Master Thesis Report

Analysis of long-term trends in piezometric series to assess the effectiveness of substitution reservoirs as a tool for managing water resources in the Marais Poitevin

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Abstract

This study analyses the long-term trends of piezometric time series to evaluate the effectiveness of substitution reservoirs as a water management tool in the Marais Poitevin. The initial step in this research is to undertake a historical analysis of the pumping data, the irrigated area, and the piezometric series. The objective of this analysis is to identify the impact of local water management measures and substitution reservoirs on water tables. The analysis of the piezometric series is based on the use of statistical tests, in particular the Standard Normal Homogeneity test and the Pettitt test, making it possible to evaluate the homogeneity of the series and to detect any significant changes in their average. In a second phase, the study uses historical and future hydrological simulations produced by the ORCHIDEE model, integrating the effects of climate change through four scenarios. The objective is to estimate the long-term evolution of groundwater levels in the absence of irrigation. The model is fed by historical SAFRAN meteorological data, as well as by four climate projections corresponding to the RCP8.5 radiative forcing scenario. Two approaches were used to estimate the level of the water table. The first one is based on soil moisture simulated by ORCHIDEE, which is used as an indicator of the natural level of the water table. The second approach is based on a linear reservoir model, which is fed by drainage and surface runoff data from ORCHIDEE simulations. The findings of this study highlight the positive impact of water management measures on groundwater levels. Furthermore, the findings show that substitution reservoirs have been set up in response to water management measures, in order to maintain irrigation while limiting the impact on groundwater in summer. However, future simulations reveal the limited effectiveness of substitution reservoirs in the future. For three out of the four climate projections studied, the number of days when it is possible to fill up the reservoirs is projected to decrease. Furthermore, the simulation based on simulated soil moisture demonstrates that the crisis threshold has been estimated to be exceeded in a natural state of the water table for the warmest scenario. Substitution reservoirs will therefore not be a solution for raising the level above the crisis threshold in summer. Finally, this study highlights the complexity of water management in the Marais Poitevin. It emphasizes the challenges posed by climate change in achieving a balance between agriculture and the ecological water needs.

Contents

1 Introduction

1.1 Context

1.1.1 The Marais Poitevin challenges

The Marais Poitevin is the second largest wetland in France (Douez et al., 2020). It is located on the western Atlantic coast and covers three departments: Vendée, Deux Sèvres and Charente-Maritime. It has an oceanic climate with abundant rainfall in autumn and winter. The area covers around 1075 km^2 (PNR, 2022). The marsh is dependent on groundwater, which feeds it when water levels are high and drains it when they are low (Lepercq & Dupeuty, 2020). The main aquifers are the Toarcian, the Dogger and the Upper Jurassic. Of these, the Dogger aquifer, which is an unconfined aquifer, is the main source of water for the marsh (Douez et al., 2020). Over the centuries, the Marais Poitevin has been transformed by human activities, evolving in line with water management and development policies. Initially, the Marais Poitevin was characterized by a policy of drainage. Since the Middle Age, the area has been considered both a strategic location and a valuable economic resource. From the 12th century onwards, the implementation of drainage systems led to significant improvements in agricultural productivity (Sarrazin, 1985). In the 17th century, Henri IV played a key role in initiating major drainage projects to develop agriculture (Suire, 2003). Until the 1980s, initiatives to drain the Marais Poitevin followed one another, changing the landscape of the region (Simon, 1998). In recent decades, local policies evolved to oppose the drying up of the Marais Poitevin and the resulting degradation of its ecosystems. In 1999, this situation led to France being condemned by the European Court of Justice for non-compliance with the Birds Directive, forcing the region to take measures to protect the marsh (Ayphassorho et al., 2016). In addition, recurrent droughts and intensive agricultural practices called for a stricter management of water resources. Today, the implemented measures are intended to restore the balance of water resources by maintaining adequate water levels to safeguard biodiversity.

The Marais Poitevin is entirely artificial and now depends on human intervention (Ayphassorho et al., 2016). Consequently, it has a complex hydrological network. It possesses an extensive network of over 8200 km of canals, which are regulated by nearly 200 structures such as sluices and dams (EPMP, 2015a). These structures have contributed to divide the marsh into four distinct areas (PNR, 2022) (see Figure 1):

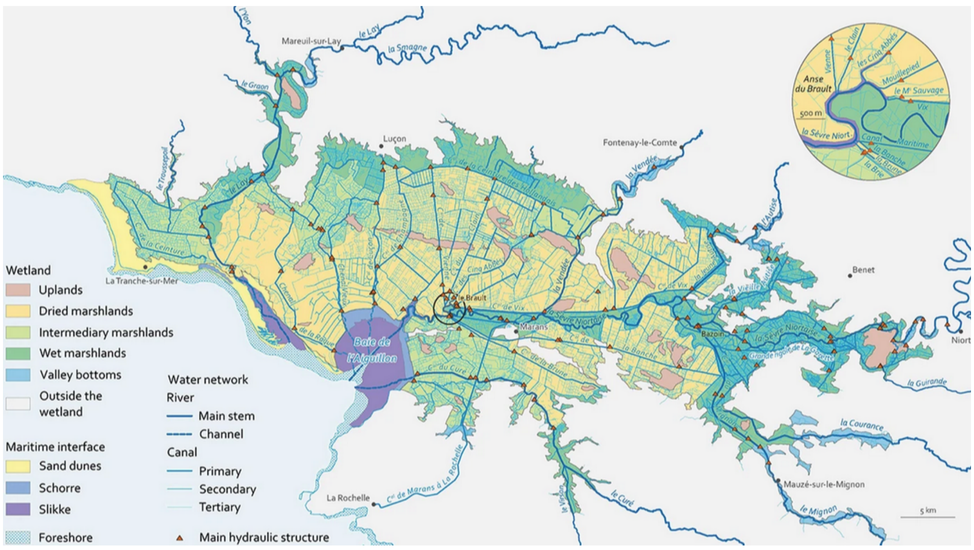


Figure 1: Types of marshland in the Marais Poitevin (Douez et al., 2020)

- The wet marsh, covering 323 km^2, is the flooding zone of the Marais Poitevin. This area is regularly submerged during floods or after heavy rainfall. It is characterised by a dense network of canals and ditches. The landscape is made up of grasslands and trees.
- The dry marsh covers 469 km^2. This marshland is a non-floodable area and is enclosed by a network of dikes and drainage systems. It is dominated by grassland and cereal crops.
- The intermediate marsh, encompassing 188 km^2, is situated between the floodable and non-floodable zones. This zone is characterised by agricultural plains that can be submerged during flood periods.
- The maritime marsh, which is subject to the influence of the tides. It covers 95 km^2.

The Marais Poitevin is a highly complex region, combining environmental, hydrological and economic issues. On the economic front, the Marais Poitevin is an essential resource for the region, thanks in particular to tourism and agriculture. Its unique landscape attracts nearly 1.4 million visitors each year (PNR, 2022). A notable attraction is the "Venise Verte" (Green Venice), where tourists can explore the marshes by boat. Tourism is the second largest economic activity in the region, after agriculture (EPMP, 2015a).

Secondly, the Marais Poitevin is characterized by its exceptional biodiversity. In 2014, it regained the label of Regional Nature Park, that it had lost in 1996 following the drying of the marsh (Carrausse, 2022). More recently, in 2023, the Marais Poitevin was awarded the Ramsar label (PNR & Conseil Scientifique et Prospectif, 2024). This label is given to wetlands of international importance. The Marais Poitevin is home to a wide variety of flora and fauna: 33 species of fish, 337 species of birds and numerous mammals. The area also plays a key role in the migration of certain aquatic and bird species (PNR, 2022). The marsh is also part of the Natura 2000 network, which aims to reconcile the conservation of biodiversity with economic and social activities (PNR, 2022). Protecting this unique ecosystem is one of the main challenges facing this region.

Finally, the Marais Poitevin is subject to two major hydrological challenges. The first is flood risk management. The marsh is located at a low altitude, which makes it particularly vulnerable to flooding. The proximity of the marsh to the sea exacerbates this risk, as attested by the 2010 storm Xynthia, which resulted in the deaths of 35 people and the submersion of 16 000 hectares of land (PNR, 2022). The second challenge is the management of water scarcity. Since the 1980s, successive droughts, caused by excessive irrigation, have significantly reduced the groundwater level, sometimes lowering it to below sea level, and dried out the watercourses in summer. This situation has led to the drying out of certain areas of the marsh and to saline intrusions into the water table, altering the ecological balance and impacting water resources.(Douez et al., 2020).

In response, water management measures have been strengthened in recent decades to protect biodiversity and water resources. A strategy implemented from 2007 onwards, aimed at securing water for agricultural needs, is the use of substitution reservoirs. These reservoirs, measuring between 10 and 20 hectares, are artificial basins designed to temporarily store water pumped from groundwater and watercourses during high-water periods (winter) for later use during low-water periods (summer) (PNR & Conseil Scientifique et Prospectif, 2024).

1.1.2 Climate change

Water is an important global and vital issue. Indeed, almost half of the world's population suffers from water scarcity (IPCC, 2023). Freshwater is a vital resource for humans and is necessary for food production. However, it is a scarce resource. It represents only 0.5 % of the Earth's total water reserves (World Meteorological Organization, 2022). This resource is threatened by rising temperatures. The latest IPCC (Intergovernmental Panel on Climate Change) report, which assesses the current state of the climate and estimates its environmental and socio-demographic impacts, highlights a temperature rise of +1.1°C in the period 2011-2020 compared to the pre-industrial period 1850-1900 (IPCC, 2022). The report highlights a clear link between human activities and greenhouse gas emissions, which are the main driver of global warming.

The hydrological cycle is directly affected by climate change. In particular, extreme events such as droughts and heavy rainfall are becoming more frequent and intense. This has a direct impact on water availability (IPCC, 2023). Moreover, since 1950, agricultural and ecological drought has increased in central and western Europe (see Figure 2).

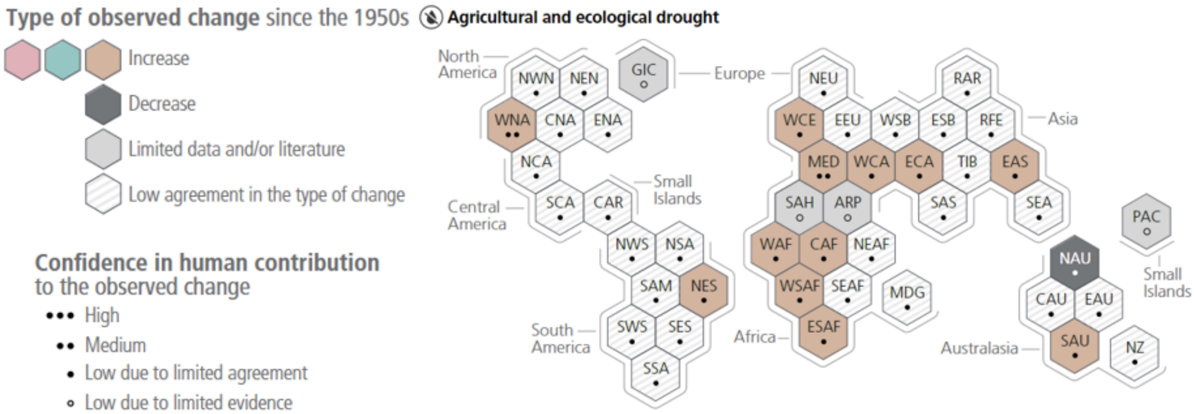


Figure 2: Observed changes in drought since the 1950s (IPCC, 2023)

Climate change is exacerbating these impacts. The IPCC has developed 5 prospective scenarios ranging from the best to the worst in order to assess the potential effects of climate change between now and 2100. These scenarios are based on different levels of anthropogenic greenhouse gas emissions. These scenarios make it possible to estimate future warming compared with pre-industrial levels. The projected impact on agriculture is largely attributed to climate change and points to negative consequences for agriculture (Figure 3). Furthermore, the predicted impact on groundwater in Europe is mixed with a medium level of confidence.

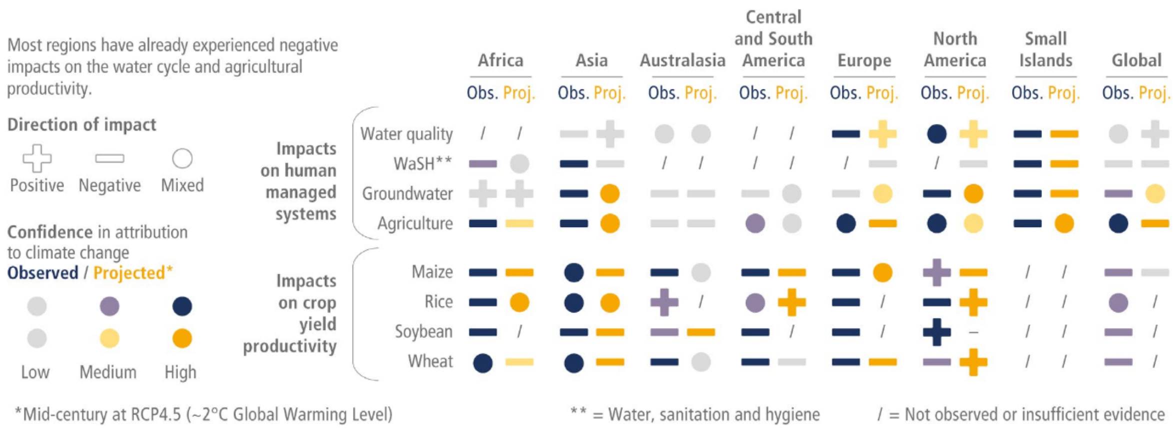


Figure 3: Observations and projections of the effects of climate change on water and agricultural productivity (IPCC, 2022)

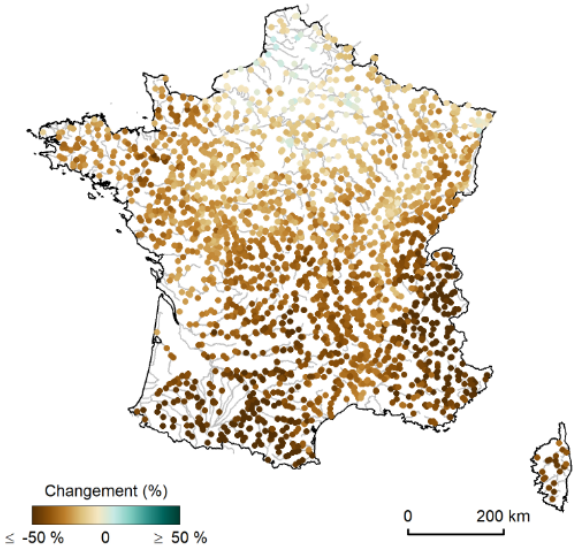


Figure 4: Evolution of the summer average daily flow rate by 2100 compared to the period 1976-2005. Data obtained from several hydrological models and 17 climate modelling chains under the RCP8.5 radiative forcing scenario. (Sauquet et al., 2025)

In France, agricultural yields are expected to be negatively affected in the spring and summer as a result of lower rainfall and higher temperatures. Similarly, winter yields are expected to decrease. In particular, the warmest scenario RCP8.5 is projected to reduce wheat yields by 21 % (Gammans et al., 2017). A study on the impact of climate change by 2100 on the hydrological cycle in France indicates that evapotranspiration is expected to increase by 30-60 % in winter and spring and decrease in summer (Dayon et al., 2018).

In addition, the Explore2 project, which aims to assess the projected impact of climate change on hydrology in France, indicates that summer river flows in France are expected to decrease by 2100 under the RCP8.5 scenario (Sauquet et al., 2025). Based on this project, the Marais Poitevin is expected to undergo a decrease in the summer average daily flow of about 30 % is expected (Figure 4). Sustainable water management is therefore becoming crucial to protect water resources and agriculture from anthropogenic climate change.

1.2 Literature Review

The hydrological state of the Marais Poitevin has evolved in recent years due to intensive irrigation, which has led to the implementation of various water management measures. It is therefore essential to trace the chronology of past events in order to understand the evolution of the water table level and to better understand the context that led local irrigators to adopt substitution reservoirs as a solution to secure water resources in summer. This review presents the evolution of irrigation practices under the influence of water management measures in the region. It then provides an overview of current knowledge of the impacts of these reservoirs on the environment. Finally, it offers a comprehensive understanding of local water management issues.

1.2.1 Early stages of water management (1980-2006)

Water management is a major issue in the Marais Poitevin. In the 1980s, the intensification of agricultural activity, reinforced by the modernisation of drainage systems, led to an increase in the irrigated area of around 50 % between 1988 and 1993 (Simon, 1998). High agricultural water demand, combined with severe droughts in 1989 and 1990, led to a deterioration in the level of the water table (Lepercq & Dupeuty, 2020). Faced with this critical situation, the public authorities have gradually oriented their policies towards a balanced and sustainable management of water resources. Therefore, in 1995, the Marais poitevin was classified as a water distribution zone (ZRE: "zone de répartition en eau"). According to article R.211-71 of the Environmental Code, a ZRE is defined as an area with chronically insufficient resources against water demand. In a ZRE, any non-domestic water withdrawal greater than or equal to 8 m^3/h is subject to authorisation and any withdrawal less than 8 m^3/h is subject to registration. At national level, Law No. 92-3 of 3 January 1992 on water marked a turning point with the introduction of planning documents such as the SDAGE at a regional level and the SAGE at the level of the catchment area. The Loire-Bretagne SDAGE was created in 1996, followed by the creation of three SAGEs between 1997 and 1998: Lay, Vendée and Sèvre-Niortaise - Marais Poitevin. The SDAGE sets general quantitative and qualitative objectives for water resources. The SAGE defines actions to be carried out locally, taking into account the objectives set out in the SDAGE.

The first restrictive measures to regulate irrigation were to reduce the duration of water abstraction. These measures were based on thresholds of river flow and groundwater levels that should not be exceeded. If the alert threshold was exceeded, water abstraction for irrigation was restricted to certain periods and could even be prohibited by prefectural decree (CACG, 2002). The first measures of this kind were introduced in 1992 in the southern Vendée, where the fixed piezometric alert levels could be lower than sea level (IIBSN, 2003). However, to face these restrictions, irrigators adapted their practices by increasing pumping rates or irrigating crops preventively. These restrictions therefore proved to be ineffective (Lafitte & Portet, 2007). From 1996, volumetric management measures were gradually introduced. This approach allocated a theoretical volume of water to each farmer. These volumes could be revised if alert thresholds were exceeded (CACG, 2002). Although these measures stabilized water withdrawals, they were not enough to avoid crisis situations until 2004 (Lafitte & Portet, 2007). Since the drought of 2003, prefectural decrees have been issued every year to anticipate crisis situations. These decrees define measures to limit water abstraction before the irrigation period (Lepercq & Dupeuty, 2020). In particular, the 2005 decree imposed a total ban on abstraction in certain sectors of the Marais Poitevin due to an exceptional drought that year (MEDD, 2007).

1.2.2 Evolution of water management towards a substitution strategy (2007-2025)

In 2002, the government launched an action plan for the Marais poitevin for the period 2003-2013 (Etat Français, 2002). This plan emphasized the need to harmonize water management measures between the three SAGEs of the Poitevin Marshes. It also introduced, for the first time, the strategy of substitution reservoirs as a solution to securing water for agriculture.

This approach is based on a consensus between farmers and water management policies. By participating in the project, farmers benefit from political and economic support for the installation of substitution reservoirs. At the same time, the alert thresholds of the piezometric levels are raised, further impacting farmers who do not adopt this system. The substitution strategy thus complements the restriction measures and allows farmers to avoid suffering directly from the raising of the warning thresholds. This strategy was finally validated and consolidated in a report published in 2007 (MEDD, 2007), which mentioned the commissioning of four substitution reservoirs in the Autize basin, with a total storage capacity of 1.6 million m^3.

Figure 5: Photo of one of the substitution reservoirs in the Marais Poitevin (Bassines non merci, 2022)

The implementation of this policy was strengthened in 2006 with the promulgation of the Law on Water and the Aquatic Environment (LEMA), which emphasises the need for sustainable water management and the use of planning tools. Consequently, the SDAGE for the period 2010-2015 was adopted in 2009, followed by the approval of the Sustainable Development and

Management Plans (PAGD) of the three SAGEs in 2011. The objectives introduced in the SDAGE 2010-2015 take into account the use of substitution reservoirs in the definition of the objectives to be achieved, in order to ensure a balanced management of water resources by reconciling environmental and agricultural issues (Comité de bassin Loire-Bretagne et al., 2009). The SDAGE 2010-2015 set target volumes to reduce spring and summer agricultural abstraction, with a reduction of around 30 % compared to previous consumption. These measures were to be implemented by 2015 for most sectors, with the exception of the Autize basin, where the target was set for 2012 due to existing substitution reservoirs equipment. In addition, the SDAGE has introduced crisis management thresholds and low-water thresholds at various points in the Marais poitevin. Flow thresholds have been defined for the watercourses and water level thresholds for the wetlands. Piezometric thresholds have also been defined, in particular a threshold for the start of the low-water period until 15 June (POEd) and a threshold for the end of the low-water period from 15 June (POEf). There are based on a daily piezometric level that must not be exceeded. These thresholds must be met in at least four out of five years. In crisis situations, groundwater management is based on crisis piezometry (PCR), a critical threshold below which only priority uses are allowed. However, these thresholds were initially indicative and compliance with them only became mandatory from the 2016-2021 and 2022-2027 SDAGEs (Comité De Bassin Loire-Bretagne et al., 2015)(Comité de bassin Loire-Bretagne et al., 2022).

The current strategy is mainly based on the respect of the low-water and crisis piezometric thresholds, adapted according to the sectors and the progress of the commissioning of the substitution reservoirs. On the other hand, the target volume strategy provided in the first SDAGE has not been renewed. The table 6 below shows the different thresholds set by the SDAGEs for each reference piezometer. It appears that these thresholds have remained unchanged from one SDAGE to another, while the deadlines for compliance have been progressively extended with each new SDAGE.

Piezometer	POEd (m NGF)			POEf (m NGF)			PCR (m NGF)			Hydrographic unit
	SDAGE (2010-2015)	SDAGE (2016-2021)	SDAGE (2022-2027)	SDAGE (2010-2015)	SDAGE (2016-2021)	SDAGE (2022-2027)	SDAGE (2010-2015)	SDAGE (2016-2021)	SDAGE (2022-2027)	
Longeville	1.5	1.5	1.5	0.3	0.3	0.3	0	0	0	Lay
Luçon	2	2	2	0.7	0.7	0.7	0.2	0.2	0.2	
Tous vents (St-Aubin)	2.2	2.2	2.2	1	1	1	0.5	0.5	0.5	Vendée
Breuil (Langon)	2	2	2	1	1	1	0.5	0.5	0.5	
Billaude (Doix)	-	-	2	-	-	1	-	-	0.5	
Aziré (Benet)	2.3	2.3	2.3	1.9	1.9	1.9	1.6	1.6	1.6	Autizes
Grand Nati (Oulmes)	4.6	4.6	4.6	3	3.2	3	2.5	2.5	2.5	
St-Hilaire Le Palud	3.5	3.5	3.5	2.4	2.4	2.4	1.7	1.7	1.7	Mignon, Courance, Guirande
Bourdet	12.1	12.1	12.1	11.2	11.2	11.2	9.6	9.6	9.6	
St-Georges du Bois	25	25	24	20.5	20.5	19.5	19.5	19.5	18.5	Curé and coastal rivers

Figure 6: Table of low-water and crisis piezometric thresholds for the three SDAGEs (Comité de bassin Loire-Bretagne et al., 2009, Comité De Bassin Loire-Bretagne et al., 2015, Comité de bassin Loire-Bretagne et al., 2022)

In parallel with the implementation of the substitution strategy, coordination between the three SAGEs of the Marais Poitevin has been strengthened with the creation of a public institution (EPMP) in 2010. This institution is responsible for the management of water and biodiversity. It has become the only collective water management organisation for the Marais Poitevin. The region is currently divided into several alert zones (see Figure 7). Each zone is monitored by reference indicators.

