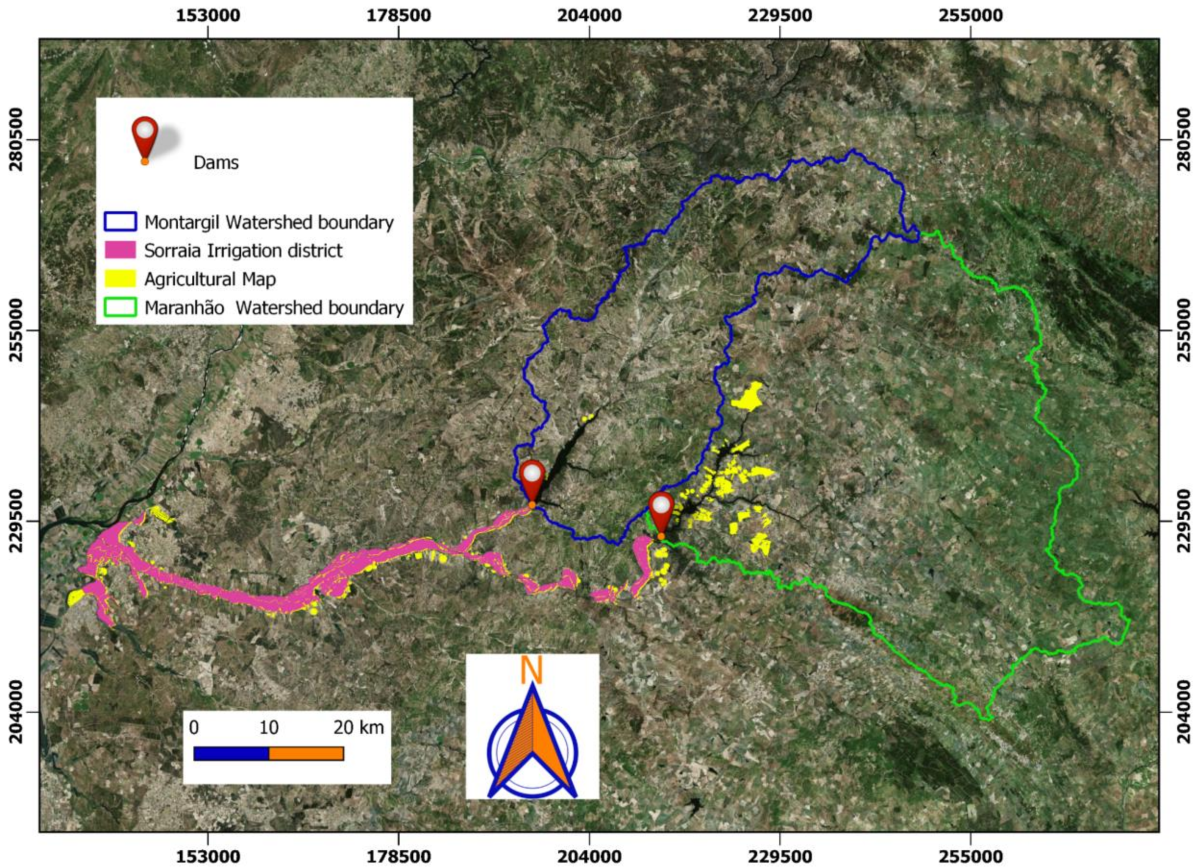

Figure 11. The Sorraia valley irrigation scheme

Using data sets from ARBVS (2022), Figure 12 shows the evolution of irrigation and stored water volumes for the Maranhão reservoir. An observation in Figure 12, considering statistical trend lines, is that the increment rate in the water used for irrigation is higher than that for the water stored in the dam, which implies a likely decrease in cumulative long-term reservoir water volume stored.

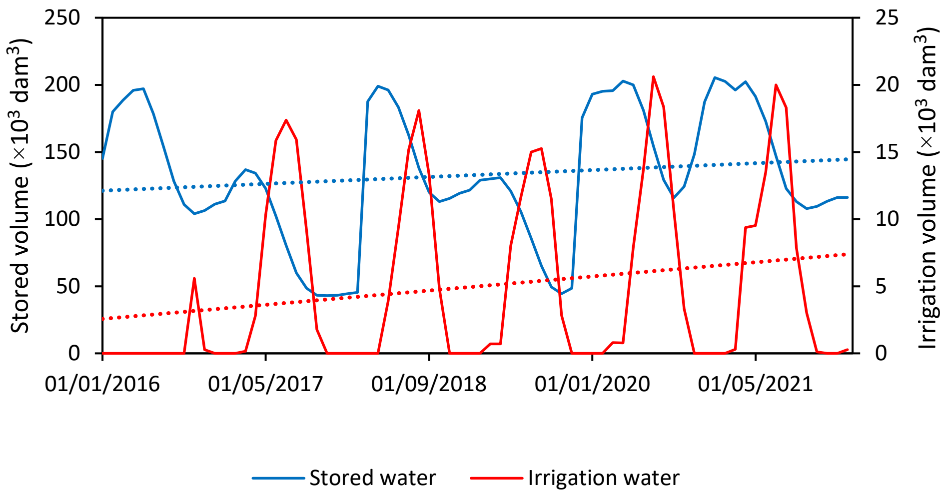

Figure 12. Time series of irrigation and stored water volumes for Maranhão reservoir.

3.7 Hydrogeology

The recharge rate is generally about 10% of the total annual precipitation. However, at some locations, recharge ranges from 21 to more than 36% of the total annual precipitation (Ribeiro & Cunha, 2010) due to geological characteristics, soil, vegetation cover, and topographical differences. Using data sets from (BGR, 2019), Figure 13 shows that most hydrogeological units in this watershed are porous. The size and whether the pores are connected determine the amounts and rates of water flow through the geologic units.

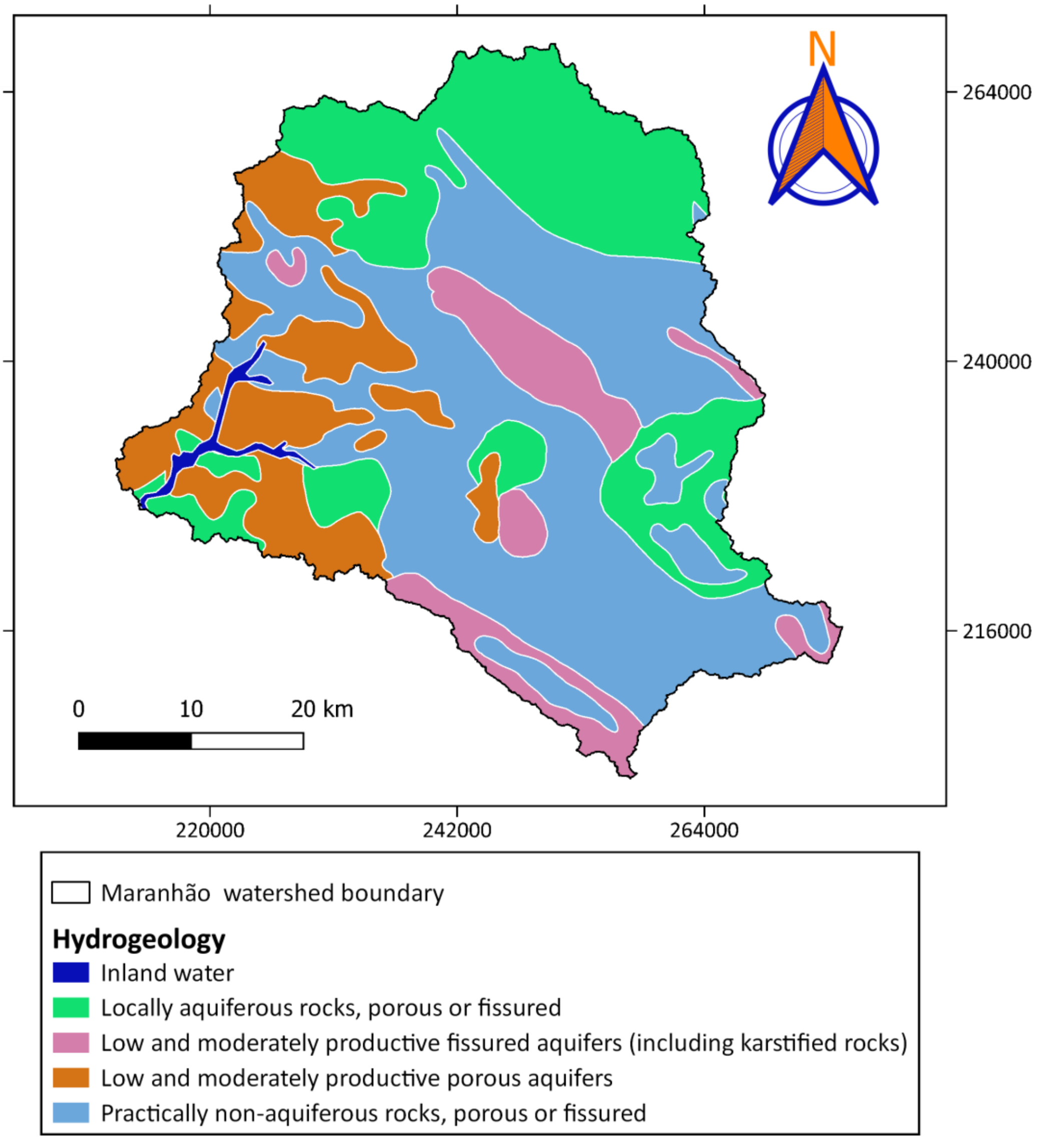

Figure 13. The hydrogeological map of the Maranhão watershed.

In addition, the watershed has a fault line mainly passing through productive and practically non-aquiferous porous rocks. The most hydrogeological diverse cross-section of the water is from the Northeast (around Serra de São Mamede Natural Park) to the West (around Maranhão reservoir) (Figure 14). Midway, the cross-section is a groundwater-surface water (GW-SW) interface.

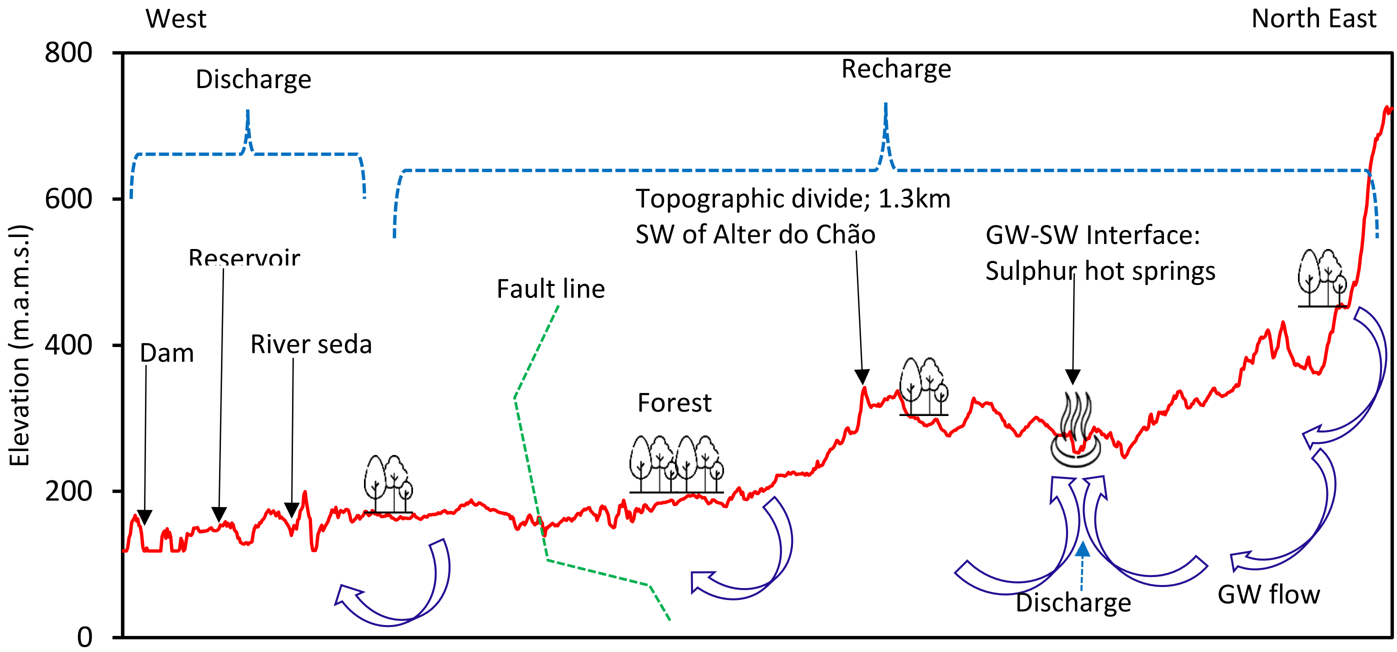

Figure 14. The hydrological cross-section of the Maranhão watershed.

3.8 Surface water and groundwater levels

Surface water datasets from the Ponte Vila Formosa (18K/01H) hydrometric station (SNIRH, 2022) indicate a mean flow rate of about $5m^3s^{-1}$ from 2001 to 2009 in the Northern part of the watershed. Record high flow rate of about $147.35m^3s^{-1}$ was recorded on 05/March/2001, whereas the lowest low was registered on 16/October/2005. In groundwater terms, despite having up to 14 groundwater stations in the watershed, only one station (station 397/87) had some consistent observed groundwater levels. Data sets from SNIRH (2022) for 2001 to 2009 reveal groundwater levels across the watershed valley range from 722.5 to 105.4m with an average of 259.4m, whereas, at station 397/87, the mean groundwater level is 244.57m.

3.9 Crop and Irrigation water needs

The crop water need refers to the amount of water needed by a crop to meet the water loss through evapotranspiration (Brouwer & Heibloem, 1986). By a crop growing under optimal conditions, the definition assumes a uniform crop, actively growing, completely shading the ground, diseases-free, and under favourable soil conditions (in terms of fertility and water) during which a crop reaches full production potential under the given environment. Climate, crop type, and growth stage are the key factors determining crop water needs. Reference evapotranspiration (ET_0) is a typical indication of the influence of the climate on crop water needs. According to data from ARBVS (2022), the crop-specific irrigated area in the Sorraia Valley (the agricultural area to which the Maranhão watershed belongs) has increased with time (Figure 15; source: (ARBVS, 2022)), and so are the crop water demand.

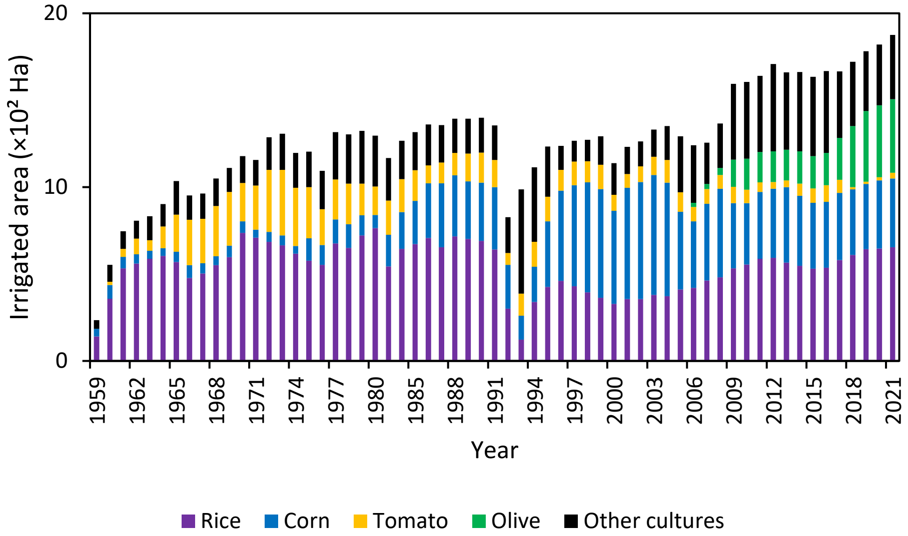

Figure 15. Irrigated area per crop in the Sorraia valley

According to Figure 15, before the 2000s, corn, rice, and tomato were the dominant crops in the valley; however, olives increasingly occupied a more significant area later. But generally, the total area under crop cover gradually increased from 1959 to 2021.

