Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2

PILOT DESCRIPTION AND ASSESSMENT

Boutonne Basin (France)

Authors and affiliation:

Nadia Amraoui, Jean-Pierre Vergnes

French Geological Survey (BRGM)

Geoscience for a sustainable Earth

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

Deliverable Data	
Deliverable number	D3.2
Dissemination level	Public
Deliverable name	Pilot description and assessment report for groundwater-surface water
Work package	WP3
Lead WP/Deliverable beneficiary	GEUS (WP3)
Deliverable status	
Version	Version 2
Date	22/02/2021

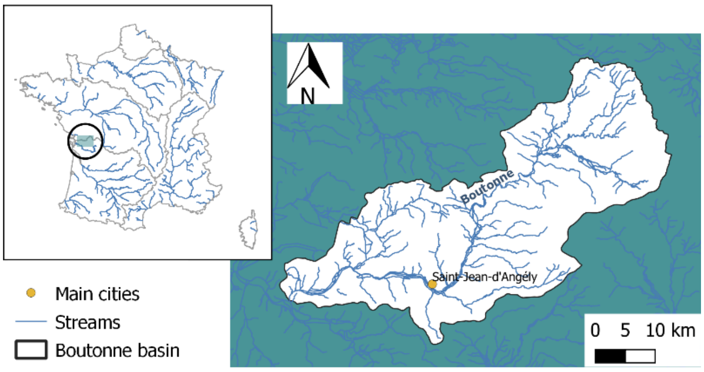
[This page has intentionally been left blank]

LIST OF ABBREVIATIONS & ACRONYMS

BDGSF	Base de Données Géographique des Sols de France
CC	Climate Change
DEM	Digital Elevation Model
EEA	European Environment Agency
FAO	Food and Agriculture Organisation of the United Nations
GCM	Global Circulation Model
GSOs	Geological Survey Organisations of Europe
IGN	Institut national de l'information géographique et forestière
ISIMIP	Inter Sectoral Impact Model Intercomparison Project
ME	Mean Error
NSE	Nash Sutcliffe Efficiency
PET	Potential evapotranspiration
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
SPLI	Standardized Piezometric Level Index
TACTIC	Tools for Assessment of Climate change ImpacT on Groundwater
SYMBO	Syndicat Mixte du Bassin de l'Or
OUGC	Organismes Uniques de Gestion Collective

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY

<table>
<tr><td>Pilot name</td><td>Boutonne basin</td><td rowspan="6">
</td></tr>
<tr><td>Country</td><td>France</td></tr>
<tr><td>EU-region</td><td>North Western Europe</td></tr>
<tr><td>Area (km^2)</td><td>1320</td></tr>
<tr><td>Aquifer geology and type classification</td><td>Limestones; fissured & karstifed aquifer</td></tr>
<tr><td>Primary water usage</td><td>Irrigation/Drinking water/Industry</td></tr>
<tr><td>Main climate change issues</td><td colspan="2">Climate variability and change influence groundwater systems and associated ecosystems both directly through recharge and indirectly through changes in groundwater use. Projected climate change might exacerbate the current tensions due to water scarcity in some sub-basin of south west of France like Charente basin. Indeed the Boutonne basin is experiencing an imbalance between available water resources and needs with important socio-economic issues for agricultural activities. Several droughts periods have been recorded in the last decades, this situation is likely to worsen under future climate, and would affect the volume of water available for different uses. Assessment of climate change impacts on water reserves and on drought severity is important for future land use planning and water resource management. Futhermore, preventing of winter flooding is also a major issues on certain points, particularly in the vicinity of the town of Saint Jean d'Angély.</td></tr>
<tr><td>Models and methods used</td><td colspan="2">Integrated Hydrological model (Numerical model, time series analysis …)</td></tr>
<tr><td>Key stakeholders</td><td colspan="2">Water Agency; SYMBO (drinking water); OUGC Saintonge (irrigation control); agricultural profession (ASA Boutonne).</td></tr>
<tr><td>Contact person</td><td colspan="2">Nadia Amraoui, BRGM French Geological Survey, n.amraoui@brgm.fr</td></tr>
</table>

The pilot of Boutonne basin is located in the west of France. The Boutonne River is the longest and the closest tributary to the mouth of the Charente River. *Aquifers in this basin correspond to sedimentary carbonate formations locally karstified*. The Jurassic aquifers (upper Jurassic, Dogger and Infra Toarcian) represent the main groundwater resource for irrigation demands and drinking water supply. The main challenge is the sustainable water resources management in connection with aquatic environments. The Boutonne basin is experiencing, in recent decades, an imbalance between available resources and needs with important socio-economic issues for agricultural activities and environmental issues.

In the framework of TACTIC project, a study of climate change impacts on aquifer recharge, groundwater levels and river discharges has been performed using the TACTIC standard climate change scenarios and the regional hydrological model of Jurassic aquifers developed with the BRGM's MARTHE computer code. It allows the simulation of flows in aquifers and river networks, including climatic and human influences. The methodology applied in this assessment is based on selected TACTIC scenarios representing an increase of global annual mean temperature by +1 and +3 degrees compared to reference period (1981-2010), under wet and dry precipitations conditions, and on the hydrological model of the Jurassic aquifers, which simulates groundwater conditions over the reference period. Four datasets representing the future climate conditions are generated by applying the delta change factors to current local dataset of precipitation, evapotranspiration and temperature. This assumes that the evolution of climatic variables is the same for the current and the future climate. Otherwise, change in groundwater abstraction in the future climate scenarios is not considered. The impact is quantified by comparing simulated results obtained with the data provided by each Tactic standard scenario for future to those simulated on the reference period (1981–2010). Annual changes in average groundwater recharge and mean groundwater levels are analysed and the seasonal responses of the system are examined at local scale in some piezometers and at stream gauges.

Predictions of future groundwater reaction to TACTIC climate change scenarios are contrasted and depend on the evolution of future precipitation (dry scenario or wet scenario). Changes are amplified in the +3 degree wet and dry scenarios compared to the +1 degree scenarios. Results show that, for +3 degree scenarios, future mean groundwater recharge is expected to increase for both dry and wet scenarios (+2% and 19% respectively) compared to recharge for the historical period leading to an increase of mean shallow groundwater level. Increase of shallow groundwater levels would concern all seasons exept spring in the case of the +3 degree wet scenario for upper Jurassic aquifer and all season for Dogger aquifer; however, the drop in the water level is more marked in summer and in autumn for the + 3 degree dry scenario.
River discharge is expected to increase in winter for all Tactic Scenarios ; Increase is more important for the +3 degree scenarios (dry and wet). However, for +1 degree and + 3 degree dry scenarios, low flows would be comparable to the reference period or slightly more severe.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and have the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project "Tools for Assessment of ClimaTe change ImpacT on Groundwater and Adaptation Strategies – TACTIC". By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments, identification, and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infra structure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (http://www.europe-geology.eu).

The present document reports on the work carried out within the TACTIC project on Boutonne pilot located in the northern part of Charente Basin in the west of France. Among the major challenge in this basin is the sustainable water resources management in connection with aquatic environments, in particular the controlled management of low water levels and winter flooding risk. In this study, climate change impacts on groundwater levels and river flow will be addressed. The challenge is to assess its effects on groundwater recharge and river flow in low and high water conditions.

3 PILOT AREA

The Boutonne pilot site is located in the west of France. Jurassic sedimentary aquifers represent the main groundwater resource for irrigation demands and drinking water supply. A natural and complex groundwater - surface water interactions is observed during low water periods. Since 1990, this basin is experiencing an imbalance between available resources and needs with important socio-economic issues for agricultural activities and environmental issues (compliance with low flow rates compatible with the functioning of aquatic environments). Several drought periods have been recorded in the last decades, this situation might be exacerbated in the future due to the climate change effects. In this project, potential future impacts of climate change on the groundwater and surface water will be assessed according to different climate change scenarios.

3.1 Site description and data

3.1.1 Location of pilot area

The pilot site of the Boutonne basin covers an area of approximately 1320 km2. It is located in the west of France (Figure 1), in the department of Deux-Serves (500 km²) for its upstream portion, and in the department of Charente-Maritime (820 km²) for its downstream part. The Boutonne River is the closest tributary to the mouth of the Charente River.

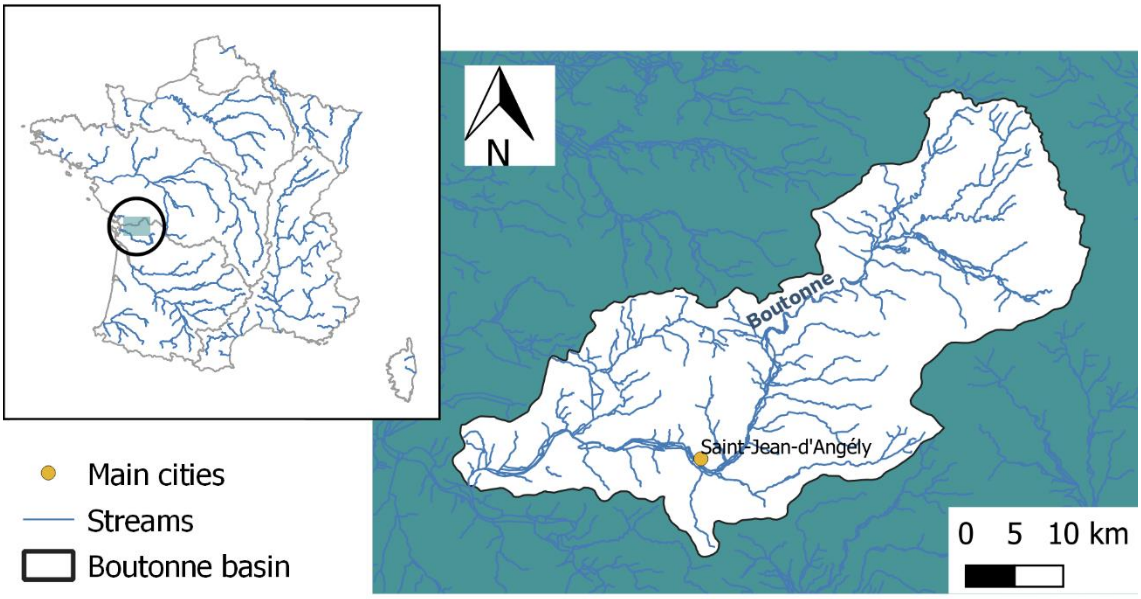


Figure 1: Location of the pilot area

3.1.2 Climate

Located not far from Atlantic Ocean, the Boutonne basin has a temperate oceanic climate with cool and well-watered winters and inter-seasons, and hot and dry summers.

