Deliverable 3.2 & 6.3

PILOT DESCRIPTION AND ASSESSMENT

Avre Basin (France)

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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 & D6.3
Dissemination level	Public
Deliverable name	Pilots description and assessment report for groundwater-surface water/ Pilots description and assessment report for adaptation
Work package	WP3 & WP6
Lead WP/Deliverable beneficiary	GEUS (WP3), IGME (WP6)
Deliverable status	
Version	Version 2
Date	23/02/2021

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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

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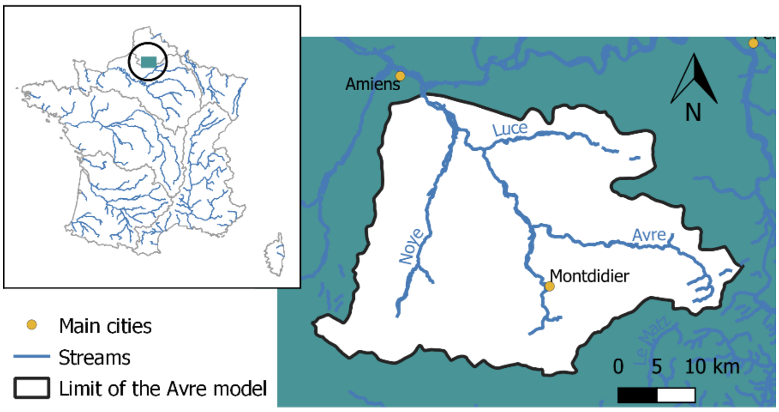
1 EXECUTIVE SUMMARY

Pilot name	Avre	
Country	France	
EU-region	North Western Europe	
Area (km²)	1 294 km²	
Aquifer geology and type classification	Chalk ; Porous and fissured aquifer	
Primary water usage	Irrigation and drinking Water	
Main climate change issues	The chalk aquifer is the main water resource used for drinking water supply and irrigation in the Somme river basin. Groundwater in this basin is in strong interaction with rivers, pond and Wetland, which represent outlets of the water table. Although this basin experienced historical groundwater floods in 2001, some of its sub-bassin, particularly the Avre sub-basin (located in the left bank of the Somme river) has known several drought periods in the past, which seem to be renewed with increased frequency in recent years. Extreme events (flood and drought) are predicted to increase under future climate, so it is important to assess the effects of climate change on the hydrological extreme and to design and evaluate adaptation measures in relatioship with water ressources managers and all groundwater users.	
Models and methods used	Integrated Hydrological model (Numerical model, time series analysis …)	
Key stakeholders	Water Agency; agricultural profession of Somme valley; AMEVA (territorial Public establishment), DDT 80 (water police)	
Contact person	Nadia Amraoui, BRGM French Geological survey, n.amraoui@brgm.fr	

The Avre pilot is located in the north of France in the Somme department. The Cenomanian-Turonian chalk represents the major geological structure in this basin. Chalk aquifer forms the main water resource for drinking water supply and irrigation uses. The groundwater is in strong interaction with rivers, pond and Wetland, which represent the water table outlets. In the past two decades, the Avre basin has experienced tensions over water resources due to growing water demand and a deficit in groundwater recharge due to several drought episodes. An intensification of extreme events is expected due to global warming, so it is important to assess the effects of climate change on groundwater resources under different warming scenarios, and to assess the relevance of adaptation measures to cope with the climate change effects.

As part of the TACTIC project, a study of climate change impacts on the chalk aquifer recharge, groundwater level and river discharge was performed. Moreover, two adaptation scenarios were tested and their effects on groundwater resources were assessed. The assessment of climate change impacts on water resources is carried out using four selected TACTIC standard climate change scenarios and the regional hydrological model of the Somme River basin developed with the MARTHE computer code from BRGM. MARTHE allows the simulation of flows in aquifers and in river networks, including climatic and human influences, from climatic variables taken as inputs for the model. The selected TACTIC standard climate change scenarios represent an increase of global annual mean temperature by +1 and +3 degrees compared to the reference period (1981-2010), under wet and dry precipitations conditions. The four TACTIC datasets representing the future climate conditions are generated by applying the delta change factors to current local dataset of precipitation, evapotranspiration and temperature. It supposes similar evolutions of climatic variables for the current and the future climate. Moreover, changes in groundwater abstraction in the future climate scenarios are not considered. The impact is quantified by comparing simulated results obtained with the data provided by each TACTIC standard scenario to those simulated on the reference period (1981–2010). Annual changes in mean groundwater recharge and mean groundwater levels are analysed and the seasonal responses of the system are assessed.