According to ARBVS (2022), Sorraia valley consists of three dams (Maranhão, Magos, and Montargil) and two weirs (Furadouro, and Gameiro weirs). Like other Mediterranean agricultural lands, Sorraia valley continually experiences water scarcity. And therefore, to meet crop water needs, water from dams is used to irrigate crops (Figure 16). However, the Magos dam contributes a tiny percentage of 0.01% compared to 46.97% and 53.01% by the Maranhão and Montargil dams.

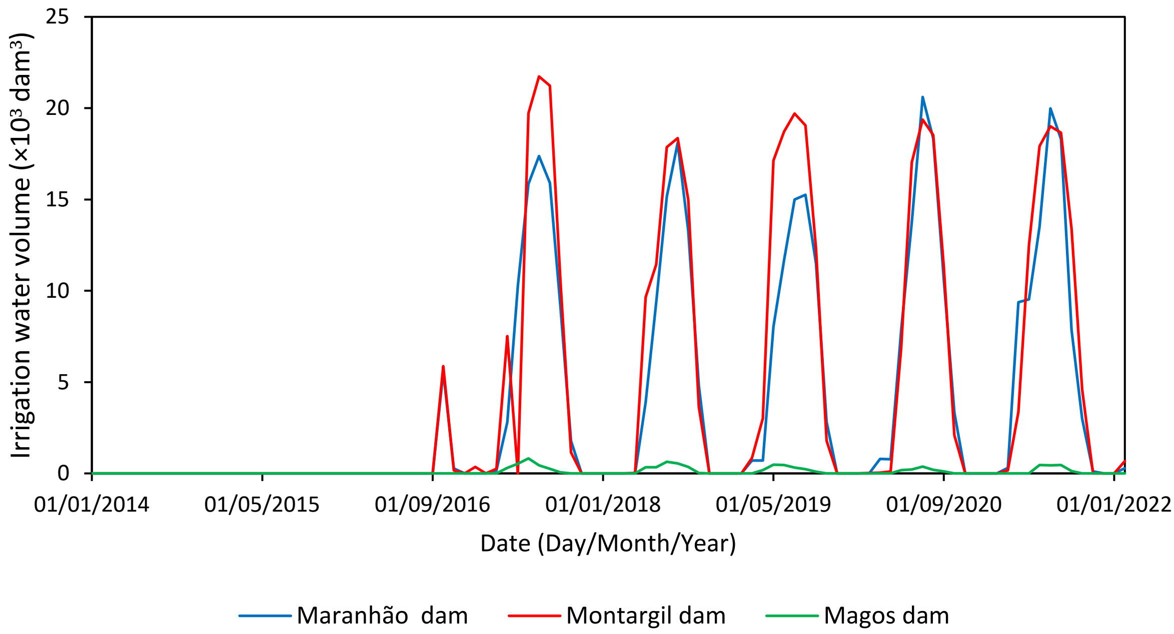

Figure 16. Irrigation water contribution of dams in Sorraia valley

According to zonal statistics, by area, rice covers about 26%, the most significant percentage of any crop in the Sorraia irrigation valley. Corn follows with 17.4%, the olive grove (11.9%), and tomatoes (4.4%), while fodder occupies 4.3%.

4: MATERIALS AND METHODS

4.1 Methodology

The study applied the MOHID Land model. The model setup involved Watershed characterisation regarding elevation, Manning coefficients, soil types, and vegetation covers. Before implementing an already calibrated and validated MOHID Land model, its performance was evaluated considering the surface water and groundwater behaviours. The evaluation was performed using the Nush-Sutcliffe Efficiency (NSE), the percent bias (PBIAS), coefficient of determination (R^2), and the root mean square error-observation to standard deviation ratio (RSR) for surface water and the last for groundwater. At this level, it was confirmed that the model is good enough to mimic the hydrogeological processes of the watershed. As in Figure 17, meteorological data from CORDEX was downloaded, extracted, and verified. Comparing observed data from SNIRH and historical modelled CORDEX data, the quality of meteorological predictions from an ensemble of regional climate models was validated. With defined climate change scenarios, climate change's impact was analyzed in the near (2024-2039) and far future (2075-2090). Simulation outputs aided computation of the water balance at the watershed scale, the impact of climate change on surface water availability, and groundwater levels. Alongside the climate change scenarios, irrigation needs were predicted, and reservoir construction was modelled for the near and far future but only under the RCP8.5 scenario. Then irrigation needs were compared with water availability in the future to ascertain if they would be met under the considered scenarios. Statements in this methodology were sequentially detailed in the subsections below.

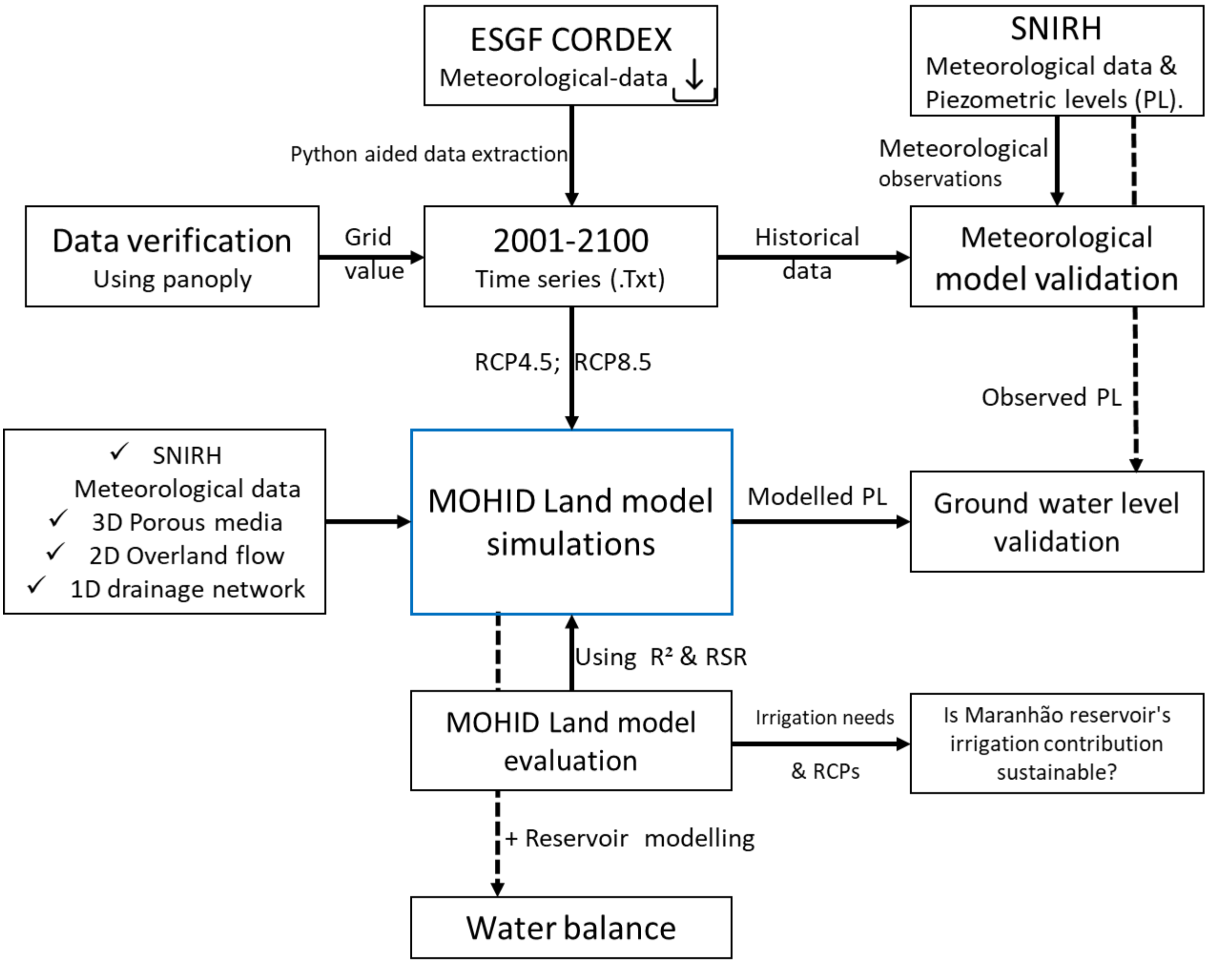

Figure 17. Methodological workflow.

4.1.1 MOHID Land model description

MOHID Land and MOHID Water are physically based and spatially distributed numerical models belonging to the MOHID Water Modelling System. MOHID Land module is uniquely a watershed mathematical or hydrological transport model designed to simulate water flow in a drainage basin and aquifer. In addition to an atmospheric component, which is not explicitly simulated but allows the input of boundary atmospheric conditions (such as precipitation variable in space and time), MOHID Land generally includes three key dimensions: (i) drainage network, (ii) 2D overland flow, and (iii) 3D porous media. According to (Oliveira et al., 2022), calculations of the free surface flow are by use of the Saint–Venant equation in its conservative form, with advection, pressure, and friction forces considered depicted in equation 1 below:

$$\frac{\partial \mathrm{Q}_u}{\partial \mathrm{t}} + V_V \frac{\partial Q_u}{\partial x_v} = -\mathrm{gA}\left(\frac{\partial \mathrm{H}}{\partial x_i} + \frac{|Q|Q_i \mathrm{n}^2}{A_V^2 R_h^{4/3}}\right) \quad \text{......... Equation 1}$$

where Q is the water flow (L^3T^{-1}), A is the cross-sectional flow area (L^2), g is the gravitational acceleration (LT^{-2}), and 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), x_i represents the XYZ directions (−), and the subscripts u and v denote flow directions. On the other hand, equation 2 below shows that the variable-saturated water flows in porous media are calculated in three directions (3D domain) using Richards' equation:

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial X_i}\left[K(\Theta)\left(\frac{\partial h}{\partial x_i} + \frac{\partial}{\partial x_i}\right)\right] - S\,(h) \quad \text{……………………………………………………………….Equation 2}$$

where: q is the volumetric water content (L^3L^{-3}), x_i represents the XYZ directions (−), and K is the hydraulic conductivity (LT^{-1}). The S corresponds to the sink term, denoting the root water uptake ($L^3L^{-3}T^{-1}$).

According to (Oliveira et al., 2020), the computation of the reference evapotranspiration rates (ETo, LT^{-1}) follows the FAO Penman-Monteith method. Crop evapotranspiration rates (ETc, LT^{-1}) are then computed by multiplying ETo with a single crop coefficient (Kc). ETc rates are then divided into crop transpiration (Tp, LT−1) and potential soil evaporation (Ep, LT^{-1}) based on (Ritchie, 1972) Ritchie et al. (1972). The Tp defines the maximum values of the sink term for root water uptake in the Richards equation. These may be reduced due to rootzone stressors following a macroscopic approach proposed by Feddes et al. (1978). On the other hand, the actual soil evaporation (Ea, LT^{-1}) is estimated by imposing a pressure threshold value to the potential evaporation values (American Society of Civil Engineers Committee on Ground Water Quality, 1996).

4.1.2 MOHID Land model implementation

The application of the MOHID Land model to the studied area involved considering a constant horizontally spaced grid, hereafter base grid, with a model resolution of 0.006º in both longitudinal and latitudinal directions (~520 m × 666 m, respectively). The grid had 140 columns and 110 rows to cover the modeled domain, with its origin location defined by the coordinates 38°45'16.5"N and 8°03'12.4"W.

Elevation data for the model was interpolated to the base grid considering the digital elevation model (DEM) from the European Environment Agency (EU-DEM) (Copernicus, 2012). The EU-DEM presents a resolution of approximately 30 m (0.00028°) and results from the combination of Shuttle Radar Topography Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data, fused by a weighted averaging approach. After the interpolation process, the minimum and maximum elevations of the watershed are 107 m and 725 m, respectively (Figure 18. a). Based on the interpolated digital terrain model (DTM), the watershed and river network delineation process considered the selected cell as the outlet. In both cases, the elevation and the slope of each cell and its neighborhood, starting in the outlet, were analysed with the river network delineation resulting from the connection of the cell centers (nodes) with the lower elevation (Figure 18. a). The defined-minimum area to consider the existence of the waterline was 10 km^2.

Additionally, an elected rectangular geometry represents the river cross-sections, with the dimensions defined according to Andreadis et al. (2013) . See Table 3 for the width and height of the cross-sections for a particular drained area. While for the nodes between those intervals, there was an interpolation of the cross-section dimensions.

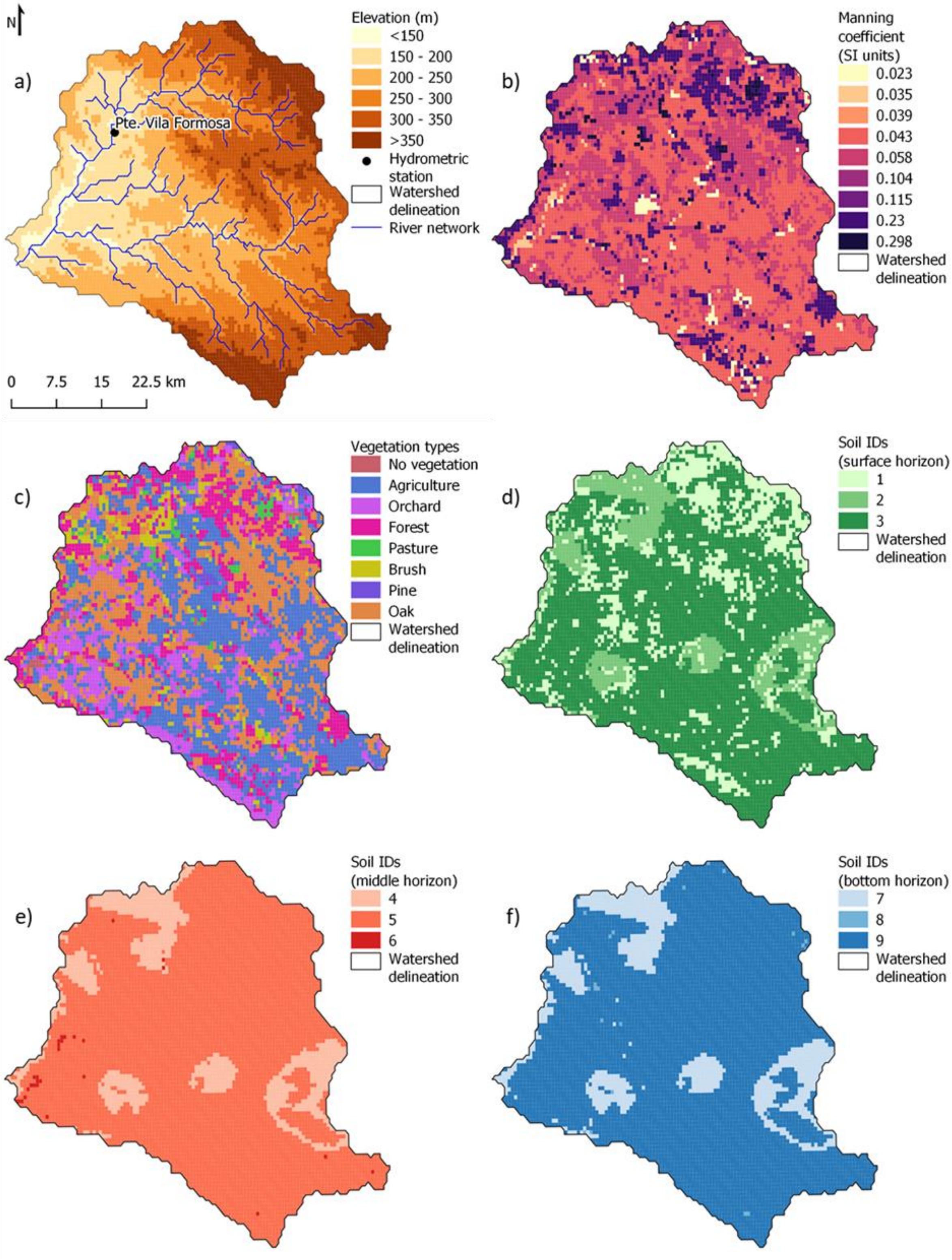

Figure 18. MOHID-Land inputs for Maranhão watershed: (a) digital terrain model and watershed and river network delineation; (b) Manning coefficient values; (c) types of vegetation; (d) identification number of the types of soil in the surface horizon; (e) identification number of the types of soil in the middle horizon; and (f) identification number of the types of soil in the bottom horizon.