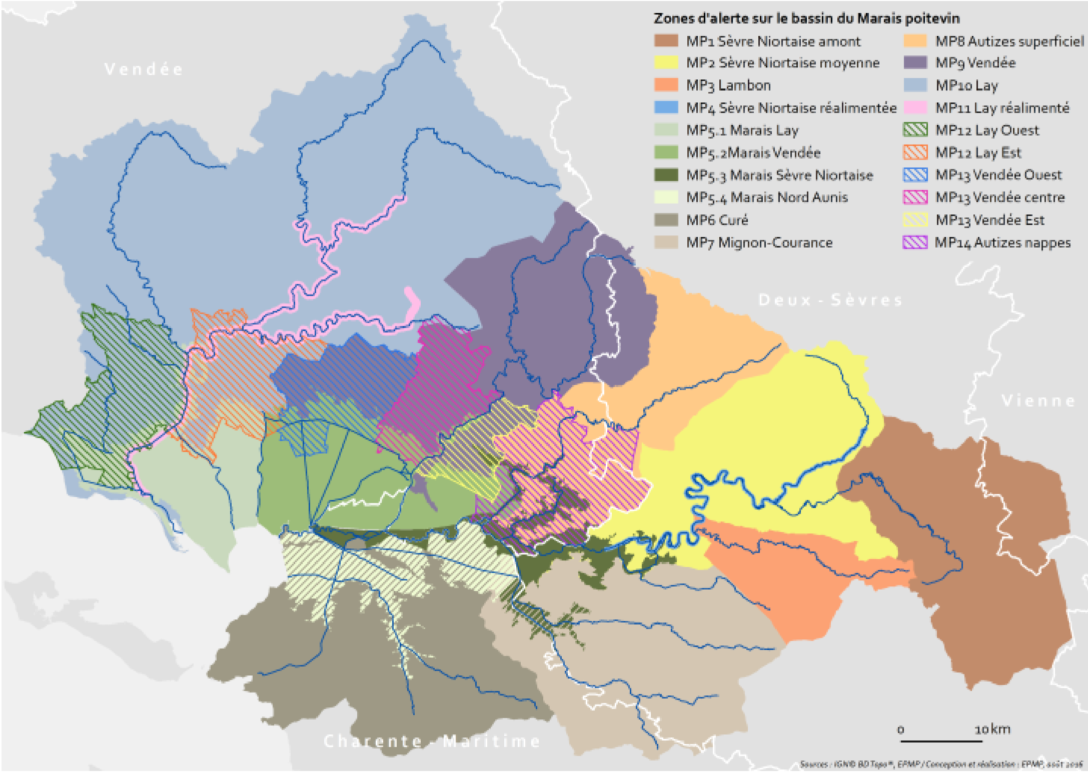


Figure 7: Marais Poitevin warning zones (EPMP, 2015b)

The EPMP has defined a protocol to be followed for agricultural water abstraction in relation to the alert thresholds defined by the interdepartmental decree of the Marais Poitevin (EPMP, 2024a). The decree defines four alert thresholds depending on the hydrological state of the marsh. These thresholds are, in order of severity: vigilance level, alert level, reinforced alert level and crisis level. The protocol is as follows: each year the EPMP allocates a volume of water to each irrigator. On the one hand, for irrigators who pump water directly into the environment, their annual volume allocation is divided according to the season. In addition, if alert thresholds are exceeded, this volume may be reduced or even lead to a total ban on water abstraction. On the other hand, irrigators connected to substitution reservoirs are not subject to the alert threshold. However, they are subject to the measures for filling reservoirs. Filling is possible from November to March if the reference piezometric level is higher than the filling threshold. These thresholds can vary from month to month. Moreover, one piezometer can be used as a reference for the filling of several surrounding reservoirs. The latest water management thresholds are summarized in the appendix in tables 46 and 47.

1.2.3 Marais Poitevin substitution reservoir projects

The strategy that was implemented from 2007 onwards with the aim of securing water for agricultural use was the utilization of substitution reservoirs. The volume of these reservoirs was established on the basis of the volume withdrawn for irrigation in 2003. The purpose of the reservoirs is to reduce the pressure of summer withdrawals by 60 %. This target is set on the basis of a 20 % reduction in summer withdrawals and a 40 % reduction that is to be achieved thanks to substitution (PNR & Conseil Scientifique et Prospectif, 2024).

The first project was initiated by the project owner "SMVSA" (Syndicat mixte du Marais poitevin, bassins de la Vendée, de la Sèvre et des Autises), between 2007 and 2012 in the Autize basin, where ten susbtitution reservoirs were constructed to store a volume of 3.2 million m^3

of water (MEDD, 2007). In parallel, a project involving five reservoirs in the Mignon basin was undertaken by the project owner "ASA des Roches", for a total volume of 1.5 million m^3 (MEDD, 2007). These reservoirs were constructed in 2010. However, as early as 2009, appeals were lodged concerning the ecological impact of these reservoirs. In the end, these reservoirs were put into service anyway, but no operating authorization was granted. This project was the subject of a legal battle with a succession of appeals and complaints between the associations of farmers and environmentalists. In 2022, the official ban on the exploitation of these substitution reservoirs was confirmed (Le Bihan, 2022). Consequently, these basins have remained non-operational since that date. A third project of substitution reservoirs was undertaken in the Vendée and in the Lay watersheds, resulting in the creation of 9 and 5 reservoirs, respectively, with storage capacities of 5.2 million m^3 and 2.4 million m^3 (Lenoiselee et al., 2021). These reservoirs were constructed between 2014 and 2019. Finally, a project to build 16 basins in 2020 is currently underway in the Sèvre Niortaise and Mignon watersheds, with the "Coop de l'eau 79" as project owner (Coop de l'eau 79, 2021). This project entails the creation of reservoirs with a water storage capacity of 8.6 million m^3 and has also given rise to significant litigation between farmers and environmentalists (Carrausse, 2022). At present, four of the sixteen reservoirs have been judged illegal, in an effort to protect the bustard, a bird species that is endangered (Paillot, 2024). In 2024, the reservoirs currently in use represent 12.42 % of the water volume intended for irrigation (PNR & Conseil Scientifique et Prospectif, 2024). The map 8 below summaries the various projects for substitution reservoirs in the Marais Poitevin.

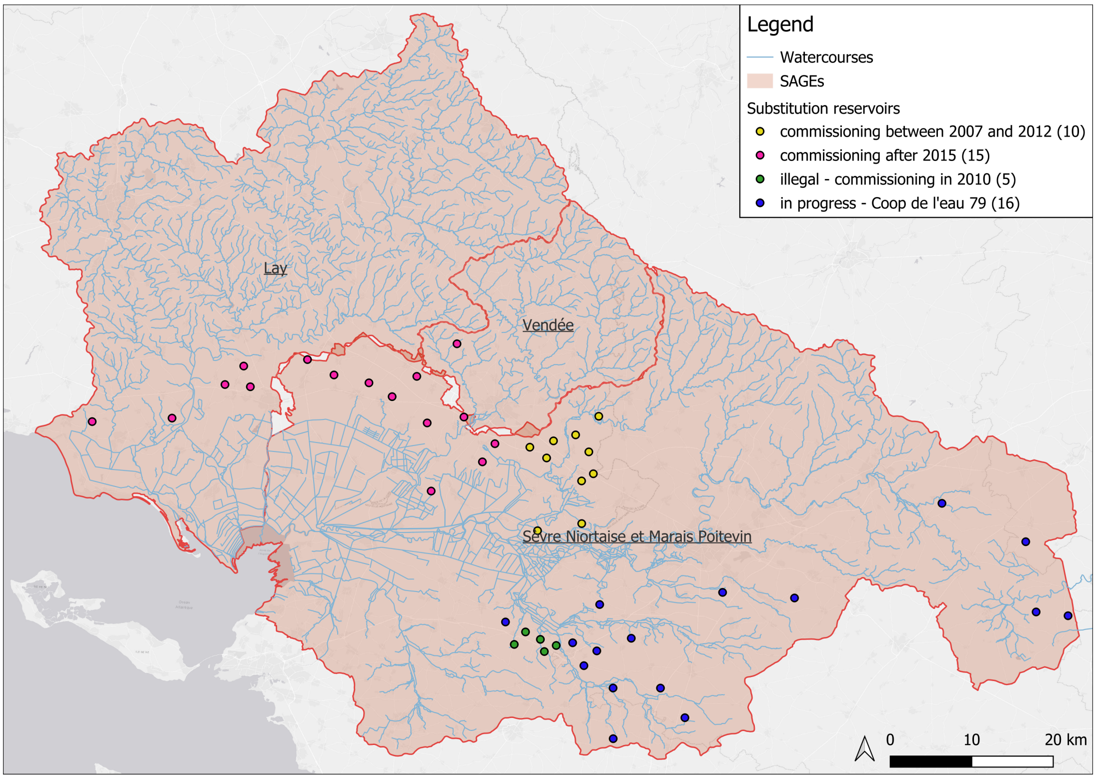


Figure 8: Map of substitution reservoirs in the Marais Poitevin

1.2.4 Substitution reservoirs: pros and cons

The functioning of substitution reservoirs, as implemented in the Marais Poitevin, with filling from groundwater, is a storage system for which there is still little documentation. However, other types of artificial reservoirs used for agriculture can be found in other countries. The Yesa reservoir, situated within the Spanish Pyrenees, represents a notable example of a mountain reservoir specifically designed for irrigation. Its construction was driven by the necessity of supplying water to the agricultural sector in the Bardenas region. The reservoir is fed by the Aragón river. The reservoir's water level is primarily influenced by precipitation and snowmelt (López-Moreno et al., 2004).

The construction of agricultural water reservoirs raises many questions about their impact on the hydrological cycle and the environment. First of all, open-air reservoirs promote evaporation, resulting in water losses. A study of the agricultural reservoirs in the Segura river basin in south-eastern Spain estimated that 8.3 % of the water intended for irrigation was lost through evaporation (Martínez Alvarez et al., 2008). This region is drier than the Marais Poitevin. Nevertheless, the phenomenon of evaporation is susceptible to intensification in response to climate change and rising temperatures. Another study on small reservoirs has also shown that evaporation can be significant and generate significant economic losses (Habets et al., 2018).

Water quality is also an issue. A study conducted in Poland in an agricultural region equipped with three artificial lakes for irrigation revealed heavy pollution of the groundwater and surface water due to agricultural activity. A significant increase in nitrate and phosphate concentrations was observed in these lakes, contributing to a process of eutrophication and a deterioration in water quality (Lawniczak-Malińska et al., 2023).

The presence of reservoirs also modifies local ecosystems by creating environments favorable to certain species and unfavorable to others, thus influencing local biodiversity (PNR & Conseil Scientifique et Prospectif, 2024). In particular, the Marais Poitevin has a very rich biodiversity and some species are endangered. This is particularly the case for the bustard, which has led to the closure of four substitution reservoir in the Marais Poitevin in December 2024 (Paillot, 2024).

Moreover, the repercussions of the substitution reservoirs on the groundwater levels are a subject of considerable debate. The BRGM (Office of Geological and Mine Research) has been mandated to assess the impact of 16 substitution reservoirs proposed by the "Coop de l'Eau 79" (Abasq, 2022). The study is based on a hydrological model with a resolution of 1 km^2, encompassing the Marais Poitevin region, and taking into account the various geological layers. The reference period used for the study is from 2000 to 2010. According to the BRGM report, the reservoirs would lead to a general increase in the water table of several meters in spring and summer in the regions where pumping would be substituted. The report also indicates a decline of approximately 50 centimeters during winter months. Furthermore, the report anticipates an augmentation in the flow of rivers at the outlet of the basin by 6 % during summer months, while a 1 % diminution is projected for winter months. However, this report has been strongly criticized. A report by the Academy of Agriculture qualifies its conclusions by pointing out the limitations of this study (Aubertin et al., 2023). The reference period is considered too short and does not take into account the effects of climate change. Furthermore, the spatial resolution of the model is considered too broad and would not allow for an accurate assessment of the local impacts of the substitution reservoirs. Then, some articles describe the project of substitution reservoirs as a "bad adaptation" to climate change.

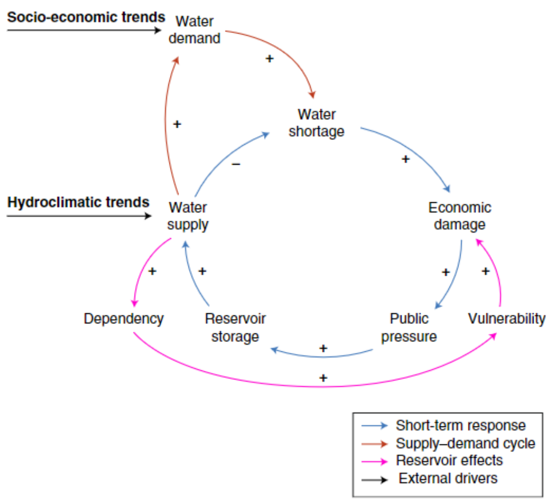


Figure 9: Loop of the reservoir effect (Di Baldassarre et al., 2018)

Increased dependence on these reservoirs for water supply could indeed increase vulnerability to episodes of intense drought, leading to economic damage. This phenomenon is called the reservoir effect and is described below (see the pink loop in the figure 9) (Di Baldassarre et al., 2018). A notable example is in Melbourne, where the increase in the number of reservoirs paradoxically accentuated the city's vulnerability during the Millennium drought (Di Baldassarre et al., 2018). This type of infrastructure, although designed to secure access to water, proves ineffective if the resource becomes insufficient. Thus, water storage facilities are sometimes perceived as a form of "bad adaptation" to climate change, because their effectiveness depends directly on the availability of water (Reghezza & Habets, 2022).

Finally, from a social point of view, access to substitution reservoirs is more expensive than direct pumping from groundwater. As a result, only farmers with sufficient financial resources can benefit from this infrastructure, which raises questions of equity and accessibility to water (Anceaux et al., 2023).

The debate on substitution reservoirs is also part of a broader discussion on current agricultural models and their sustainability in the face of climate change. In 2022, cereal crops, dominated by maize and wheat, accounted for 49 % of the agricultural land, while grassland accounted for 21 % (EPMP, 2024b). Especially cultivation of cereals necessitates a large amount of water. In summary, although these substitution reservoirs are considered to be a solution against water scarcity, it raises several environmental and hydrological issues that require more in-depth studies to assess its real impact.

1.3 Description of the project

The main aim of this study is to analyze long-term trends in the piezometric time series, with a view to evaluating the effectiveness of substitution reservoirs as a tool for managing water resources in the Marais Poitevin.

Firstly, the study focuses on exploring the spatial and temporal evolution of water withdrawals, irrigated areas and piezometric time series. These analyses highlight the evolution of the hydrological situation of the Marais Poitevin under the influence of water management measures and the establishment of substitution reservoirs.

The second stage of the project entails the use of historical and future hydrological simulations produced by the ORCHIDEE model, integrating the effects of climate change through four scenarios. The objective is to estimate the long-term groundwater level evolution that can result from ongoing climate change, and how this evolution can impact the future effectiveness of the substitution reservoir (potential to be filled in winter and risks of drastically low groundwater levels in summer).

2 Materials and Methods

The method is composed of two sections. The first part presents the methodology applied to the analysis of piezometric series and data on pumping and irrigated areas. The second part explains the methodology applied to estimate the historical and future piezometric level using the ORCHIDEE model.

2.1 Analysis of piezometric series and irrigation practices

The initial phase of the work entailed the collection of all the data necessary for the present study. This phase also encompassed a literature search with the objective of establishing a chronology of water management measures and the commissioning dates of substitution reservoirs in the Marais Poitevin, as outlined in the introduction 1.

2.1.1 Data collection

The data used in the present study has been obtained from a variety of sources. The number of data items and their sources are summarized in the table 1 below.

Type of Data	Source	Details
Piezeometric data	ADES	139 piezometers (start date between 1985 and 1996)
Pumping data	BNPE	2383 pumping stations (volume pumped per year from 2008 to 2022)
Irrigation data	Agreste	Irrigated area per commune in 2000, 2010, and 2020

Table 1: Data collection summary

The piezometric data used in this study are derived from the ADES website (National database of groundwater data) (ADES, 2024). The unit used for piezometric series is the meter NGF (General Levelling of France). This unit gives the altitude in meters of the water table level in relation to the 0 level of Marseille. The Marais Poitevin region is equipped with 139 piezometers for the monitoring of groundwater.

The pumping data were collected from the National Database of Quantitative Water Extractions (BNPE) (BNPE, 2024). The study area has a total of 2383 pumping stations. These data are derived from the annual charges associated with water resource abstraction, in accordance with article L. 213-10-9 of the French Environment Code. Irrigators are required to report the volume of water withdrawn annually if the quantity exceeds 10000 m^3 per year. However, for the Marais Poitevin, situated within a water distribution zone (ZRE), this threshold is reduced to 7000 m^3. The pumping data encompass the period from 2008 to 2022. In this study, as the substitution reservoirs were mainly filled by direct pumping from groundwater, the volume of surface water and groundwater used for irrigation was analyzed separately.

The Agreste website provides statistical data concerning the agricultural sector in France (Agreste, 2020). In this study, the irrigated area per commune was analyzed. An area is considered irrigated if it has been watered at least once during the year (MTECT, 2024). The census is carried out every ten years. The irrigated area is available for the years 2000, 2010 and 2020. However, in 2020, data from 103 of the 341 communes in the Marais Poitevin are subject to statistical confidentiality. Moreover, the data for 64 communes are not available in 2000. In order to study the evolution of irrigated areas, only communes with data available for the three years 2000, 2010 and 2020 were retained, i.e. a total of 182 communes.

2.1.2 Exploratory data analysis

The second phase of the work encompasses an exploratory analysis of pumping and irrigated area data. The objective is to identify temporal and spatial trends within these data sets. This exploration involves both individual analysis of each data set and cross-analysis between them. Additionally, for each variable, the potential relationship with the implementation of substitution reservoirs is examined in order to assess their role in these observed trends.

In order to highlight local trends, the Marais Poitevin has been divided into six hydrological units, which are groupings in sub-basins. These groups were formed based on the division of the water management zones defined by the EPMP (EPMP, 2015b). The resulting map is shown below in Figure 10. This scale facilitates the observation of the influence of local water management strategies and substitution reservoirs on pumping data and piezometric series.

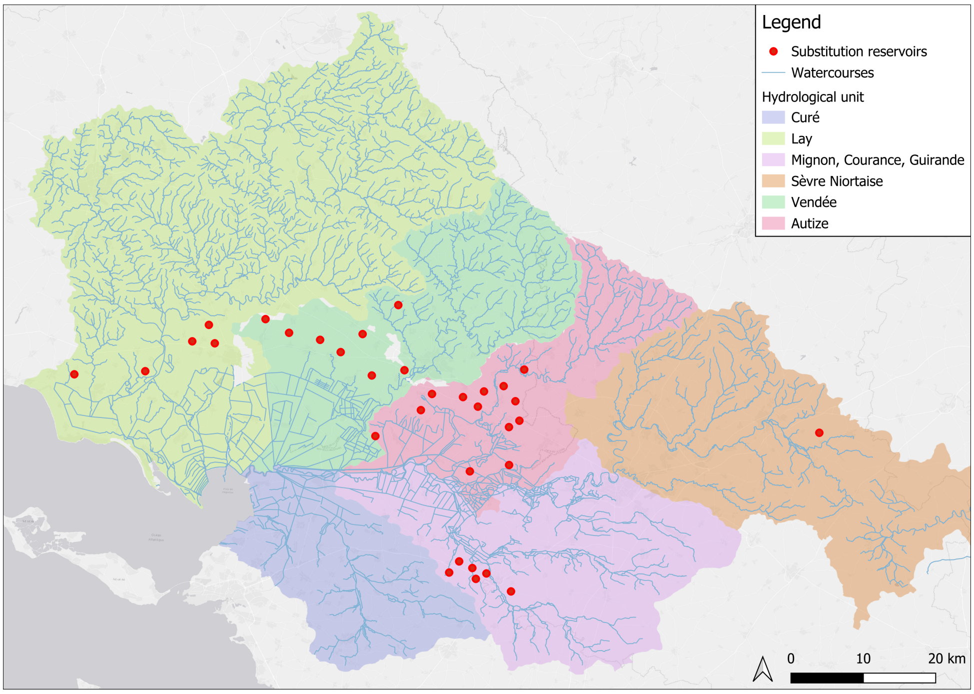


Figure 10: Map of hydrological units in the Marais Poitevin

The objective of this section is therefore to enhance the comprehension of the evolution of irrigation practices in this hydrologically complex region, particularly in the context of substitution reservoirs as a water management tool.

2.1.3 Statistical analysis of piezometric series

The Marais Poitevin has been hydrologically modified by the installation of an extensive network of canals and pumping stations. As a result, many systems have been set up to monitor river flows and groundwater levels. Of the 139 piezometers, only a few were selected for further analysis based on the following four criteria: long time series, few or no missing data, strategic location and monitoring by the SAGEs. The piezometers monitored by SAGEs are used to establish measures to maintain specific groundwater levels. A total of 27 piezometers were selected, as shown in Figure 11. Of these, 10 are located far from the susbtitution reservoirs, while 17 are located nearby. The selected piezometric series start between 1985 and 1996. All subsequent analyses were carried out on these selected piezometers only.