The meteorological data (rainfall, temperature and Potential Evapotranspiration "PET") are available in daily time steps in both meteorological stations located in the Boutonne basin over a regular grid of 8-km resolution given by the meteorological analysis system SAFRAN (Quintana-Segui et al. 2008). The mean annual rainfall ranges between 820 mm in the north (Brioux meteorological station) and 910 mm in the south of the basin (St-Jean- d'Angély meteorological station). At the basin scale, the mean annual rainfall and PET values calculated over period 1958-2018 are 850 mm/year and 822 mm/year respectively (see Figure 2 for rainfall).

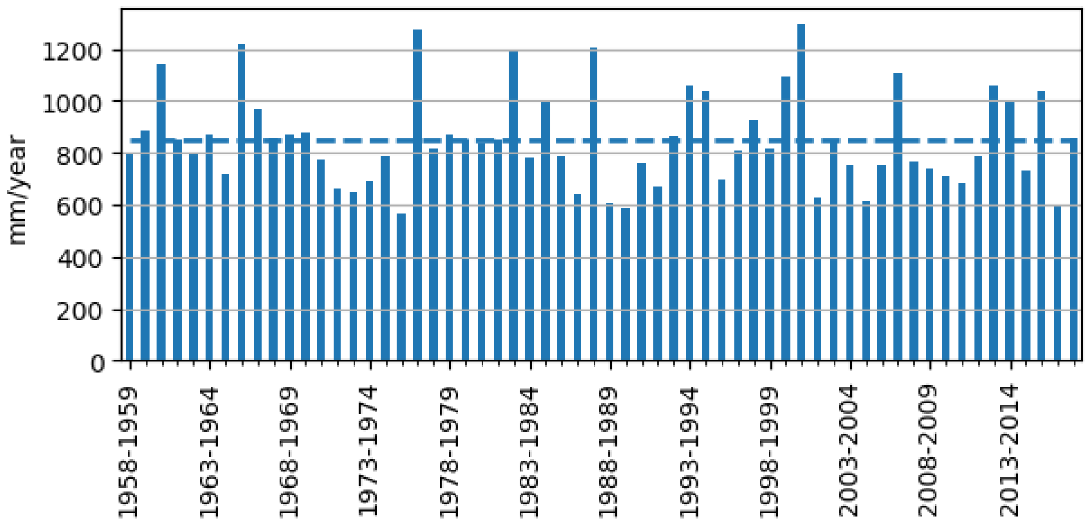


Figure 2 : Time series of the precipitation (mm/year). The dashed line corresponds to the mean value over period.

3.1.3 Topography and soil types

The Boutonne basin is mainly composed of plains. The topography varies from 3 metres (above sea level a.s.l) at the downstream of the Boutonne River at the confluence with the Charente River and can reach 190 metres (a.s.l) at the upstream of the basin (Figure 3). The digital elevation model (DEM) data are available at a 25-m spatial resolution. Four major soils types are present in the basin according to Geographical Database of French Soils: Luvisoil on the Miellois plateau, Cambisols and regosoils in the large part of basin and Fluvisoil in the valley bottoms (Figure 4).

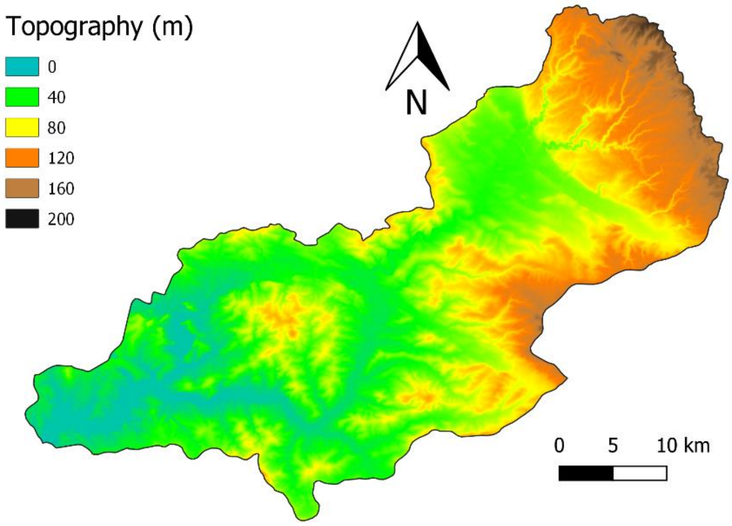


Figure 3 : Topography of Boutonne pilot site (DEM with grid resolution of 25 m, IGN)

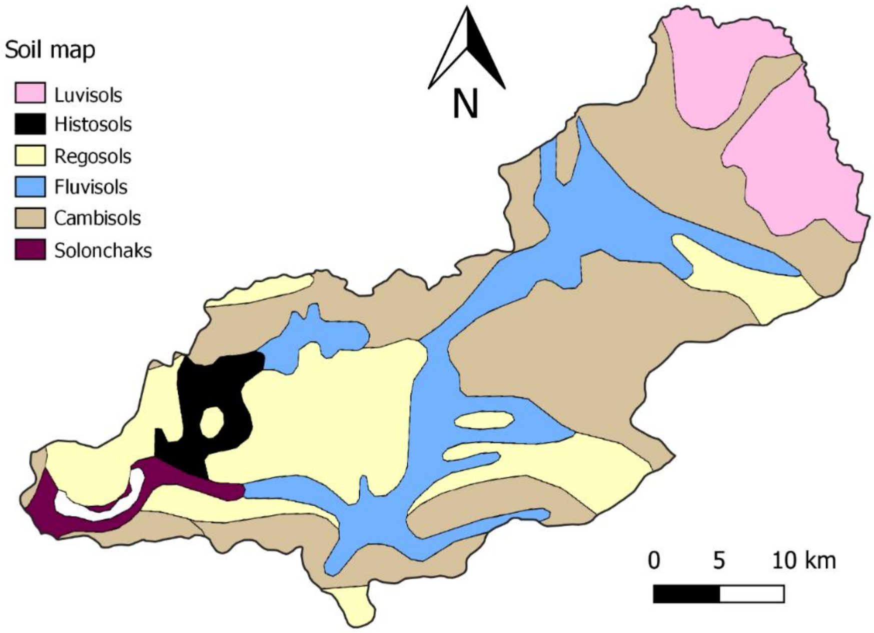


Figure 4 : Soil map of Boutonne basin from BDGSF (Geographical Database of the French Soils)

3.1.4 Geology/Aquifer type

- Geology

The Boutonne basin corresponds geologically to the northern edge of the Aquitaine basin, characterized by the outcrop of Jurassic horizons, covered by transgressive deposits of the Upper Cretaceous (Cenomanian series). The general basin structure and the different geological levels encountered are illustrated in the Figure 5.
Oriented globally northeast / southwest, the basin is mainly located on the Jurassic formations. The northern half of the basin is characterized by the presence of faults aligned along ONO-ESE

direction that structure the landscape. The northern part of the basin corresponds to the southern part of the Melle Dome, which is characterized by the Lias and Dogger formations. This dome is limited by two major faults that surround the Boutonne valley and collapse the basement more than 100 meters (Figure 5). The basement is visible in the Béronne valley and gradually dipping southward under Jurassic and Cretaceous sedimentary formations. Thereby the most recent formations are outcropping to the south of the basin, while the older ones are visible at the outcrop to the north.
In the southern part of this fault system, there is a second compartment limited to the south of Chizé by another fault. Outcrops of the Oxfordian and basal Kimmeridgian (Upper Jurassic) characterize this compartment. South of Dampierre, a major fault aligned along ONO-ESE direction delimits the downstream part of the Boutonne valley characterized by outcrops of the Upper Kimmeridgian (Upper Jurassic), Tithonian and Cretaceous.

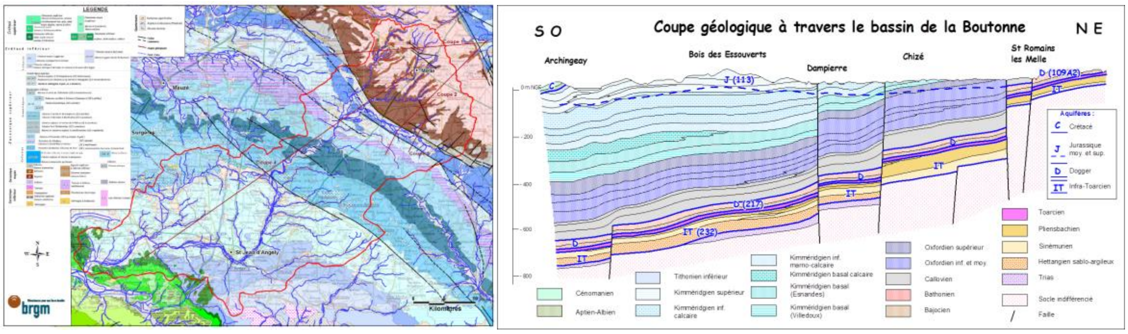


Figure 5 : Geological map and geological cross section through the Boutonne basin *[Lavie J. (2005) after Lemordant Y. (1998)]*

- *Aquifer type*

Aquifers in the study area correspond to sedimentary carbonate formations locally karstified. Four main aquifers are identified in the Boutonne basin in the stratigraphic order:
The Lower Jurassic or Infra-Toarcian aquifer (Lias): this reservoir consists essentially of dolomitic and sandstone limestones of the Pliensbachian, Hettangian and Sinemurian sedimentary formations. This aquifer rests on a bedrock, which constitutes its substratum. Groundwater is mainly confined under Toarcien marl, the thickness of the reservoir can reach 60 meters. This aquifer is recharged by the effective precipitations, by the faults affecting the series and being able to put in contact this aquifer with another more superficial one (Dogger) and probably by losses of rivers (Béronne, Légère) in the areas where the aquifer is outcropping.
The Middle Jurassic or Dogger aquifer: This aquifer is composed of all the Dogger stratigraphic units. The reservoir is mainly constituted by Oolitic limestones. The Bathonian is particularly karstified. This aquifer rests on the Toarcian marls that separate it from the underlying aquifer of the Infra-Toarcien. The total thickness of this aquifer can reach 50 m on the studied area.
Groundwater is mainly unconfined in the whole area north of the Boutonne Faults; the aquifer becomes confined by sinking under the marly formations of the Callovian and the Oxfordian. Groundwater flow directions in this aquifer are comparable to those of the infra-Toarcien aquifer (Figure 6). More locally and on its unconfined part, it follows the flow directions of the hydrographic network.