Table 3. Cross-section dimensions according to the drained area for model setup

Drained area (km^2)	Width (m)	Height (m)
1.00	-	-
10.00	2.00	0.04
49.18	4.61	0.19
86.80	6.22	0.24
143.70	8.12	0.30
395.33	13.84	0.45
748.75	19.38	0.58
2577.41	37.20	0.97

To identify the land uses in each grid cell, Corine Land Cover (CLC) 2012, with a resolution of 100 m (Copernicus, 2012), was used. Each land use present in the CLC map and identified in the Maranhão watershed was associated with (i) a given Manning coefficient, according to Pestana et al. (2013), and (ii) a corresponding vegetation class from the MOHID-Land database. Many polygons are visible after loading the related shapefile, corresponding to a land-use type. After defining these relationships, the information interpolation to the base grid follows, and the resulting grid shows that Manning coefficients vary between 0.023 and 0.298 s $m^{-1/3}$ (Figure 18. b). At the same time, the most represented types of vegetation are agriculture (35%) and oak (28%) (Figure 18. c).

Crop coefficient (Kc) values must be defined to simulate the vegetation processes. The K_c values for each type of vegetation in Maranhão watershed had defined stages for the beginning, mid-season, and late-season, according to the changes in the model codes to mimic vegetation processes. Establishing K_c values followed the criteria by Allen et al., 1998., for agriculture (Summer and Winter crops), orchard, pasture, and brush, while pine, oak, and forest crop coefficients were defined based on those values proposed by Corbari et al. (2017) (Table 4).

Table 4. Crop coefficient (K_c) values for each vegetation type's initial stage and mid-and late seasons.

Type of vegetation	Crop coefficient		
	Initial stage	**Mid-season**	**Late season**
Agriculture (Summer crops)	0.15	1.15	0.95
Agriculture (Winter crops)	0.70	1.15	0.30
Orchard	0.40	0.90	0.65
Forest	0.15	0.80	0.15
Pasture	0.30	0.75	0.75
Brush	0.40	0.40	0.40
Pine	0.15	0.80	0.15
Oak	0.15	0.80	0.15

Mualem–van Genuchten hydraulic parameters were obtained from the multilayered European Soil Hydraulic Database (Tóth et al., 2017). However, while that database contains data at depths of 0, 0.05, 0.15, 0.3, 0.6, 1.0, and 2.0 m, with a resolution of 250 m, only data at depths of 0.3, 1.0, and 2.0 m were considered to the current application. Thus, the porous media in the studied domain was divided into six layers, with a thickness of 0.3, 0.3, 0.7, 0.7, 1.5, and 1.5 m from surface to bottom (vertical grid), with the maximum soil depth defined as 5.0 m. These layers were organized according to three different horizons characterised by the soil hydraulic properties acquired from the selected depths of the referred soil database. The information at 0.3 m depth represents the two top layers (0-0.6 m), the values at 1.0 m depth reflect the two intermediate layers (0.6-2.0 m), and the information at 2.0 m depth represents the two bottom layers (2.0-5.0 m) (Table 5). It is important to refer that, since MOHID-Land corrects the soil depth according to the surface slope, the thickness of the bottom layer of the studied domain presents a variation between 0.68 m and 1.5 m, corresponding to a minimum and maximum soil depth of 4.18 m and 5.0 m, respectively. Figure 18.d, e, and f show the spatial variation of the soil types in surface, middle and bottom horizons, with each ID corresponding to a different type of soil.

Table 5. Mualem–van Genuchten hydraulic parameters by soil horizon

Horizon	**Layers**	**Soil database depth**	**ID**	**θ_s**	**θ_r**	**η**	**$K_{sat, vert}$**	**α**	**ι**
	(m)	**(m)**		**(m^3 m^{-3})**	**(m^3 m^{-3})**	**(-)**	**(m s^{-1})**	**(m^{-1})**	**(m)**
Surface	0 – 0.6	0.3	1	0.491	0	1.193	1.64×10^{-6}	3.47	-4.3
			2	0.409	0	1.134	5.05×10^{-6}	7	-5
			3	0.465	0	1.116	2.26×10^{-5}	12.84	-5
Middle	0.6 – 2.0	1	4	0.384	0	1.121	4.29×10^{-6}	7.17	-5
			5	0.413	0	1.119	1.43×10^{-6}	2.27	-5
			6	0.432	0	1.17	9.93×10^{-7}	3.36	-5
Bottom	2.0 – 5.0	2	7	0.384	0	1.121	4.29×10^{-6}	7.17	-5
			8	0.432	0	1.17	9.93×10^{-7}	3.36	-5
			9	0.413	0	1.119	1.43×10^{-6}	2.27	-5

As referred to in the model description, MOHID-Land relates the horizontal and vertical saturated hydraulic conductivities according to the horizontal factor (f_h) parameter value, set to 10. Finally, for the initial conditions, we assumed that the water table has a depth corresponding to 5% of the soil depth in each cell. The soil is saturated below this depth and at field capacity above it. Model output locations in Figure 19 are mainly groundwater stations, the river downstream, and dam locations with a defined output time of 86400 seconds, thus yielding daily nodal results.

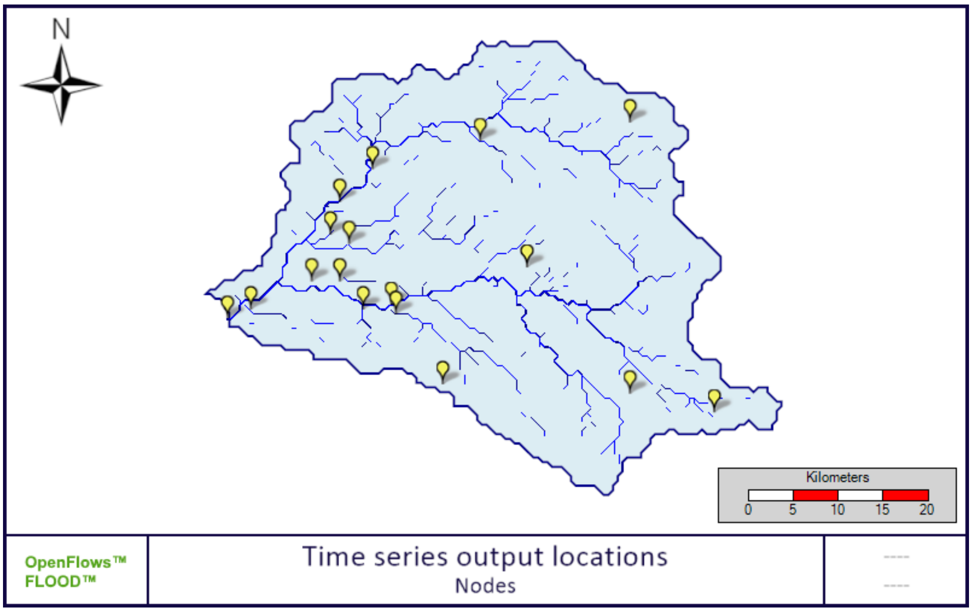

Figure 19. Framed time series output node locations

Model calibration involved changing parameters. Figure 20 shows model performance evaluation by comparing simulated and measured monthly streamflows. The simulation was for seven years, from 01/January/2001 to 31/December/2008. The calibration strategy looked at adjusting selected model parameters one at a time, within specified ranges, to minimise discrepancies between simulated and observed streamflow in the selected hydrometric stations. The calibration period was from 01/January/2002 to 31/December/2003, while the validation period ran from 01/January/2004 to 31/December/2008. Model warm up considered an entire year, starting 01/January/2001 and finishing on 31/December/2001.

Informed calibration followed the most sensitive parameters unveiled by Oliveira et al. (2020). These factors affect values of streamflow in MOHID-Land, and to this extent, the parameters` modifications took effect in the surface and channel Manning coefficients, the crop coefficients, the vertical saturated hydraulic conductivity, the dimensions (height and top and bottom widths) of the river cross-sections (Table 6), the multiplying factor relating the vertical and horizontal saturated hydraulic conductivities (f_h).

Table 6. Cross-section dimensions according to the drained area for model calibration.

Drained area (km^2)	**Width** (m)	**Height** (m)
1.00	1.00	0.20
10.00	2.00	0.25
49.18	4.61	1.00
86.80	6.22	1.00
143.70	8.12	1.50
395.33	13.84	2.00
748.75	19.38	2.00
2577.41	37.20	3.00

Model validation focused on reducing the difference between simulated and observed streamflow using the exact calibrated model parameters and considering the same hydrometric station of Ponte Vila Formosa (18K/01H). Four statistical parameters, namely, coefficient of determination (R^2), the root mean square error-observation to standard deviation ratio (RSR), the Nush-Sutcliffe Efficiency (NSE), and the percent bias (PBIAS), whose computations (equations 3 to 4) yielded significant values (Table 7), confirmed the readiness of the model for scenarios simulation.

$$\mathrm{R}^2 = \left[\frac{\sum_{i=1}^{p}(Q_i^{obs}-Q_i^{mean})(Q_i^{sim}-Q_i^{mean})}{\sqrt{\sum_{i=1}^{p}(Q_i^{obs}-Q_{mean}^{obs})^2}\sqrt{\sum_{i}^{p}(Q_i^{sim}-Q_{mean}^{sim})^2}}\right]^2$$ ……………………………………………Equation 5

$$\mathrm{RSR} = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{p}(Q_i^{obs}-Q_i^{sim})^2}}{\sqrt{\sum_{i=1}^{p}(Q_i^{obs}-Q_{mean}^{obs})^2}}$$ ……………………………………………Equation 6

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{p}(Q_i^{obs}-Q_i^{sim})^2}{\sum_{i=1}^{p}(Q_i^{obs}-Q_{mean}^{obs})^2}\right]$$ …………………………………………… Equation 7

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{p}(Q_i^{obs}-Q_i^{sim})^2}{\sum_{i=1}^{p}Q_i^{obs}} \times 100$$ …………………………………………… Equation 8

Where Q_i^{obs} and Q_i^{sim} are the observed and simulated flow on day one, respectively, Q_{mean}^{obs} and Q_{mean}^{sim} : the observed and simulated mean flow for the analysed period, respectively, and p is the total number of days in this period. When RSR ≤ 0.7 and R^2 > 0.5, the results of the modelled streamflow are considered satisfactory (Moriasi et al., 2007). PBIAS's optimal value is 0.0, and low-magnitude values indicate accurate model simulation. Positive and negative values demonstrate model under and overestimation, respectively. The NSE ranges from -1 to 1.0, with 1.0 being the optimal value, and is used to evaluate the relative magnitude of residual variance compared to the observed data variance. Values less than 0.0 imply that the mean observed value is a better predictor than the simulated value, while values between 0.0 and 1.0 are categorized as acceptable performance levels (Oliveira et al., 2020).

Table 7. Statistical model performance evaluation

Statistical parameter	**Calibration**	**Validation**
NSE	0.31	0.52
PBIAS	-38.33	-3.37
R^2	0.64	0.53
RSR	0.83	0.70

Surface water flow and groundwater validation then followed. In terms of surface water, the flow was used to compare modelled and observed quantities, and according to statistics and Table 7, the two vary in similar patterns.

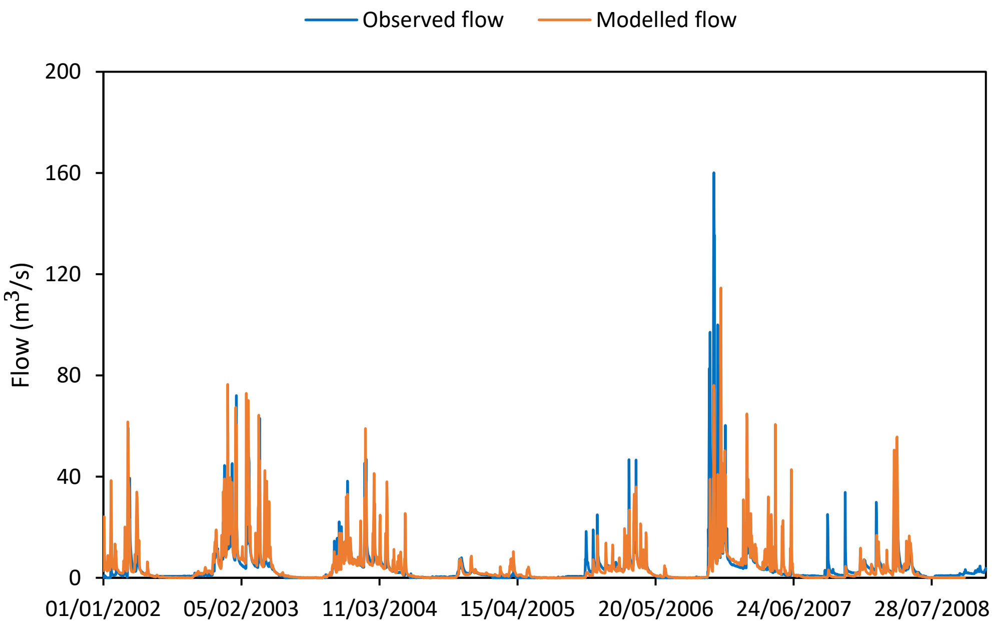

Figure 20. Surface water flow validation

For groundwater, this subsection shows the extent to which the modeled groundwater levels (GWLs) (from model calibration and validation phase) resemble piezometric recordings obtained from SNIRH (2022). 14 piezometric stations within the watershed (Figure 21) had groudwater level records. Only station 397/87 had fairly consistent piezometric records making it a station of interest.

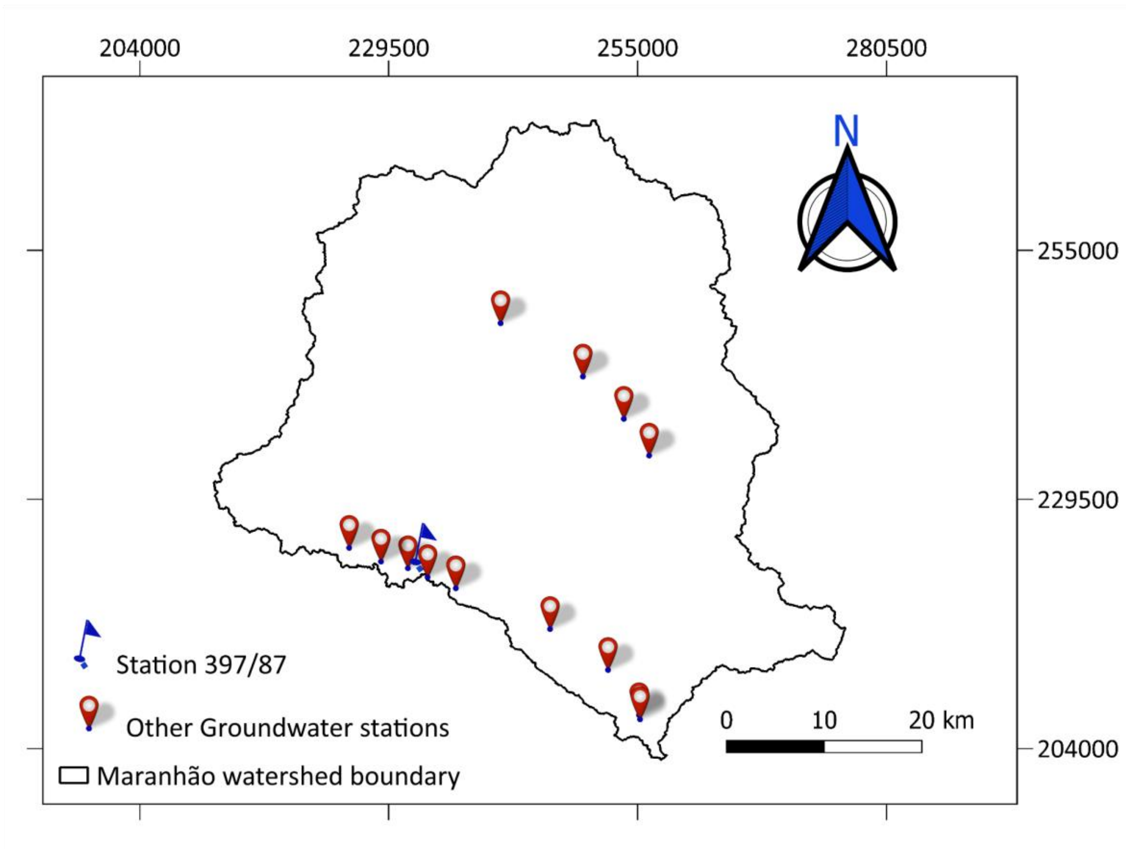

Figure 21. Location of piezometric stations in Maranhão watershed.