Two adaptation scenarios were defined based on a reduction in water demand for drinking water supply and irrigation. Their impacts on groundwater levels and river flows were assessed. The first scenario SA1 assumes a 20% reduction in withdrawals for drinking water supply, and the second scenario SA2 assumes a 30% reduction in irrigation withdrawals during irrigation period. The Somme model was used to simulate the groundwater level and river flow over the 1981-2010 period under the two adaptation scenarios. The results were compared to the reference simulation (without abstractions reduction) to assess the effects on the groundwater level and the river flow.

For the Avre basin, dry TACTIC climate change scenarios with lower precipitations show higher impacts on the groundwater conditions than wet scenarios with higher precipitations. Such results are due to a global increase of potential evaporation whatever the considered scenarios, meaning much less effective rainfall available for groundwater recharge for dry scenarios. Dry scenarios show longer drought periods with decreases of groundwater levels during all the years that can reach about -6 m (on the plateaus) in periods of lower water table (e.g. in summer) for the worst scenario (i.e. the 3°C dry scenario). River discharges decreases throughout all the year with -20 % of the river base flow expected for the 3°C dry scenario with respect to the 1981-2010 period. The wet scenarios show increases of groundwater levels (reaching +1.5 m locally) and river discharges (+ 9% maximum) during winter. Absolute changes are nevertheless lower for the wet scenarios than for the dry scenarios.

Concerning the tested adaptation scenarios, the scenario assuming a drinking water withdrawals reduction has a local impact on groundwater level, at and around wellfield. On the other side, the scenario assuming an agricultural abstractions reduction has an impact on groundwater level over a large area in Santerre plateau and Avre basin upstream where agricultural boreholes density is greater.

At the territorial level, the development of adaptation scenarios to mitigate climate change need to be done with territory actors. A participative approach involving the main actors of the territory (socio-economic actors, institutional users, etc.) and mobilizing foresight instruments should be privileged.

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 has 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 and 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 the TACTIC activities in the pilot Avre River Basin located in the Northern France, in the Picardie province. Climate change effects groundwater levels, river flow is analysed, and the relevant of two adaptation scenarios is discussed.

3 PILOT AREA

The chalk aquifer forms the main water resource of the Somme administrative county located in the north of France. This unconfined aquifer is directly connected to the Somme River and its associated tributaries. The Avre River basin corresponds to the most impacted sub-basin of the Somme River basin in terms of groundwater abstractions, mainly for supplying irrigation demand and drinking water needs (Amraoui et al., 2014). Since the 90s, the overexploitation of the underlying aquifer has resulted in a decrease of the river discharges over this basin, leading to conflicts between the different usages (Arnaud, 2017). Moreover, the majority of the climate models predict an increase of the severe drought frequency over this sub-basin in the future, which could reinforce this problem. We intend in this project to evaluate the potential impact of climate change scenarios and to assess the effects of some adaptation scenarios on the water resources of this pilot area.

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The case study corresponds to the Avre River basin and covers an area of about 1294 km^2 located in the north of France (cf. Figure 1). It corresponds to the main affluent of the Somme River and its sub-basin is located on the left bank. The total length of the river is 60 km. At the upstream, its path crosses tertiary terrains and then go on through the chalky plateau of the Santerre until reaching the Somme River.