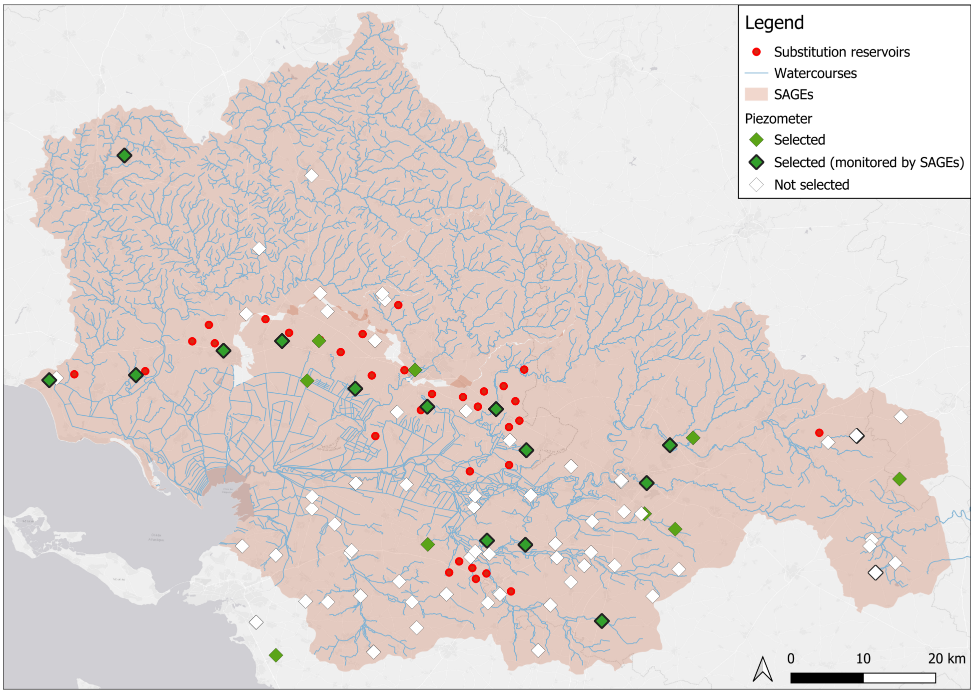


Figure 11: Map of the piezometers in the Marais Poitevin

To determine whether a significant shift occurs over time, two homogeneity tests were applied to the piezometric time series. These tests are designed to detect whether a significant change in the mean occurs within the time series. The two statistical tests used were the Pettitt test and the Standard Normal Homogeneity test (SNHT). The Pettitt test is a non-parametric test whose null hypothesis states that there is no change in the time series. This test was performed at a 5 % significance level. This test makes no assumptions about the distribution of the data. The SNH test, on the other hand, assumes that the time series are normally distributed and independent. These statistical tests were applied to the daily piezometric series and to the annual minimum of the daily piezometric series. The piezometers were grouped according to the date of the detected rupture, obtained from the annual minimum of the daily piezometric level. A temporal and spatial analysis of these ruptures was carried out in order to investigate the possible influence of substitution reservoirs and water management measures on these time series.

Secondly, a correlation was made between the average annual piezometric level and annual rainfall in order to identify the water tables most affected by rainfall and those most affected by human activity.

2.2 Simulation of the piezometric level using the ORCHIDEE model

The second objective of this project is to use the ORCHIDEE model to estimate historical and future groundwater levels. However, the level of the groundwater simulated by ORCHIDEE seems to be erroneous. This could be explained by the fact that the groundwater reservoir in ORCHIDEE does not retain the water due to a too short residence time constant and due to parameterization errors. Thus, instead of directly using the groundwater level simulations, two alternative approaches were employed to estimate the water table levels. The first approach is based on the soil moisture simulated by ORCHIDEE, which is used as an indicator of the natural groundwater level. The second approach is based on a linear reservoir model, which is fed by drainage and surface runoff data from ORCHIDEE simulations. These simulations were applied to three piezometers: Luçon, Breuil-le-Langon and Saint-Coutant, which are free aquifers. For each piezometer, the corresponding hydrological variables simulated by ORCHIDEE were extracted.

This phase is mainly aimed at evaluating the future effectiveness of the current strategy of substitution reservoirs in the Marais Poitevin. More specifically, it consists of counting the number of days during which the reservoirs can be filled in the future, according to the defined filling thresholds.

2.2.1 Description of the ORCHIDEE model

Developed by the Institut Pierre-Simon Laplace (IPSL), ORCHIDEE is a land surface model that simulates water, energy and carbon balances (see Figure 12).

The model operates at a spatial resolution of 8 km x 8 km and a time step of 30 minutes. The model is forced by atmospheric data. In each grid cell, the vegetation is composed of several plant types (PFT), which are its own characteristics. 15 PFTs are used in ORCHIDEE, ranging from bare soil to boreal natural grassland. For each grid cell, the soil is 2 m deep and is characterized by its dominant texture. The dominant texture determines the soil water retention properties. The ORCHIDEE model then assumes an exponential decrease in hydraulic conductivity with depth due to soil compaction, and an increase at the surface due to root presence (Huang et al., 2024). Within the model, at each time step, soil moisture is redistributed vertically according to the Richards equation in an unsaturated medium, considering the processes of infiltration, evaporation, root absorption, and drainage. To ensure the highest degree of accuracy, soil moisture is discretized across 22 layers in the soil. As such, the total soil moisture can be integrated over the 2 m soil tile. River flows are computed using a high-resolution routing model. The model includes three linear reservoirs: a stream reservoir that stores river discharge for horizontal flow transfer, a slow reservoir simplified as a free aquifer that stores drainage for producing base flow, and a fast reservoir that stores surface runoff for producing overland flow. The river discharge of one grid cell is fed by the base flow and overland flow produced by this grid cell, as well as the river discharge from the upstream grid cell. The simulations used here do not account for irrigation, so that the simulated hydrology can be assumed as "natural", apart from land cover and climate change influences.

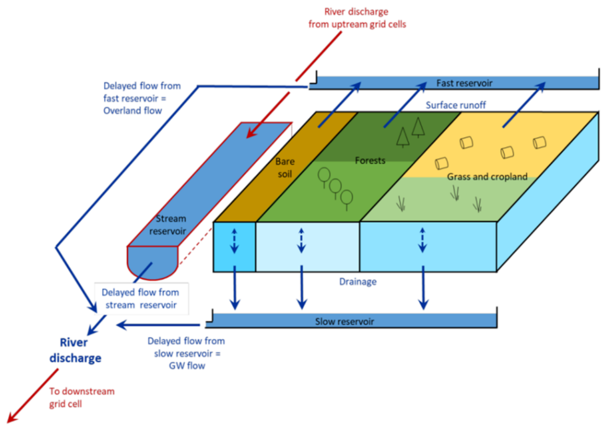


Figure 12: Diagram of the main hydrological processes (excluding evapotranspiration and snow) in an ORCHIDEE grid (Sauquet et al., 2024)

2.2.2 Historical and projected atmospheric data set used to force ORCHIDEE

The ORCHIDEE model is fed by atmospheric data. In this study, the data used are the SAFRAN meteorological dataset and four climate projections, which are summarized in the table 2.

Type of Data	Dataset	Details
Historical	SAFRAN	Meteorological data over France from 1959 to 2022
Projection	ECEarth.HadREM3	”Warm and dry”
Projection	HadGEM2.CLM4	“Warm and contrasted precipitation”
Projection	HadGEM2.ALADIN	“Warm and humid”
Projection	CNRMCM5.ALADIN	”Future changes relatively minor”

Table 2: Atmospheric dataset summary

SAFRAN is a meteorological dataset over France from 1959 to 2020. It has a spatial resolution of 8 km x 8 km and a temporal resolution of 1 hour. This dataset provides atmospheric variables for forcing the ORCHIDEE model. These variables are air temperature, precipitation, specific humidity, wind speed, air pressure, downward longwave and shortwave radiation, and the annual CO_2 concentration observed in the atmosphere.

The climate projections applied in this study were developed as part of the Explore2 project, which aimed at assessing the impact of climate change on water resources in France by the year 2100. To this end, a range of projections were constructed in accordance with the approach outlined below (see Figure 13) (Évin et al., 2024).

First, three greenhouse gas emission scenarios (Representative Concentration Pathways) for 2100 defined by the IPCC were considered: RCP8.5, RCP4.5 and RCP2.6. For each of these scenarios, six global climate models (GCMs) were used to simulate climate evolution on a global scale. These models were then coupled with regional climate models (RCM) to obtain higher resolution climate simulations. To improve the accuracy of the projections, bias correction methods were applied to the climate simulations. Finally, these projections were used to force nine hydrological models to assess the impact of climate change on the hydrological cycle. In this study, the ORCHIDEE hydrological model was used to simulate future hydrological trends. The Explore2 project selected four contrasting projections, known as ”storylines” (Marson et al., 2024) for the RCP8.5 emission scenario. Their names include the GCM and RCM models used to produce the ‘GCM.RCM’ storyline. These projections are considered equally likely. The first, ECEarth.HadREM2, corresponds to the warmest scenario, characterized by intense warming and dry conditions throughout the year. The second, HadGEM2.CLM4, represents a scenario with high temperatures and contrasting precipitation depending on the season. The third projection HadGEM2.ALADIN shows significant warming accompanied by an increase in precipitation. Finally, the last one CNRMCM5.ALADIN shows few significant changes compared to current conditions. These different projections make it possible to explore a wide range of possible climatic and hydrological developments in the futur under the RCP8.5 scenario.

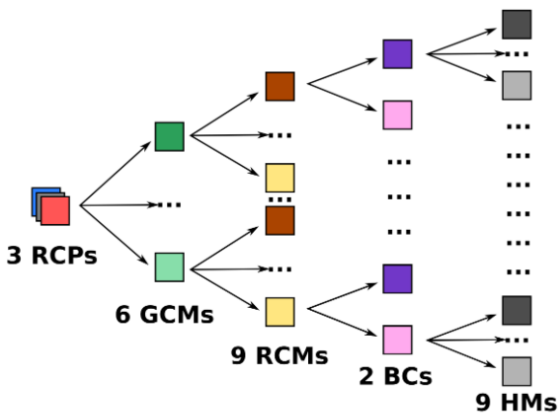


Figure 13: Modelling chain (Évin et al., 2024)

2.2.3 Historical simulation of piezometric levels

The first stage consists of estimating the level of the water table using the simulations produced by ORCHIDEE, based on the SAFRAN meteorological database. The aim is to check whether it is possible to reproduce the natural variations of the water table based on simulations with ORCHIDEE, which does not take pumping into account.

Simulation of piezometric levels based on soil moisture.

In the ORCHIDEE model, soil moisture is defined as the variation in water content in 2 meters of soil, measured in millimeters. This indicator was employed to estimate the natural state of the groundwater level. In order to compare the soil moisture with the piezometric series, the two series have been standardized for each piezometer. However, it should be noted that ORCHIDEE does not incorporate the effect of irrigation in its hydrological simulations. Consequently, the impact of pumping, which is particularly pronounced during summer months, is absent in the model. Therefore, for Luçon and Breuil-Le Langon, which are more strongly impacted by pumping, the observed and simulated series were standardized over a sub-period less influenced by water abstractions. The standardization process for each series is outlined in equation (1):

$$Z = \frac{X - \mu}{\sigma} \tag{1}$$

where Z is the standardized value, X is the initial value, μ is the average of the series over the chosen period and σ is the standard deviation of the series over this same period.

After standardization, the Nash-Sutcliffe coefficient was used as a performance indicator. It evaluates how well the simulated variable S_i matches the corresponding observations O_i. The Nash-Shutcliffe coefficient is expressed as below values ranging from $-\infty$ to 1 :

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} \tag{2}$$

A Nash-Sutcliffe coefficient superior to 0.75 is indicative of a good model. A value between 0.36 and 0.75 corresponds to a satisfactory model, while a coefficient below 0.36 indicates a less satisfactory performance (Eryani et al., 2022). Furthermore, the Pearson correlation coefficient between the simulated and the observed values was computed in order to evaluate the strength of the relationship between them.

Simulation of piezometric levels by designing a linear reservoir model with surface runoff and drainage as input.

The second approach consisted of designing a linear reservoir model to estimate the groundwater level using surface runoff and drainage simulated by ORCHIDEE as input data. Linear reservoir models are based on the principle of conservation of mass (3) and on a linear relationship between output flow rate and storage (4). The output depends on the time constant of the reservoir.

$$\frac{dS}{dt} = D(t) - Q(t) \tag{3}$$

$$\frac{S(t)}{K} = Q(t) \tag{4}$$

In this study, a model of two linear reservoirs was designed to estimate the piezometric levels as illustrated in the following diagram 14.

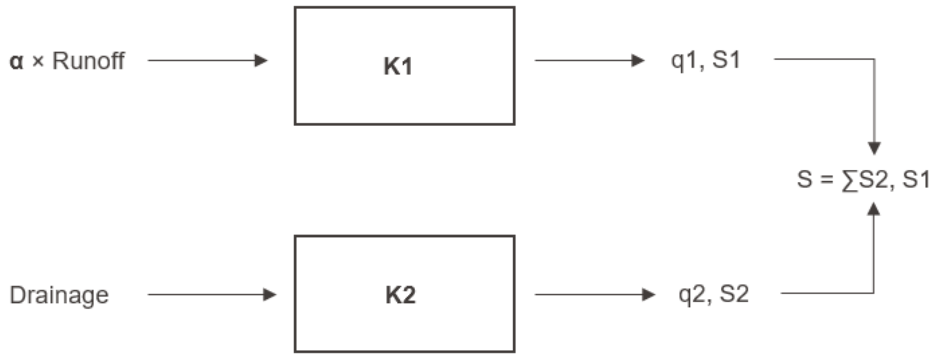


Figure 14: Linear reservoir model

One reservoir is fed by a factor α of the surface runoff, while the other is fed by drainage. The final storage is calculated by adding the storage of the two reservoirs. Only a portion of the surface runoff is used because the surface runoff is much higher compared to the drainage simulated by ORCHIDEE. Therefore, the time constants K1 and K2 and the surface runoff input factor α were calibrated to achieve the most accurate representation of the reality of the groundwater level. Moreover, the drainage was advanced by 60 days because the drainage simulated by ORCHIDEE proved to be too slow in comparison with reality. The calibration process was conducted through an iterative approach, with the objective of attaining the optimal Nash-Sutcliffe between the simulated values and the observed values.

Then the observed and simulated series were standardized according to the same principle as for the first approach, i.e. by standardizing over a sub-period less influenced by pumping (Equation 1). Similarly, the Pearson correlation coefficient was calculated to evaluate the performance of the simulation.

2.2.4 Simulation of piezometric levels by 2100

The last stage of this project consists of estimating the long-term trends of the piezometric series, from 1960 to 2100 using the two approaches described above. The objective is to assess the impact of climate change on the filling of the substitution reservoirs and on the groundwater levels in summer. The following analyses were applied to the four climate projections under RCP8.5 radiative forcing scenarios.

The first step is to make the ORCHIDEE historical and future simulations comparable. However, over the common period chosen for the standardization of observations and simulations with SAFRAN forcing, the variables simulated with SAFRAN forcing and those from climate projections do not necessarily have the same mean or standard deviation over this period. For instance, over the period 2015-2020, the average soil moisture is 638 mm for the SAFRAN forcing, while it is 606 mm for the 'ECEarth.HadREM3' climate projection and 663 mm for the 'HadGEM2.CLM4' climate projection. In order to debias these series and make them comparable, the mean and standard deviation of the simulation with SAFRAN forcing over the chosen standardization period are used as a reference. These values are then applied to standardize the projected simulations. Therefore, it makes possible to correct the bias between projected simulations and simulation from SAFRAN forcing, and thus obtain a more consistent estimate of the future evolution of piezometric level.

3 Results and Discussion - Historical

3.1 Irrigation practices in the Marais Poitevin

This section examines the temporal and spatial evolution of the volume of water pumped for irrigation and the irrigated area. It also presents the correlation between these two variables.

3.1.1 Temporal and spatial analysis of the volume of water pumped for irrigation

The study area includes a total of 2383 pumping stations, of which 2279 are used for irrigation, representing 95.6 % of the pumping stations. Of the volume pumped for irrigation, 70 % is from groundwater. The figure 15 below shows the volumes pumped by commune, distinguishing between groundwater and surface water abstractions. It can be seen that groundwater pumping is mainly located in the vicinity of substitution reservoirs. On the other hand, surface water abstraction is concentrated upstream of substitution reservoirs.

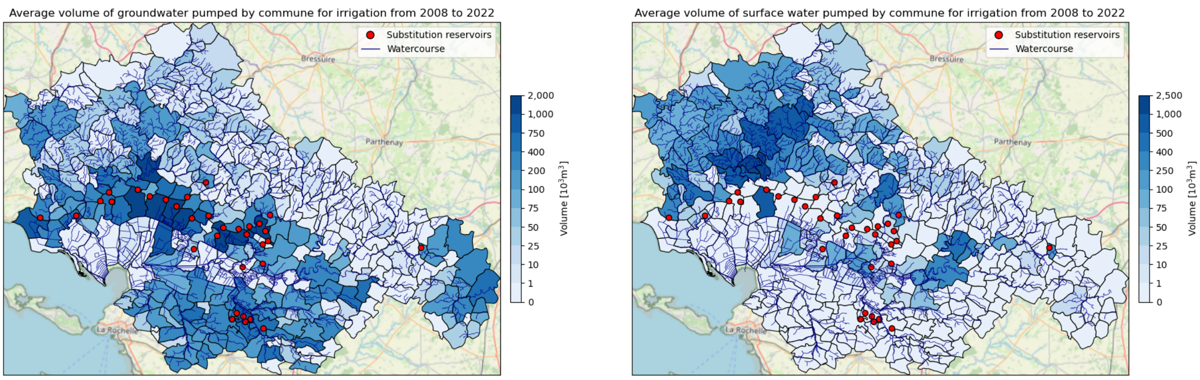


Figure 15: Average volume of water pumped for irrigation by commune from 2008 to 2022 (BNPE)

The following graph 16 shows the evolution of the number of pumping stations used for irrigation in the Marais Poitevin. Between 2008 and 2022, the number of pumping stations decreased by 29 % for groundwater abstraction and by 23 % for surface water abstraction.

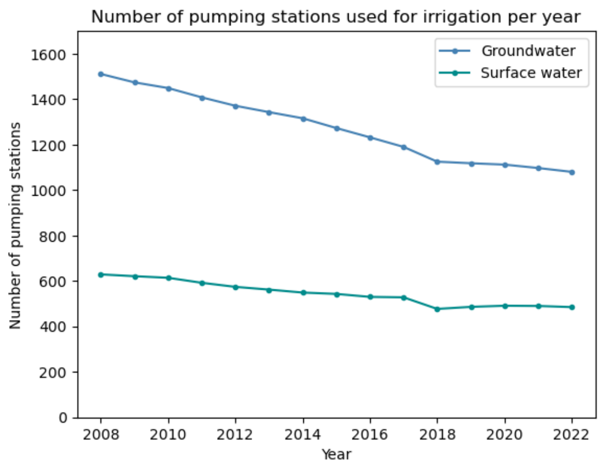


Figure 16: Number of pumping stations used for irrigation per year (BNPE)

The next two graphs 17 show the evolution over time of the volume of water pumped for irrigation between 2008 and 2022 in the Marais Poitevin. The first graph shows a decrease in the volume pumped from groundwater and a slight increase in the volume pumped from surface water. Moreover, if we consider only those communes that currently have substitution reservoirs, the volume pumped from groundwater has increased.

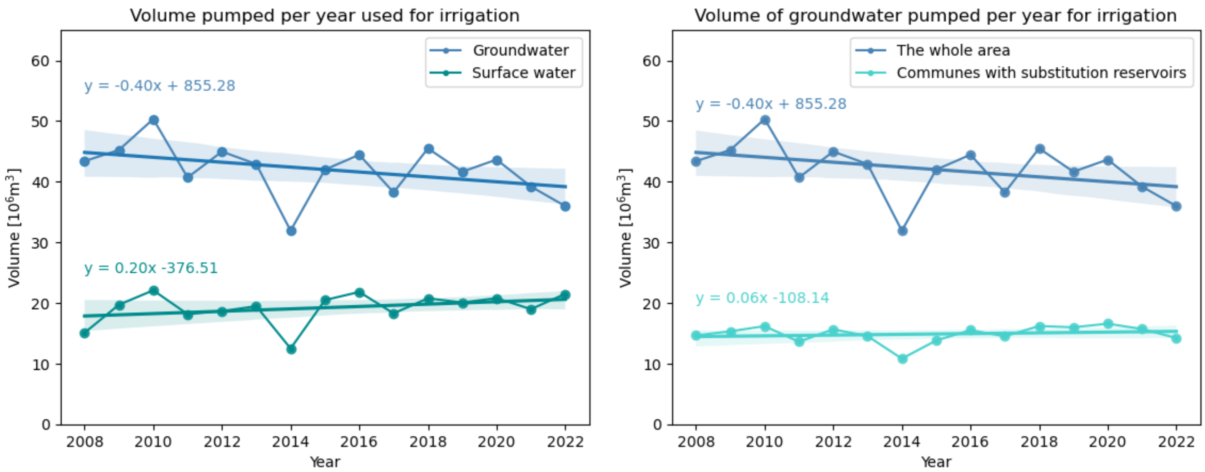


Figure 17: Volume of water pumped per year used for irrigation (BNPE)

The change in the total volume of groundwater pumped for irrigation per commune between 2008-2012 and 2018-2022 is shown in Figure 18. The change in the volume of water pumped between these two periods is not uniform from one commune to another. In several communes, particularly in the southern part of the Marais Poitevin, the volume pumped has decreased by more than 15 %. On the other hand, in the northern part of the Marais Poitevin, most communes show an increase in groundwater abstraction in 2018-2022 compared to 2008-2012.

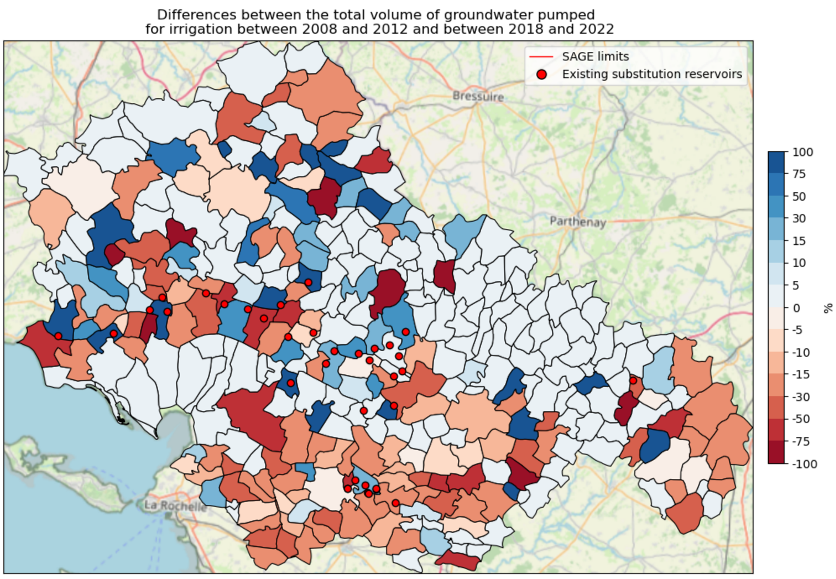


Figure 18: Change in the total volume of groundwater pumped for irrigation per commune between 2008-2012 and 2018-2022. (BNPE)

Finally, an analysis of the evolution over time of groundwater abstraction per hydrological unit in the Marais Poitevin shows that these trends vary from one unit to another. As shown in Figure 19 below shows, between 2008 and 2022, the volume pumped decreased in the Mignon, Curé, Sèvre Niortaise and Lay sectors, while it increased in the Autize and Vendée basins.