Despite data availability from 31/08/1993 to 28/02/2022, no station had reasonably consistent data except station 397/87 (station of interest). A few stations closed in the early 2000s, making it hard to have data for validating corresponding modelled data from 2002 to 2008. Though for a short period, Figure 22 shows that GW levels follow similar trends for modelled and observed instances of station 397/87. Precipitation amounts received in the area explain the groundwater trends since it is the primary recharge contributor.

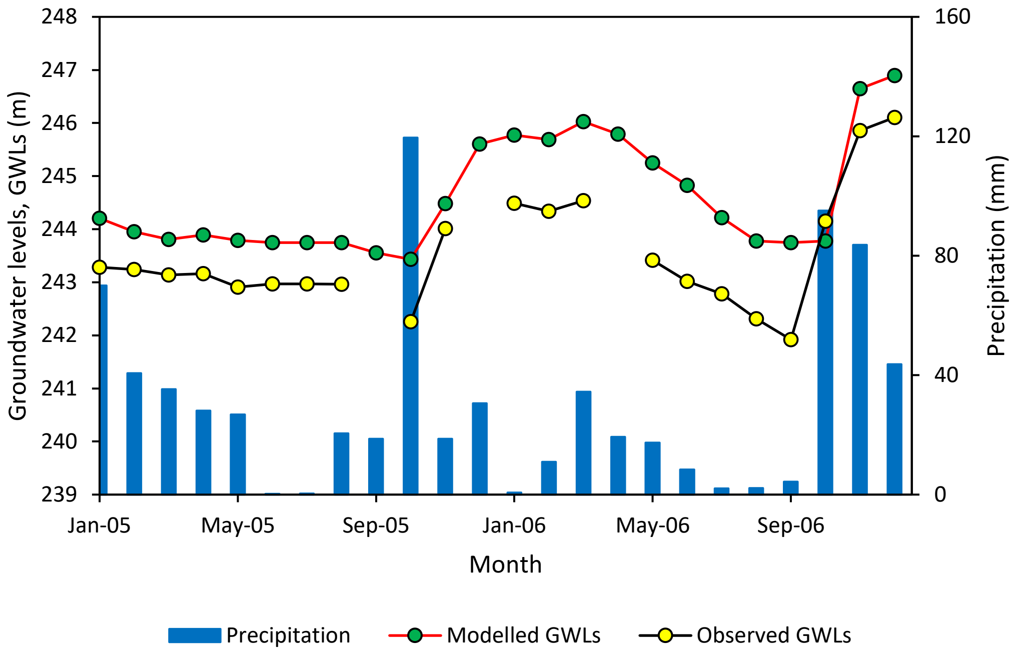

Figure 22. Validation of Maranhão groundwater levels (station 397/87).

Figure 22 shows a smaller period than the model calibration and validation period because few groundwater observations exist for the period of interest. In addition, there is a slight statistical difference (0.14 meters according to mean) between the observed and modelled GWLs (see Table 8) of station 397/87.

Table 8. The statistical description of groundwater levels.

Statistical parameter	**Groundwater level (m)**	
	Observed	**Modeled**
Mean	244.57	244.71
Standard Error	0.07	0.02
Median	244.56	244.38
Mode	243.75	243.75
Standard Deviation	0.75	1.01
Sample Variance	0.57	1.03

The discrepancy in the datasets showed in Figure 22 is most likely due to elevation differences caused by the interpolation behaviour of the model. As in Table 9, modelled GWLs corresponds to a grid that proportionally covers a larger area while observed GWLs aligns to a punctual location of identical elevation. For the station of interest (397/87), the elevation difference between modelled and reality is 2 meters. And these 2 meters, due to MOHID's interpolative behaviour, account for the gap between modelled and observed GWLs.

Table 9. The elevation difference between modelled and observed groundwater levels.

Station ID	**Elevation (m)**	
	Equivalent grid cell (in the model)	Station (in reality)
370_5	257	253
371_45	302	297
384_103	311	313
384_2	302	310
396_161	215	218
396_162	228	226
396_235	236	238
397_168	246	248
397_87	247	245
411_194	303	301
411_256	338	342
412_94	347	351
426_238	423	427
426_347	416	424

A consistent negligible difference (0.14m and 2m, respectively) for descriptive mean and elevation between modelled and observed confirms a close to perfect fit between modelled and observed groundwater levels. Hence validated that the GWLs output of the model in the scenarios will be the most intimate depiction of the reality in the Maranhão watershed.

4.1.3 Model scenarios and simulations

All model scenarios and subsequent simulations consisted of the same validated parameters for modules of digital terrain, porous media, reservoir, runoff, time series locations, and vegetation. On the other hand, the boundary conditions of precipitation, temperature, relative humidity, wind velocity, and solar radiation varied according to the RCP and hence the simulation period (Table 10). All boundary conditions were daily values except solar radiation, which was hourly.

Table 10. Boundary conditions` categories and periods for simulations

	Simulations					
	1	2	3	4	5	6
Simulated period (years)						
2001-2008	✓	✗	✗	✗	✗	✗
2024-2039	✗	✓	✗	✓	✗	✓
2075-2090	✗	✗	✓	✗	✓	✗
Boundary conditions						
Observed	✓	✗	✗	✗	✗	✗
Predicted (RCP 4.5)	✗	✓	✓	✗	✗	✗
Predicted (RCP 8.5)	✗	✗	✗	✓	✓	✓

Simulation 1 corresponds to calibration and validation. Simulations 2 and 3 make up the RCP 4.5 scenario for the near and far future, respectively. Simulations 4 and 5 make up the RCP 8.5 scenario for the near and far future, respectively. A unique simulation six consisted of new reservoir modelling combined with a worst-case scenario (RCP8.5) predicted temperature and precipitation.

4.1.4 Meteorological data

The ERA5 Reanalysis dataset (CDS, 2017) consisted of meteorological conditions used as model input for calibration and validation processes. Figure 23 shows the observed time series where T and P depict temperature and precipitation, respectively.

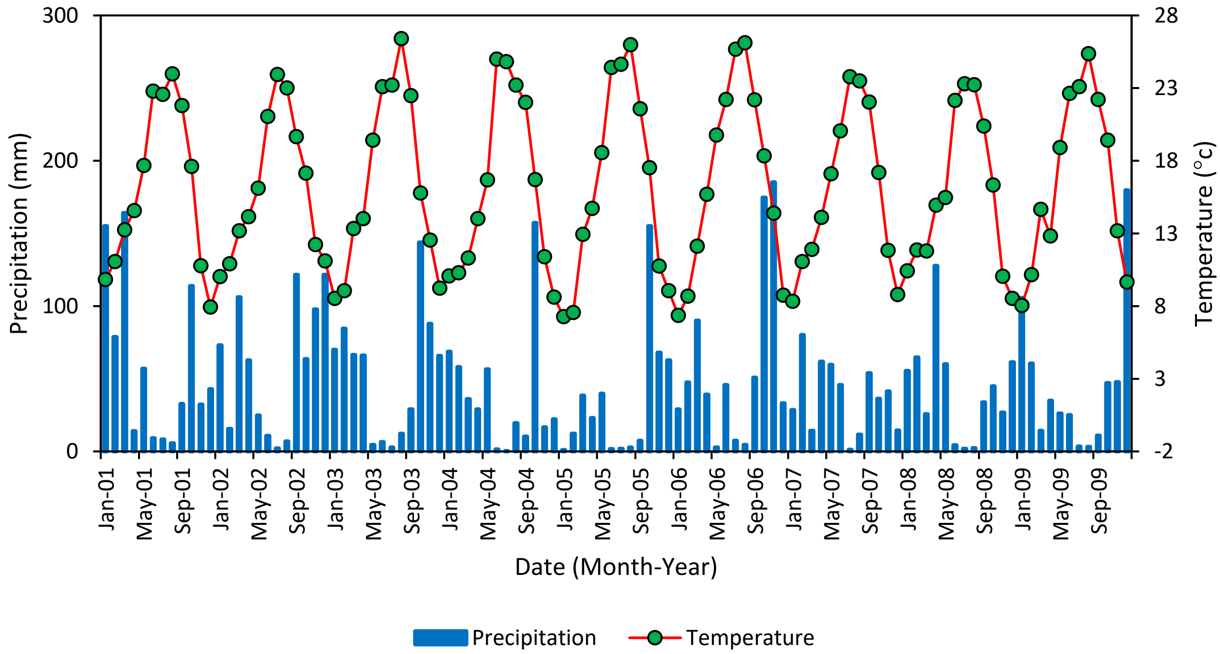

Figure 23. ERA5 temperature and precipitation for the Maranhão watershed

The source of scenarios (RCP 4.5 and 8.5) data sets is Jacob et al. (2014) using an ensemble of models. On the website, various datasets are available under the CORDEX project and output production. Multiple aspects were selected and finally downloaded, the data needed for this study. The selections included domain (EUR-44), experiments (historical, rcp45, and rcp85), experiment family (historical and Rcp), RCM model (RCA4), time-frequency (daily), and variable-long name (Near-surface air temperature, near-surface relative humidity, precipitation, and other meteorological variables). The modelled meteorological data were not bias-corrected because they seemed in range with the observed values from the same area (Figure 24 andFigure 25).

Scenarios RCP4.5 and 8.5 predict an increase in temperature and a decrease in precipitation for the Maranhão watershed. Table 11 shows that RCP8.5 indicates an additional 5.9% increase in average annual temperature and a further 9% decrease in yearly precipitation compared to RCP4.5.

Table 11. Percentage change in average annual precipitation and temperature per scenario

	Period	**Average annual precipitation**	**Average annual temperature**
Reference values	1989 - 2021	570mm	16.5ºC
		Predicted mean change (%)	
RCP4.5	2006 -2100	-8.7	6.9
RCP8.5	2006 -2100	-17.7	12.8

As seen in Figure 24, the predicted precipitation and temperature don't deviate abnormally from the observed values; hence these predictions are suitable for modelling application without bias correction. Figure 25 shows even a more apparent trend for temperature. However, instead of graphing the predicted data since 2006, predicted data starting in 2022 (a year away from the recently observed data) was plotted to alow for significant use of observed data.

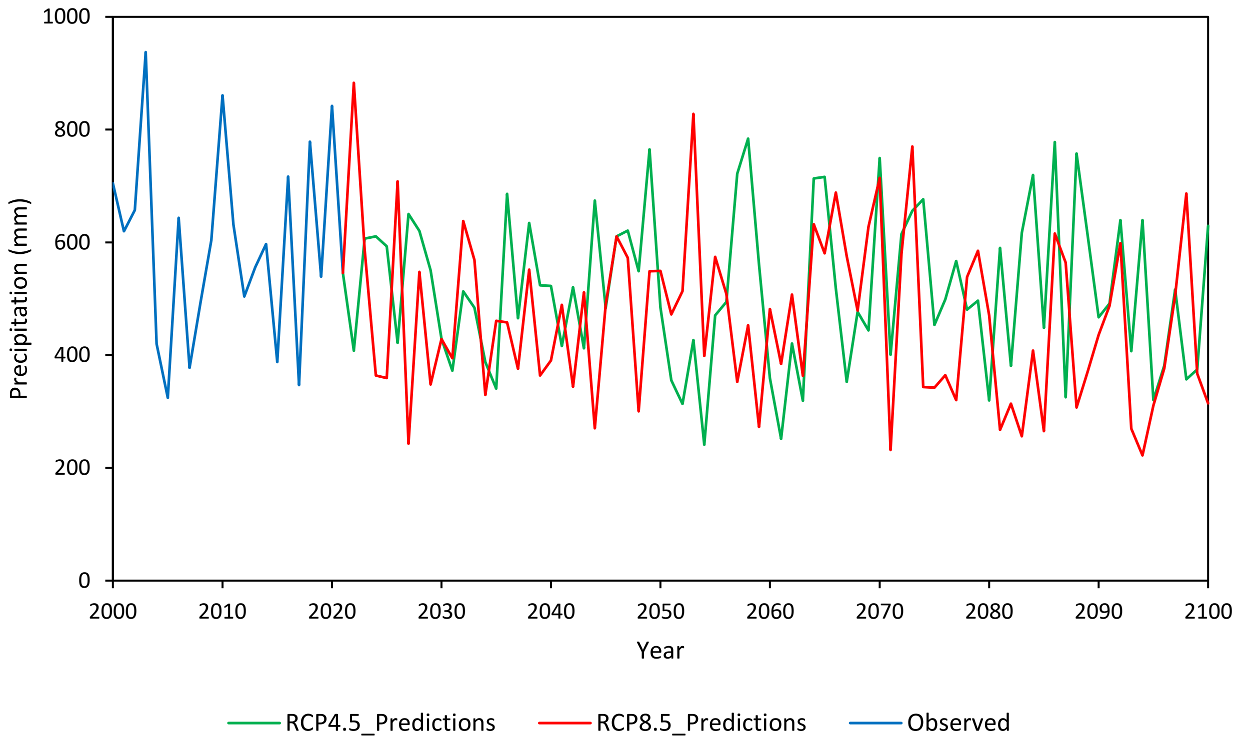

Figure 24. Maranhão's total annual precipitation for the twenty-first century

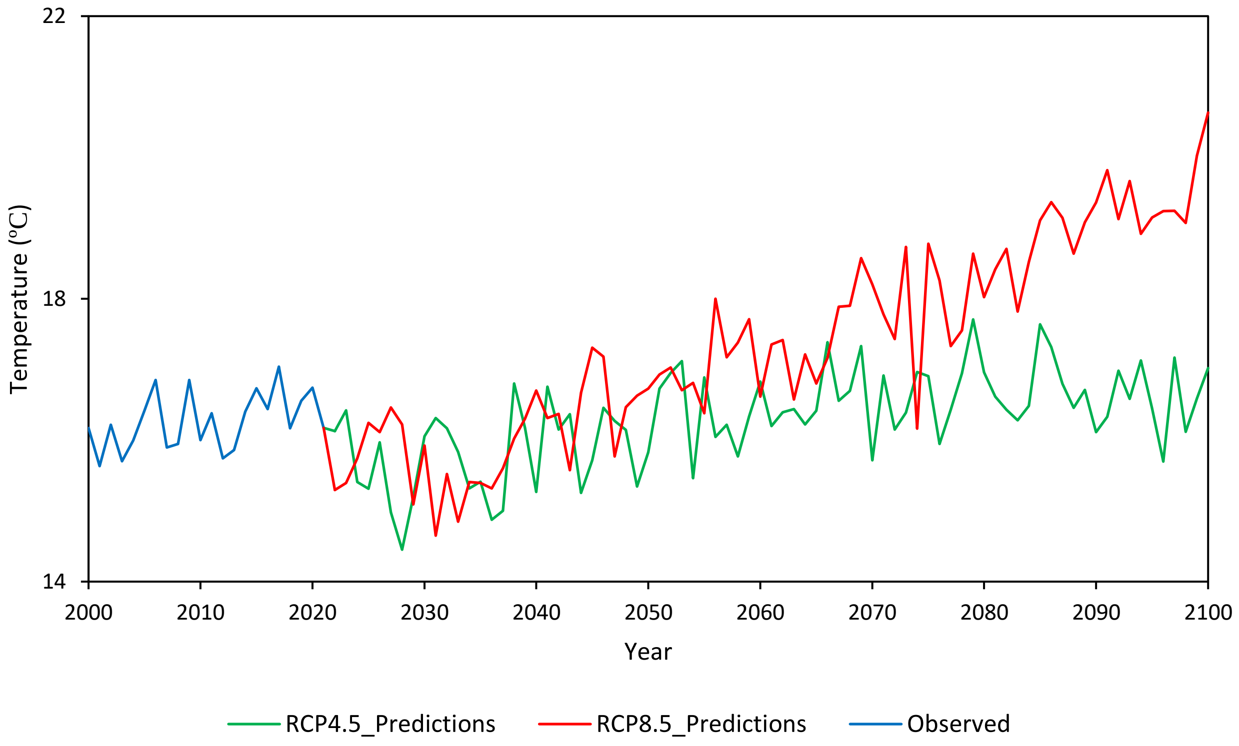

Figure 25. Maranhão's mean annual temperature for the twenty-first century

Meteorological validation is intended to answer the question of how good do regional climate models predict climate in the Maranhão watershed by comparing historical climate predictions from these models with the temperature and precipitation observed in the watershed. For a period of 2001 to 2008, observed daily temperature is from Albufeira do maranhão (19J/04F) station whereas daily precipitation is from Alter do chão (18L/01UG), Avis (19J/03UG) and Seda (19K/01UG) stations (SNIRH, 2022). Precipitation mean is similar for modelled and observed; wheras for temperature, there is a slight variation according to Table 12. Hence the meteorological data from CORDEX is good enough to be used for scenario modelling in this study.