Upper Jurassic aquifer: Located south of the Secondigné-Chef-Boutonne fault corridor, this aquifer, with heterogeneous characteristics, consists of marl-limestone series that are altered on the surface. The substratum of this aquifer is formed by a characteristic level, locally called "blue bench", which means unmodified gray marly limestones, located at 20 to 30 meters deep. This is an unconfined aquifer drained by streams in some areas or draining streams in others. Interactions between groundwater and surface water are complex and can be reversed according to the seasons.

The Upper Cretaceous (Cenomanian) aquifer: Located in the confluence area between the Boutonne and the Charente, the Cenomanian aquifer corresponds to sand, sandstone and limestone with clay levels, which results in a multiplication of interconnected or independent reservoir levels. Groundwater is unconfined free but can be locally confined under an impermeable level.

Other aquifers, more marginal, are encountered on this basin. North of the Boutonne fault, the tertiary surface formations, sometimes reservoir, are drained by small springs or by the underlying Dogger groundwater. The quaternary alluvium and colluvium, because of their small thickness (a few meters at most), constitute "relay" horizons for the large underlying aquifers that are drained by rivers.

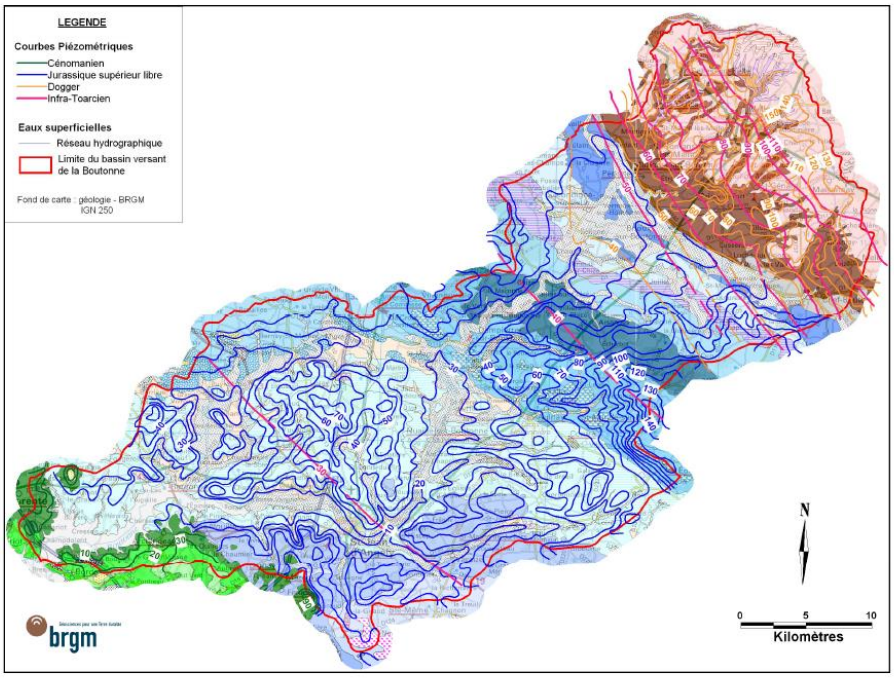


Figure 6 : Piezometric map of Jurassic aquifers showing the main groundwater flow direction in Boutonne basin (Bichot et al., 2005).

3.1.5 Surface water bodies

The Boutonne river spring is located at Chef-Boutonne at an altitude of about +90 meters above sea level (a.s.l) in the Dogger formations. In its upstream part, it flows from east to west between two faults, mainly on the Dogger and Lower and Middle Oxforden formations. It receives on this

section and on the right bank the waters coming from the following rivers: the Sumptuous, the Béronne and the Belle. These tributaries are flowing on Dogger and Lias formations.
In the middle part, between the confluences with the Belle and the Vau, the Boutonne River has a direction northeast / southwest. The hydrographic network is less developed. Thus, on the Oxfordian formations superior to the Upper Kimmeridgian, the Boutonne receives only a few streams on the left bank (Bellesebonne, Bondoire and Vau)
Downstream from the confluence with the Vau, the Boutonne flows on the higher Kimmeridgian formations on which the hydrographic network is well developed. Thus in this downstream sector, the Boutonne receives on the right bank tributaries (La Bredoire, La Saudrenne, Padome, La Nie). On the Left Bank, the Boutonne River receives the following tributaries: Le Pouzat, La Soie, and the Trézence, via the Sainte Julienne canal.
In this sector, between Dampierre and Saint Jean d'Angely, the Boutonne is, at low water period, perched in relation to the unconfined and superficial aquifer of the Upper Jurassic (Lavie J (2005)).
The Boutonne river flow is monitored at the gauging station of Saint-Séverin-sur-Boutonne. The average annual flow at this station is 5.52 m^3/s; Table 1 summarizes some information about this station and the Saint-Jean-d'Angély station located downstream. The monthly (natural) flows calculated over 50 years is reported in Figure 7.

Table 1 : Flow gauge information

Flow gauge ID	*Surface km2*	*Name of station*	*River water level data period*	*River Flow data period*
R6092920	535	La Boutonne à Saint-Séverin-sur-Boutonne [Moulin de Châtre]	*1972 - 2001 - 2020*	*1969 -* 1998 - 2021
R6142927		Boutonne[total] at Saint-Jean-d'Angély	*Not available*	*2011-2021*

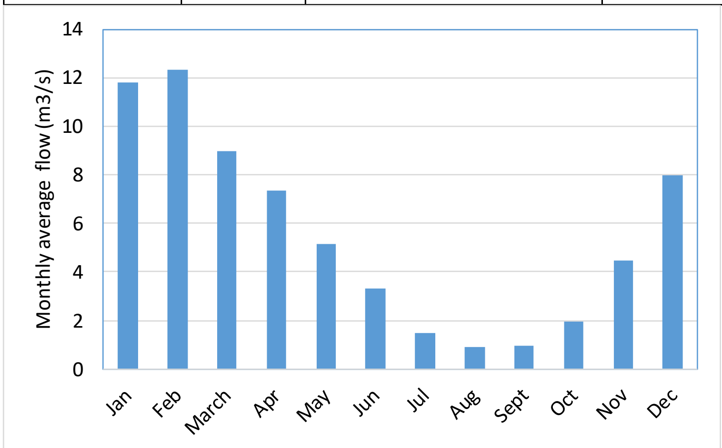


Figure 7 : *Monthly average flow at Saint-Séverin-Sur-Boutonne calculated over 50 years (Banque hydro : http://www.hydro.eaufrance.fr/)*

3.1.6 *Hydraulic head evolution*

Groundwater table of Jurassic aquifers is monitored at several observation boreholes (piezometers). Piezometers locations are reported in Figure 8. Concerned aquifer and the monitoring period are reported in Table 2.

Table 2 : Groundwater observation points

Piezometer ID	Name	Aquifer	Period
06357X0062/S	Villenou	Lower Kimmerigien	**1992-2018**
06358X0012/S	Fosses	Infra-Toarcien	2006-2009
06364X0001/P	Chail	Dogger	1993-2001
06366X0006/P	Ensigne	upper Jurassic	**1992-2018**
06367X0126/P	Lesvaux	Dogger	**1993-2001**
06367X0138/S	Outre 2	Infra-Toarcien	**1990-2018**
06367X0172/F	Outre 1	Dogger	**1990-2018**
06367X0195/S	Tillou	Infra-Toarcien	2005-2011
06601X0012/S	Poimier	upper Jurassic	**1992-2018**
06603X0093/P	Paizay	upper Jurassic	**1993-2018**

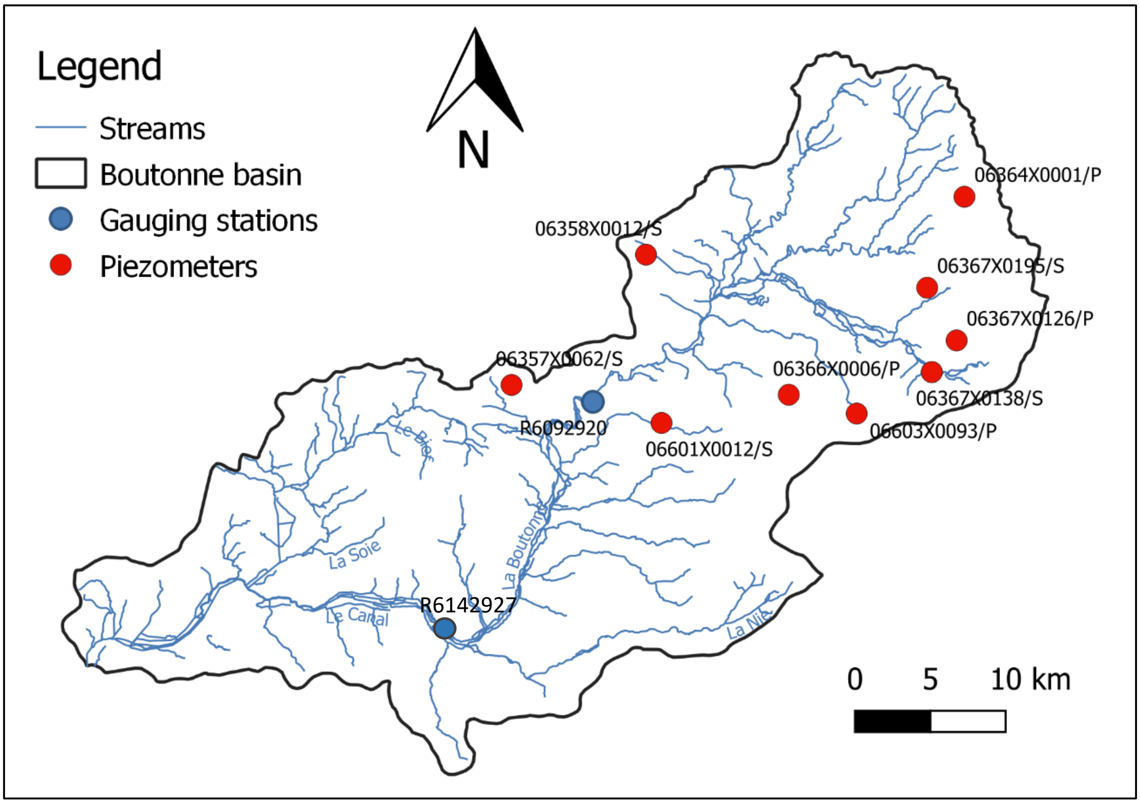


Figure 8: Gauging stations and piezometers over the Boutonne River basin.