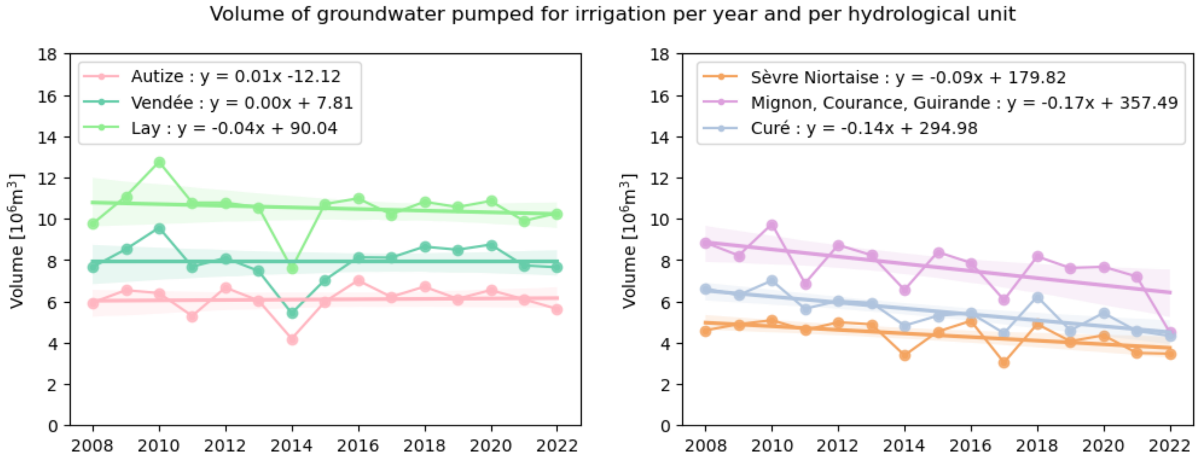


Figure 19: Volume of groundwater pumped for irrigation per year and per hydrological unit (BNPE)

When considering only the volume pumped by the communes that currently possess a substitution reservoir, the trend is reversed in the Lay, where the volume pumped increased (Figure 20). In the Sèvre Niortaise and Mignon basins, the decline of the volume pumped is less pronounced for these communes. Furthermore, in the Autize and Vendée basins, the trends in pumped volume do not change significantly for the communes with a substitution reservoir. Finally, the Curé basin does not have a substitution reservoir and is therefore not represented in the graph.

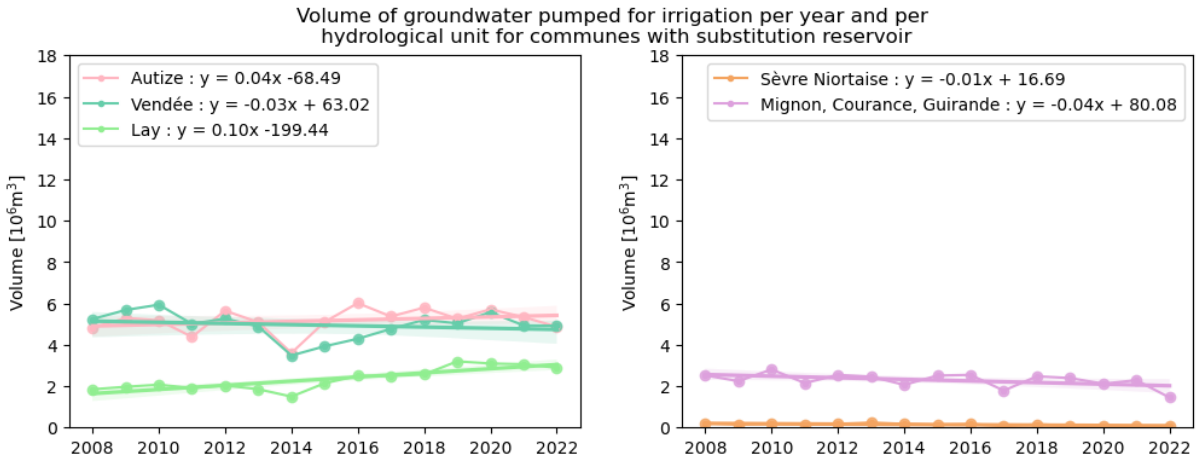


Figure 20: Volume of groundwater pumped for irrigation per year and per hydrological unit for communes with substitution reservoirs (BNPE)

3.1.2 Temporal and spatial analysis of irrigated areas

Figure 21 presents the share of irrigated area per commune for the three following decades: 2000, 2010 and 2020. The figure demonstrates that the communes with the largest irrigated areas are principally located in the vicinity of substitution reservoirs. However, it should be noted that data is not available for some communes for the years 2000 and 2020. Indeed, in 2020, 103 communes are listed as being in statistical secrecy, while in 2000, data are not available for 64 communes.

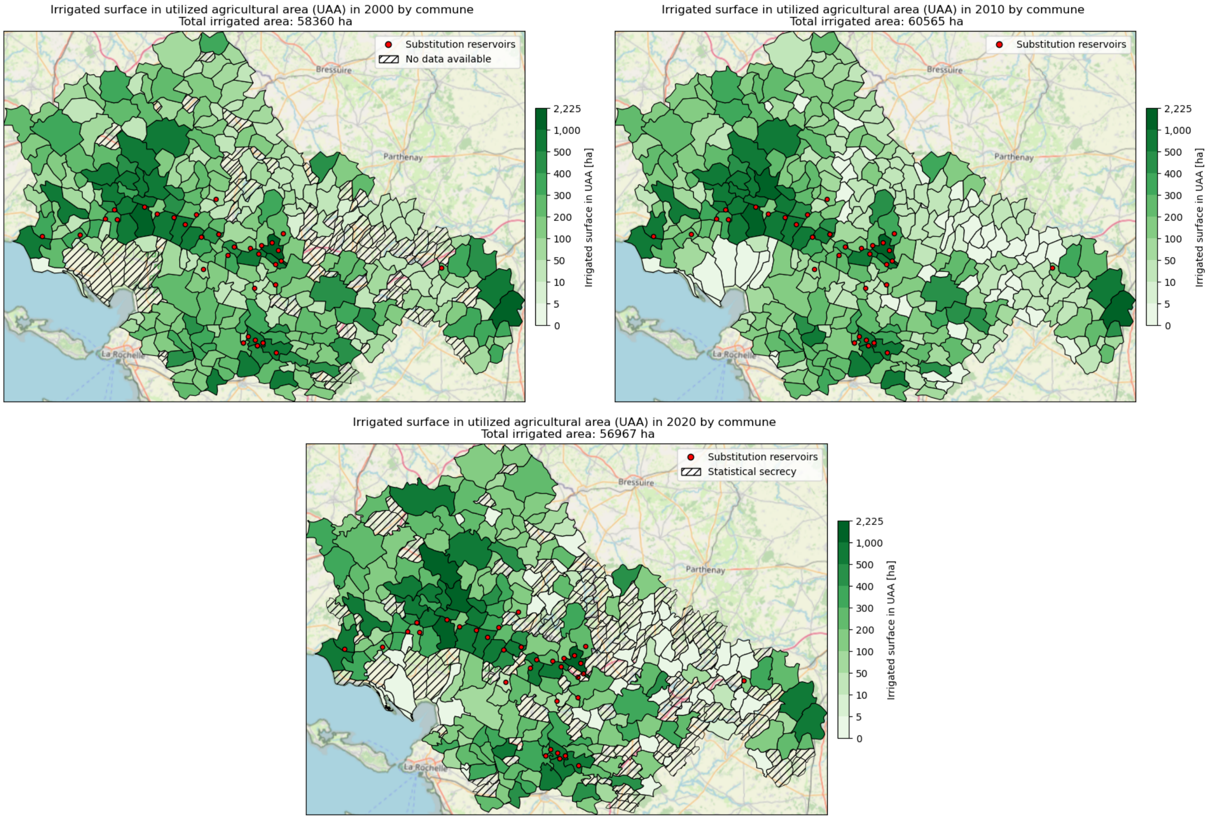


Figure 21: Share of irrigated areas per commune for the years 2000, 2010 and 2020 (Agreste data)

In order to analyze the evolution of irrigated areas over time, only the communes listed for these three decades were analyzed, i.e. a total of 182 out of 341 communes. The total irrigated area within the study zone exhibited an approximate augmentation of 5.7 % from 2000 to 2010, subsequently followed by a 6.0 % increase between 2010 and 2020. The augmentation in irrigated area is more pronounced in communes that currently include substitution reservoirs, with an increase of 12.0 % between 2000 and 2010 and 12.1 % between 2010 and 2020 as illustrated in Figure 22.

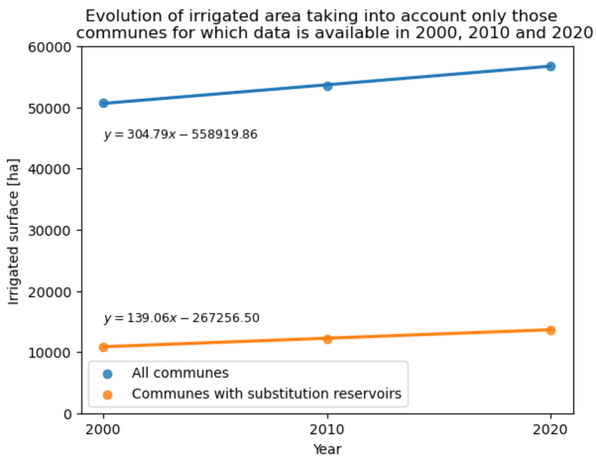


Figure 22: Evolution of irrigated area in the Marais Poitevin (Agreste data)

3.1.3 Relationship between irrigated area and volume of water pumped for irrigation

The following analyses are made on the basis of the communes for which the irrigated area data are available. As demonstrated in Figure 23, communes with a high proportion of irrigated land are also those that pump the largest volumes of water. A strong positive correlation is observed, with an R^2 of 0.65 in 2020 and 0.62 in 2010. Furthermore, the slope of the linear regression is slightly higher in 2010 than in 2020, which indicates that, for the same volume of water pumped, the irrigated area is larger in 2020 than in 2010. Indeed, between 2010 and 2020, the volume of water pumped for irrigation decreased by 11 %, while the irrigated area increased by 6 %. Furthermore, the graph demonstrates that the linear relationship is more pronounced and nearly proportional for communes with substitution reservoirs in 2020, exhibiting a slope close to 1 and an R^2 of 0.79. In those communes, the volume pumped and the irrigated area increased by 6 % and 12 %, respectively, between 2010 and 2020.

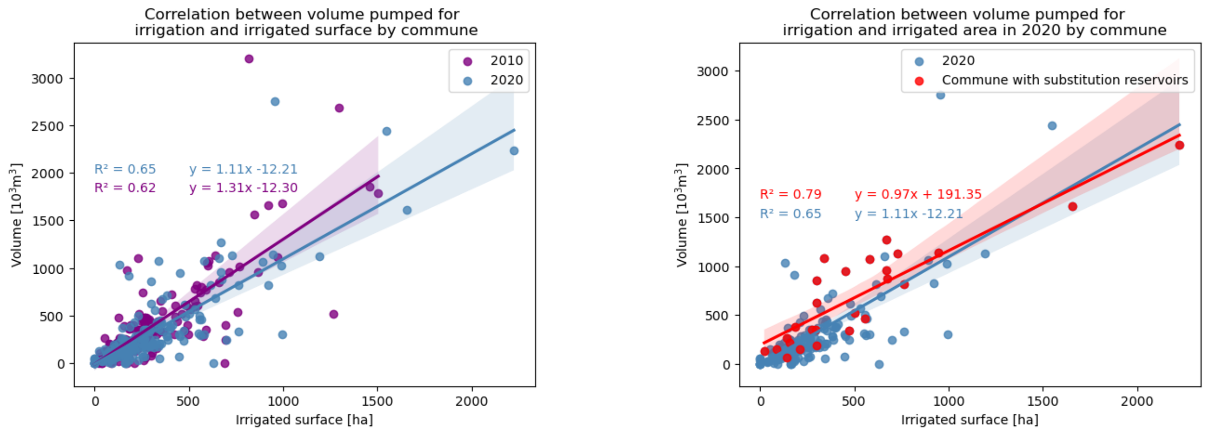


Figure 23: Correlation between volume pumped and irrigated area (BNPE and Agreste data)

Finally, Figure 24 illustrates the correlation per commune between the change in irrigated area and the change in volume pumped for irrigation between 2010 and 2020. This correlation is close to 0, which indicates that between 2010 and 2020, an increase in the irrigated area of a commune did not necessarily evolve with an increase in the volume of water withdrawn.

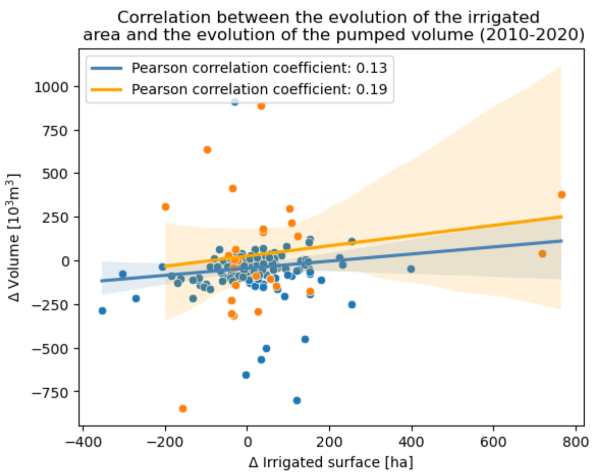


Figure 24: Correlation between the change in irrigated area and the change in volume of water pumped between 2010 and 2020. (BNPE and Agreste data)

3.2 Analysis of piezometric levels

This section presents the analysis of the 27 piezometric time series selected according to the criteria defined in the method. It includes the results obtained with the statistical tests to determine whether a significant change in the level of the water table has occurred. Subsequently, a spatial and temporal analysis of these piezometric series is presented.

3.2.1 Analysis of the rupture dates of the piezometric series

For almost all selected piezometers, a significant rupture in the piezometric series is detected by at least one of the statistical tests. The table 25 below shows for each piezometer the date of the associated rupture, the distance to the nearest reservoir and its commissioning date.

	Hydrological unit	Piezometer	Date of the break (Petitt test)	Date of the break (SNHT)	Distance from the nearest substitution reservoir [km]	Date of commissioning of the nearest substitution
Piezometer near the substitution reservoir	Autize	St Pierre-Le-Vieux	2006		1,7	2007
		Azire Benet	2007		3,1	2010
		Oulmes	2007		2,5	2007
	Mignon, Courance, Guirande	Saint Hillaire La Palud	2006	1999	2,3	2010
		Bourdet	2006		6,7	2010
		Courçon			4,9	2010
	Vendée	Nalliers	2007	2006	0,2	2017
		Sainte Radégonde	2012	1997	5,9	2017
		Fontenay-Le-Comte	2012		1,5	2015
		LeLangon		2020	2,9	2019
		Billaude-Doix	2014		1,0	2016
		Petit Magnil			4,1	2017
	Lay	St-Benoist sur Mer			1,4	2017
		St Aubin-La-Plaine	2014		1,5	2014
		Luçon	2014		1,6	2015
		Longeville sur mer		2019	3,6	2019
	Sèvre Niortaise	Pamproux			5,2	2008
Piezometer far from the substitution reservoir	Mignon, Courance, Guirande	Prissé		2012	11,2	-
	Lay	Forage des Ajoncs			26,1	2016
	Sèvre Niortaise	Aiffres	1999		15,3	2010
		François		1991	17,3	2008
		Saint Gelais	2007	1991	20,7	2008
		Prahecq			10,8	2010
		St Coutant			11,7	1998
		St Sauvant			12,8	2008
		Niort			18,2	2010
	Curé	Salles-sur-mer	2007		26,5	2010

Figure 25: Summary of detected break dates for each minimum annual of the daily piezometric series

The earliest detected ruptures occurred in 1991 and 1999. The Aiffres piezometer is one of the piezometers for which a strong visible change in its piezometric series is evident, as shown in the piezometric series illustrated in Figure 26. During the 1990's, the summer piezometric levels were chronically below sea level. The rupture observed in 1999 corresponds to the implementation of measures that restricted pumping activities (CACG, 2002), leading to raise the summer piezometric level by about 20 m.

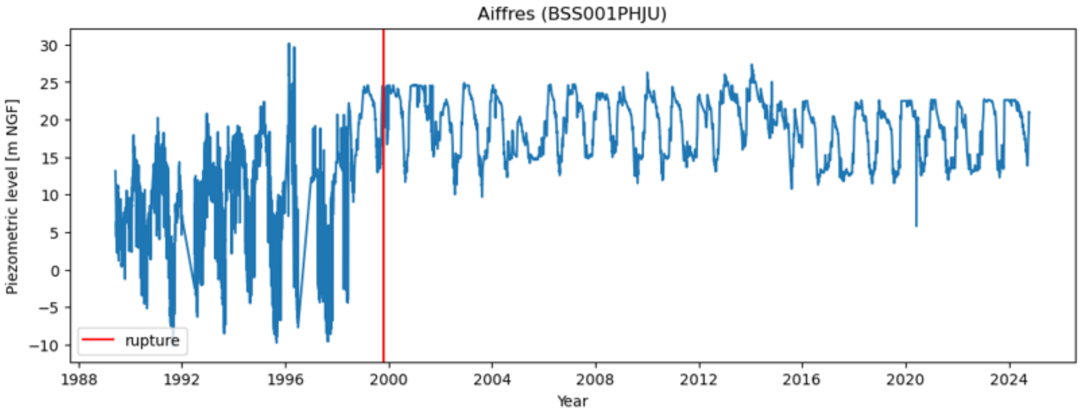


Figure 26: Piezometric profile - Aiffres

Furthermore, the periods 2006-2007, 2012 and 2014 are dates of ruptures detected for multiple piezometers. For 76 % of the piezometers with a rupture, the rupture occurred before the date of commissioning of the nearest substitution reservoir. A notable example is the Bourdet piezometer (Figure 27), where the rupture in 2006 occurred four years before the reservoirs in this catchment area were commissioned. This rupture corresponds to compliance with the crisis piezometric threshold. Furthermore, in 2005, a year marked by severe drought conditions, the water table level at Bourdet attained its maximum recorded level during the summer months. This period coincided with a prefectural decree prohibiting all pumping activities. The natural low-water piezometric level at the Bourdet piezometer is approximately 11.7 m NGF (MEDD, 2007). Since 1989, the low-water piezometric level has been observed to decrease during the summer months as a result of pumping activities. However, prior to 1988, the impact of pumping on this period appears to have been negligible.

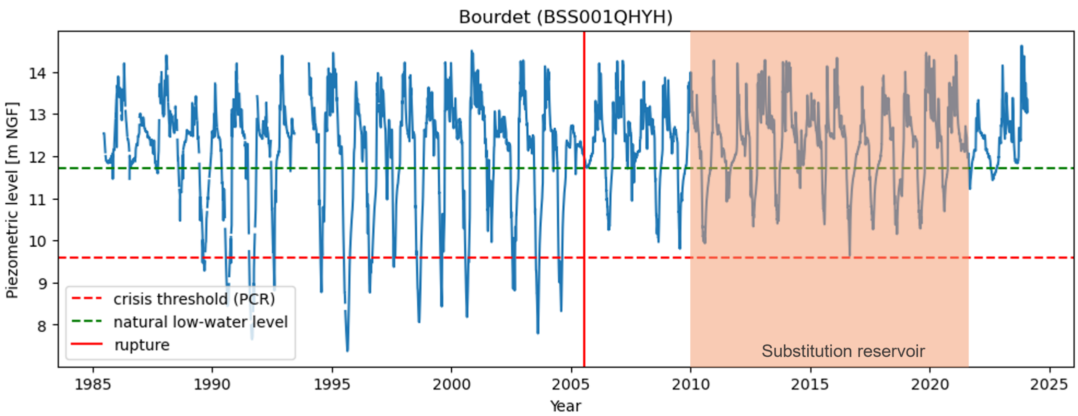


Figure 27: Piezometric profile - Bourdet (orange zone: proximity of active substitution reservoir)

Another interesting example is the piezometric series in Luçon illustrated in Figure 28. In this case, the rupture date corresponds to two events: the installation of the substitution reservoirs and the compliance with the crisis piezometric level. Before the rupture of 2014, there was a strong depletion of groundwater level during summer months, attributable to excessive pumping.

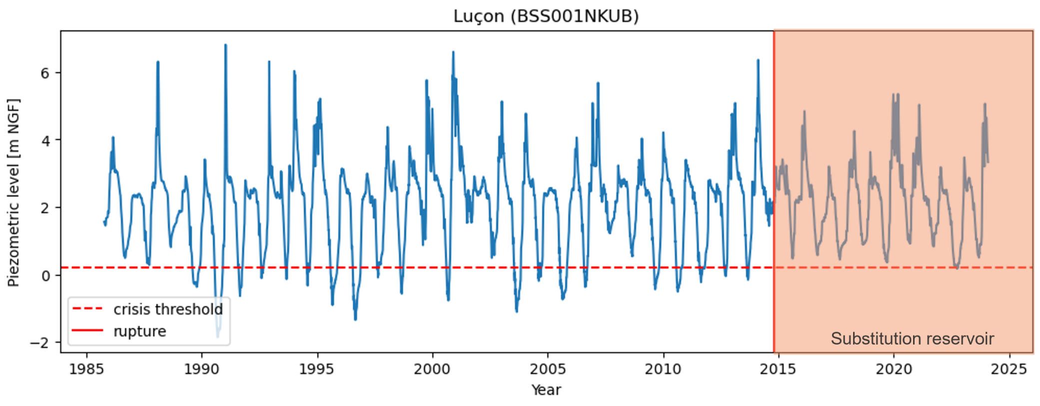


Figure 28: Piezometric profile - Luçon (orange zone: proximity of active substitution reservoir)

Figure 29 shows the spatial distribution of the piezometers classified by date of rupture. Two distinct groups can be identified. The piezometers that experienced ruptures between 2006 and 2007 are predominantly situated within the Mignon and Autize basins. In this region, the substitution reservoirs were commissioned between 2007 and 2012. The piezometers exhibiting a rupture date after 2012 are predominantly situated within the Vendée and Lay watersheds. In this sector, the reservoirs were commissioned after 2015. Finally, the Sèvre Niortaise sector contains the piezometers with the oldest rupture and those with no significant rupture. This area also has fewer reservoirs than the other catchment areas.

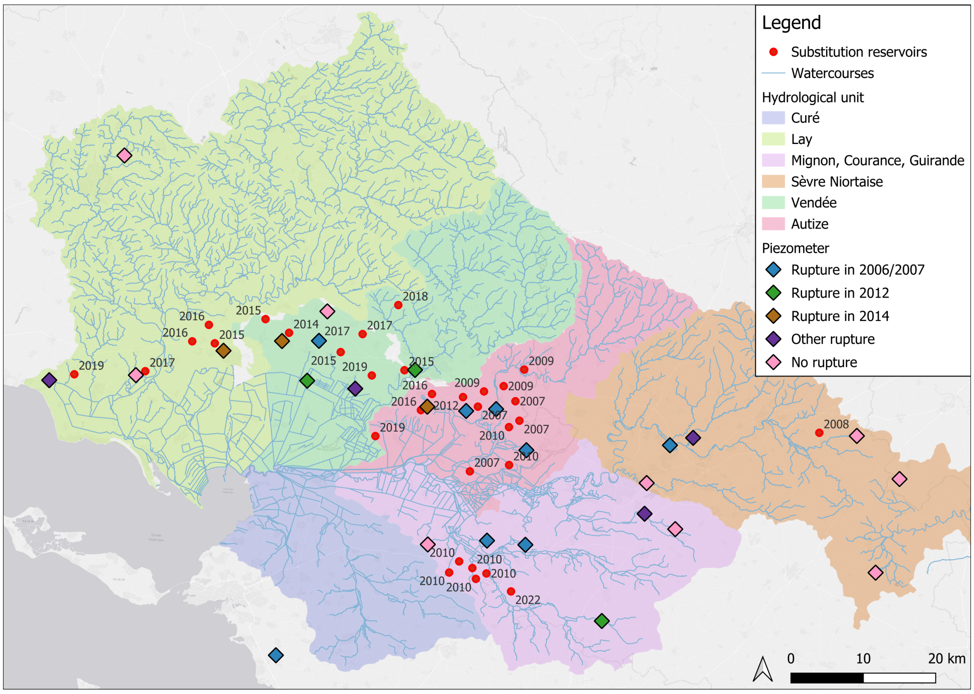


Figure 29: Piezometers grouped by date of rupture

Finally, for each piezometer, the R^2 between the mean annual piezometric level and the annual precipitation was calculated (Figure 30). The median R^2 for piezometers with a rupture is 0.49, while for piezometers without rupture it is 0.71. Furthermore, the R^2 values show a greater dispersion for the piezometers with a rupture. This indicates that the water table level is less influenced by precipitation in areas where the piezometers exhibit a rupture. Furthermore, the majority of the piezometers with a rupture are located near substitution reservoirs (Table 25). These areas also display a high pumping density (Figure 15). Therefore, the water table is more influenced by human activities in the vicinity of the substitution reservoirs, and this reduces the influence of precipitation variability.