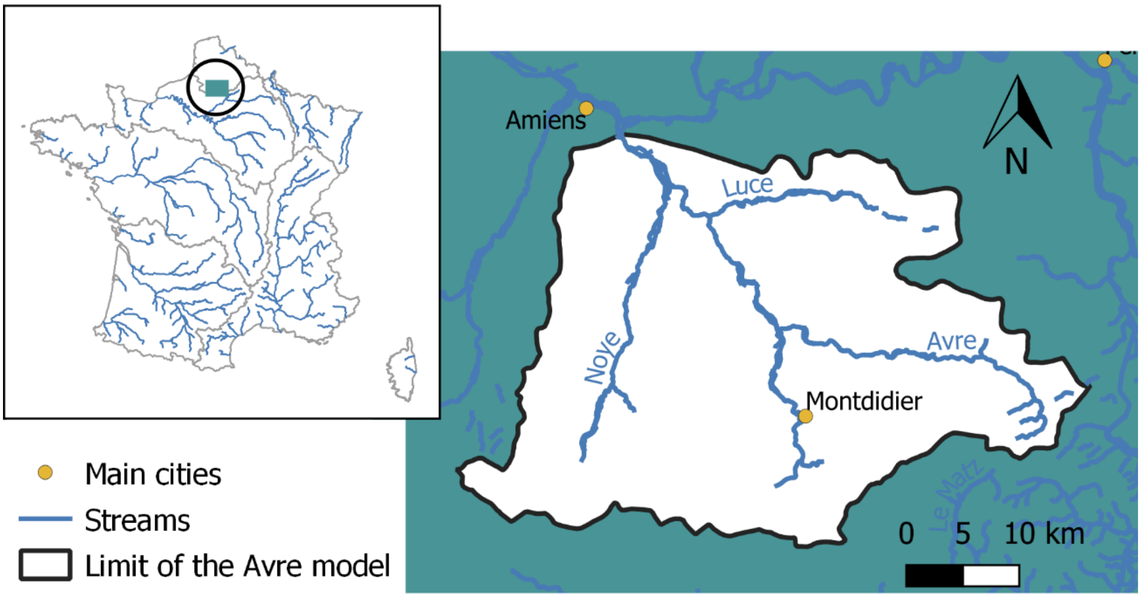


Figure 1: Location of the pilot area

3.1.2 Geology/Aquifer type

According to the BDLISA French hydrogeological reference system (https://bdlisa.eaufrance.fr/), the Cenomanian-Turonian chalk of the Somme River watershed represents the major geological structure of the Avre River sub-basin (green areas in Figure 2). It extends over the whole basin while some tertiary terrains covers the south and the east of the basin. A quaternary upper layer with a 1-m thickness (Ypresian period) is also present in the southeast of the basin. Ancient to recent alluviums characterized the downstream of the Avre riverbed.