3.1.7 Land use

The Boutonne pilot is a rural and weakly urbanized area dominated by agricultural land use (Figure 9). The most important wooded area of the basin is at the limit of the departments of Charente-Maritime and Deux-Sèvres. Alluvial forests are present very intermittently along the rivers.
There are two urban areas on the basin: Saint-Jean-d'Angély and Melle. Elsewhere, the population is distributed sparsely over the territory.

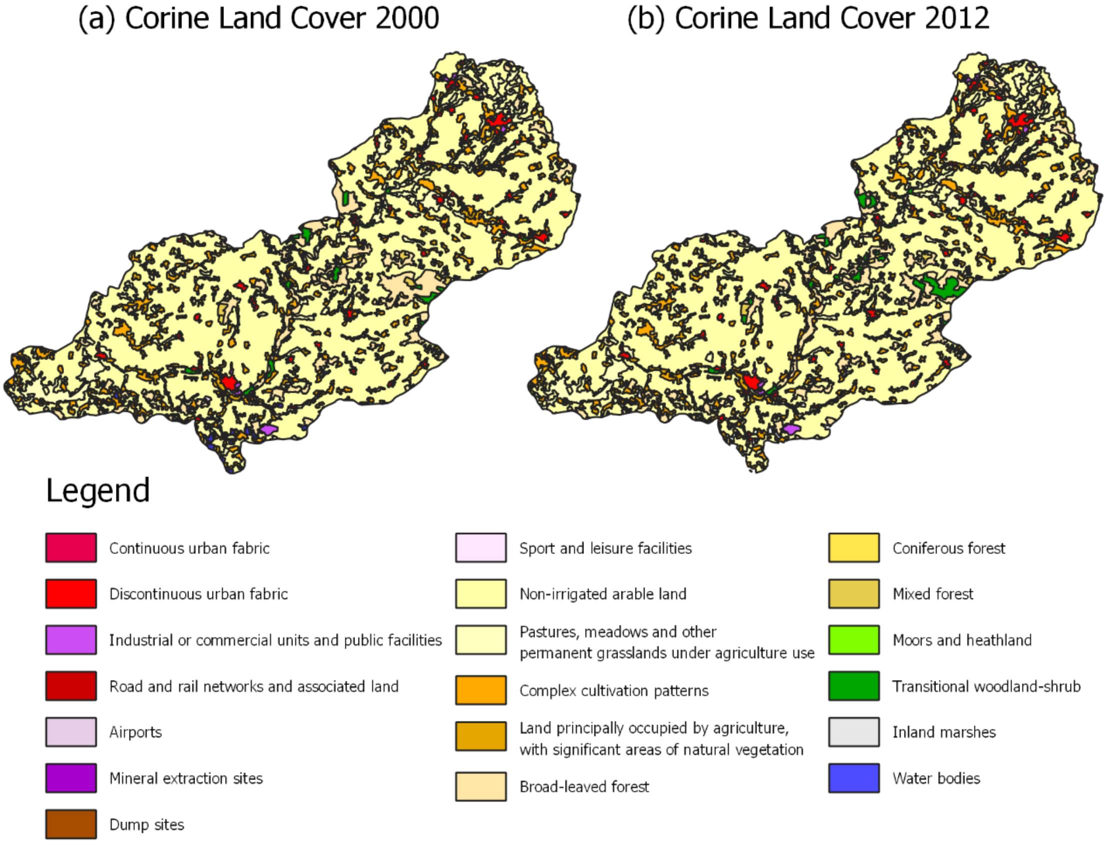


Figure 9: Land use maps from CORINE Land Cover (2000 and 2012)

3.1.8 Abstractions/irrigation

The Boutonne site pilot is under strong anthropic pressure since several years. From a quantitative point of view, abstractions for crop irrigation represent 73% of total water uses (concentrated over 4 to 5 months in summer), followed by the drinking water supply with 17.35% (spread over 12 months and peak consumption in hot season) and finally industrial use with 9.56% spread over 12 months (Sage Boutonne 2016). Water withdrawals are mainly carried out in the upper Jurassic aquifers, with boreholes of some tens of meters deep mainly located in the valleys, and in the Dogger and especially the Infra-Toarcien for the upstream part of the basin (Bichot et al 2005). Figure 10 show the location of boreholes and abstractions according to the type of water use and aquifer.

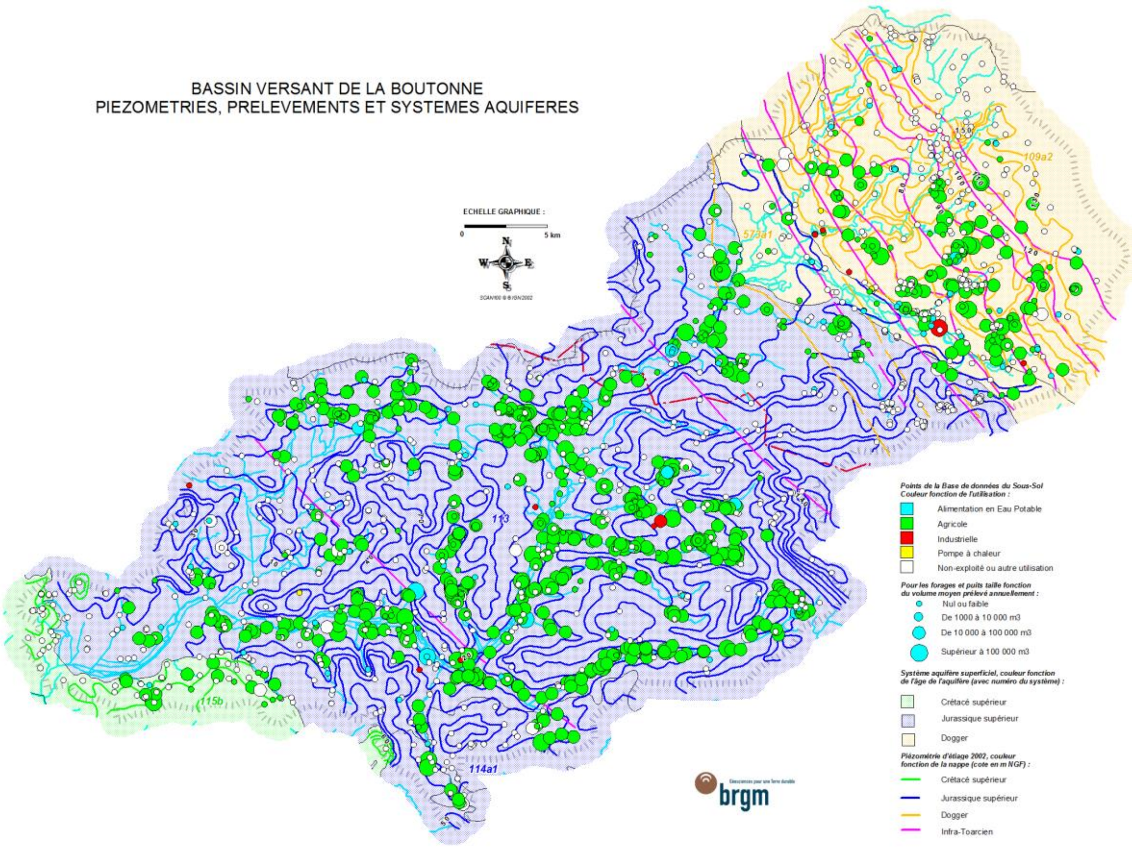


Figure 10 : Location of boreholes and abstractions according to the type of water use and aquifer (Bichot et al. 2005)

3.2 Climate change challenge

The Boutonne pilot site is located in the North-western Europe region where an increase of precipitation in winter is expected in accordance with the EEA map (Figure 11).

Existing hydrological impact studies based on projections ensemble from sept GCMs and median emission scenario A1B (Explore 2070 project) have shown a decrease of the inter-annual average river discharge by 2070 compared to reference period (1960-1990). However, for the most optimistic GCM model (GFDL-CM2.1), river discharge in the winter could be higher (20% to 40%) compared to reference period and could lead to flooding downstream of the basin (Stollsteiner 2012). A drop in average flow is expected in summer for this watershed.