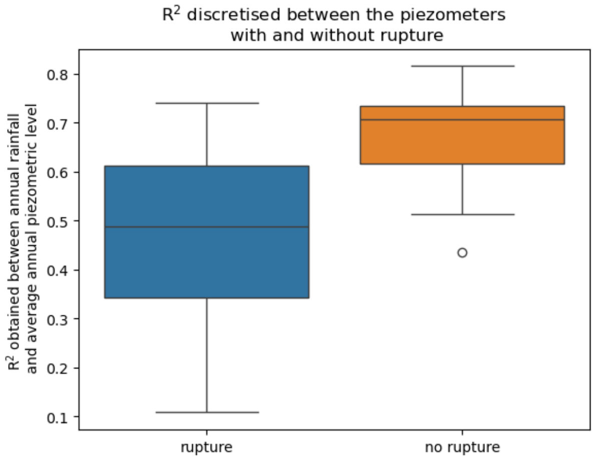


Figure 30: Box plots of the R^2 obtained between the annual rainfall and the average annual piezometric level discretised between the piezometers with and without rupture.

3.2.2 Temporal analysis of piezometric series

In order to assess and understand the temporal variations in the piezometric series, the piezometers were grouped according to their date of rupture. The results presented below focus on the piezometers with a significant rupture in 2006-2007. Only the piezometers with a rupture date in 2006-2007 that does not coincide with the commissioning of the nearest substitution reservoir were analyzed (thus excluding the Oulmes and St-Pierre-le-Vieux piezometers). Altogether 6 piezometers meet these criteria. For the sake of comparison, their piezometric series were standardized over their entire respective periods. Then, monthly averages were calculated for three different periods. The first period is the period before the rupture, i.e. before 2006. The second period, from 2006 to 2009, is the period after the rupture but not influenced by substitution reservoirs, as all the reservoirs close to these piezometers were commissioned in 2010. The last period, after 2009, is influenced by the substitution reservoirs.

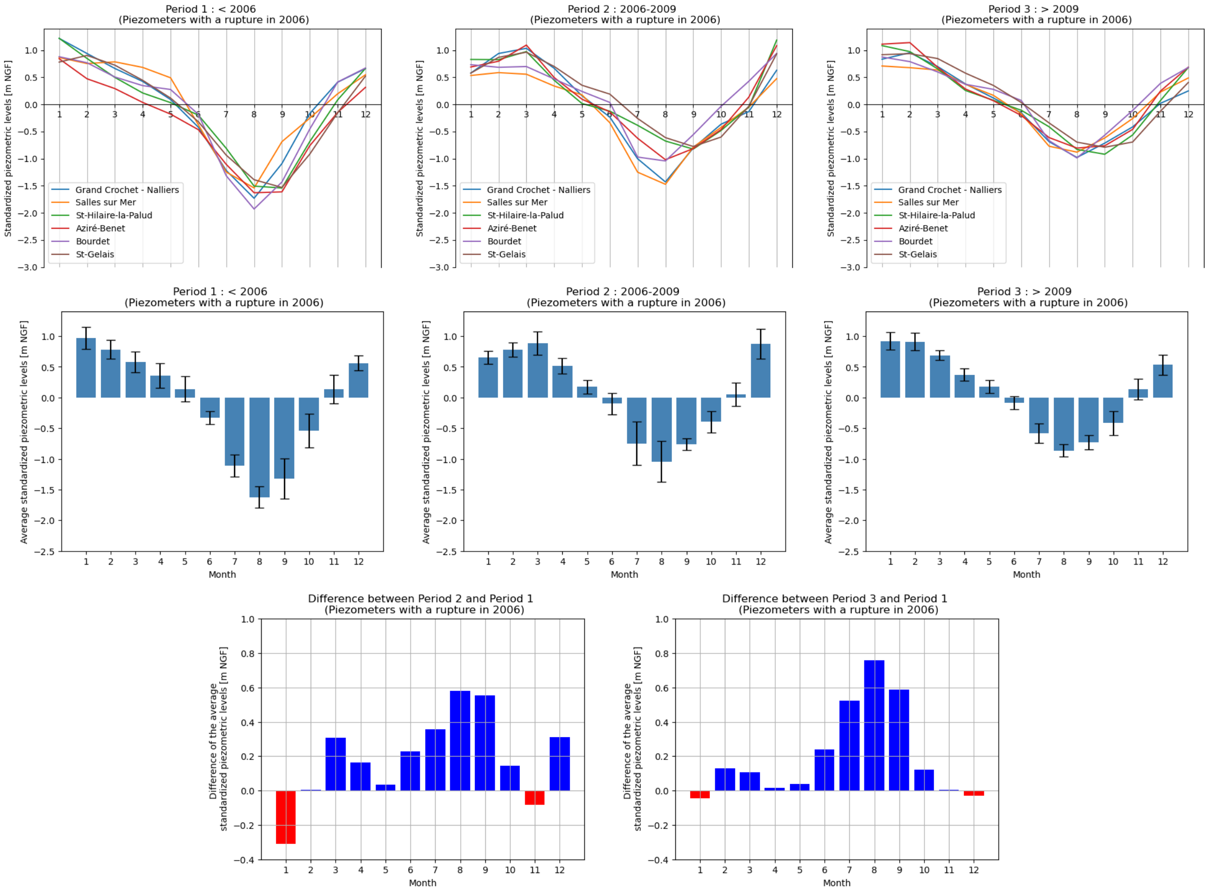


Figure 31: Piezometers with a rupture in 2006/2007: (1) Average standardized piezometric series per month over the three periods. (2) Average of the monthly averages of the standardized piezometric series for the three periods. (3) The differences of the average of the monthly averages of the standardized piezometric series between the three periods.

Figure 31 shows an important increase in piezometric levels during the summer months from 2006 onwards, even before the substitution reservoirs were commissioned. However, this improvement is more variable during the period 2006-2009, as indicated by the black bars representing the standard deviation, compared to the period after 2009. The standard deviation of the average monthly piezometric levels is higher in summer for the period 2006-2009 than for the other months of the year. In addition, a slight drop in piezometric levels is observed in January and December after 2009 compared to the period prior to 2006. Finally, a more important drop in piezometric levels in January is observed over the period 2006-2009.

A similar analysis was carried out for the piezometers with a rupture in 2012 (Figure 32). For these piezometers, the period between the rupture and the start of the substitution reservoirs is between 2012 and 2014, as the nearest reservoirs were commissioned from 2015. An improvement of the piezometric levels in summer is visible between 2012 and 2014, with a greater increase during this period than after 2014 compared to the period before the rupture. Between 2012 and 2014, the standard deviation is higher in winter than in summer. A decrease of the piezometric levels compared to the period prior to 2012 is observed in March and April for the period 2012-2014 and in December and January for the period after 2014.

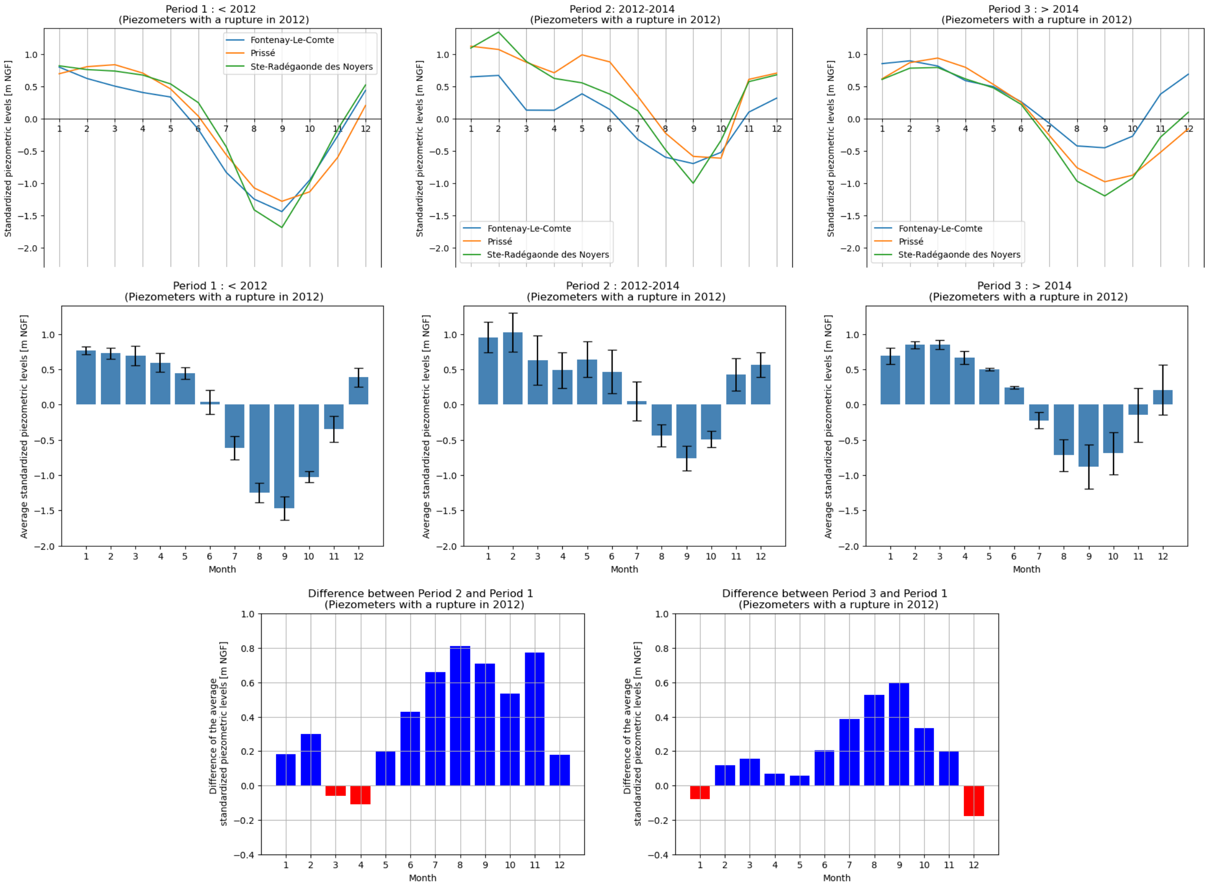


Figure 32: Piezometers with a rupture in 2012: (1) Average standardized piezometric series per month over the three periods. (2) Average of the monthly averages of the standardized piezometric series for the three periods. (3) The differences of the average of the monthly averages of the standardized piezometric series between the three periods.

Finally, the same analysis was carried out for all the piezometers, taking into account only two periods, one before and one after the commissioning of the substitution reservoirs. The trends observed for the period influenced by substitution reservoirs are the same, with an increase in piezometric levels in summer and a slight decrease in winter (Figure 48 in the Appendix).

3.3 Discussion

The first stage of this study aimed at analyzing the spatial and temporal evolution of water abstraction, irrigated area and groundwater levels in the context of the progressive implementation of substitution reservoirs and water management measures in the Marais Poitevin.

Firstly, the results demonstrated that the communes with the largest irrigated area are also those which withdraw the greatest volumes of water for irrigation. However, between 2010 and 2020, the irrigated area increased by approximately 6 %, while the volumes of water pumped for irrigation decreased by 11 %. An initial hypothesis to explain this reversal trend is based on climatic conditions. The year 2020 was wetter than 2010, with annual rainfall of 903 mm compared to 709 mm in 2010, and summer rainfall of 137 mm in 2020 compared to 125 mm in 2010. Consequently, it can be assumed that irrigators had less need to extract water to irrigate crops in 2020. In addition to the initial hypothesis, a secondary hypothesis is the presence of illicit pumping activities, consequently not included in the official volumes declaration. In particular, the year 2020 was characterized by the global Coronavirus pandemic, during which the French population was under nationwide confinement. It has been reported that certain farmers allegedly exploited this period to undertake pumping and irrigation activities for their crops. This practice led to the issuance of several fines during this period (Source: discussion with members of the Federal Office for Biodiversity (OFB)).

Then, the results show that the volume of water pumped for irrigation increased by 6 % between 2010 and 2020 in communes with substitution reservoirs, while the total volume pumped decreased. This phenomenon is probably explained by an increased concentration of withdrawals in the vicinity of these reservoirs. Furthermore, the gradual implementation of substitution reservoirs since 2007 has led to the progressive closure of many pumping stations not connected to this infrastructure (Lenoiselee et al., 2021). The presence of these reservoirs seems to have favored more localized water abstraction, probably also allowing irrigation of the surrounding areas. However, between 2010 and 2020, the irrigated area increased by 12 % in the communes equipped with substitution reservoirs, which is twice as fast as in the other communes, which suggests that these infrastructures have contributed to an intensification of irrigation in these areas.

Next, different dates of rupture were found in different hydrological units. In the Lay basin, the ruptures were detected in all the piezometers at the time of commissioning of the substitution reservoirs. In particular, the Luçon and St-Aubin-la-Plaine piezometers, which have a rupture in 2014, are located less than 2 km from the reservoirs commissioned in 2015. Furthermore, the rupture of these piezometers corresponds to the moment when the crisis piezometric threshold is respected. Moreover, it is observed that groundwater abstraction remained constant between 2008 and 2022 in the Lay watershed. Consequently, the reservoirs appear to have been a solution to guarantee compliance with crisis levels while maintaining the same volume of groundwater withdrawn. This substitution can be considered a real substitution, with the volume of water withdrawn during the autumn and winter months replacing the volume that would have been withdrawn during the summer and spring months.

In the Autize sector, a pioneer in the development of substitution reservoirs (with 10 reservoirs commissioned between 2007 and 2012), groundwater abstraction has also remained constant. However, this region is also a pioneer in the implementation of water management measures, the first of which date back to 1996 (CACG, 2002). These measures have reduced the volume allocated to farmers for irrigation. However, the available pumping data do not allow to analyze the volumes abstracted before 2008. The reservoirs have therefore been added to these measures and contributed to compliance with the crisis threshold for the Oulmes and St-Pierre-le Vieux piezometers.

In the Vendée basin, the dates of ruptures were detected between two and ten years before the commissioning of the substitution reservoirs, with the exception of the Breuil-Langon piezometer (see table 25). These ruptures correspond to the compliance with the crisis piezometric thresholds. In particular, the ruptures in 2012 coincide with the implementation of PAGD (sustainable development and management plans) of the SAGE Vendée. Therefore, in this region, the ruptures appear to be more closely associated with water management measures. However, it is notable that compliance with the crisis threshold does not appear to be accompanied by a decrease in the volume withdrawn (see Figure 19). Indeed, the volume pumped for irrigation remained constant between 2008 and 2022. It is possible that a different trend may emerge if the analysis was performed over the period 2008-2012. However, as this period is relatively short, it is more influenced by weather conditions,thereby diminishing its significance. It would also be useful to analyze earlier pumping records, but they are not available in the BNPE database.

The Mignon, Courance and Guirande basins then show a strong downward trend in groundwater abstraction. In these sectors, the Bourdet and Saint-Hilaire piezometers recorded a rupture in 2006, although the closest substitution reservoirs were not commissioned until 2010. The date of the rupture corresponds to the respect of the piezometric crisis threshold. Compliance with this threshold is largely due to the management measures taken, in particular the prefectural decrees that have limited pumping from 2005 (Lepercq & Dupeuty, 2020).

In addition, the Sèvre Niortaise and Curé catchments area also show a significant drop in groundwater abstraction. In addition, the piezometers with the oldest rupture dates and those without ruptures are in this sector. These ruptures are therefore entirely due to the progressive implementation of water management measures in this region, as this sector contains only one reservoir. The oldest break was detected in 1991. This date corresponds to the promulgation of the 1992 Water Law, which led local politicians to implement water management measures to protect the marsh.

Finally, in the Mignon, Sèvre Niortaise and Curé sectors, measures to reduce water abstraction appear to have been more restrictive than in other regions. These sectors are currently the subject of a project for the construction of 16 substitution reservoirs (Coop de l'eau 79, 2021). These reservoirs would therefore complement the restrictions already in place and provide a solution for farmers to be less constrained by pumping restrictions.

To conclude, the temporal analysis of the standardized monthly average levels highlighted the positive impact of the water management measures on the level of the water tables in summer. However, the periods considered, between the date of the rupture and the installation of the reservoirs, are very short. Thus, the observations made during this period are more influenced by the meteorological conditions. For example, the important drop in the groundwater level observed in January between 2006 and 2009 coincides with a deficit of winter rainfall during this period. Similarly, the years 2012-2014 were relatively wet, which could bias the interpretation of the rise in the piezometric level in summer during this period. Furthermore, these analyses have also made it possible to identify the influence of the substitution reservoirs on the level of the water tables. In particular, a drop in winter levels has been observed compared to the period prior to the installation of the reservoirs, which can be explained by the fact that they pumped groundwater in winter. Finally, the substitution reservoirs were set up in addition to the water management measures and have helped to maintain higher levels in summer.

3.4 Limitations and Challenges

This work has several limitations. The first is data availability. Pumping data are only available from 2008, which prohibits any analysis prior to that date. However, many water management measures were implemented well before that date and significant changes in the piezometric series are visible from 2006 onwards. For instance, in the Marais Poitevin, it is known that the volume of water used for irrigation decreased by 22 % between 2005 and 2009 (Michel, 2023). It is therefore not possible to analyze how these measures affect the volumes of water abstracted before 2008. Furthermore, the change in the volume pumped between 2008 and 2022 was not subjected to statistical tests to assess the significance of these trends. The use of such tests would have provided a better understanding of whether the observed variations result from natural fluctuations or real changes induced by water management measures and substitution reservoirs.

Moreover, the pumping data do not take into account the seasonal variations of pumping. However, it is important to be aware of these variations, as water measures change from month to month. Moreover, as the reservoirs only pumped between November and March, the current data do not allow an analysis of the evolution of withdrawals within the same year under the influence of these reservoirs.

In addition, not all farmers declare the volumes they extract. Only extractions above 7000 m^3 are subject to declaration, which means that the total volume extracted is likely to be underestimated. Moreover, press articles report the existence of illegal pumping, which is regularly sanctioned, adding to the uncertainty about the actual volumes used (Roche, 2022).

Then, the available data on irrigated areas only cover three decades, which makes it difficult to analyze long-term trends. In addition, it is difficult to assess the evolution of irrigated area throughout the Marais Poitevin because some of this data is subject to statistical confidentiality for certain communes.

As a result, there are several possibilities for further study. Firstly, many of the substitution reservoirs visible in the satellite images are neither monitored nor declared. These are likely to be reservoirs owned by private farmers. A more detailed study of this issue would make it possible to assess their impact on water resources and enrich the analysis. Secondly, only 27 piezometers were analyzed here. The analysis of additional piezometers would strengthen the interpretation of the piezometric series and provide a more complete view of the evolution of groundwater levels. Furthermore, only one rupture was analyzed per piezometric series, even though other ruptures occurred at different times. Studying these secondary breaks would allow for a more in-depth analysis of the influence of the various water management measures on groundwater levels. Lastly, river flows were not analyzed in this study. This analysis could enrich the understanding of the hydrological situation in the Marais Poitevin.

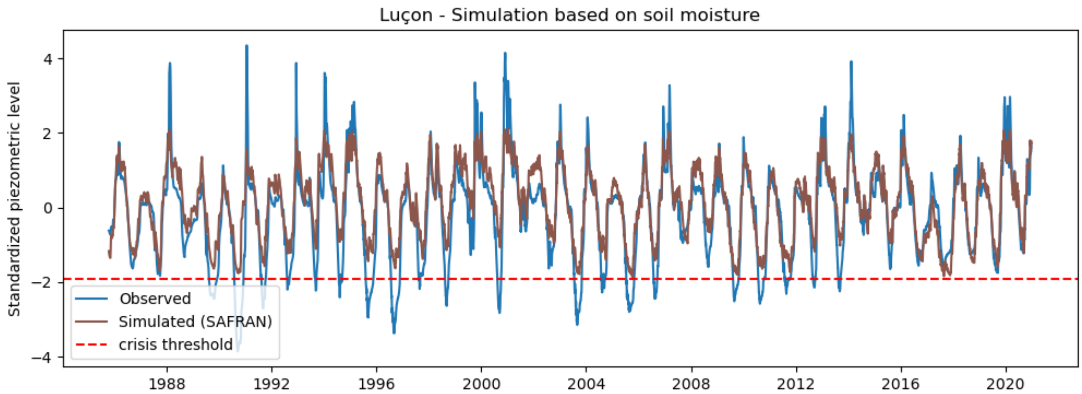
4 Results and Discussion - Climate change

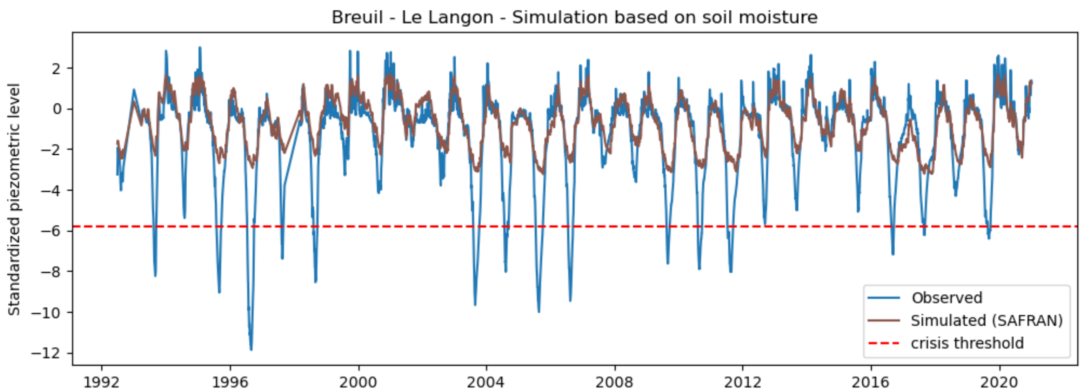
The main objective of this part is to evaluate the efficiency of the substitution reservoirs in the future. This section presents the results obtained for the two approaches to reproduce the water tables levels based on hydrological variables simulated by the ORCHIDEE model. The first part presents the results of the simulations based on SAFRAN historical meteorological data, for three piezometers: Luçon, Breuil-le-Langon and St-Coutant, which monitors free water tables. The observed piezometric series for each are displayed in Figure 49 in the Appendix. The second part presents the results obtained under future climate projections with the RCP8.5 radiative forcing scenarios up to 2100, for the Luçon piezometer only.