Table 12. Descriptive statistics of the meteorological data

Statistical parameter	Daily temperature (°C)		Daily precipitation (mm)	
	Observed	Modelled	Observed	Modelled
Mean	15.78	14.95	1.40	1.40
Standard Error	0.12	0.14	0.08	0.08
Median	15.30	13.41	0.00	0.00
Mode	19.30	15.89	0.00	0.00
Standard Deviation	5.89	7.05	4.39	4.00
Sample Variance	34.71	49.76	19.28	16.07
Kurtosis	-0.76	-0.79	34.61	26.37
Skewness	0.16	0.45	5.16	4.57
Range	32.30	32.33	52.00	43.17
Minimum	2.60	1.34	0.00	0.00
Maximum	34.90	33.67	52.00	43.17

4.1.5 Meteorological data comparisons based on simulation periods

Frequency distribution comparisons (Table 13) consider a longer past period than the reference. The past period is now 2000–2015, and although the calibration/validation period was 2000 – 2008, frequency comparisons are only suitable for equal periods (and hence data values). Since the future simulation period length was 15 years, we increased the past period to 15 years.

Table 13. Frequency distribution table of meteorological data

	2000-2015	**2024-2039**		**2075-2090**	
Data limits	Past	RCP4.5	RCP8.5	RCP4.5	RCP8.5
	Frequencies of daily Temperature ranges				
(°C)					
0-5	108	195	203	77	58
6-10	1069	1198	1213	1070	792
11-15	1600	1747	1727	1777	1582
16-20	1164	1031	959	968	1026
20-25	1330	894	968	925	844
25-30	508	702	671	772	954
31-35	65	77	102	253	555
36-40	0	0	1	2	33
	Frequencies of daily Precipitation ranges				
(mm)					
0-5	5212	5322	5373	5284	5403
6-10	346	281	264	302	258
11-15	173	123	109	130	95
16-20	70	47	49	63	43
20-25	24	38	22	28	20
25-30	13	17	13	16	15
31-35	3	5	7	9	4
36-40	2	5	3	3	4
41-45	1	3	1	2	1
46-50	0	0	2	2	0
51-55	0	0	1	2	0
56-60	0	3	0	3	1

On a trend from past through near to long term future, Table 13 reveals that extreme temperature and precipitation events will increase. However, only significantly higher mean daily temperatures will become more frequent in the case of temperature. On the other hand, both very high and meager total daily precipitation amounts will become more frequent in the future.

4.1.6 Irrigation model (Predicting Irrigation water demands)

In Sorraia Valley, irrigation and rainfall meet crop water needs. According to Brouwer and Heibloem (1986), irrigation water need (IN) is the difference between the crop water need (ET crop) and that part of the rainfall effectively used by the plants (Pe). Determining irrigation water needs requires determining crop water needs (a product of ET_O and K_c), the amount of water needed to saturate the soil for land preparation by puddling (SAT), the amount of percolation and seepage losses (PERC), the amount of water needed to establish a water layer (WL), and Pe. For this study, current IN data was available, and our interest was near and far future IN values for the Maranhão watershed, which we got using MOHID Land model applied at the plot scale. A validated plot scale model was implemented using MOHID for corn and olive crops. Rice also covers a large area of Maranhão farmland but was not considered for irrigation needs modelling because rice beds need to be flooded with about 20cm of water above the surface, an aspect MOHID Land cannot simulate. However MOHID-Land model can accurately estimate soil water balance and aboveground biomass growth (Ramos et al., 2018; Simionesei et al., 2018).

In summary, MOHID Land uses meteorological data, crop parameters, and management practices to compute the ET_o. A product to K_c and ET_o yields an estimate of ET crop. A proportion of ET crops not met by Pe is the irrigation needs.

4.1.7 Reservoir modelling

According to Calejo et al. (2011), the irrigation of the municipalities of Alter do Chão, Fronteira, Crato, and Avis will come from the water of the Seda stream through a reservoir (Crato) to be created by a dam in this same stream at latitude 39.263046 and longitude -7.568222 (upstream from the Maranhão reservoir) at Couto de andreiros (18L/01H) hydrometric station (Figure 4). The estimated average annual inflow in the Crato dam section is about 52 hm^3 from 1941/42 to 1996/97. The impact of the Crato dam on turbine volume reduction in Maranhão and Montargil is likely to be only about 3% (Calejo et al., 2011). The average annual volume turbined in Crato is 24.6 hm^3. Whereas the characteristics of the Crato dam are those contained in the "Reformulation of the Crato Dam Project, Access to the Crowning and Environmental Impact Study" (COBA, 2003), dam construction will be in Couto de Endreiro (Calejo et al., 2011). During operation, the Crato dam must guarantee a minimum reserve volume of 8hm^3 for public supply, so the water supply for irrigation exists when the water level in the dam is above the level 250m. The preferable dam coverage will benefit a total area of 8,939 ha to be divided into five blocks: Alter do Chão and Fronteira (6,153 ha); Benavila (1796 ha); right bank of Maranhão (404 ha); Avis (362 ha); and Crato (224 ha). Reservoir installation at 270m is sufficient to guarantee a minimum pressure greater than 4 bar in at least 63% of the dominated area, given other guaranteed pressures.

5: RESULTS

Under this section, simulation results are presented and, in many cases, compared based on the climate change scenarios (RCP4.5 and 8.5) and simulation periods of reference (2001-2008), near future (2024-2039) and long-term future (2075-2090).

5.1 Relationship between precipitation and groundwater level

In a Mediterranean environment with no artificial recharge schemes, almost all groundwater in the Maranhão watershed is due to direct recharge (recharge by precipitation). It is, therefore, essential to explore the relationship (Figure 26) between groundwater level and the chief recharge contributor, precipitation—a similar relation between surface water and precipitation is presented in Figure 27. Exploring this relationship enables to understand after how long do changes in precipitation explain changes in groundwater. If the period is shorter say a month or less, then annual groundwater level changes can be attributable to precipitation changes.

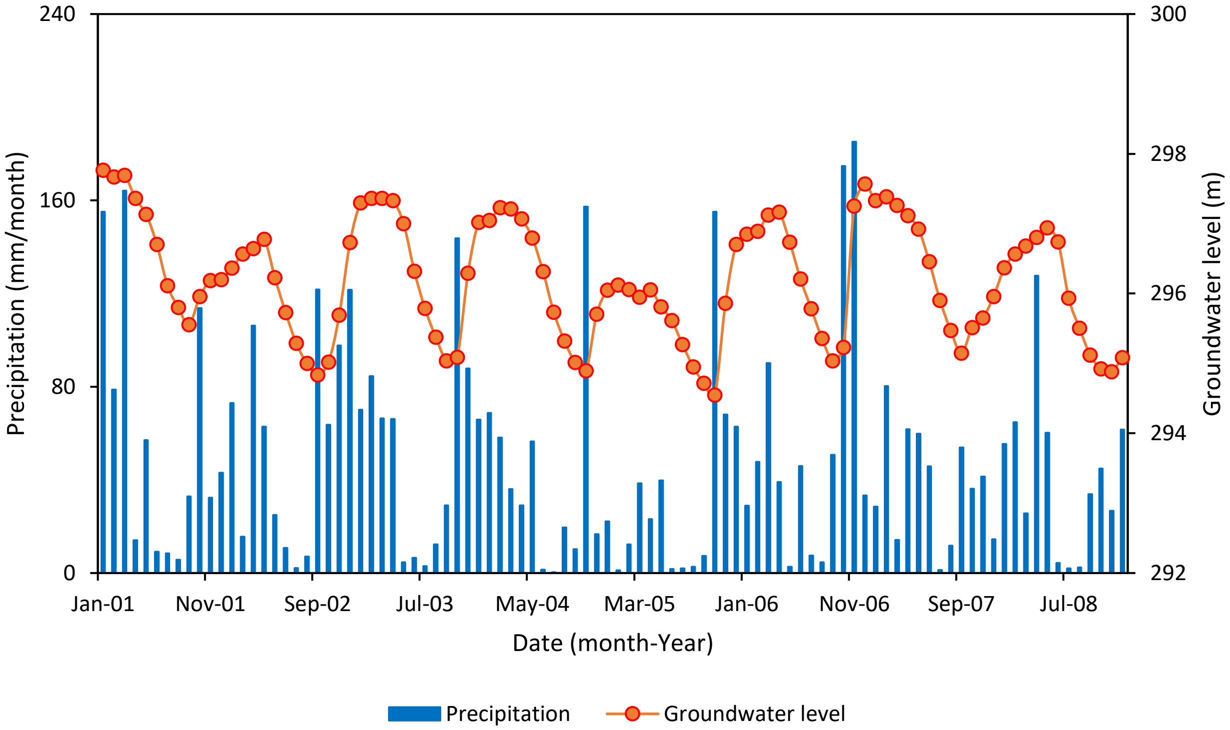

Figure 26. Relationship between groundwater level and precipitation

Figure 26 shows a delay in the groundwater level peak compared to precipitation, which is the time lag. The time lag, in this case, is about a one-time step, corresponding to about a month. Further correlation statistics confirm that a one-time step time lag yields a 0.16 correlation value between groundwater head and precipitation. The only positive correlation of 0.16 demonstrates that the rechargeable portion of rainfall received in the Maranhão watershed at any given period will be part of groundwater storage within almost a month. Unlike groundwater levels, surface water and precipitation (Figure 27) almost fluctuate similarly with very little or no time lag, most likely because the watershed is small and the runoff takes a short time to reach channels.

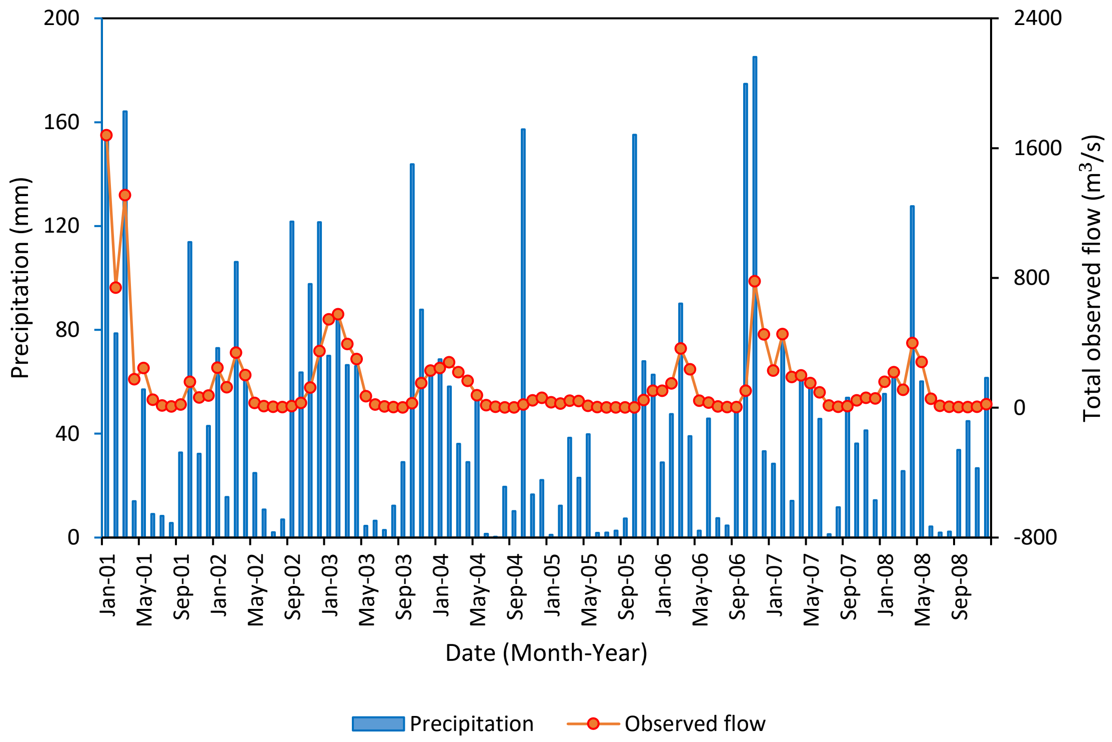

Figure 27. Relationship between observed flow and precipitation

5.2 Surface water

In this study, simulations output different surface water parameters such as channel water depth, channel water level, channel flow (discharge), channel volume, velocity, and groundwater flow to channels. However, channel discharge was considered (Figure 28) because discharge informs about water availability for irrigation and public supply and implies changes in the ecosystem integrity/functions.