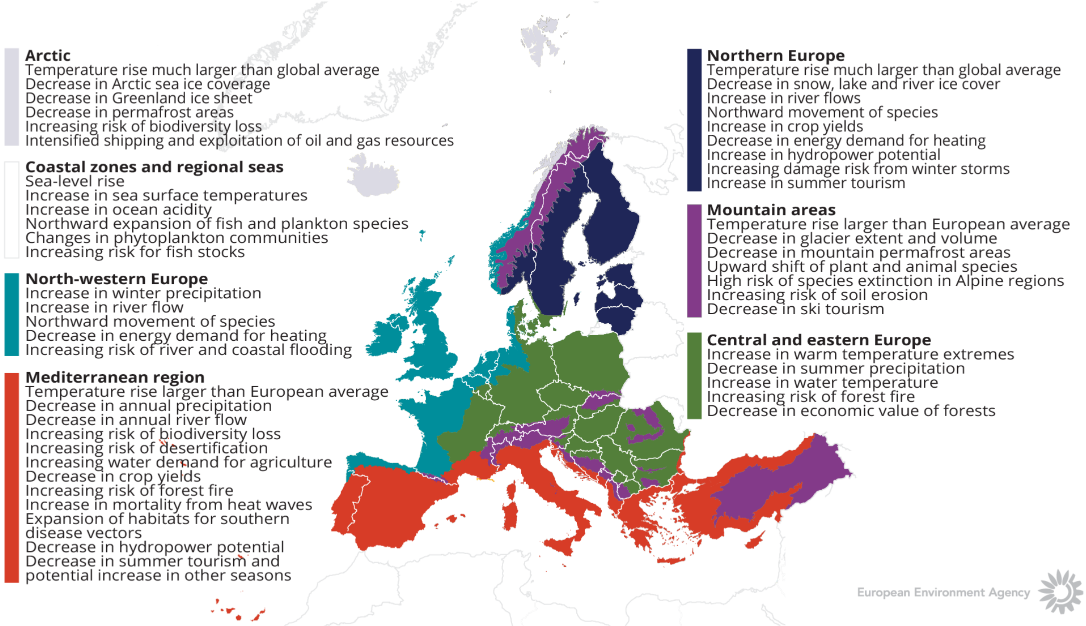


Figure 11 : Key observed and projected impacts from climate change for the main regions in Europe (European Environment Agency)

4 METHODOLOGY

The assessment of climate change effects on groundwater resources in Boutonne basin is performed using the TACTIC standard climate change scenarios and the regional hydrological model of Jurassic aquifers developed with BRGM's MARTHE computed code (see TACTIC toolbox reference).

4.1 Climate data

In this study, TACTIC standard climate change dataset are used to assess climate change impact on groundwater resources in Boutonne pilot under +1 and +3 degrees global warming scenarios considering low and high precipitation conditions.

4.1.1 TACTIC standard Climate Change Scenarios

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5°C global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set where selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature where calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflects outliers.
5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).

6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCM combinations were employed:

Table 4.1. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	4.5	noresm1-m
	"Wet"	6.0	miroc-esm-chem
3-degree	"Dry"	8.5	hadgem2-es
	"Wet"	6.0	miroc-esm-chem

4.2 Hydrological modelling of climate change

The regional hydrological model of Jurassic aquifers in Poitou Charentes (Jurassic aquifers model) has been developed in its first version in 2007 (Putot et al., 2007) and completed, updated and recalibrated in 2011 (Douez et al 2011). This last version was improved by integrating daily surface water balance computation (Amraoui et al. 2018, Vergnes et al 2020). The Jurassic aquifers model was developed with the MARTHE computer code (Thiéry, 1993, 2015a, 2015b). MARTHE allows the simulation of flows in aquifer systems and river networks, including climatic and human influences. Surface water balance (runoff and aquifer recharge) is calculated from climate data (rainfall, potential evapotranspiration) and soil parameters using the lumped hydrological model GARDENIA (Thiéry, 2015a). More detail on the MARTHE functionalities are available in the Tactic toolbox.

The methodology applied to assess climate change effects on groundwater resources is based on:

i) the four selected TACTIC scenarios representing an increase of global annual mean temperature by +1 and +3 degrees compared to the reference period (1981-2010) under wet and dry conditions
ii) the hydrological model of the Jurassic aquifer which simulates the groundwater conditions over the current period.

Four datasets representing the future climate conditions are generated by applying the delta change factors to current local dataset of precipitation, evapotranspiration and temperature. It assumes that the evolution of climatic variables is the same for the current and the future climates. The groundwater recharge, groundwater level and river discharge evolutions were simulated over the period 1958-2018 using current local climate data and future climate data generated for the four Tactic scenarios. It is assumed that there is no change in groundwater abstraction for the future climate scenarios. Only the results over the 1981-2010 period were used to assess the climate change impacts on groundwater and surface water resources.

4.2.1 Model description

The Jurassic aquifers model covers an area of 19,280 km^2 and entirely includes the Boutonne basin (Figure 12). This model integrates the data described in paragraph 3.1. Built from a geological model, the main Jurassic aquifers and the aquitards that separate them are represented there. The model has 8 layers described from top to bottom: 1- Bri du Marais ; 2 - Cretaceous and alterites ; 3 - Weathered Upper Jurassic (aquifer), 4 - Unaltered Upper Jurassic, 5 - Dogger (aquifer), 6 - Toarcian, 7 - Infra-Toarcian (aquifer) and 8 - the basement. The spatial extension of these layers and the main aquifers present in the Boutonne basin (upper Jurassic aquifer, Dodder aquifer and Infra-Toarcian aquifer) are shown in Figure 13.

The model is discretized in 1 km square meshes. Boundary conditions of the imposed potential type are applied to the northeast, southwest and west of the regional model and correspond either to large deep faults or to the ocean. Elsewhere, no flow limits are applied. The hydrographic network taken into account represents 3050 km of linear streams. The Jurassic aquifers model considers groundwater and river withdrawals (agricultural, drinking water supply and industrial). The model run in unsteady state condition and allows simulating the fluctuations of the groundwater levels and flow in the associated rivers as well as the interactions between groundwater and surface water. The 2011 version of the model runs in transient mode at a monthly time step and is calibrated over the period 2000-2007. More details on this model are reported in Douez et al 2011.

In this study, we used the 2018 version of the Jurassic aquifer model. In this version, surface water balance (runoff and aquifer recharge) is calculated with a daily time step from spatial distributions of climate data, including daily rainfall, potential evapotranspiration and soil parameters, using the lumped hydrological model GARDENIA. In addition, the hydrodynamic calculation is done at a weekly time step (Amraoui et al., 2017).

The model was updated over the period 1958-2018 with daily climatic data. Concerning water abstractions in aquifer and river, as the data are not available outside the calibration period (2000-2007), the assumption of average monthly withdrawals calculated based on data known between 2000 and 2007 was considered for the period prior to 2000 and that subsequent to 2007.

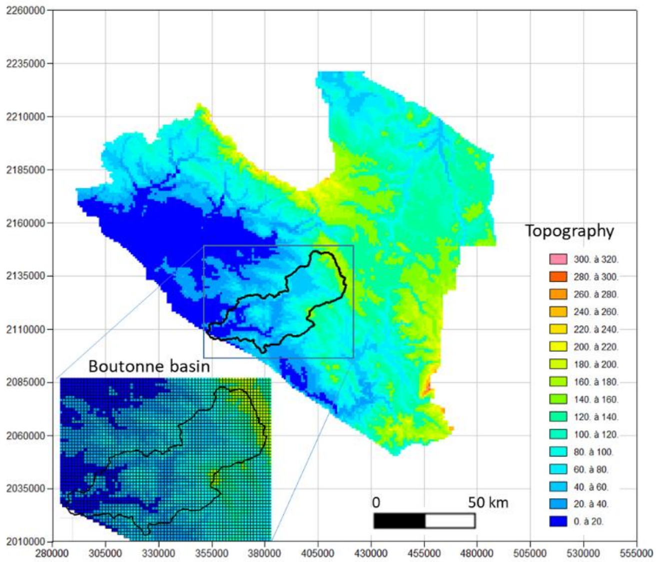


Figure 12 – Location of Boutonne watershed in the Jurassic Aquifers Model – the black outline represents the limits of the basin on a topographic map background

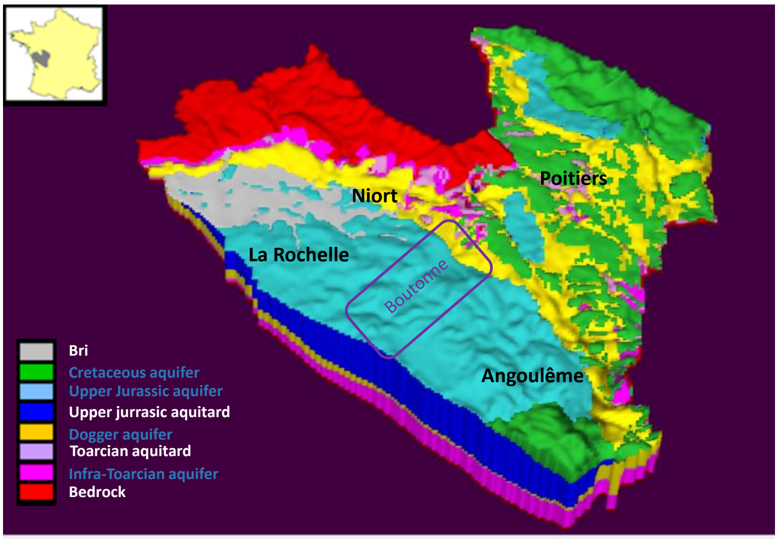


Figure 13 : Extension of the Jurassic Model layers and the main aquifer present in Boutonne basin.

4.2.2 Model calibration

Calibration consists in adjusting the model parameters in order to reduce the difference between the observed and simulated values at the observation points (groundwater time series and river flow rates measured at the gauging stations).

The Aquifers Jurrasic model was already calibrated in 2011 based on aquifers regional knowledge, groundwater levels and river flows observations. Calibrated parameters are: the hydraulic conductivities and the storage coefficient maps (for the 8 layers of the model), recharge and river bed conductance.

Calibration carried out within the framework of TACTIC concerns only the Boutonne basin. The GARDENIA parameters was calibrated according to the daily climatic data and soil parameters. Calibrated parameters are the soil capacity, partition coefficient between surface runoff and infiltration and percolation delay. The calibration was achieved over the 2000-2007 period by trial and error approach. The periods before and after the calibration period were used to initialize the simulation and to validate the model. The location of the piezometers and gauging stations used in the evaluation of model calibration is shown in Figure 8.