4.1 Historical simulation of piezometric level

4.1.1 Simulation of piezometric levels based on soil moisture

The first simulation consists of using the soil moisture simulated by ORCHIDEE as an indicator of the natural level of the water table. The observed and simulated piezometric series were standardized over a common period with minimal influence from pumping. Specifically, the standardization periods were 2015-2020 for the Luçon piezometer, and all months from November to March from 1992 to 2020 for the Breuil-le-Langon piezometer. For the St-Coutant piezometer, the standardization was performed over the entire period because it is less impacted by summer pumping. The corresponding simulated and observed series are presented in Figure 33, and the match with observed values is summarized in Table 3.





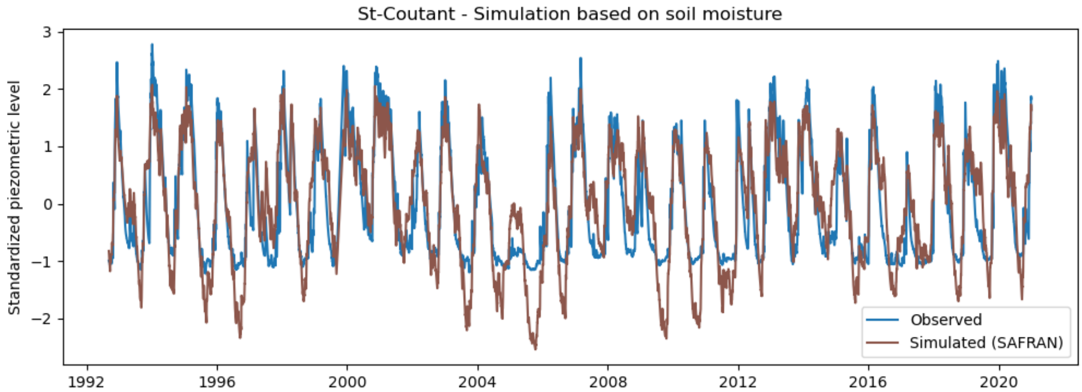


Figure 33: Simulation of three piezometric series based on soil moisture. Standardization period: Luçon (2015-2020); Breuil-le Langon (Nov to Mar from 1992 to 2020); St-Coutant (1992-2020)

Piezometer	**Whole period**	**Standardization period**		**Filling period**
		NS	Period	
Luçon	0.77	0.86	2015-2020	0.73
Breuil - Le Langon	0.51	0.65	November to March (1992-2020)	0.65
St-Coutant	0.73	0.73	Whole period	0.75

Table 3: Nash-Sutcliffe coefficients obtained for the water table level simulation based on soil moisture along different periods, for the three pizeometers.

These results show that soil moisture simulated by ORCHIDEE provide an acceptable indication of the groundwater level, especially if we keep in mind that the observed levels are severely impacted by pumping, overlooked in ORCHIDEE. In particular, at the Luçon piezometer the Nash-Sutcliffe coefficient is about 0.77 over the whole period. However, the simulation is less accurate for the Breuil-Le Langon piezometer with a Nash-Sutcliffe coefficient of 0.51. For these two piezometers, the summer levels are less successfully simulated. This is attributable to the fact that the simulation does not take into account irrigation. A more in-depth examination of the correlation between the simulated and observed values reveals that the model overestimates the lowest observed levels (see Figure 34) for the Breuil-Le Langon and Luçon piezometers.

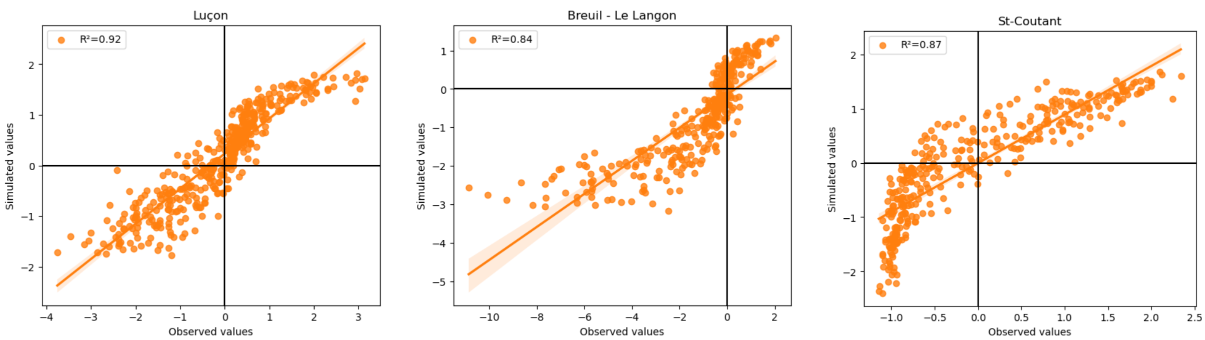


Figure 34: Correlation between simulated and observed standardized monthly average piezometric levels (based on soil moisture)

In contrast, soil moisture appears to be less consistent for St-Coutant piezometer. Despite a high Nash-Sutcliffe coefficient, the soil moisture does not accurately reflect the water table during the summer months, which is underestimated by the model. Unlike the situations observed in Luçon and Breuil-Le Langon, Saint-Coutant is less affected by pumping. Consequently, the summer level should have been well represented by the ORCHIDEE model. Thus, the soil moisture simulated by the model is not a good indicator of the level of the water table in this case.

Finally, the piezometric levels during the substitution reservoirs recharge period, from November to March, are adequately simulated for these three piezometers.

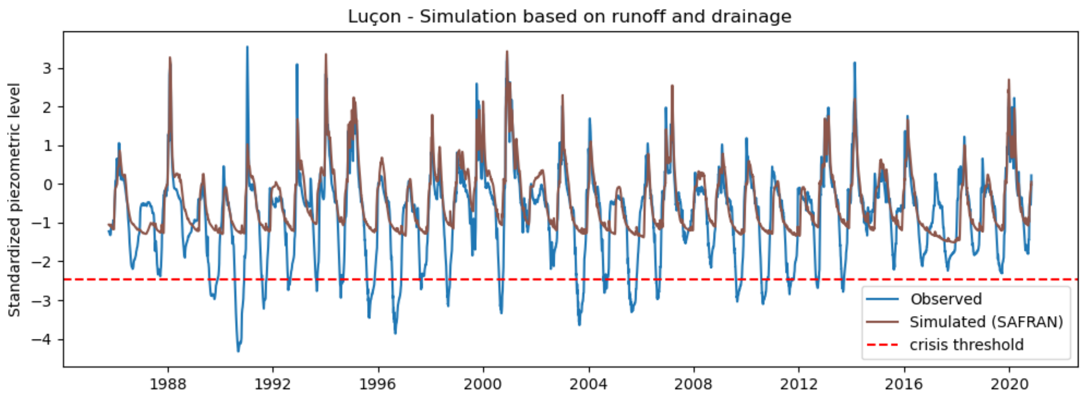
4.1.2 Simulation of piezometric levels based on surface runoff and drainage

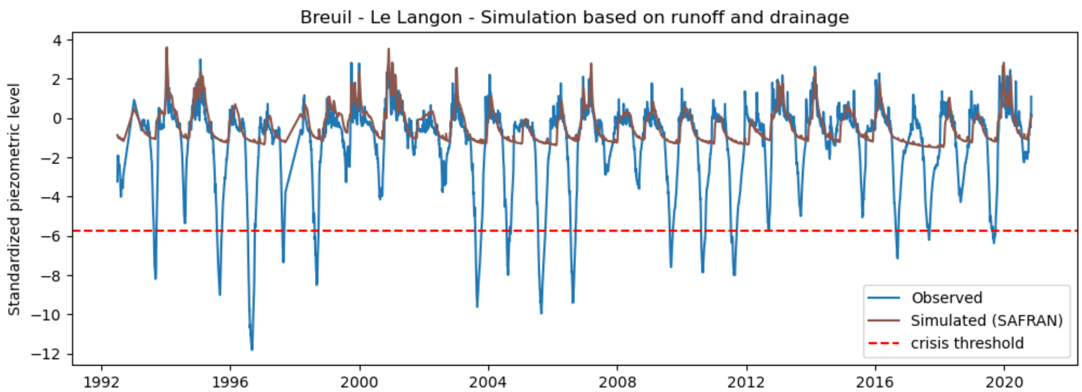
The second simulation consists of simulating the groundwater levels using a linear reservoir model with surface runoff and drainage simulated by ORCHIDEE as input data. Subsequent to calibration, Table 4 provides a summary of the values of the linear reservoirs parameters for the simulations of the three piezometers. The table provides the time constants of the reservoirs, the proportion of surface runoff allocated to the first reservoir and the time-lag of the drainage.

Piezometer	**K1 (day)**	**K2 (day)**	α	**Time lag of drainage (day)**
Luçon	9	9	0.08	60
Breuil-Le Langon	6	6	0.08	60
St-Coutant	15	8	0.08	60

Table 4: Values of the parameters of the linear-reservoir model obtained after calibration

In this case, Luçon is standardized on the filling period (November to March) because the initial standardization period 2015-2020 turns out to be a period in which the drainage simulated by ORCHIDEE fails (Figure 35).





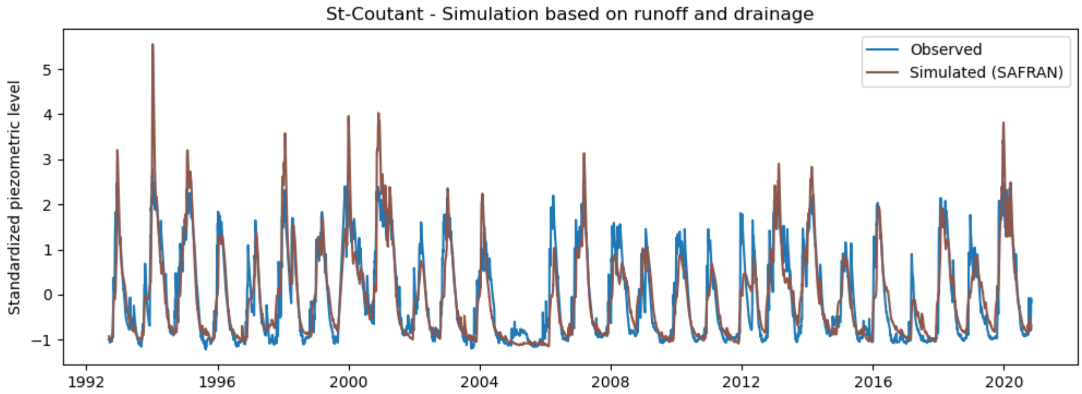


Figure 35: Standardized simulation of piezometric series based on surface runoff and drainage for the three piezometers. Standardization period: Luçon (Nov to Mar from 1987-2020); Breuil-le Langon (Nov to Mar from 1992 to 2020); St-Coutant (1992-2020)

In this simulation, the piezometric level at the Luçon and St-Coutant piezometers is successfully simulated with relatively high Nash-Sutcliffe values as shown in the table 5 below. However, the piezometric level at Breuil-Le Langon is less well simulated with a Nash-Sutcliffe value of 0.13 over the whole period.

Piezometer	**Whole period**	**Standardization period**		**Filling period**
		NS	Period	
Luçon	0.57	0.69	November to March (1987-2020)	0.69
Breuil - Le Langon	0.13	0.38	November to March (1992-2020)	0.38
St-Coutant	0.78	0.78	Whole period	0.64

Table 5: Nash-Sutcliffe coefficients obtained for the water table level simulation based on surface runoff and drainage.

Finally, the correlation between the observed and simulated values shows an overestimation of the lowest and highest levels, and an underestimation of the average levels, for the piezometers influenced by pumping, namely Luçon and Breuil-Le Langon (Figure 36). Conversely, for the St-Coutant piezometer, the relationship between the observed and simulated values is almost linear. Compared to the first simulation, this one is more accurate in reproducing the level of the water table in Saint-Coutant.

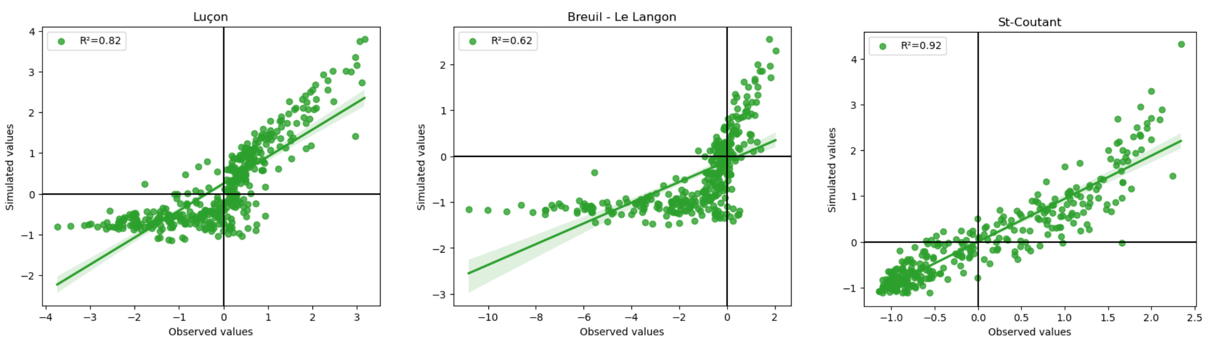


Figure 36: Correlation between simulated and observed standardized monthly average piezometric levels (based on surface runoff and drainage)

An important aspect of this work is to try to reproduce the level of the water table as closely as possible during the filling of the reservoirs. The filling period is from November to March and is only possible if the level of the water table is above the filling threshold. The filling threshold is not constant over the filling period and is defined according to the groundwater recharge period. Figure 37 shows the filling threshold for the Luçon piezometer.

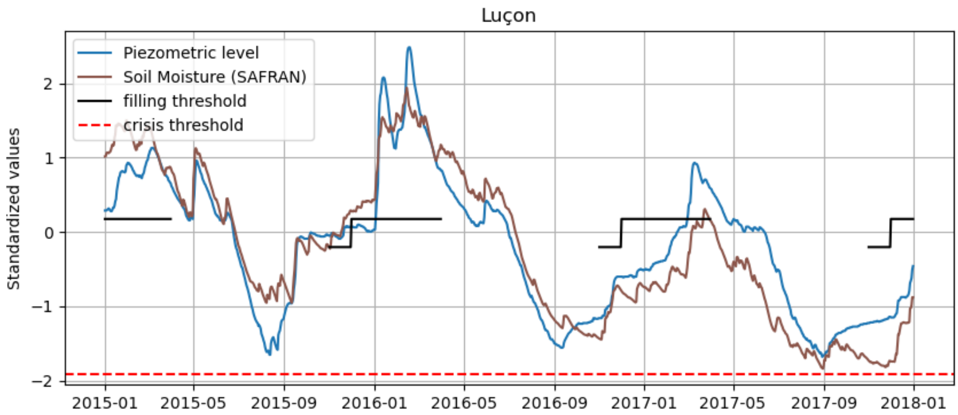


Figure 37: Standardized piezometric level at Luçon piezometer : in-depth observation of the filling threshold

Figure 38 shows the percentage of days when the substitution reservoirs can be filled with respect to the number of filling days, as observed and simulated at the Luçon piezometer. It is observed that this percentage is well reproduced by both types of simulation. However, it is noticeable that the simulation based on surface runoff and drainage seems to underestimate the filling percentage. Furthermore, it should be noted that in 2017, it was almost impossible to fill the reservoirs. In addition, between 1985 and 1993, even if there were no reservoirs in the Marais Poitevin, it would not have been possible to fill them either.

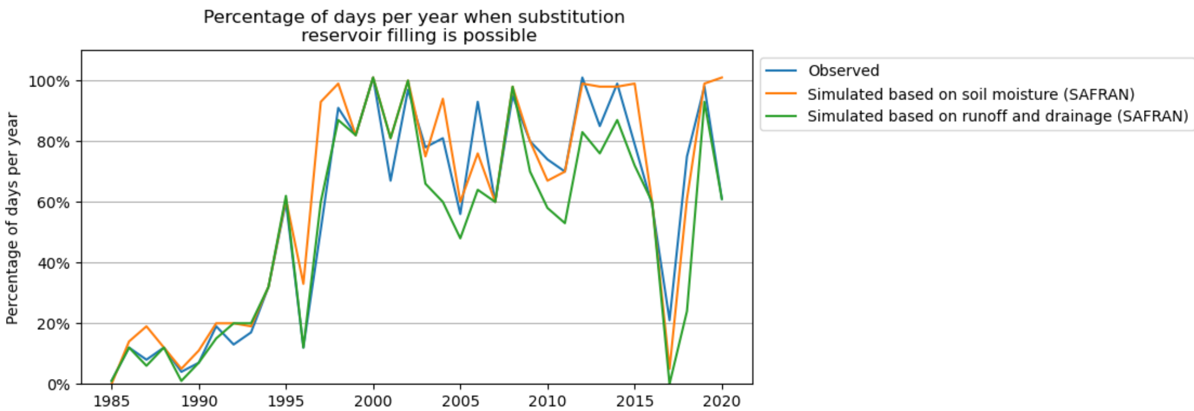


Figure 38: Percentage of days per year when substitution reservoirs filling is possible at Luçon piezometer (% with respect to the number of days of the filling period)

In conclusion, Table 6 below compares the Nash-Shutcliffe coefficients obtained for the two simulations. Both approaches are appropriate for the simulation of the piezometric level at the Luçon piezometer. However, the first simulation is more accurate for Breuil- le Langon piezometer, while the second is more accurate for St-Coutant piezometer.

Piezometer	Altitude	Type of simulation	Whole period	Filling period
Luçon	8 m	Simulation 1	0.77	0.73
		Simulation 2	0.57	0.69
Breuil - Le Langon	4 m	Simulation 1	0.51	0.65
		Simulation 2	0.13	0.38
St-Coutant	133 m	Simulation 1	0.73	0.75
		Simulation 2	0.78	0.64

Table 6: Nash-Sutcliffe coefficient obtained for both simulations (simulation 1: based on soil moisture, simulation 2: based on surface runoff and drainage)

4.2 Future simulation of piezometric levels by 2100

The final section of this study presents future simulations of groundwater levels at the Luçon piezometer, based on four climate projections for the RCP8.5 emission scenario. These projections were selected as part of the Explore2 project and cover a wide range of scenarios, from the wettest to the driest. Each climate scenario is represented by a color code, in accordance with the Explore2 methodology (Marson et al., 2024) :

- Orange scenario: ECEarth.HadREM3
- Purple scenario: HadGEM2.CLM4
- Green scenario: HadGEM2.ALADIN
- Yellow scenario: CNRMCM5.ALADIN

4.2.1 Simulation of piezometric levels by 2100 based on soil moisture

Figure 39 shows, for each climate change scenario, the average, minimum and maximum annual soil moisture projected by ORCHIDEE by 2100 in the grid cell containing the Luçon piezometer. First of all, the 'orange' scenario is the one in which the average annual soil moisture decreases the most significantly by 2100. The 'purple' and 'green' scenarios, which are considered to be intermediate, show an equivalent decrease in soil moisture but less marked than in the 'orange' scenario. Finally, the 'yellow' scenario, which represents the wettest conditions, shows a decrease in minimum annual soil moisture, while maximum annual soil moisture tends to increase.

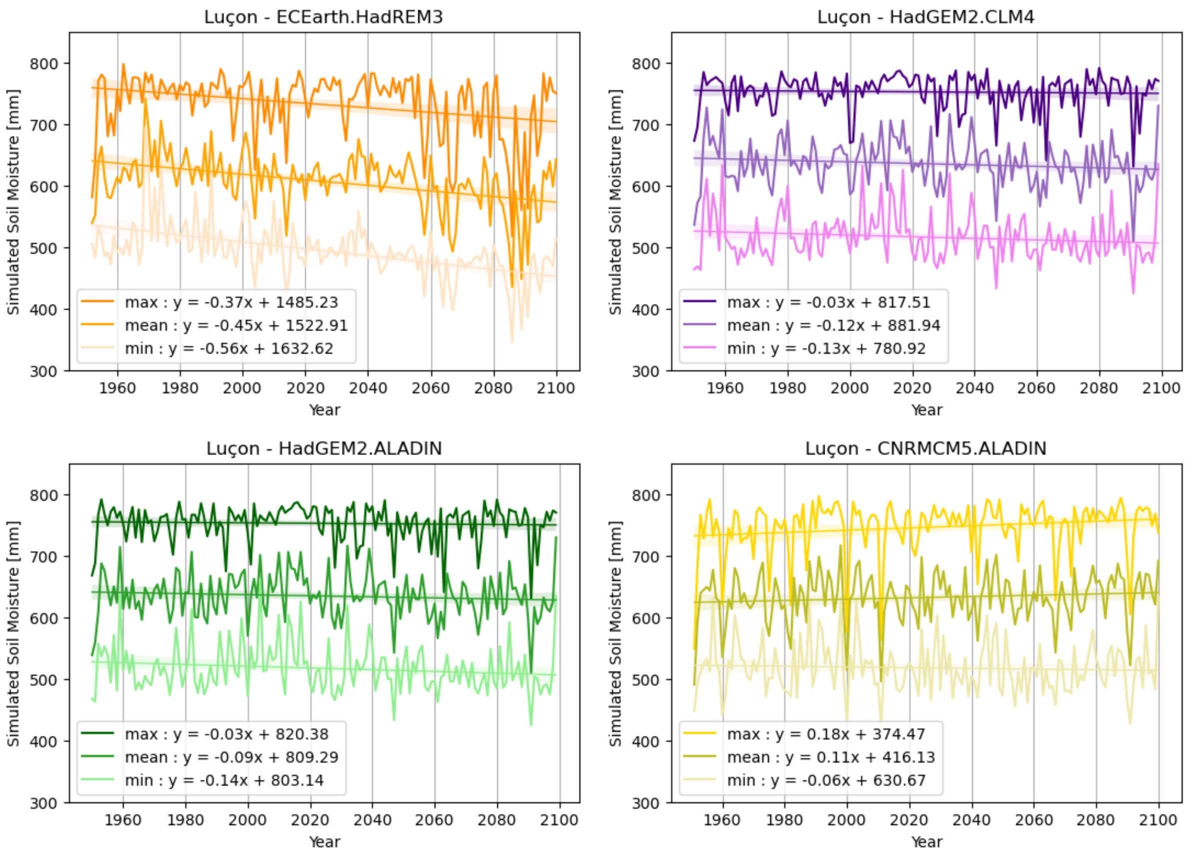
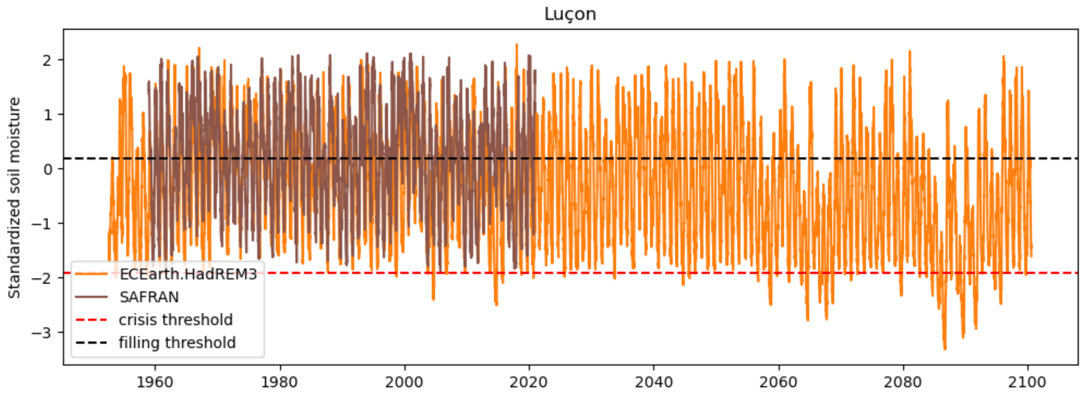
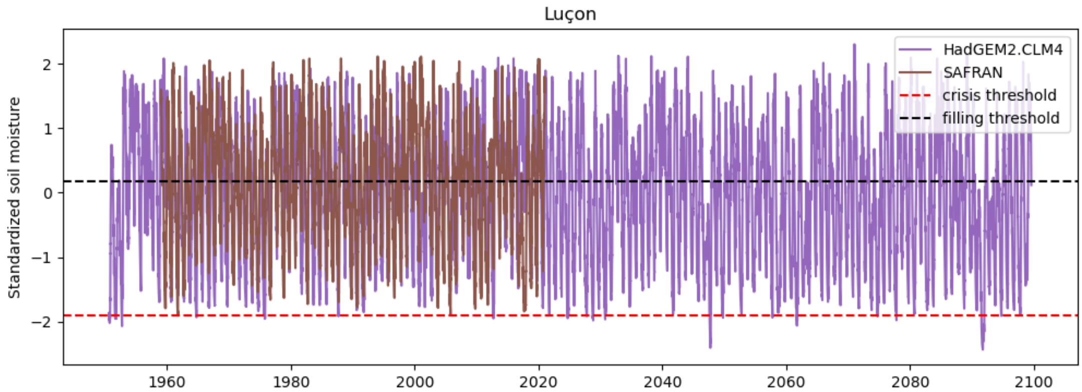
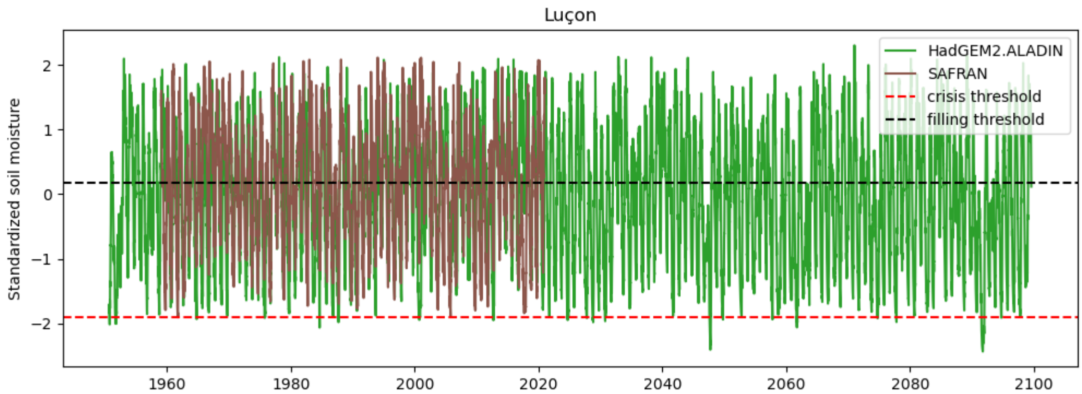