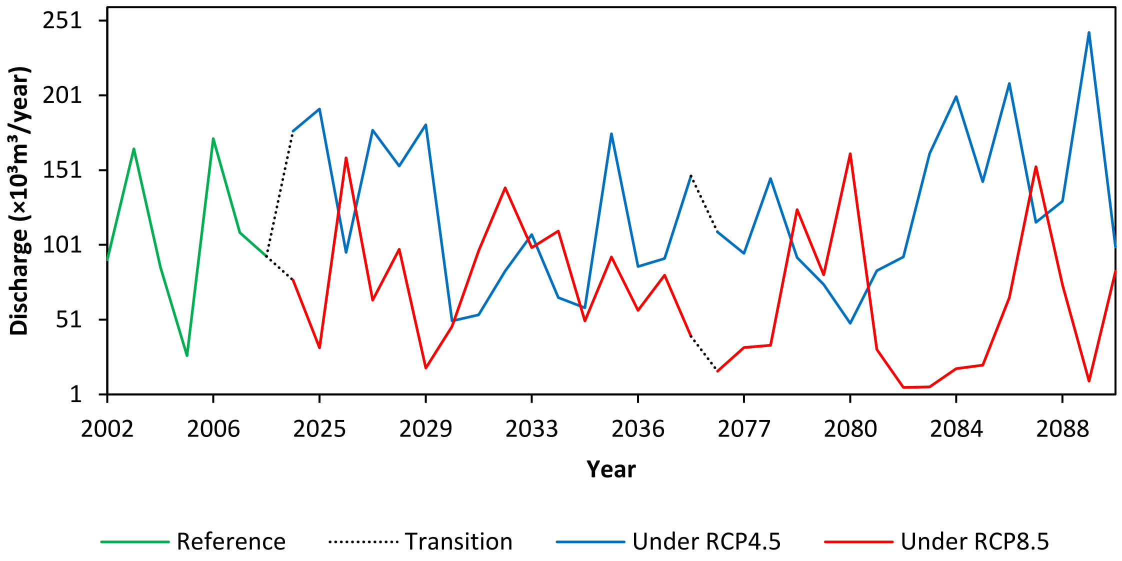

Figure 28. Discharge under climate change scenarios

Simulations yield stream discharge increase under RCP4.5 and decrease under RCP8.5. Statistically, RCP4.5 exhibits a mean discharge increase of about 16% for the near and long-term, whereas RCP8.5 simulations indicate an average 36% discharge decrease during the same period. Worth noting is that long-term simulations output more considerable stream flow changes compared to near-term simulations. Generally, low stream discharges will remain more frequent than high discharges (Table 14).

Table 14. Percentage Frequency of total discharge ranges

	2000-2015	2024-2034		2075-2090	
Data limits	**Reference**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
(m^3/month)	percentage Frequency of total discharge ranges				
15-50000	96	97	99	96	99
50001-90000	2	3	1	3	1
90001-123602	2	0	0	1	0

5.3 Groundwater levels

Groundwater levels per station per scenario and simulation period are visualised. At the temporal scale, groundwater levels decrease with time under RCPs4.5 and 8.5 climate change scenarios. Statistics In Table 15 indicate a 0.02-0.77% (0.1 to 2m) mean decrease in groundwater levels under those climate scenarios, with long-term simulations predicting a further 0.07% average decrease in GWLs compared to the near future simulations.

Table 15. Percentage change in groundwater levels per station

	Mean groundwater levels				
	2001-2008	2024-2039		2075-2090	
GW stations	**Reference value** (m)	**RCP4.5** (%Δ)	**RCP8.5** (%Δ)	**RCP4.5** (%Δ)	**RCP8.5** (%Δ)
370_5	256.07	-0.12	-0.16	-0.11	-0.25
371_45	298.47	-0.15	-0.21	-0.15	-0.31
384_2	299.82	-0.05	-0.15	-0.03	-0.25
384_103	309.70	-0.25	-0.32	-0.25	-0.48
396_161	214.51	-0.14	-0.16	-0.17	-0.48
396_162	225.80	-0.28	-0.44	-0.25	-0.77
396_235	234.64	-0.39	-0.46	-0.38	-0.62
397_87	244.73	-0.19	-0.31	-0.16	-0.36
397_168	244.71	-0.29	-0.37	-0.29	-0.49
411_194	301.02	-0.25	-0.32	-0.24	-0.42
411_256	334.94	-0.15	-0.21	-0.12	-0.23
412_94	345.99	-0.08	-0.14	-0.07	-0.38
426_238	422.16	-0.05	-0.06	-0.06	-0.20
426_347	414.17	-0.13	-0.16	-0.13	-0.26

On a spatial scale, the Maranhão will soon experience a slight groundwater increase and a significant decrease in different watershed parts. In Figure 29, both scenarios generally show groundwater decrease in the long-term future; however, RCP8.5 indicates even a further decline. The Northeastern part of the Maranhão experiences most groundwater level decreases. In summary, on spatial scale, groundwater level will vary from -0.82% to 0.89% (-3.1 to 3.4m) under both scenarios and periods.

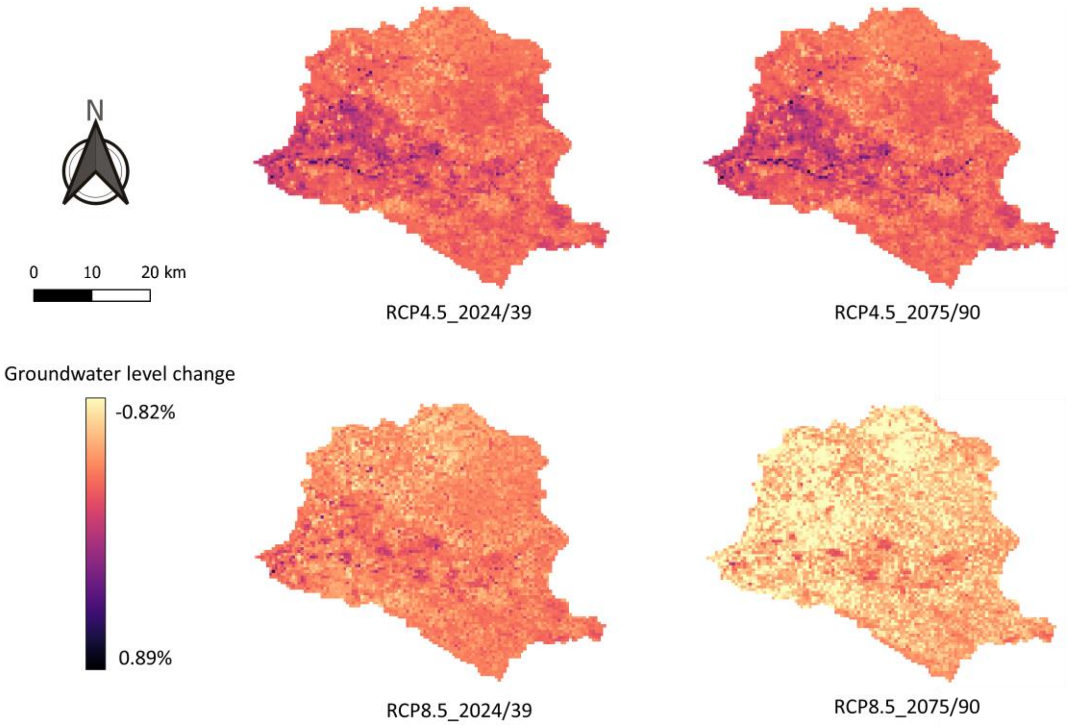

Figure 29. Percentage groundwater level change in the Maranhão watershed

5.4 Water balances

Water balance compiles by MOHID Land are processed and availed because they aid in clarifying whether Maranhão faces (or is prone to) climate change-related water shortages and (or) determining if climate change will exacerbate or limit future water shortages. The water balance (Tables 16 to 18) is illustrated by equation 9, to which input (total precipitation) and outputs (evapotranspiration and outlet flow volume) are mathematically related.

$$TP = ETP + Q \quad \text{……………………………………………. Equation 9}$$

In equation 9, P is total precipitation, ETP is evapotranspiration, and Q is outlet flow volume. By applying the laws of mass conservation to water balance (European Commission, 2015), inputs to the system equal outputs and changes in storage (equation 10). The law is observed for the presented annual water balance considering the following assumptions. Maranhão watershed is a closed system that assumes insignificant anthropogenic interventions (water imports and exports) to the watershed, minor water exchanges with neighbouring watersheds, and low variation in basin water storage in the long term. The Maranhão watershed's outlet flow volume is precisely runoff. Likewise, the channel, soil, and surface storage at the beginning of each year made up the total initial storage. The sum of evaporation and transpiration yielded evapotranspiration. The change in storage relates the difference between inputs and outputs with total initial storage between the year under consideration and a year ahead; therefore, the change in storage closes the water balance.

$$IN = OUT \pm \Delta S \text{ .... Equation 10}$$

In equation 10, IN, OUT, and ΔS represent inputs, outputs, and changes in storage, respectively. The percentage error quantifies the extent to which the water balance has been closed concerning the principal input, precipitation. A negative percentage error meant underestimating some water balance components, whereas a positive value implied an overestimation.

Table 16. The Maranhão water balance for reference scenario (TP – total precipitation, ET – evapotranspiration).

Year	TP	Outlet	ETP	Initial storage			ΔS	Error
				Soil	Surface	Channels		
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(%)
2001	714.0	512.0	314.0	2048.5	0.0	0.0	37.6	5.3
2002	605.2	140.5	367.4	1897.8	0.2	0.9	10.4	1.7
2003	506.2	255.2	326.2	1983.0	0.4	2.1	-50.5	-10.0
2004	383.1	133.0	330.0	1959.4	0.3	1.3	2.8	0.7
2005	365.3	41.6	283.9	1877.7	0.1	0.5	-1.7	-0.5
2006	695.6	265.9	349.3	1918.5	0.2	1.1	-5.3	-0.8
2007	467.7	168.8	370.5	2003.6	0.4	1.6	35.1	7.5
2008	479.6	144.2	352.3	1898.1	0.1	0.7	0.0	

Table 17. The Maranhão water balance for near future period (2024-2039) for RCP 4.5 and 8.5 scenarios (TP – total precipitation, ETP – evapotranspiration).

Year	TP	Outlet	ETP	Initial storage			ΔS	Error
				Soil	Surface	Channels		
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(%)
	RCP 4.5							
2024	610.5	273.8	343.0	2008.2	0.4	1.9	4.9	0.8
2025	593.2	296.7	336.8	1997.6	0.3	1.4	3.5	0.6
2026	421.7	148.2	321.8	1953.8	0.3	1.4	4.3	1.0
2027	650.3	274.8	339.1	1902.0	0.1	0.8	4.5	0.7
2028	620.5	237.6	320.9	1933.0	0.2	1.5	5.3	0.9
2029	550.6	280.6	332.9	1989.8	0.3	1.3	4.3	0.8
2030	428.8	77.6	328.2	1923.3	0.1	0.8	2.1	0.5
2031	372.3	83.8	329.9	1943.2	0.2	1.7	2.4	0.7
2032	512.8	129.2	315.0	1900.2	0.1	0.9	5.5	1.1
2033	484.1	166.8	324.8	1962.7	0.2	1.5	-2.0	-0.4
2034	387.5	101.6	343.4	1955.7	0.6	2.6	-2.6	-0.7
2035	340.4	91.1	312.2	1901.5	0.4	2.1	14.0	4.1
2036	685.9	271.1	335.4	1826.8	0.0	0.3	-16.9	-2.5
2037	465.4	133.7	363.2	1919.7	0.8	2.9	25.2	5.4
2038	634.2	142.0	319.4	1866.0	0.1	0.7	-3.2	-0.5
2039	523.7	227.3	343.3	2035.4	2.0	5.3	0.0	
	RCP 8.5							
2024	363.9	119.7	311.3	1944.5	0.2	1.0	2.8	0.8
2025	359.2	49.7	325.1	1875.1	0.1	0.6	2.0	0.6
2026	708.0	246.3	334.7	1857.3	0.1	0.7	-1.3	-0.2
2027	242.8	99.2	307.5	1982.8	0.9	2.6	9.4	3.9
2028	547.6	151.8	325.2	1812.8	0.0	0.3	4.2	0.8
2029	347.8	28.8	318.6	1878.8	0.0	0.6	2.7	0.8
2030	428.5	72.0	277.5	1876.0	0.0	1.1	3.3	0.8
2031	394.7	150.2	334.3	1951.6	0.2	1.1	2.9	0.7
2032	637.6	215.2	359.7	1859.1	0.1	1.0	4.9	0.8
2033	568.5	153.2	323.7	1916.9	0.1	0.9	1.4	0.2
2034	329.3	170.7	321.0	2005.4	0.7	2.1	5.7	1.7
2035	460.9	77.6	296.2	1839.4	0.0	0.6	2.8	0.6
2036	458.3	143.8	335.3	1923.1	0.2	1.1	4.3	0.9
2037	376.0	88.4	344.8	1898.3	0.1	0.8	2.8	0.7
2038	551.4	124.9	379.1	1838.8	0.0	0.4	4.4	0.8
2039	364.0	61.6	319.6	1881.6	0.1	0.6	0.0	

Table 18. The Maranhão water balance for far future period (2075-2090) for RCP 4.5 and 8.5 scenarios (TP – total precipitation, ETP – evapotranspiration).

Year	RCP 4.5							
	TP	Outlet	ETP	Initial storage			ΔS	Error
				Soil	Surface	Channels		
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(%)
2075	453.4	169.6	345.5	1948.8	0.2	1.0	-23.5	-5.2
2076	498.7	147.3	326.0	1908.9	0.8	2.1	30.3	6.1
2077	566.7	225.0	337.9	1905.7	0.1	1.1	4.9	0.9
2078	480.6	143.0	334.5	1904.9	0.1	0.7	3.5	0.7
2079	496.8	115.4	346.8	1904.3	0.1	0.9	-2.8	-0.6
2080	319.3	75.1	333.8	1940.6	0.5	1.5	9.3	2.9
2081	590.4	129.7	301.8	1843.3	0.0	0.5	-1.9	-0.3
2082	381.0	143.6	316.5	2000.8	0.9	2.8	8.7	2.3
2083	616.8	250.6	343.2	1915.6	0.1	0.9	5.4	0.9
2084	719.7	309.6	365.1	1933.2	0.1	0.9	5.6	0.8
2085	448.1	221.6	341.9	1972.5	0.2	1.1	-6.2	-1.4
2086	777.9	323.2	315.8	1863.7	0.2	0.7	15.7	2.0
2087	325.5	179.5	320.3	1985.8	0.3	1.7	1.0	0.3
2088	757.3	201.4	361.8	1812.3	0.0	0.3	7.4	1.0
2089	611.0	375.9	353.2	1996.0	0.5	2.8	4.7	0.8
2090	467.1	153.9	326.9	1875.8	0.0	0.7	0.0	
	RCP 8.5							
2075	342.4	25.7	297.8	1849.3	0.0	0.5	-7.8	-2.3
2076	364.2	50.0	296.4	1875.1	0.2	1.3	13.3	3.6
2077	319.9	52.4	285.1	1880.1	0.0	1.0	2.5	0.8
2078	538.5	192.8	329.5	1860.4	0.0	0.6	4.2	0.8
2079	585.2	125.3	308.6	1872.5	0.0	0.6	4.5	0.8
2080	470.6	250.6	344.1	2017.8	0.4	1.8	3.6	0.8
2081	267.5	48.1	341.6	1891.3	0.1	0.9	1.8	0.7
2082	313.9	8.8	312.7	1768.1	0.0	0.1	2.7	0.8
2083	256.1	9.3	245.7	1757.8	0.0	0.1	2.0	0.8
2084	408.3	28.1	298.8	1756.9	0.0	0.2	3.2	0.8
2085	265.3	31.8	259.6	1834.8	0.0	0.6	-5.6	-2.1
2086	615.8	101.6	334.9	1814.4	0.0	0.5	12.3	2.0
2087	564.4	237.1	354.3	1979.3	0.4	2.2	4.3	0.8
2088	307.0	114.9	341.5	1949.4	0.2	1.0	0.9	0.3
2089	371.0	15.3	275.7	1800.0	0.0	0.2	-0.5	-0.1
2090	436.0	128.9	337.5	1879.2	0.2	1.4	0.0	

During this study, the MOHID Land model was less erroneous at water balances at yielded an average statistical error of about 0.7%. For each period in the water balance, the last year (either 2008, 2039, or 2090) in water balance, it's impossible to calculate the percentage error because we have no proceeding year with which to compare the initial storage. Table 16 shows that evapotranspiration accounts for most of the water loss in the Maranhão watershed. There is significant variation in the water output by outlet flow or evapotranspiration from the watershed. Soil stores more water in the system compared to channels and the surface.