The Villenou, Poimier, Ensigne and Paisay piezometers are considered for the Upper Jurassic aquifer, the Outres 1 and Chail piezometers for the Dogger aquifer and the Outres 2 piezometer for the infra-Toarcian aquifer. In addition, the river discharges measured at the Saint-Severin-sur-Boutonne and Saint-Jean-d´Angély gauging stations allow assessing the restitution by the model of the river flow. Examples of comparison between the simulated and observed values of groundwater level and river discharge are shown in Figure 14 and Figure 15. In addition, statistical criteria (Root Mean Square Error: RMSE, Mean Error: ME and the Nash criteria) were calculated on the basis of the monthly values of the hydraulic head and the flow rate over the observation period (Figure 16).

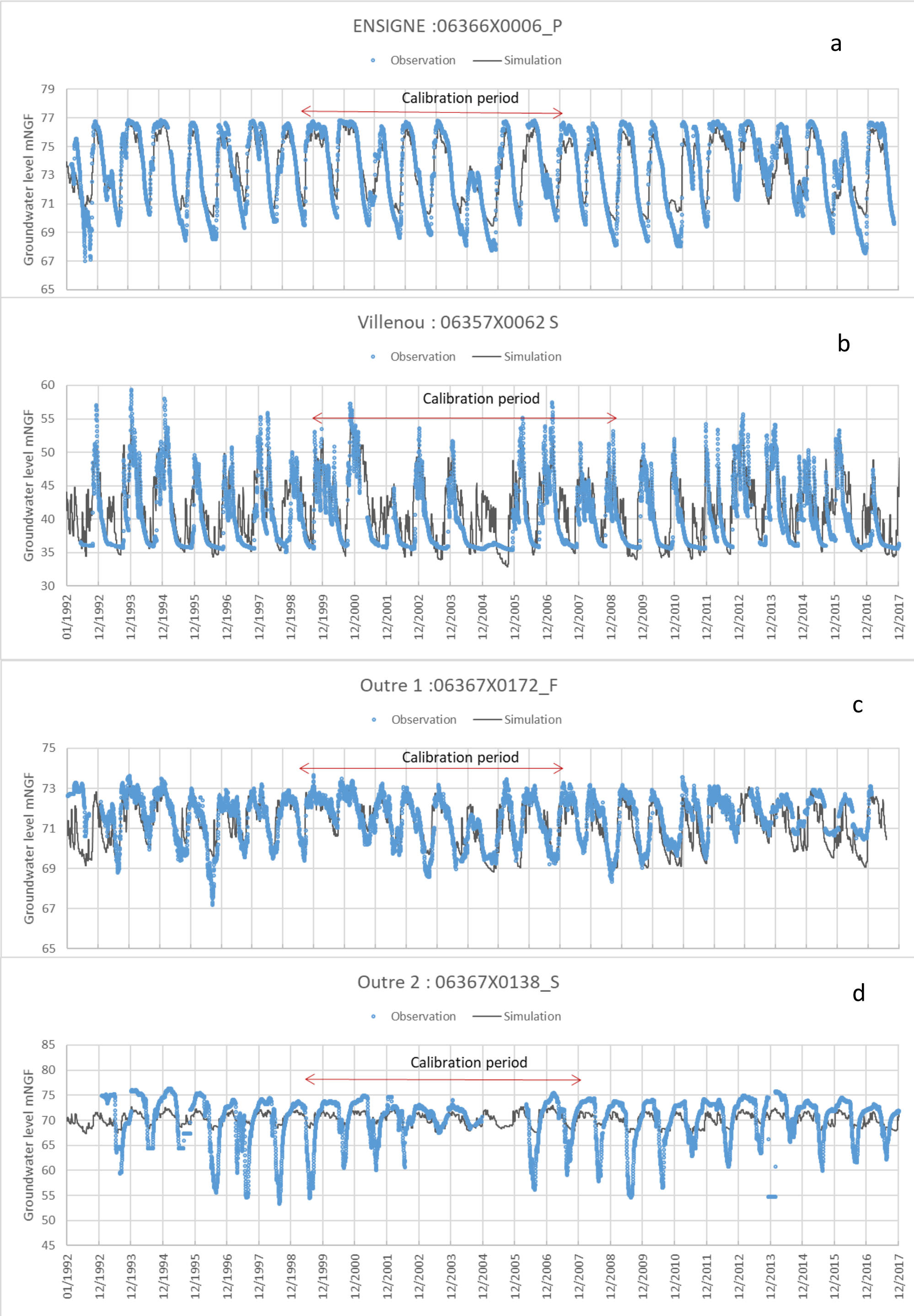


Figure 14 : Example of observed and simulated groundwater levels in piezometers located in Upper Jurassic aquifer (a and b), Dogger or Middle Jurassic aquifer (c) and in Infra-Toarcian aquifer (d).

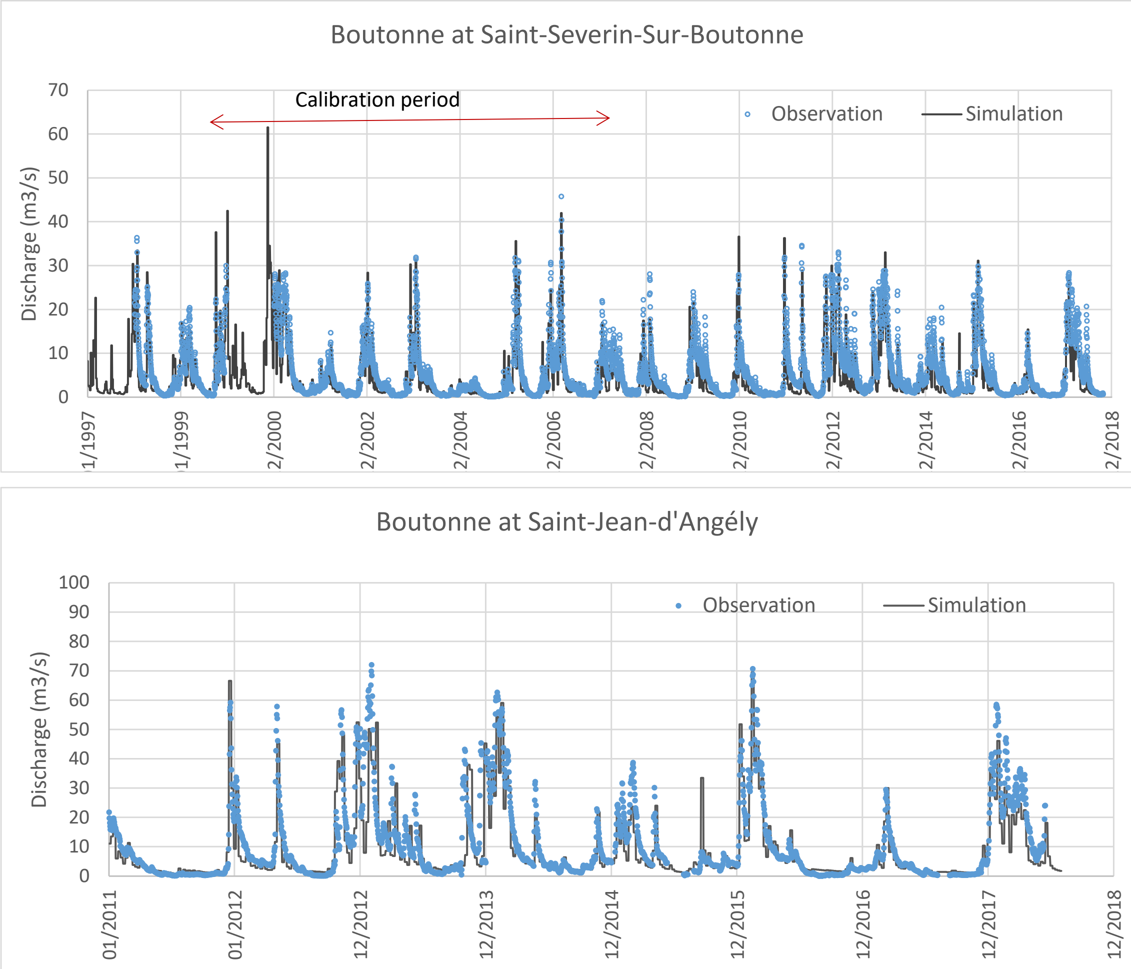


Figure 15 : Observed and simulated discharges in Boutonne River at two gauging stations.

		Groundwater level								River Discharge		
Aquifers and River name		Upper Jurassic				Dogger		Infra Toarcien		Boutonne River		
Observation points		ENSIGNE	VILLENOU	POIMIER	PAIZAY	OUTRE1	CHAIL	OUTRE2		Saint-Severin-Sur-Boutonne	Saint-Jean-d'Angély	
Statistical criteria	Time scale	Values	Values	Values	Values	Values	Values	Values	Unit			Unit
NASH SUTCLIFFE (NSE)	Monthly	0.86	0.79	-0.17	0.41	0.55	0.54	0.28		0.85	0.86	
ROOT MEAN SQUARE ERROR (RMSE)	Monthly	0.97	2.72	2.34	0.78	0.73	1.64	4.52	m	2.16	4.32	m3/s
MEAN ERROR (ME)	Monthly	-0.09	1.73	-0.43	-0.53	-0.31	0.70	0.03	m	-1.07	-1.52	m3/s

Figure 16 : Statistical criteria on various observations points for groundwater level and River discharge at the scale of Boutonne basin.

The Upper Jurassic and Dogger groundwater dynamics are well reproduced by model with a bias of -0.53 to 1.73 and a RMSE of 0.73 and 2.72 m respectively. For the Infra-Toarcian aquifer, mainly captive in the study area, the piezometers Outres 2 and Tillou are strongly impacted by pumpings located near the piezometers. Given that the model calculates a mean groundwater level over a 1-km resolution grid, the pumping influence cannot be reproduced at this scale. Note that the few observation points in the Dogger and Infra Toarcien aquifers make it difficult to assess the quality of the model in the middle and in the downstream area of the basin.

River discharges at Saint-Severin sur-Boutonne and at Saint-Jean-d´Angély stations are well reproduced by the model with a Nash criteria of 0.86 and 0.85 respectively; (NSE criterion is considered to be very good when it is greater than 0.7 and bad when it is lower than 0.5).