Figure 39: Projected simulated soil moisture at the Luçon piezometer

The soil moisture simulated by ORCHIDEE has been shown to be a reliable indicator of historical water table levels, and is thus used here to assess their future evolution. As seen previously, the standardization period that offers optimal conditions is the 2015-2020 period at the Luçon piezometer. The average and standard deviation of the SAFRAN historical series over this period are therefore used as a reference to standardize the four scenarios. They are respectively 638 mm and 38 mm. As mentioned in the method the climate scenarios do not exhibit the same interannual variations. Therefore, they do not necessarily exhibit equivalent mean values over the short 2015-2020 period. For instance, the 'orange' scenario exhibits an average humidity of 606 mm over the 2015-2020 period, while the 'purple' scenario displays a higher average of 663 mm. The average and standard deviation of SAFRAN over the period 2015-2020 are therefore used to standardize the climate projections, which helps to center the two standardized times around the same zero over the full historical period.


Luçon
Standardized soil moisture
ECEarth.HadREM3
SAFRAN
crisis threshold
filling threshold
1960
1980
2000
2020
2040
2060
2080
2100


Luçon
Standardized soil moisture
HadGEM2.CLM4
SAFRAN
crisis threshold
filling threshold
1960
1980
2000
2020
2040
2060
2080
2100


Luçon
Standardized soil moisture
HadGEM2.ALADIN
SAFRAN
crisis threshold
filling threshold
1960
1980
2000
2020
2040
2060
2080
2100

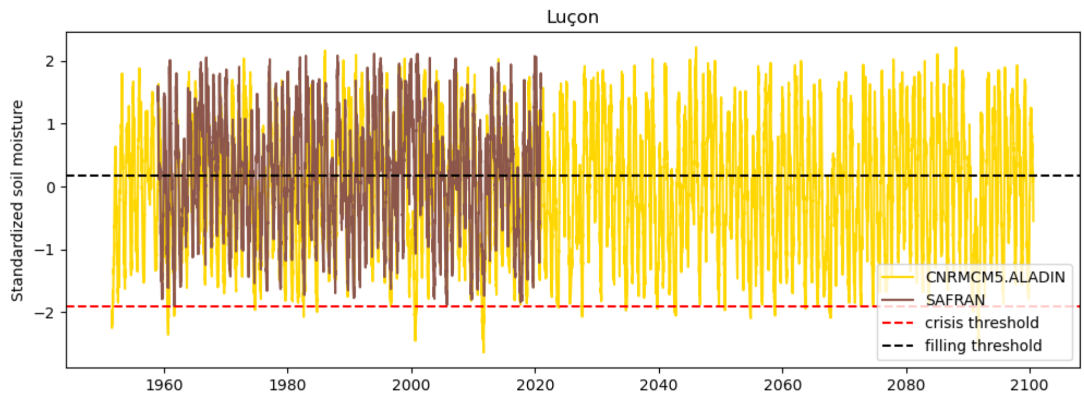


Figure 40: Standardized simulated projected piezometric level based on soil moisture at Luçon piezometer. Standardization period: 2015-2020

Standardised future projections and historical SAFRAN data for the Luçon piezometer are presented in Figure 40. A visual inspection of the four scenarios reveals that the projected piezometric levels will exceed the crisis threshold in the future, which is not the case under the SAFRAN historical forcing. This excess is more pronounced in the 'orange' scenario, as confirmed by Figure 41, showing that the crisis level is exceeded during 19 % of days per year in 2080-2100 for the 'orange' scenario, compared to 1 % for the other scenarios. Note that 19 % of the year corresponds to 76 % of the summer season (three months).

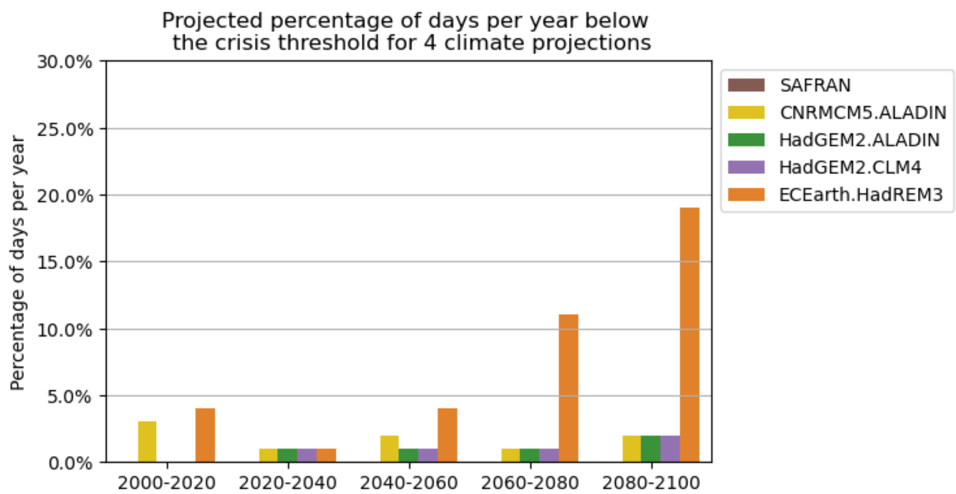


Figure 41: Projected percentage of days per year below the crisis threshold for the four climate projections at Luçon piezometer

4.2.2 Simulation of piezometric levels by 2100 based on surface runoff and drainage

The long-term trends of the simulated piezometric series of Luçon obtained from the linear reservoir model fed by surface runoff and drainage from ORCHIDEE are presented in Figure 43. These simulations are obtained by applying the same calibration performed with the historical SAFRAN series.

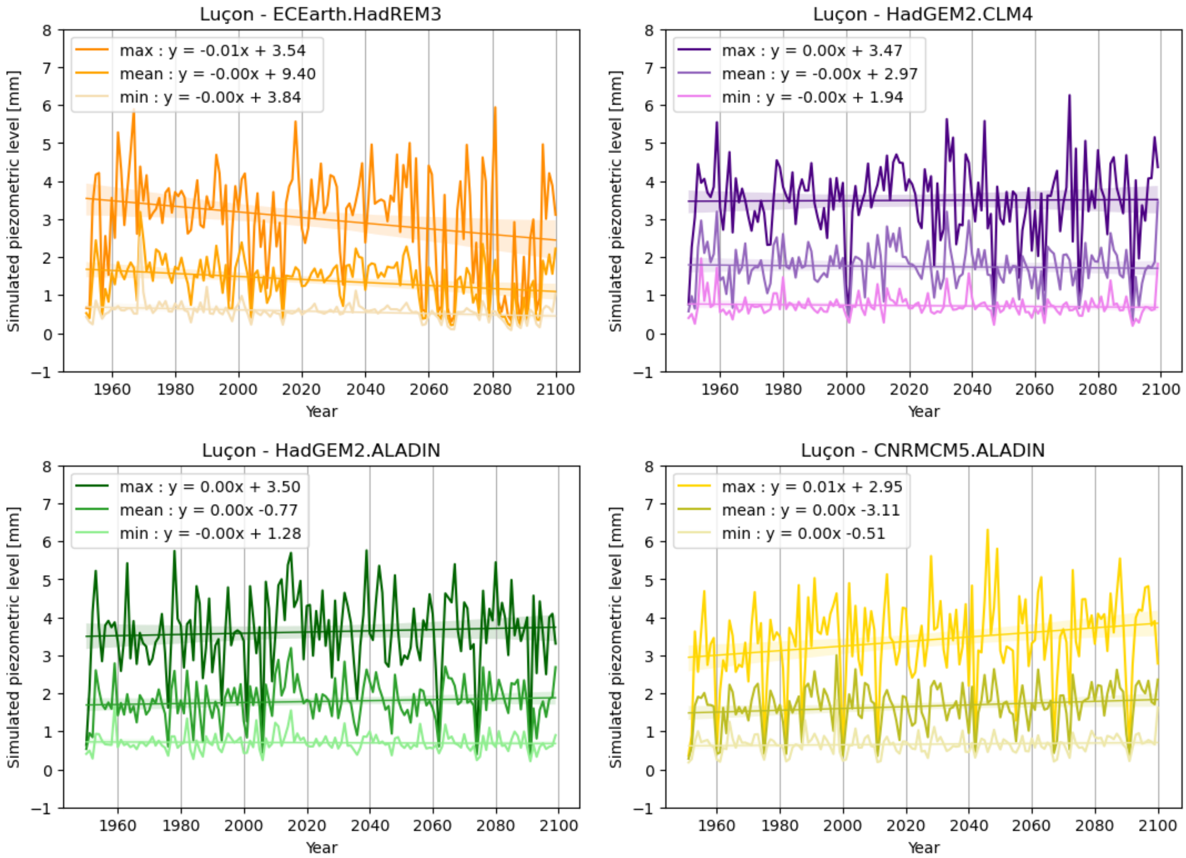
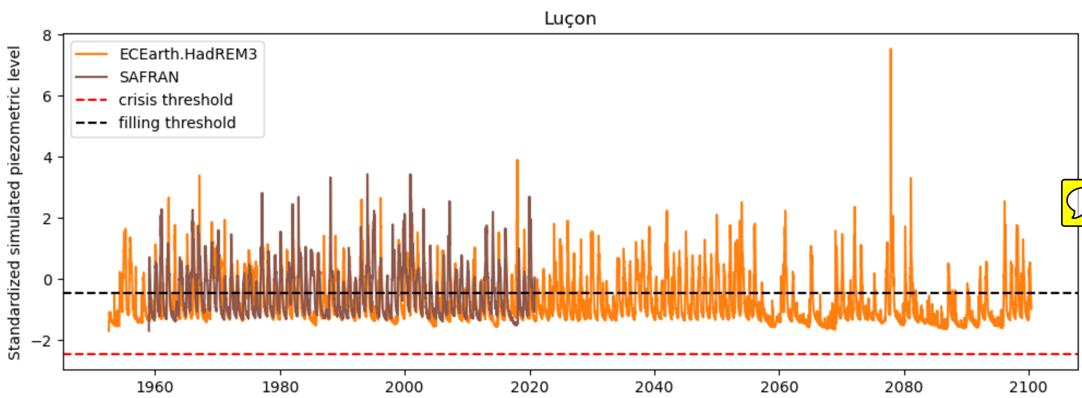


Figure 42: Projected simulated piezometric level based on surface runoff and drainage at Luçon piezometer

In this simulation, the trends are less marked than in the previous simulation. In this case, an augmentation in the mean annual groundwater level is to be expected for the 'green' and 'yellow' scenarios, while a diminution in mean levels is projected for the 'orange' and 'purple' scenarios. The piezometric level projections have been standardized with the mean and standard deviation of the SAFRAN historical simulation over the filling period from 1992 to 2020 which is the best standardization period for this simulation in order to minimize the effect of pumping. They are represented in the figure 43 below for the Luçon piezometer. It can be observed that, the crisis level is never reached in this simulation.



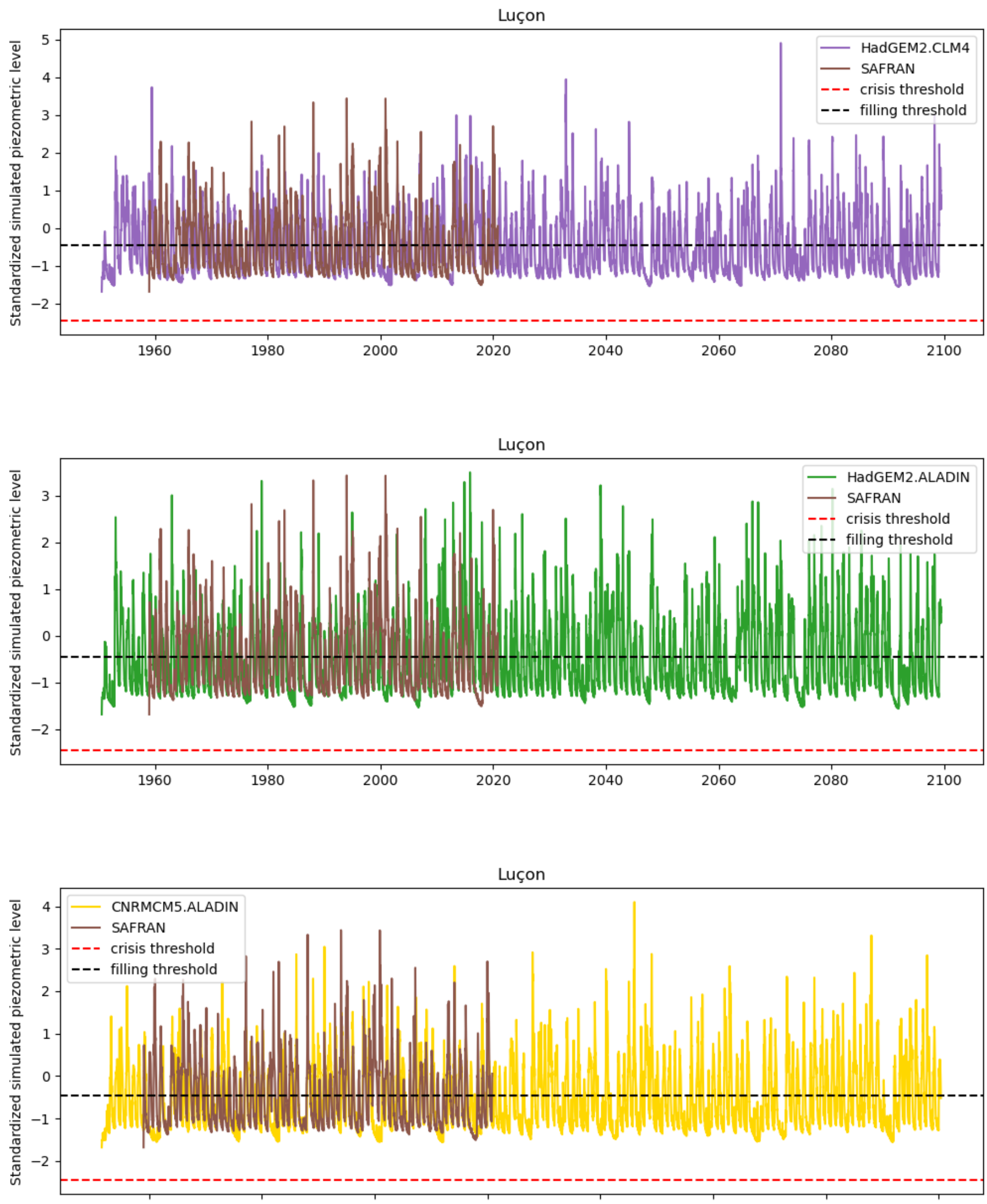


Figure 43: Standardized simulated projected piezometric level based on surface runoff and drainage at Luçon piezometer. Standardization period: November to March from 1987 to 2020

4.2.3 Projected filling period of the substitution reservoirs for the four climate scenarios at Luçon piezometer

Figure 44 shows, for each simulation, the percentage of days when the substitution reservoirs at the Luçon piezometer can be filled with respect to the number of filling days, while Figure 45 illustrates the change in the number of days when filling is possible in comparison with the 2000-2020 period.

Firstly, for the 'orange' scenario, the period 2080-2100 shows that filling is possible 35 % of the time with respect to the filling period for the first simulation and 28 % for the second. This corresponds respectively to a decrease of 25 % and 19 % compared to the 2000-2020 period. For the 'green' and 'purple' scenarios, the decrease is respectively 22 % and 18 % compared to 2000-2020 period for the first simulation and 13 % and 11 % respectively for the second simulation. Finally, the 'yellow' scenario, corresponding to the wettest conditions, indicates an increase of 14 % (first simulation) and 15 % (second simulation) in 2080-2100 compared to 2000-2020.

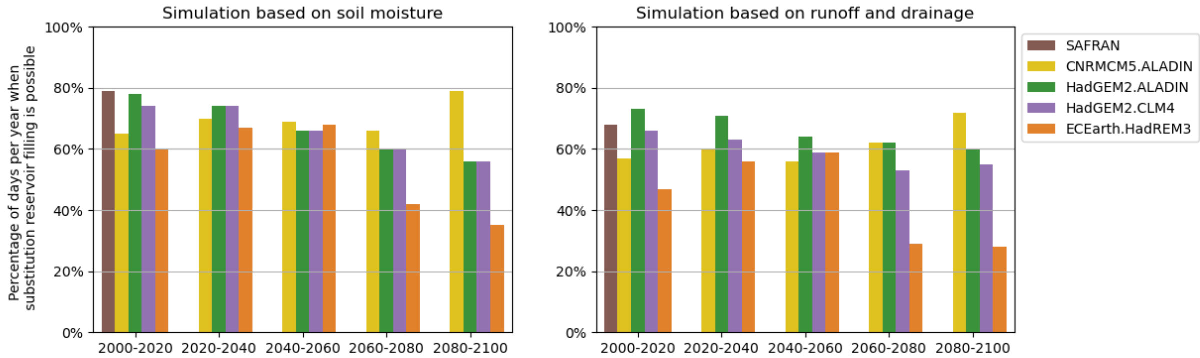


Figure 44: Luçon piezometer: evolution of the number of days per year when substitution reservoir filling is possible for the four climate projections (% with respect to the number of days of the filling period)

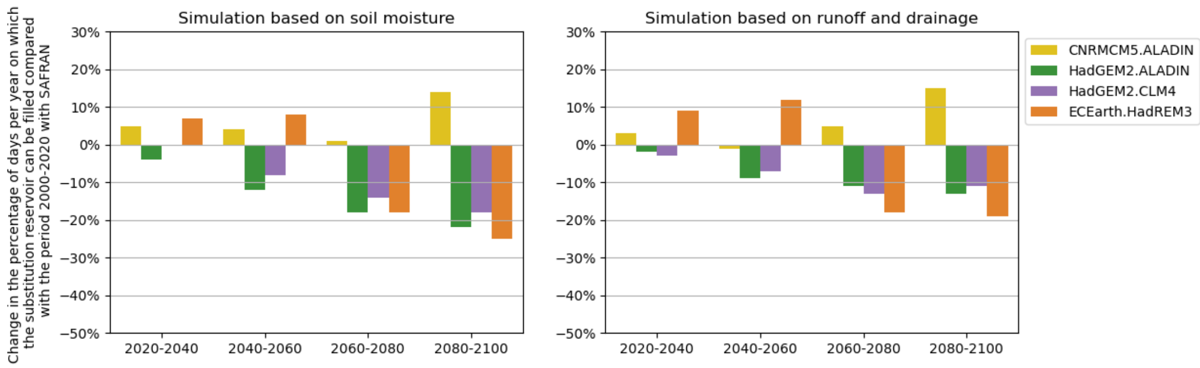


Figure 45: Change in the percentage of days per year on which the substitution reservoir can be filled compared with the period 2000-2020 (% with respect to the number of days of the filling period)

4.3 Discussion

The above results demonstrate that the soil moisture simulated by ORCHIDEE is a good indicator of the natural level of shallow water tables. The model manages to reproduce not only the average level of the water tables, but also the level during the filling period. The performance coefficients obtained for the filling period are satisfactory, thus allowing a relatively reliable simulation of the number of substitution reservoirs filling days.

However, the accuracy of the simulation varies according to the piezometers. Specifically, the simulations at the Luçon piezometer demonstrates superior performance in comparison to the Breuil-Le Langon piezometer. This difference is even more pronounced when the simulation is based on drainage and surface runoff. One hypothesis that may explain these disparities is based on the interaction between the water tables and the marsh. The proximity of the Breuil-Le Langon and Luçon piezometers to the marsh causes groundwater-marsh interactions (MEDD, 2007). Consequently, the water table is influenced by both rainfall and water from the marsh, thereby establishing a hydrological equilibrium between the marsh and the water table. This interaction appears particularly pronounced at Breuil-Le Langon, which is located at an altitude of only 4 meters, which is close to sea level. ORCHIDEE does not currently incorporate these interactions into its simulations, which can therefore skew the results, which is particularly evident in the performance of the simulations at the Breuil-Le Langon piezometer.

Additionally, it has been demonstrated that soil moisture does not serve as an effective indicator of the water table level at St-Coutant piezometer. The ORCHIDEE model calculates soil moisture for a soil depth of 2 m, while the St-Coutant piezometer measures at a greater depth. As a result, the residence time of water at St-Coutant is likely longer than the one simulated by ORCHIDEE. Consequently, for this piezometer, the simulation based on surface runoff and drainage is more suitable.