P, ETP, and Q represent precipitation, evapotranspiration, and outlet flow volume in Figures 30, 31, and 32. On the other hand, ETP:P and Q:P ratios depict the proportions of evapotranspiration and outlet flow volume per millimeter of precipitation received in the watershed. ETP:P and Q:P ratios better represent water availability in the watershed, as in Figures 30, 31, and 32. Unlike evapotranspiration and outlet flow volume quantities, these ratios relate the lost water amounts to what was received. As such, an increase in ETP:P ratio implies an increase in water loss by evapotranspiration to received precipitation, whereas an increase in Q:P proportions implies an increase in runoff proportions.

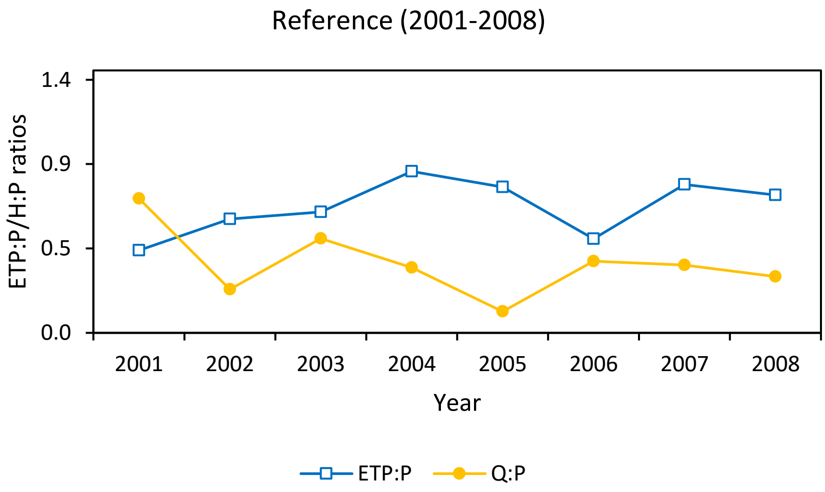

Figure 30. Maranhão's evapotranspiration and outlet flow volume proportions for the reference period

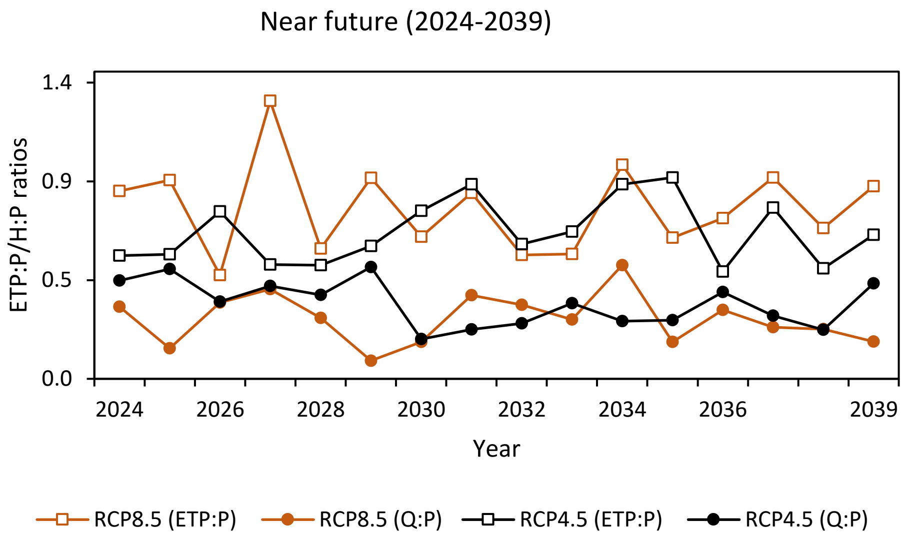

Figure 31. Maranhão's evapotranspiration and outlet flow volume proportions for the near future

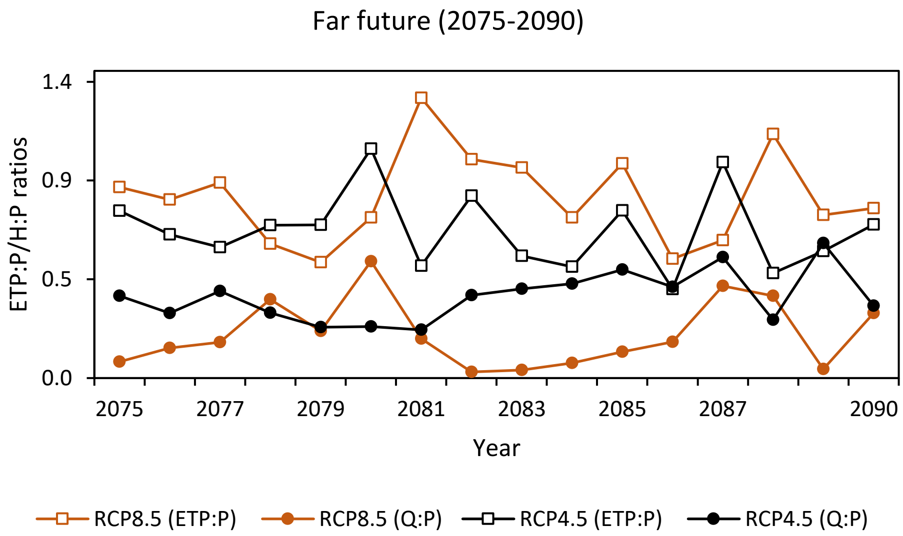

Figure 32. Maranhão's evapotranspiration and outlet flow volume proportions for the far future

The ratios in Figures 30, 31, and 32 generally show significant variations in water proportions that ETP and H will consume due to climate change. The interpretation is relative, with an increase in ETP:P, meaning either an increase in ETP with almost constant P or an almost constant ETP with decreasing P. Under all periods, ETP:P ratio is generally higher than the Q:P ratio. Under the reference period (Figure 30), ETP:P and Q:P ratios are almost constant, with their variation slightly increasing from near to far future for both climate change scenarios of RCP4.5 and 8.5. In some cases, especially under the RCP8.5, the ratio exceeds 1, meaning either more ETP than the total precipitation received or decreasing precipitation with a relatively constant ETP in that particular year. For both scenarios, ETP:P ratio averagely increases by 5% in the near years and 8% in the long term future compared to the reference period. Q:P ratio averagely decreases by 6% in the near years and 8% in the long term future for both scenarios and simulation periods.

5.5 Irrigation needs

Two of the three most grown crops in the watershed were considered for irrigation needs predictions by plot scale modelling. The two crops of Corn (Zea mays) and olive (Olea europaea) were considered. Figure 33 and Figure 34 don't only represent the irrigation needs but also other defined parameters to which it is closely linked. Figures 33 and 34 show TP and ETo denoting total precipitation and reference evapotranspiration, respectively. In the same figures, ETa and IN denote actual evapotranspiration and irrigation needs, respectively. Generally, irrigation needs vary slightly for Corn and Olive during near and far future periods. Also, Olive exhibits higher irrigation needs than corn. Statistically, irrigation needs for corn increased by 0.4% in the first simulation period and 0.2% in the far future. In other words, irrigation needs for corn increased at a decreasing rate throughout the study period. On average, irrigation needs for Olive decreased by 0.2% in the first simulation period and then increased by 0.1% in the second.

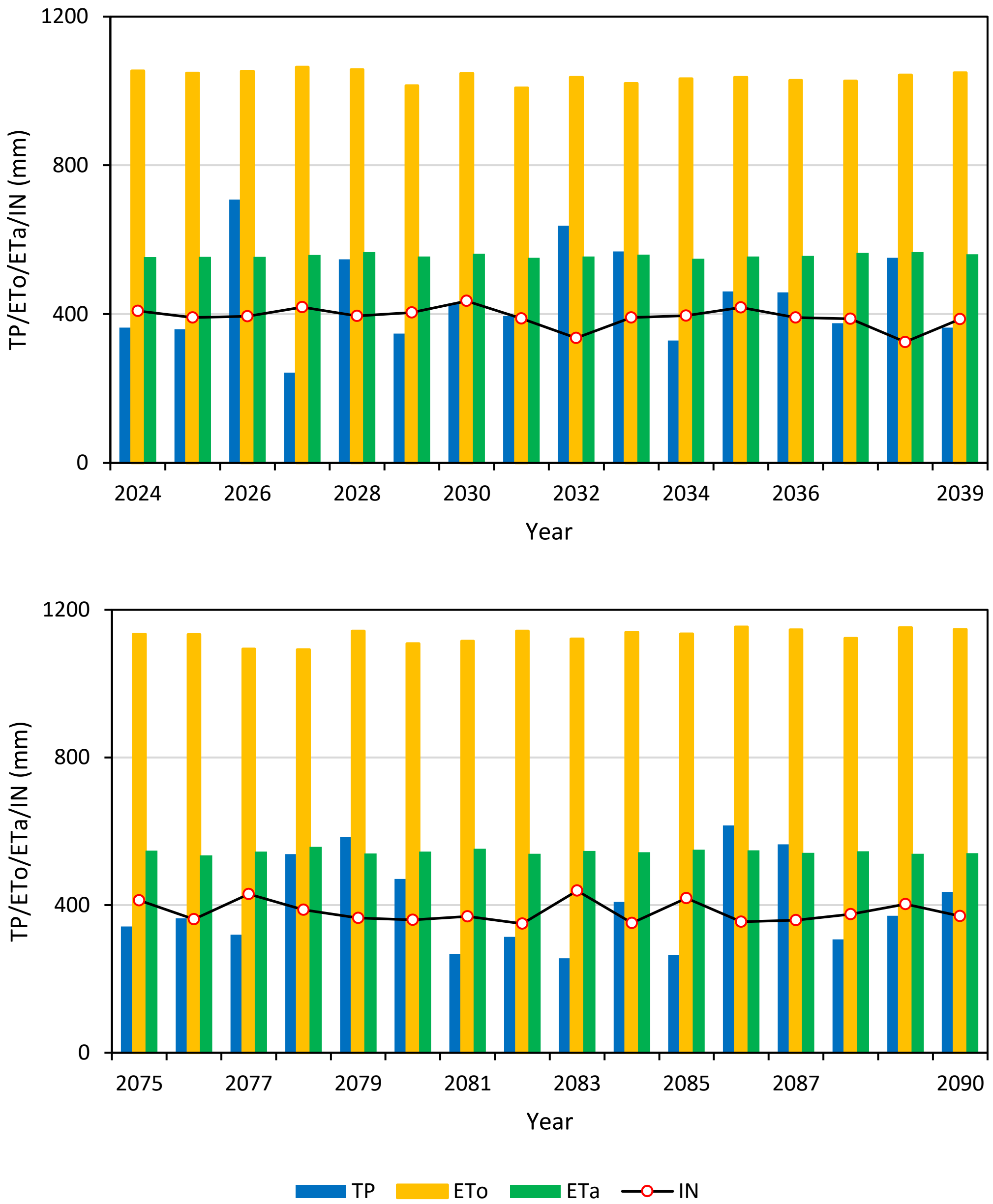

Figure 33. Irrigation needs predictions for corn

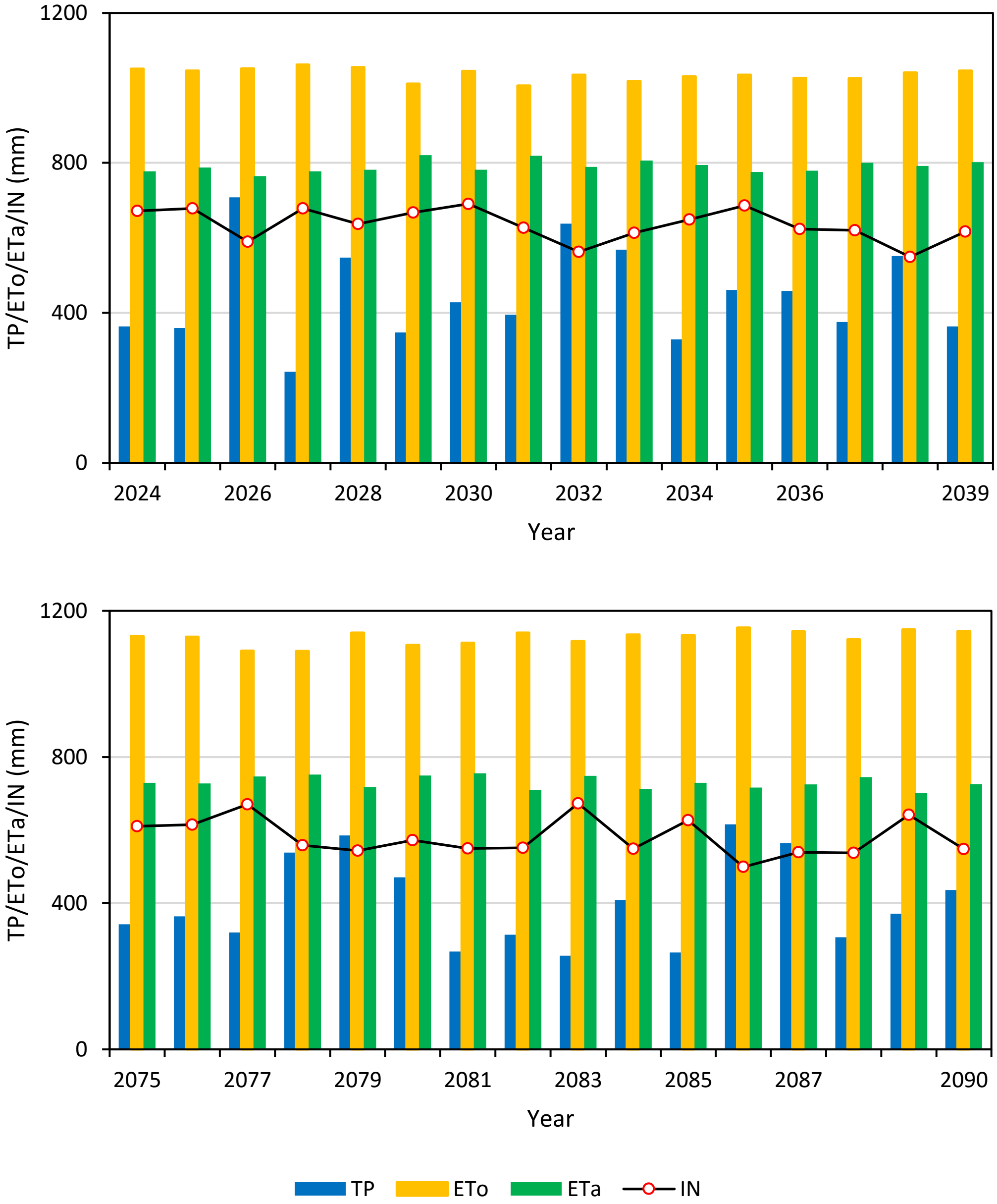

Figure 34. Irrigation needs predictions for Olive

The available datasets for irrigation from ARBVS (2022) showed that the total irrigation needs in the Sorraia irrigation district were met by waters from the three reservoirs of Montargil, Maranhão, and Magos (Figure 16). However, this study focused on the Maranhão watershed. Thus, it was necessary to calculate the irrigation needs for the Maranhão watershed, meant to be satisfied by the Maranhão reservoir, as shown in Table 19, where IN stands for irrigation needs. Annual percentage changes in irrigation needs for corn and olive were computed for the near and future periods. Annual average percentage changes representative of the watershed were computed. Sorraia valley`s irrigation needs for 2018, 2019, 2020 and 2021 are 892.8mm, 999.7mm, 953.3mm and 1081.7mm, respectively. Using

2021 observed irrigation needs from ARBVS (2022) and the average annual percentage changes, irrigation predictions for the Sorraia irrigation district were computed for the short and long term. Still using another dataset (ARBVS, 2022), of amounts of irrigation water per reservoir per year (Figure 16), an average percentage of irrigation water contributed by Maranhão was 46%, multiplied by Sorraia irrigation predictions to get Maranhao irrigation needs predictions presented in Table 19. Outlet flow volume from Maranhão was the available water for irrigation, and the percentages of irrigation needs that could be met were computed. Compared to the 46% of irrigation needs that water from Maranhão could satisfy in 2022, the reservoir will, on average, meet about 27% of annual irrigation needs in the near years and about 20% in the long term, according to statistical analysis. The percentage difference represents approximately a 19% decrease in Maranhão reservoir`s contribution to irrigation needs in the near years and a further 7% decrease in the long term.