4.3 Uncertainty

The most important sources of uncertainty concern the data on groundwater and river water withdrawals, which volumes are not known before 2000. The assumption of averaged monthly withdrawals calculated from data known between 2000 and 2007 was considered for the period prior to 2000 and that subsequent to 2007.

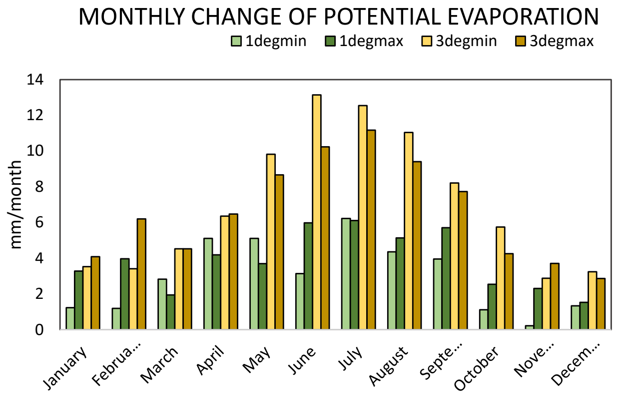
Moreover, uncertainties linked to conceptual model should be underlined, they are linked to the ignorance of the Karst network upstream of the basin, therefore high hydraulic conductivities were considered in these areas to simulate the rapid flow generated by the Karst network. In addition, faults are not taken into account in the model but their impact on the aquifer geometry is considered.

5 RESULTS AND CONCLUSIONS

Climate change effects on groundwater recharge, groundwater levels in the Jurassic aquifers and the associated stream flows are assessed for Tactic standard scenarios. The impact is evaluated by comparing simulated results obtained with the data provided by each Tactic future standard scenario to those simulated on the reference period (1981–2010). Annual changes in mean groundwater recharge and mean, low and high groundwater levels are estimated, and the seasonal responses of the system are analysed at local scale for some piezometers and stream gauges.

5.1 Effects of change in future precipitation and Evaporation on groundwater recharge

The inter-annual averages of observed monthly precipitation and PET calculated for the reference period (1981-2010) were compared to those projected by the four Tactic scenarios. Change in monthly precipitation and PET are reported in Figure 17. An increase in autumn and winter precipitations is expected for 3 scenarios (+1°C wet, +3°C dry and wet). Precipitation rise is also expected in summer for +1°C wet and +3°C wet scenarios. Monthly change in PET shows an increase for all scenarios, particularly in summer under +3°C global warming.
30-years mean groundwater recharge calculated by the hydrogeological model for the reference and future (Tactic scenarios) periods are reported in Figure 18. It should be reminded that future changes in precipitation patterns, landscapes and land uses, which could affect the future groundwater recharge, are not included in the scope of this study.
Except the +1°C dry scenario, wich expects a slight drop in mean recharge, the other scenarios project an increase in future recharge. In fact, compared to mean recharge for historical period, the mean recharge over future period will increase by +6% for 1°C wet scenario, by +2% for 3°C dry scenario and by 19% for 3°C wet scenario.



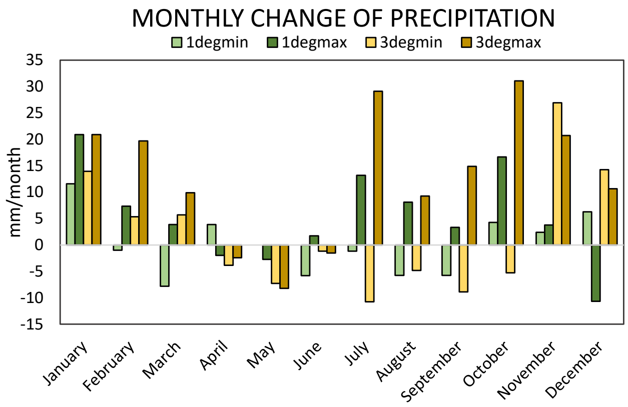


Figure 17: Monthly change of precipitation and Potential Evaporation under +1°C and +3°C for the 4 Tactic standard scenarios

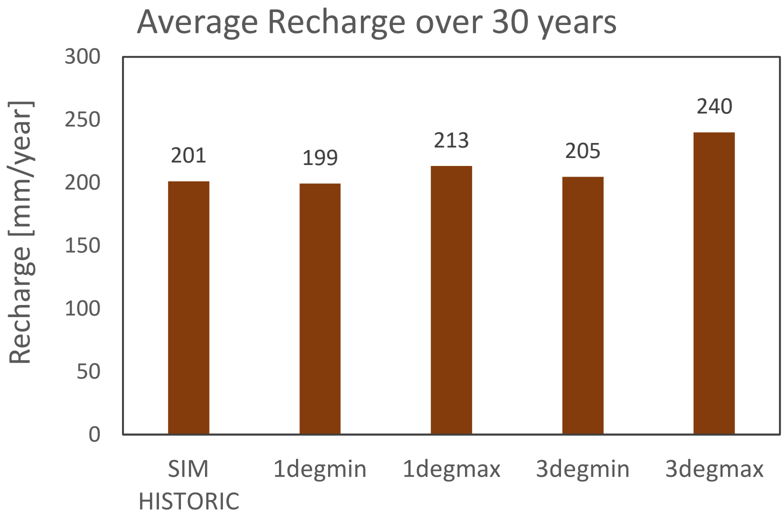


Figure 18 : 30-years mean groundwater recharge for the reference period (SIM Historic) and for the Tactic standard scenarios (under 1°C and 3°C global warming)

5.2 Effects on groundwater conditions and river flow

Results will focus on changes in shallow groundwater and river flow. Over the Boutonne basin, water abstractions are mainly carried out in the shallow groundwater of the upper Jurassic aquifers, in the Dogger aquifer and especially in the Infra-Toarcian for the upstream part of the basin. In addition, interactions with surface water occur with the upper Jurassic aquifer and in the northern part, in outcrop zones of the Dogger and Infra Toarcian aquifers.

5.2.1 Change in shallow groundwater

The mean shallow groundwater levels for the reference period (1981-2010) and for the future periods (two time slices in which the global annual mean temperature had increased by 1°C and 3°C compared to reference period) are calculated from the gridded simulated groundwater levels calculated by MARTHE over the simulation period and edited with a time interval of 30 days. Change in mean shallow groundwater levels is assessed for the 4 Tactic standard scenarios by comparing mean shallow groundwater levels for future periods with that of the reference period. In the same way, changes in dry and wet periods are also analysed.
The Figure 19 shows the relative changes in mean shallow groundwater levels between the four future Tactic simulations and the reference period (1981-2010) computed for each grid cell. in addition, the change of the 5% quantile of the simulated 30 periods (Future Q5 – Past Q5) and the 95% quantile (Future Q95 – Past Q95) are used to represent respectively the lowest groundwater level period and the highest groundwater levels during winter

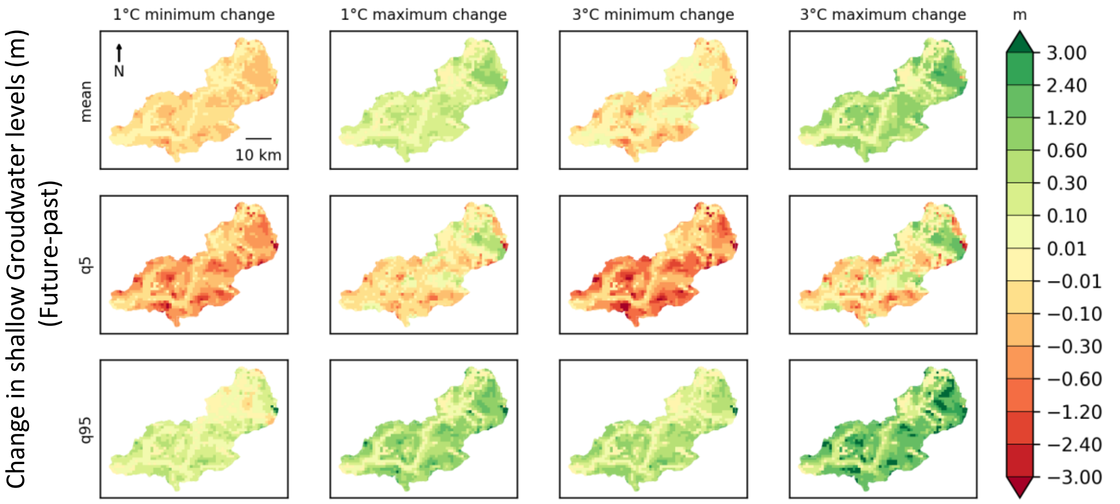


Figure 19 : Changes in mean, low and high shallow groundwater levels simulated with the four TACTIC standard scenarios.

The results are consistent with the wet and dry scenarios whether for the 1°C and 3°C scenarios and corroborate with changes in precipitations and groundwater recharge (see §5.1). It seems that for wet Tactic scenarios (1 degree max change and 3 degree max change), impact on mean groundwater levels under 3 degree is greater than under 1 degree warming with higher mean

groundwater levels. Nevertless, for dry Tactic scenarios, drop in mean groundwater level concern the whole basin under 1 degree warming whereas it is mainly located on plateaus under 3 degree warming.
The increase in mean groundwater levels over future period for 1 degree max change and 3 degree max change Tactic standard scenarios is explained by an increase in future recharge. Groundwater level rise is more marked on the plateaus than on the wet valley. The rise is more important for scenario 3°C wet (max change) and can reach locally more than 2 m.
Groundwater change in low water periods is more important compared to the mean and can reach -2.5 metres in plateaus. Decrease in groundwater level is more important for dry scenarios and for +3 degree.
Change in high groundwater level is more important for 1 degree and 3 degree wet scenarios and it remains significant for the 3 degree dry scenario.