A main objective of this study is to accurately reproduce the evolution of the groundwater level during the substitution reservoir filling period, in order to assess their future effectiveness. The simulations demonstrate favorable outcomes for this period. For instance, in 2017, the filling of the reservoirs was almost impossible due to a lack of rainfall (Lenoiselee et al., 2021). Both simulations effectively captured this deficit and accurately estimated the number of days favorable for reservoirs filling.

Future projections reveal an increase in the crisis threshold being exceeded for the simulation based on soil moisture in the four climate scenarios, while the second simulation does not show any exceedance. One possible hypothesis is that the simulation based on soil moisture underestimates the level of the water table without irrigation in summer or that the second simulation overestimates the natural level of the water table. For the Luçon piezometer, the simulation of the water table level based on soil moisture is very accurate over the period 2015-2020, with a Nash-Sutcliffe coefficient of 0.86. This suggests that this approach better reproduces the current situation, although it may not reflect the natural state of the water table.

Finally, when the crisis threshold is reached, only priority uses, such as the supply of drinking water, are authorized. Farmers pumping directly from groundwater tables will therefore be more affected than those connected with substitution reservoirs. Furthermore, the crisis threshold has been estimated to be exceeded in a natural state of the water table. Substitution reservoirs will therefore not be a solution for raising the level above the crisis threshold in summer. Then, farmers connected to reservoirs will also be affected by climate change. The trends expected are the reduction in the number of filling days projected by 2100 in three out of four scenarios. Thus, if future weather conditions do not allow for sufficient filling of the reservoirs, these infrastructures will not constitute a reliable solution for ensuring the security of agricultural water in the future.

4.4 Limitations and Challenges

The ORCHIDEE model has certain weaknesses that sometimes make the simulations unreliable. This study has highlighted the limitations of the ORCHIDEE model in the simulation of hydrological variables. Studies conducted on the performance of this model have shown good performance in reproducing stream flow, with an efficiency of 76.4 % (Huang et al., 2024). Nevertheless, the simulation of drainage in ORCHIDEE is not representative of reality. The drainage is too weak and its consequent delay in relation to the observations in the study area are important. Consequently, the model occasionally fails to simulate drainage, resulting in periods without drainage, as evidenced by the Luçon piezometer mesh between 2016 and 2017. Consequently, further development of drainage simulations is recommended for future research.

Furthermore, ORCHIDEE tends to be more humid than other models, a phenomenon attributable to its incorporation of CO_2 in its evapotranspiration calculations. Consequently, an increase in CO_2 concentrations in the future is associated with a decrease in evapotranspiration in the model, thus favouring a more humid climate (Évin et al., 2024). Consequently, if drier models were considered, the observed trends may be amplified.

5 Conclusion

The present study aimed to analyze the long-term trends of piezometric series in order to evaluate the effectiveness of substitution reservoirs as a water management tool in the Marais Poitevin. The findings indicated that restrictions on agricultural pumping had a favorable impact, with a significant improvement in summer groundwater levels for most of the piezometers studied.

Substitution reservoirs were introduced to supplement these measures, allowing farmers to irrigate without being subject to pumping restrictions during the summer period. Nevertheless, the initial strategy set out in the 2003-2013 action plan for the Marais Poitevin (Etat Français, 2002) on substitution reservoirs was not aimed at increasing the irrigated area. However, the present study has shown that this infrastructure has contributed to an increase in irrigation of 6 % in the region while the volume pumped for irrigation has decreased by 11 % between 2010 and 2020.

Therefore, although substitution reservoirs appear to be a viable option at present, enabling irrigation while limiting the impact on groundwater in spring and summer, they do not appear to be a sustainable response to climate change. Projections under the RCP8.5 radiative forcing scenario indicate that the efficiency of substitution reservoirs may be limited in the long term, as their use is highly dependent on rainfall and therefore on groundwater recharge. The increased reliance of farmers on these reservoirs could thus prove problematic, as future climatic conditions could compromise their filling and, by extension, reduce irrigation capacities.

Furthermore, for all the climate projections studied, the piezometric threshold is expected to be exceeded to a greater extent. Thus, the increase in periods of drought in the future is likely to have a significant impact on farmers who pump directly from groundwater, with pumping restrictions likely to become increasingly severe if the current piezometric crisis thresholds are maintained. Substitution reservoirs will therefore not be a solution for raising the level above the crisis threshold in summer as the projection are made without irrigation. In this context, better adaptation to climate change would require in-depth reflection on the current agricultural model and a shift towards crops that require less water.

Finally, the next step of this work could be to develop a more local hydrological model that incorporates the geological formations and the interactions between the water table and the marsh, which would allow a more accurate simulation of groundwater levels. For instance, an improvement in the parameterization of ORCHIDEE to better correspond to local hydrology and correctly describe groundwater volumes would make it possible to simulate groundwater levels without using the indirect approaches used in this work. Therefore, better consideration of these factors would improve the relevance and understanding of the results obtained.

Then, this study focused on the quantitative impact of water management measures and substitution reservoirs on groundwater. Nevertheless, there are other aspects that merit exploration. Firstly, the impact of reservoirs filling on groundwater recharge and biodiversity has not been studied here. In addition, the evaporation losses from the reservoirs and the deterioration of the water quality could be analyzed in order to assess their economic and environmental consequences. A more comprehensive approach would thus facilitate a more precise identification of the advantages and disadvantages of this infrastructure and the consideration of alternatives that are better suited to the challenges posed by climate change.

6 Appendix

6.1 Table of fill and alert thresholds

Water managment zone	Piezometer	April 1st to May 31st	June 1st to September 11th	September 11th to October 31st
MP1	Pamproux	87.96	87.96	87.26
			87.4	87.16
		87.26	87.26	87.06
MP1	Saint Coutant	129.16	129.16	128.66
			128.75	128.51
		128.66	128.53	128.36
MP2	Saint Gelais	31	31	30
			30.5	29.5
		30	30	29
MP3	Niort	25	25	21.53
			23.5	20.78
		24	22	18.98
		17.88	17.88	17.88
MP6/MP5.4	Forges	17.16	16.9	12.6
			16.15	15.41
		16	16	15.21
MP7	Le Bourdet	12.22	12.22	11.22
			12.1	10.72
		12.02	12.02	10.22
MP7	Saint-Hilaire-la-Palud	3.59	3.59	2.4
			3.4	2.14
		3.29	3.29	1.75
MP10	Les Ajoncs à la Roche-sur-Yon	81.5	81.5	81.5
		80	80	80
MP12.1	Longeville sur Mer	1.55	1.55	0.35
		1.5	1.3	0.1
		1.2	1.10	0.01
		0	0	0
MP12.2	Luçon	2.05	2.05	0.75
		2	1.8	0.28
		1.7	1.5	0.21
		0.2	0.2	0.2
MP13.1	Saint Aubin la Plaine	2.35	2.35	1.05
		2.3	2	0.56
		2	1.65	0.51
		0.5	0.5	0.5
MP13.2	Breuil-Le Langon	2.05	2.05	1.45
		2	1.9	0.70
		1.8	1.650	0.52
		0.5	0.5	0.5
MP13.3	Doix	2.05	2.05	1.05
		2	1.6	0.56
		1.7	1.3	0.51
		0.5	0.5	0.5
MP14	Oulmes	4.65	4.65	3.05
		4.6	4	2.8
		3.55	3.1	2.51
		2.5	2.5	2.5
MP14	Aziré-Benet	1.65	1.65	1.65

(grey)	vigilance threshold
(yellow)	alert threshold
(orange)	reinforced alert threshold
(red)	crisis threshold

Figure 46: Water management thresholds (Etat Français, 2023)

Hydrological unit	Piezometer	Filling period (month/day)	Filling threshold [m NGF]
Autize	Grand Nati - Oulmes	▪ 01/11 – 29/02 ▪ 01/03 – 31/03	▪ > 4 ▪ > 4.6
Vendée	Doix	▪ 01/11 – 15/11 ▪ 16/11 – 30/11 ▪ 01/12 – 29/02 ▪ 01/03 – 31/03	▪ > 1 ▪ > 1.7 ▪ > 2 ▪ > 2.2
	Breuil – Le Langon	▪ 01/11 – 30/11 ▪ 01/12 – 31/12 ▪ 01/01 – 29/02 ▪ 01/03 – 31/03	▪ > 1.4 ▪ > 1.7 ▪ > 2 ▪ > 2.2
	Saint-Aubin-la-Plaine	▪ 01/11 – 30/11 ▪ 01/12 – 31/12 ▪ 01/01 – 29/02 ▪ 01/03 – 31/03	▪ > 1 ▪ > 1.5 ▪ > 2.3 ▪ > 2.5
Lay	Luçon	▪ 01/11 – 30/11 ▪ 01/12 – 31/03	▪ > 2 ▪ > 2.4
	Saint-Benoist sur Mer	▪ 01/11 – 31/01 ▪ 01/02 – 31/03	▪ > 2.4 ▪ > 2.5
Mignon, Courance, Guirande	Le Bourdet	▪ 01/11 – 31/01 ▪ 01/02 – 29/02 ▪ 01/03 – 31/03	▪ > 12.22 ▪ > 12.3 ▪ > 12.48
	Saint-Hilaire la Palud	▪ 01/11 – 30/11 ▪ 01/12 – 31/12 ▪ 01/01 – 31/01 ▪ 01/02 – 29/02 ▪ 01/03 – 31/03	▪ > 3.6 ▪ > 3.7 ▪ > 3.9 ▪ > 4 ▪ > 5

Figure 47: Filling thresholds in the Marais Poitevin (Lenoiselee et al., 2021)

6.2 Average standardized piezometric levels per month for the 27 selected piezometers

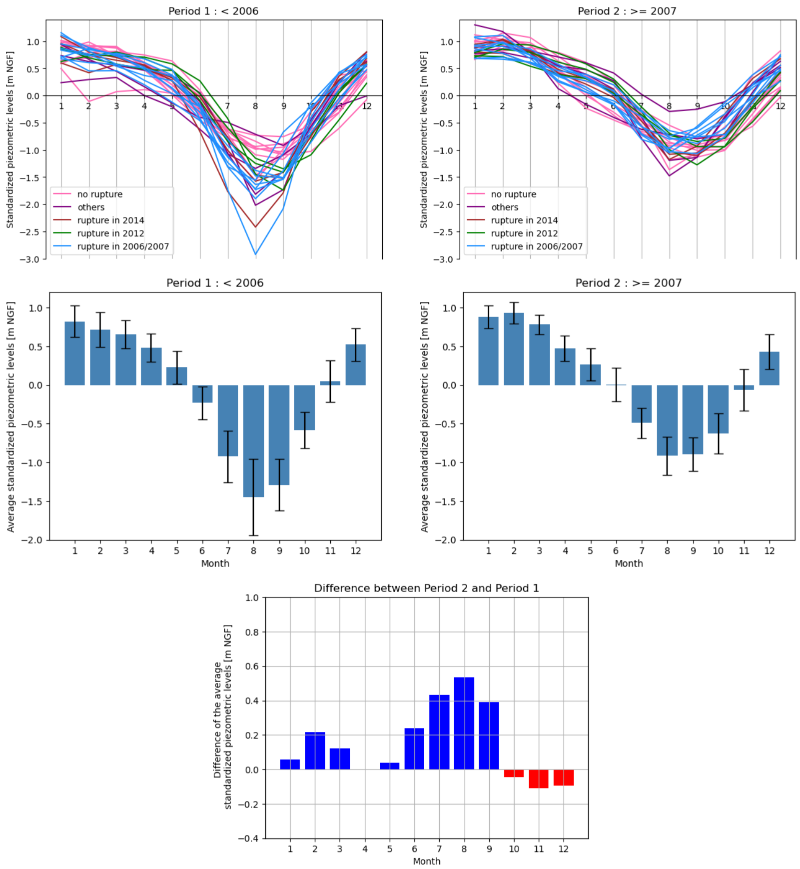


Figure 48: 27 selected piezometers: (1) Average standardized piezometric series per month over the three periods. (2) Average of the monthly averages of the standardized piezometric series for the three periods. (3) The differences of the average of the monthly averages of the standardized piezometric series between the three periods.

6.3 Piezometric time series

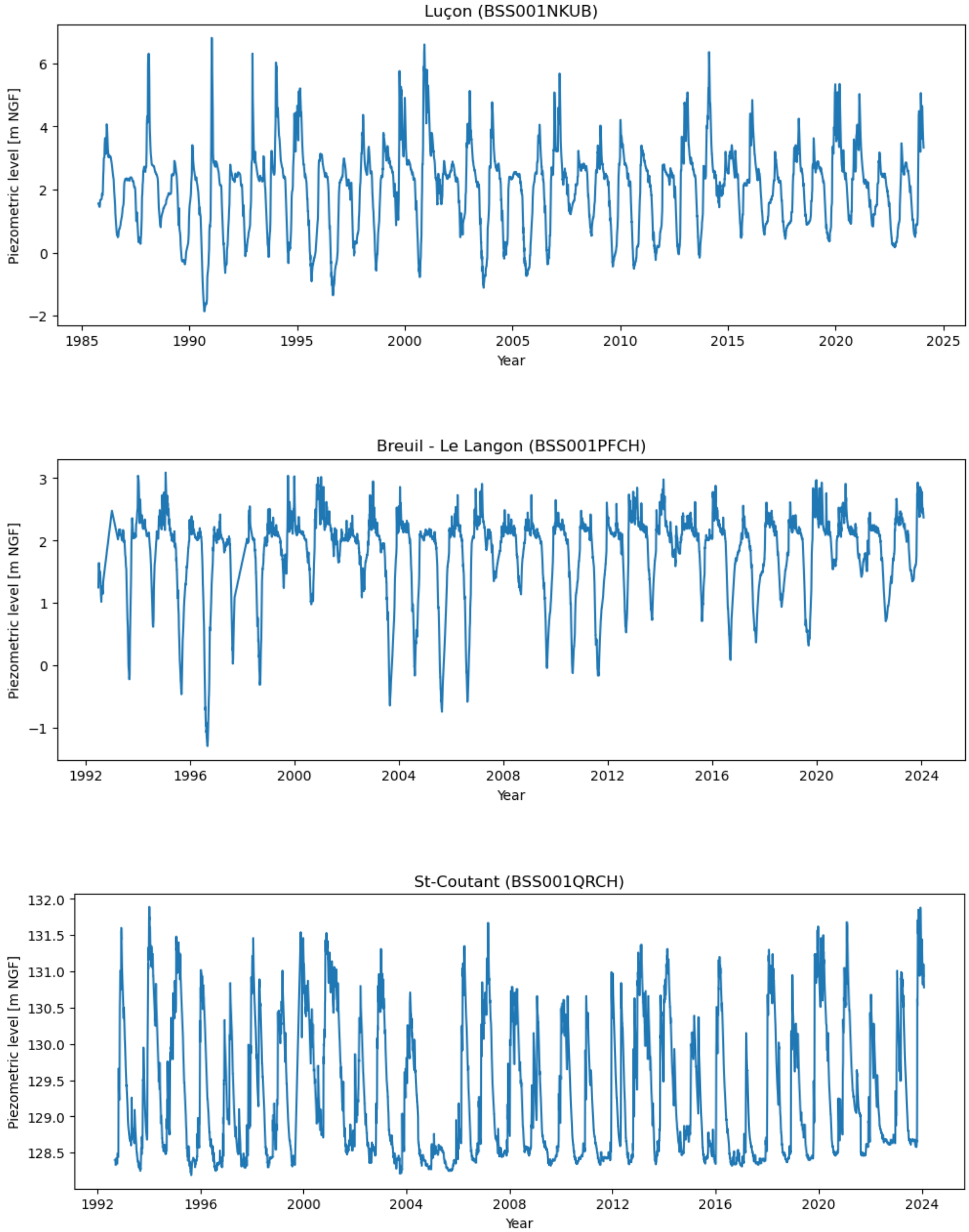


Figure 49: Piezometric time series for Luçon, Breuil-le Langon and St-Coutant piezometers

6.4 Future simulation of piezometric levels

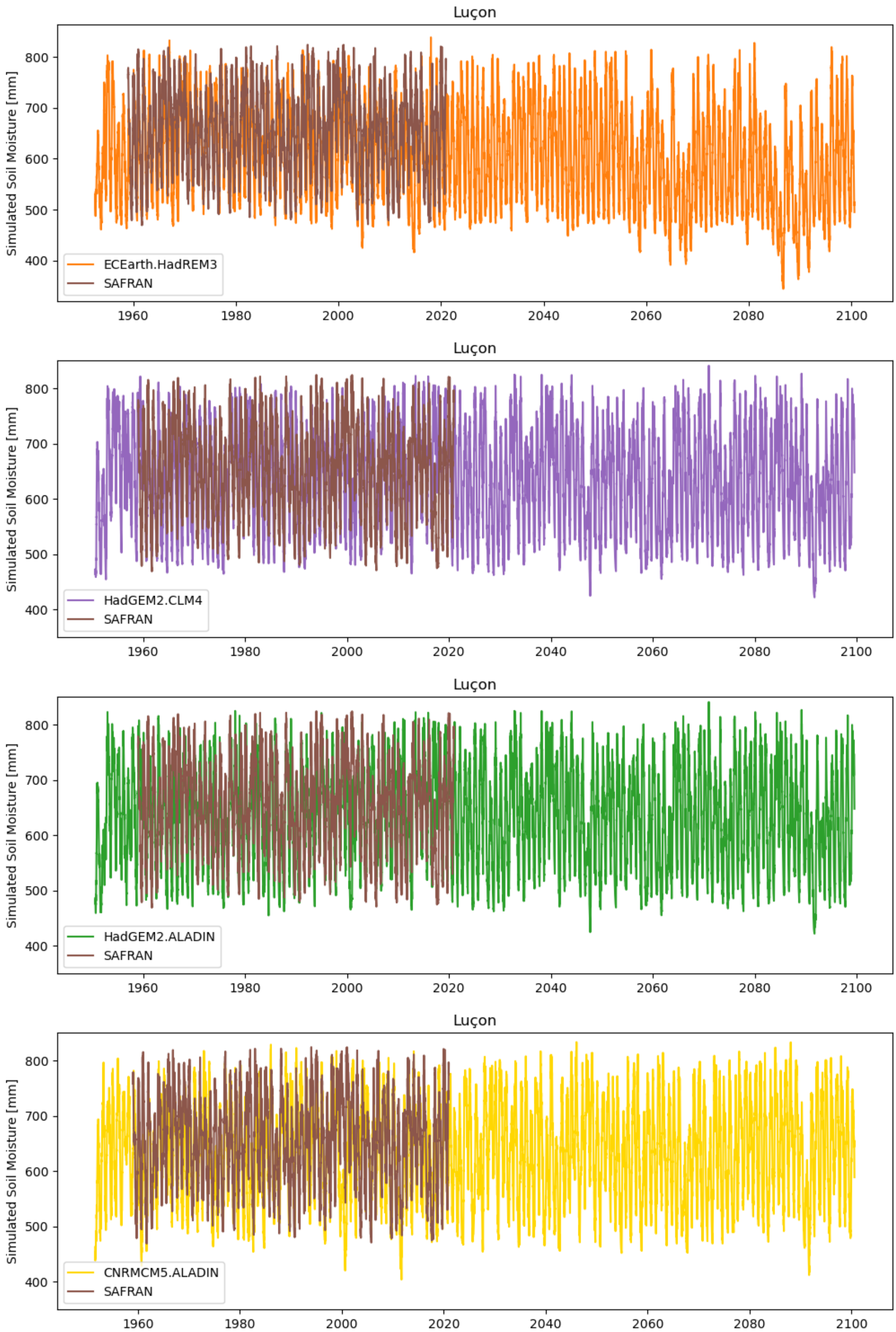


Figure 50: Simulated projected piezometric level based on soil moisture at Luçon piezometer

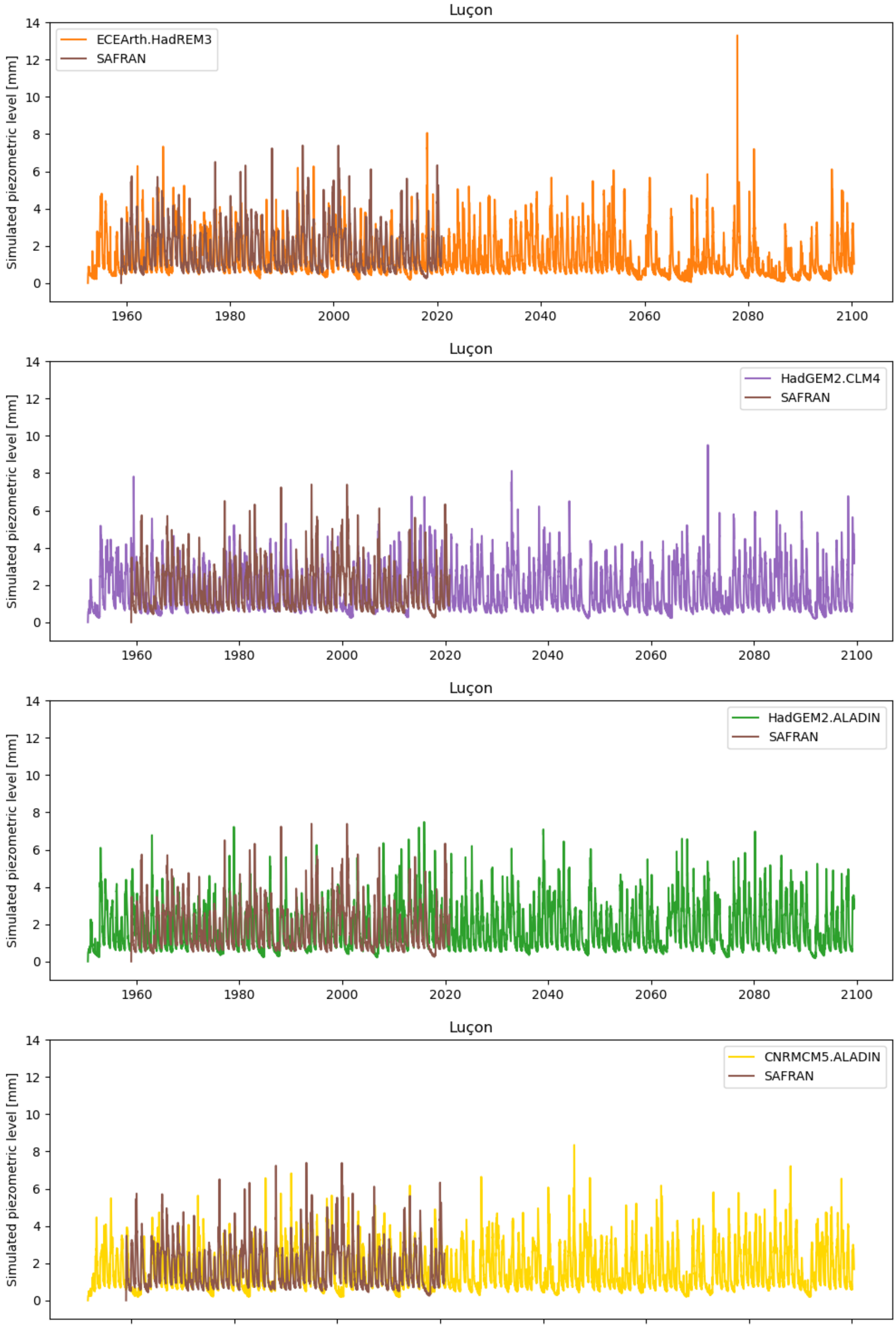


Figure 51: Simulated projected piezometric level based on surface runoff and drainage at Luçon piezometer

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