Table 19. Irrigation needs of the Maranhão watershed for the near and far future

Year	Sorraia IN (mm)	Maranhão IN (mm)	Under RCP8.5 scenario	
			Available water (mm)	Potential irrigation (%)
	In the near years			
2024	1060.0	487.6	119.7	24.6
2025	1042.4	479.5	49.7	10.4
2026	979.2	450.4	246.3	54.7
2027	1083.0	498.2	99.2	19.9
2028	1019.2	468.8	151.8	32.4
2029	1055.0	485.3	28.8	5.9
2030	1114.1	512.5	72.0	14.1
2031	1001.8	460.8	150.2	32.6
2032	883.9	406.6	215.2	52.9
2033	995.4	457.9	153.2	33.5
2034	1031.4	474.4	170.7	36.0
2035	1089.7	501.2	77.6	15.5
2036	1004.1	461.9	143.8	31.1
2037	997.0	458.6	88.4	19.3
2038	859.9	395.5	124.9	31.6
2039	994.6	457.5	61.6	13.5
	In the far future			
2075	1048.8	482.4	25.7	5.3
2076	986.9	454.0	50.0	11.0
2077	1124.4	517.2	52.4	10.1
2078	975.6	448.8	192.8	43.0
2079	934.4	429.8	125.3	29.1
2080	952.2	438.0	250.6	57.2
2081	946.8	435.5	48.1	11.0
2082	922.2	424.2	8.8	2.1
2083	1142.0	525.3	9.3	1.8
2084	922.9	424.6	28.1	6.6
2085	1076.5	495.2	31.8	6.4
2086	884.8	407.0	101.6	25.0
2087	926.0	426.0	237.1	55.7
2088	945.1	434.7	114.9	26.4
2089	1070.8	492.6	15.3	3.1
2090	949.5	436.8	128.9	29.5

Understanding the irrigation needs of Corn and Olive required an analysis of the biomass yield (kg/ha) because it implies season length and health of crops. On average, the biomass yield of corn and olive decreased by about 2% in the near future simulation period and 6% in the far future.

5.6 Reservoir modelling

Since MOHID Land model cannot estimate evaporation during reservoir modelling, presenting a complete water balance from such a scenario is inappropriate because evapotranspiration would be underestimated. However, this study quantified the impact of reservoir construction on watershed water balance under RCP8.5 scenario by computing the percentage change between the outlet flow volume (water balance component) of the reservoir modelling scenario and the reference scenario. Reservoir construction under the climate change scenario decreased Maranhão's outlet flow volume by more than 50% in the near and long term.

6: DISCUSSION

RCP4.5 is associated with a less pronounced decrease in precipitation and rise in temperature than RC8.5. Even though different hydrological outcomes for surface water, groundwater, and water balance are presented, most of their changes are justifiable by variations between the climatic projections of RCP4.5 and 8.5. Despite the MOHID Land model using land use and land cover (LULC) as vegetation indices, the study did not consider any LULC scenarios; therefore, the amount of meteorological changes is crucial.

Regarding surface water, stream discharge increased under RCP4.5 and decreased under RCP8.5. Even though meteorological predictions for both scenarios indicated a decrease in precipitation for both RCPs, precipitation decrease under RCP4.5 was smaller. Additionally, RCP4.5 was associated with a slight temperature increase, which could have resulted in less water evaporating from streams. Far future simulations yielded more considerable stream flow changes mainly because they were associated with more extreme meteorological changes than the near-term simulations. Like predictions of reduced precipitation (Figure 24), the low stream discharge would dominate Maranhão in the future. Moderate stream discharge events would remain almost constant because high-intensity precipitation would generate adequate runoff (Guan et al., 2016) to keep stream volumes reasonable. Maranhão is a rural watershed, with a significant portion covered vegetation/forests, under a pronounced increase in temperature during the RCP8.5; this vegetation could substantially transpire and hence uptake more water from deep layers, which reduces baseflow contribution of groundwater to stream discharge. Since Maranhão is hilly to mountainous, groundwater contributes substantially to streamflow (Somers & McKenzie, 2020), and therefore a decrease in precipitation available for recharge would, in turn, reduce stream discharges. Even though RCP4.5 is associated with an increase in stream discharge, the increase is almost significantly smaller than RCP8.5's decrease, meaning Maranhão would generally experience a decrease in stream discharge. The decrease in surface water flow would threaten ecological integrity through decreased base flow and less water available for irrigation and human consumption. The decrease in stream discharges under RCP8.5 could be responsible for the decrease in water levels in Maranhão reservoir, whose useful volumes meet irrigation needs by a small percentage on average (Table 19). Hence farmers could use accumulated water storage for previous years to meet the irrigation needs.

Groundwater changes: a decrease in precipitation and an increase in soil transpiration due to an increase in temperature, resulting in less water available for recharge, accounting for the average groundwater level decrease on a temporal scale within the watershed. The decrease in However much the precipitation predictions imply a reduction, the number of high-intensity precipitation events will also increase, and the impact of these events on groundwater recharge is almost the same.

The impact of decreasing groundwater is because high-intensity precipitation events allow less time for water to infiltrate (Guan et al., 2016); with the watershed receiving more water than it can infiltrate at a particular time, runoff generation increases resulting in more discharge, especially under RCP4.5. More runoff means less water is left to infiltrate, offset the soil moisture deficit and finally allow recharge. The decrease in groundwater levels could also be attributed to enhanced discharge since the watershed has significant forested areas (Figure 6). When evapotranspiration attains its maximum, deep-rooted trees can uptake water past the soil profile (Benyon et al., 2006), thus directly reducing the groundwater levels. Under temporal evaluation (Table 15), the decrease in groundwater levels of 0.02 to 0.77 % (0.1 to 2m) is due to a likely reduction in annual net recharge (decrease in predicted precipitation). Despite the geological material of watershed being porous (Figure 13), meaning can facilitate recharge (more so if the pores are connected, but as long the annual recharge is zero or smaller than discharge (uptake by trees and flow to surface water), then groundwater levels will decrease. Being porous can partially explain the slight increase in groundwater levels in some parts of the watershed under RCP4.5. Spatially (Figure 29), Northeastern Maranhão exhibited the most remarkable decrease in groundwater levels under both scenarios may be due to a combined impact between soils (Figure 8), geology (Figure 10), and land use land cover (Figure 6) through regulating surface flow, infiltration and recharge processes. According to the geological map (Figure 10), the situation in northeastern Maranhão could partly be attributable to geology, with plutonic rocks as the underlying rocks being low permeability, meaning more precipitation could be required to fill the less unconnected pores. Despite northeastern Maranhão having some of the most elevated points in the watershed, the implementation of the MOHID Land model did not involve specifying the geological properties beyond 5m from the surface, meaning the vertical hydraulic conductivity was under represented, compared to horizontal conductivity, resulting in low recharge as more water flows towards the west. But also, most part of northeastern Maranhão is covered by clay loams (cambisols) soil type (Figure 8) with significant clay quantities. Clay minerals tend to have a platy crystaline habit and lie flat in alluvial deposits (Freeland, 2013) and this facilitates subsurface lateral flow in both saturated and unsaturated conditions (Zaslavsky & Rogowski, 1969) hence less recharge. Long-term simulations predict a further 0.07% average decrease in GWLs compared to the Near future simulations because the far future is associated with more significant predicted meteorological variations. A decrease in groundwater levels could reduce soil moisture availability for groundwater-dependent ecosystems (GDEs) in the watershed, notably herbs (Figure 6) which according to Eamus et al. (2016) are surface-dwelling GDEs.

The mean water balance error is 0.7%, corresponding to about 3.5mm per year, meaning that MOHID Land is a good model for watershed-scale water balances. According to Ágreda et al. (2015), the western Mediterranean region's changing climate has significantly increased the atmospheric evaporative demand, which accounts for most evapotranspiration-related water loss in the Maranhão watershed. As applied by (Church et al., 1995), the water balance analysis also featured computation of ETP:P and Q:P ratios, a rare but essential way of analysing the water balance components since it represents the proportions of evapotranspiration and outlet flow volume per unit of precipitation received in the watershed. ETP:P ratio averagely increases by 5% in the near years and 8% in the long term future compared to the reference period. The increase in ETP:P ratio partly indicates that evapotranspiration enhanced by climate change could be a reality in Maranhão. Higher evapotranspiration means the plant will require more water to carry out its physiological processes and sustain optimum growth, resulting in more significant irrigation requirements (Iqbal & Arif, 2010). The increase in ETP:P could be due to predicted decrease in precipitation, and high ETP seen in the water balance. Q:P ratio averagely decreases by 6% in the near years and 8% in the long term future for both scenarios and simulation periods. The decrease in Q:P is due to faster decrease in outlet flow volume than precipitation.

Generally, irrigation needs vary slightly for Corn (Figure 33) and Olive (Figure 34) during near and far future periods. Also, Olive exhibits higher irrigation needs than corn mainly because, according to results, Olive trees transpire more Corn plants. Statistically, irrigation needs for corn increased by 0.4% in the first simulation period and 0.2% in the far future. In other words, irrigation needs for corn increased at a decreasing rate throughout the study period. On average, irrigation needs for Olive decreased by 0.2% in the first simulation period and then increased by 0.1% in the second. An increase in irrigation needs for Corn or Olive in the far future is likely because meteorological predictions indicate a dryer and hotter climate for Maranhão. According to Pope (2020), plants must use more water for transpiration to keep cool and produce biomass in the dryer and hotter weather.

On the other hand, a decrease in irrigation needs for Olives in the first simulation period is least expected and could be attributed to the methodology in which plant development considers heat units, meaning each degree increase in temperature contributes to plant growth. With the predicted increase in temperature, plants grow faster, and hence a decreased growth period or season, leading to less biomass. Less biomass requires less water to produce by the plants.

Reservoir construction under the climate change scenario decreased Maranhão's outlet flow volume by more than 50% in the near and long term. The more than 50% decrease in downstream Maranhão's outlet flow volume could be due to the combined impact of climate change, decreasing water availability, and new upstream reservoir intercepting and storing runoff. However, the overestimation could be due to inaccurate reservoir data used.

7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study has researched watershed management under climate change scenarios, a case study of the Maranhão watershed, which lies in Portugal's irrigation district of Sorraia and belongs to the Tagus, the regional river basin. The study used various data, namely observed meteorological data from SNIRH and predictions from the CORDEX project, among other data sources.

With meteorological predictions indicating a dryer and hotter Maranhão, an already validated MOHID Land model was used to run RCP scenarios, after which quantified the impact of climate change on the watershed water balance, surface water, and groundwater levels. Furthermore, an already validated plot scale irrigation model was used to predict irrigation needs for Olive and Corn. Even though rice is among the most famously grown crops, It was not considered because of MOHID Land's inability to model up to 20cm of water above the land surface, a typical practice in rice growing beds.

Despite the model outputting various parameters, only stream discharge was presented since an analysis of other parameters revealed that they vary by the same proportions as discharge. Also, stream discharges generally decreased with slight increments experienced under RCP4.5 may be due to a slight increase in the number of high-intensity rainfall events. Climate change further impacted the hydro-reactivity of Maranhão through a mean decrease of groundwater levels, more so at the temporal scale. The decrease in groundwater levels is mainly attributable to less water (predicted precipitation) available for recharge in the future. A decrease in groundwater levels could reduce soil moisture availability for groundwater-dependent ecosystems (GDEs) in the watershed, notably herbs. Also, climate change could have aided water losses through increased surface water evaporation and soil transpiration. Spatial scale evaluation revealed continued impacts of -3.1 to 3.4m change with Northeastern Maranhão experiencing most groundwater level decrease except a few patches of the watershed that indicated a slight increase in groundwater levels under RCP4.5 for an unclear reason such as a combined impact between soils (Figure 8), geology (Figure 10), and land use land cover (Figure 6) through regulating surface flow, infiltration and recharge processes.

Generally, the water balance had a small error meaning the MOHID Land model effectively distributed precipitation during simulations. The water balance outputs were mainly due to evapotranspiration, as it was the dominant water loss parameter for all simulations. The ETP:P and Q:P ratios aided a more analytical display of the climate change impact on the water balance. ETP:P ratio averagely increased by 5% in the near years and 8% in the long term future compared to the reference period indicating that evapotranspiration enhanced by climate change could be a reality in Maranhão. The increase in ETP:P could be due to predicted decrease in precipitation, and high ETP seen in the water balance. Q:P ratio averagely decreased by 6% in the near years and 8% in the long term future for both scenarios. The decrease in Q:P is due to faster decrease in outlet flow volume than precipitation. Therefore, climate change had significant impacts on the watershed water balance. By choosing to adapt to climate change by building a reservoir in the upper part of the watershed, farmers could not have enough water to irrigate their crops in the future because the upstream reservoir will reduce the amount of water reaching the downstream areas.

With a climate change (RCP8.5) related 19% decrease in Maranhão reservoir`s contribution to irrigation needs in the near years and a further 7% decrease in the long term, irrigation agriculture in Sorraia could be rendered unsustainable if no action is taken in the future. For reservoir construction under the climate change scenario, the more than 50% decrease in downstream Maranhão's outlet flow volume could be due to the combined impact of climate change, decreasing water availability, and new upstream reservoir intercepting and storing runoff. At the same time, the overestimation could be related to inaccurate reservoir data.

7.2 Limitations and uncertainties

Challenges in this study were diverse, from data collection to organising the enormous outputs of the MOHID Land model and making sense of them. However, the challenges related to inadequate and inaccessible data were more impactful, for example, the insufficient data on observed groundwater levels from SNIRH. Out of the fourteen stations in the Maranhão watershed, only one has fairly consistent data to validate groundwater levels. Therefore it was impossible to link the explanation of observed changes in surface water to groundwater for the calibration process using observed values. Model performance evaluation using groundwater levels for statistical parameters would be possible if sufficient and reliable groundwater level data were available. Secondly, the dimension and operation parameters of the proposed dam in the Crato, the northern part of the Maranhão watershed, were inaccessible. Therefore, it was impossible to model the impact of climate change on the proposed reservoir. Instead, the impact of constructing this new upstream reservoir on water reaching an already existing downstream reservoir, Maranhão, was assessed.

The inability of the MOHID Land model to estimate the amount of evaporation and infiltration from the reservoir was yet another limitation. It was, therefore, invalid to compute a water balance for the Maranhão watershed under the reservoir modelling scenario. As a bypass to this limitation, a water balance component, outlet flow of Maranhão during the reference, and reservoir modelling scenarios were compared. Though could be argued that estimating evaporation from reservoir can be a post processing issue, the time available for this study could not allow that hence if an estimation by the model would be better making it a limitation.

7.3 Recommendations

The future inline study could consider a downscale method for simulating irrigation needs using a deeper soil for the plot scale combined with the imposition of the boundary condition of groundwater level simulated at the watershed scale. A similar depth for the plot scale and watershed scale model could link groundwater availability and processes to the irrigation needs of some crops, such as olives, whose deep roots could have access to shallow groundwater. In this study, the soil depth was 2m and 5m for plot and watershed scale simulations, respectively.

MOHID Land model should be modified to include losses by evaporation and infiltration as this will allow complete comparison of watershed water balances that involve reservoir modelling.

Since evapotranspiration and resultant irrigation needs for olive trees are higher than most crops grown on Maranhão farms, In the far future, farmers could consider growing drought-tolerant crops (notably Olive) varieties under little or no irrigation. Still, proper water and nutrient management should be considered for sustainable Olive growth and yields.

With the unique capacities of simulating climate change scenarios, simulating climate change adaptation measures such as reservoir construction, and output water balances at a watershed scale, the MOHID Land model is a powerful research tool. Researchers should use it as its outputs could guide decision-making on sustainable resource management, especially during the climate change crisis.

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