5.2.2 Seasonal change in shallow groundwater levels

Seasonal changes in shallow groundwater levels are analysed for the 3 degree Tactic scenarios (dry and wet) over two piezometers located in the upper Jurassic aquifer (Ensigne) and in the Dogger aquifer (Outre 1) respectively. The monthly mean groundwater levels reported in Figure 20 were calculated from simulated groundwater levels over the reference period and for future climate.
This figure shows that for the upper Jurassic aquifer, for the dry scenario (3 degree min change), monthly mean water level increases slightly (0.20 m) in winter. On the other hand, the decrease in the water level is more marked in summer and in autumn (between -0.3 m and -0.5 m).The wet scenario (3 degrees max change) shows a more significant increase in the water table from August to the end of spring with a maximum reached in autumn (+0.8m).
For shallow Dogger aquifer, in the northern part of the basin, under dry scenario, monthly mean groundwater level is similar to that of historical period in winter but it is slightly lower for the other seasons. However, under wet scenario, monthly mean groundwater level is higher whatever the season.

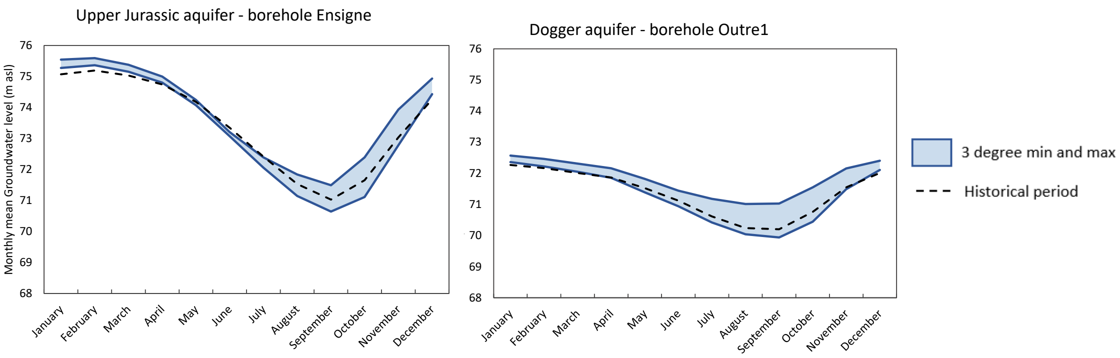


Figure 20 : Monthly mean groundwater level calculated over 30 years for historical period and under 3°C wet and 3°C dry Tactic standard scenarios.

5.2.3 *Change in river flow*

In the same way, monthly mean river flows were calculated over 30-years at two gauging stations located over the Boutonne river (Saint-Severin and Carillon at the basin outlet) for the historical period and for the future period of the four Tactic standard scenarios. The results are showns in Figure 21. For low flow periods (june to septembe), and under dry scenarios (1degree minchange and 3 degree minchange) slighly low water levels are expected. However, under wet scenarios, river discharges are expected to be higher than for the reference period. Otherwise, for high flow period (november to march), river discharges are expected to increase. This increase is more important for the 3 degrees scenarios (dry and wet).

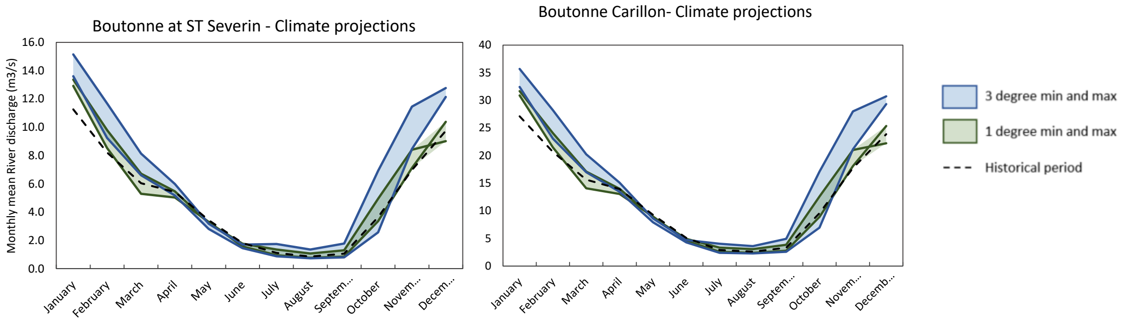


Figure 21 : Monthly mean river discharges at the two Boutonne gauging stations calculated over 30 years for the reference period and for the Tactic standard scenarios

As described above, the Tactic scenarios consider the same dynamic between different events in the historical dataset and in the dataset representing the future. Consequently, the impact will only concern the amplitude of the events and not their occurrences. For +3 degree scenarios (dry and wet) historical floods experienced by the Boutonne basin are expected to be greater in terms of amplitude. Figure 22 shows the historical flooding flood peaks (red circle) under the 3 degree minchange scenario.

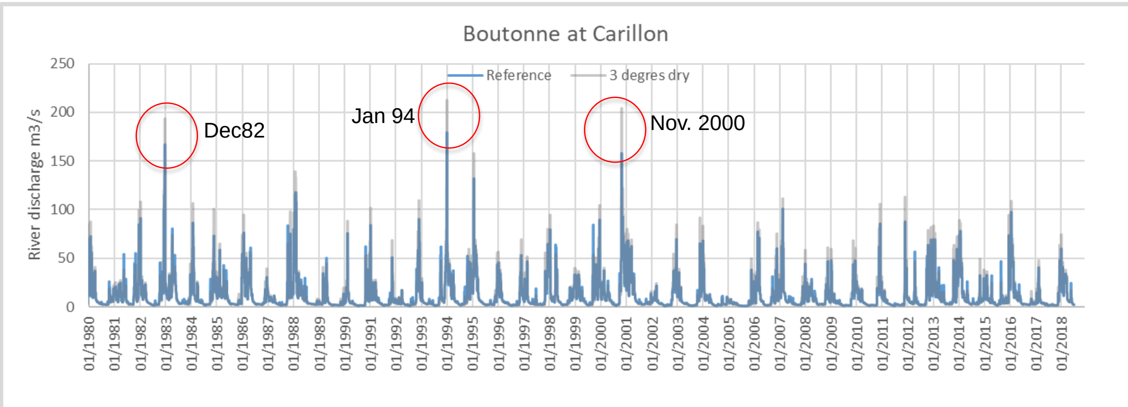


Figure 22 – Simulated river discharges values under current climate and for the +3 degree dry Tactic scenario.

5.3 Conclusion

Predictions of future groundwater reaction to TACTIC climate change scenarios are contrasted and depend on the evolution of future precipitation (dry scenario or wet scenario). Changes are amplified in the +3 degree, wet and dry scenarios, compared to the +1 degree scenarios. Results show that, for +3 degree scenarios, future mean groundwater recharge is expected to increase for both dry and wet scenarios (+2% and 19% respectively) compared to the mean groundwater recharge for historical period, leading to an increase of the mean shallow groundwater levels. Increases of shallow groundwater levels would concern all seasons, except spring in the case of the +3 degree wet scenario for the upper Jurassic aquifer, and all seasons for Dogger aquifer. However, decreases in the water level are more marked in summer and in autumn for the + 3 degree dry scenario.

River discharge is expected to increase in winter for all Tactic scenarios. Increase is more important for the +3 degree scenarios (dry and wet). However, for +1 degree and + 3 degree dry scenarios, low flows would be comparable to the reference period or slightly more severe.

6 REFERENCES

Amraoui N., Thiery D., Vergnes J-P., Arnaud L., Rousseau M., Lanini S et Caballero Y. (2017) – Aqui-FR - un système multi-modèle hydrogéologique à l'échelle nationale : travaux 2015-2016. Rapport final BRGM/RP-66683-FR, 192 p., 118 ill., 4 ann.

Bichot.F., Thinon-Larminach.M., Touchard.F., Bailly. D. (2005) - Synthèse hydrogéologique par bassins versants de la région Poitou-Charentes. Relations nappes-rivières. Rapport BRGM/RP-53767-FR, 130 p.

Douez (2008) : Bassin versant de la Boutonne – État des lieux de la qualité des eaux par rapport au paramètre nitrate – Rapport BRGM RP-56404-FR, 49 p., 24 ill.

Douez O., Bichot F. et Petit L. (2011). Contribution à la gestion quantitative des ressources en eau à l'aide du modèle Jurassique de Poitou-Charentes. BRGM/RP-59288-FR, 411 p., 286 ill., 2 ann., 4 planches hors texte.

Lavie J. (2005) - Avis sur la mise en oeuvre d'un programme de type RESOURCES dans la zone d'alimentation des captages pour l'Alimentation en Eau Potable du secteur Nord-Boutonne (79). Rapport BRGM/RP-53768-FR, 59 p., 11 ill., 3 tab., 2 ann.

Lemordant Y. (1998) - Bassin de la Boutonne – Relations nappe-rivière – délimitation de la nappe d'accompagnement. Rapport BRGM R 40095, 37 p., 16 fig., 4 ann.

Putot E., Bichot F. (2007). CPER 2000-2006 Phase 4 - Modèle Infra-Toarcien Dogger : calage du modèle hydrodynamique en régime transitoire. BRGM/RP- 55742-FR, 94 p., 86 ill., 7 tab., 8 ann.

Quintana-Seguí P, Le Moigne P, et al. (2008). Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over France. Journal of Applied Meteorology and Climatology, 47 (2008), pp. 92-107

SYMBO (2017) – Projet de territoire du bassin versant de la Boutonne : Stratégie et programme d'action. 95p.

SYMBO (2007) : Les assèchements de cours d'eau sur le bassin versant de la Boutonne : Partie1 : historique des assèchements de cours d'eau. 85 p.

SAGE boutonne (2016): Schéma d'aménagement de gestion des eaux de la boutonne, document adopté par la CLE (commission de l'eau) le 7 juillet 2016

Thiéry, D., 2015a. Code de calcul MARTHE – Modélisation 3D des écoulements dans les hydrosystèmes - Notice d'utilisation de la version 7.5. Rapport BRGM/RP-64554-FR, 306 p., 150 fig. http://infoterre.brgm.fr/rapports/RP-64554-FR.

Thiéry, D., 2015b. Modélisation 3D du transport de masse et du transfert thermique avec le code de calcul MARTHE – version 7.5. Rapport BRGM/RP-64765-FR, 324 p., 158 fig. http://infoterre.brgm.fr/rapports/RP-64765-FR.pdf