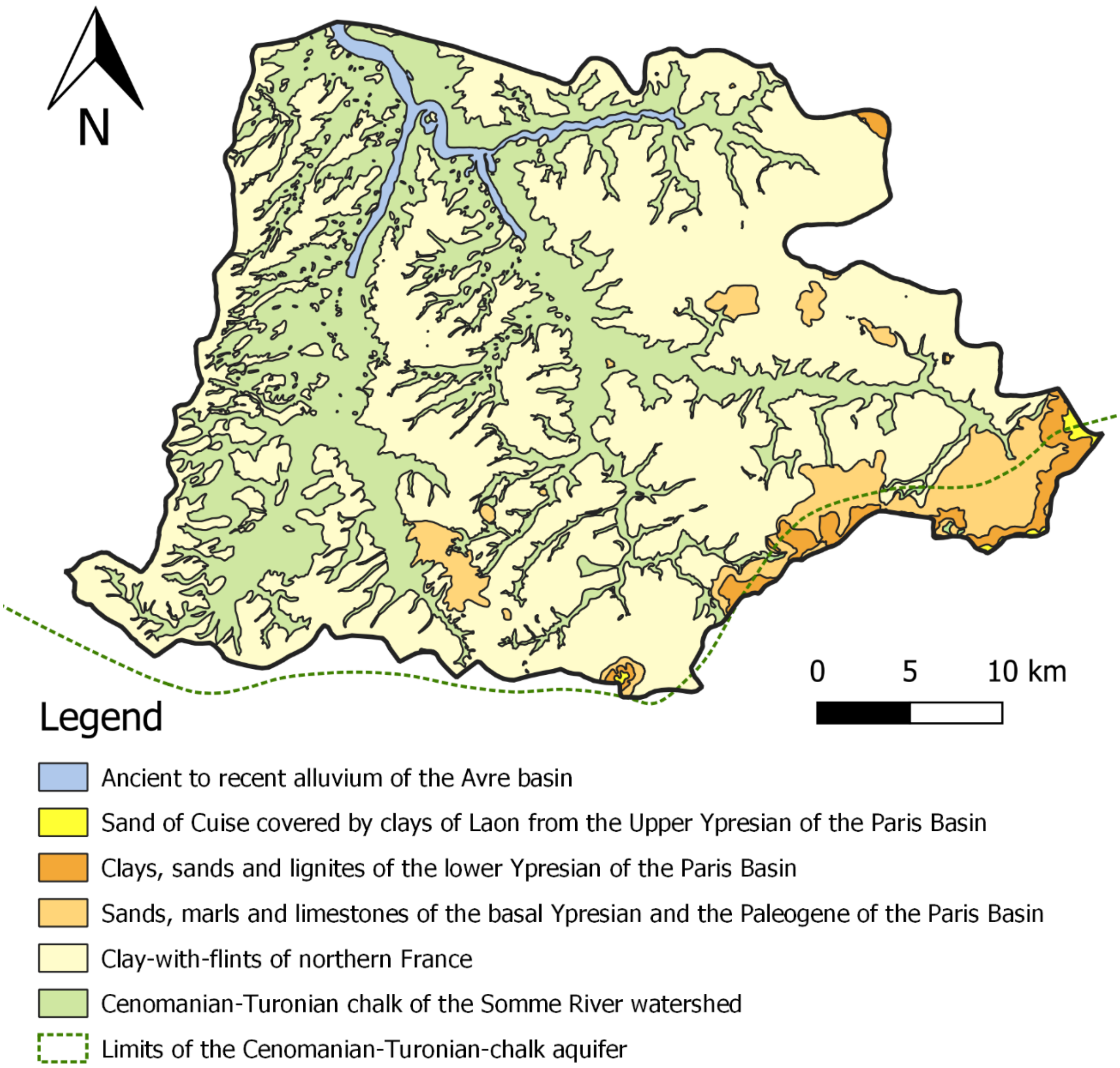


Figure 2: Groundwater bodies of the Avre River basin classified by geological type as defined in the BDLISA (database of aquifer system delineation) French hydrogeological reference system (https://bdlisa.eaufrance.fr/).

The upper chalk cretaceous formation is an extending and powerful reservoir fed by effective rainfall falling over the basin. The water table is unconfined. Groundwater flows toward the valley through fissures generally developed in the upper part of the chalk (in the tertiary terrains) and then feeds the river in the bottom of the valley. An underlying flow occurring in the coarse alluviums of the River characterized the bottom of the valley.

3.1.3 Topography and soil types

The topography varies from 23 m.a.s.L at the downstream of the Avre River to a maximum of 189 m.a.s.l. reached in the southwest of the basin (Figure 3). The area is predominantly flat with shallow valleys. The soils in the basin mainly belong to the Luvisols group according to the FAO classification (Figure 4). Alluvial plains are characterized by Regosols, Histosols and Fluvisols. Others such as Cambisols are also found in the basin.

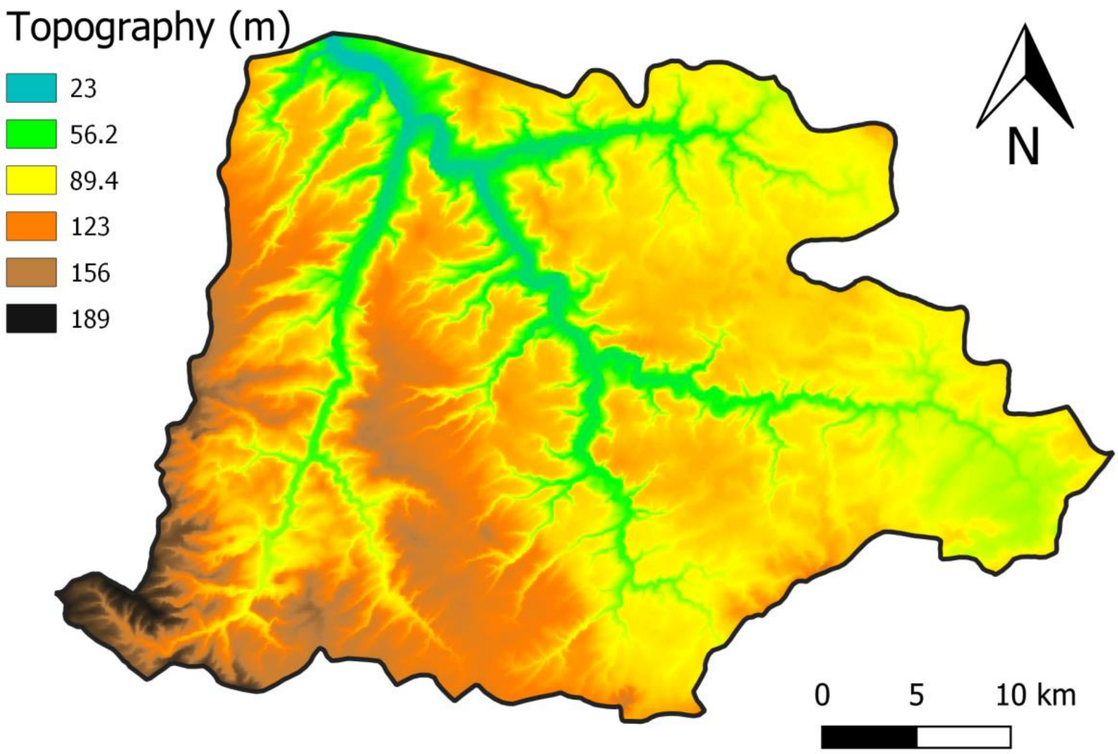


Figure 3: Topography of the Avre River basin from the BDALTI Digital Elevation Model (IGN) (25-m resolution)

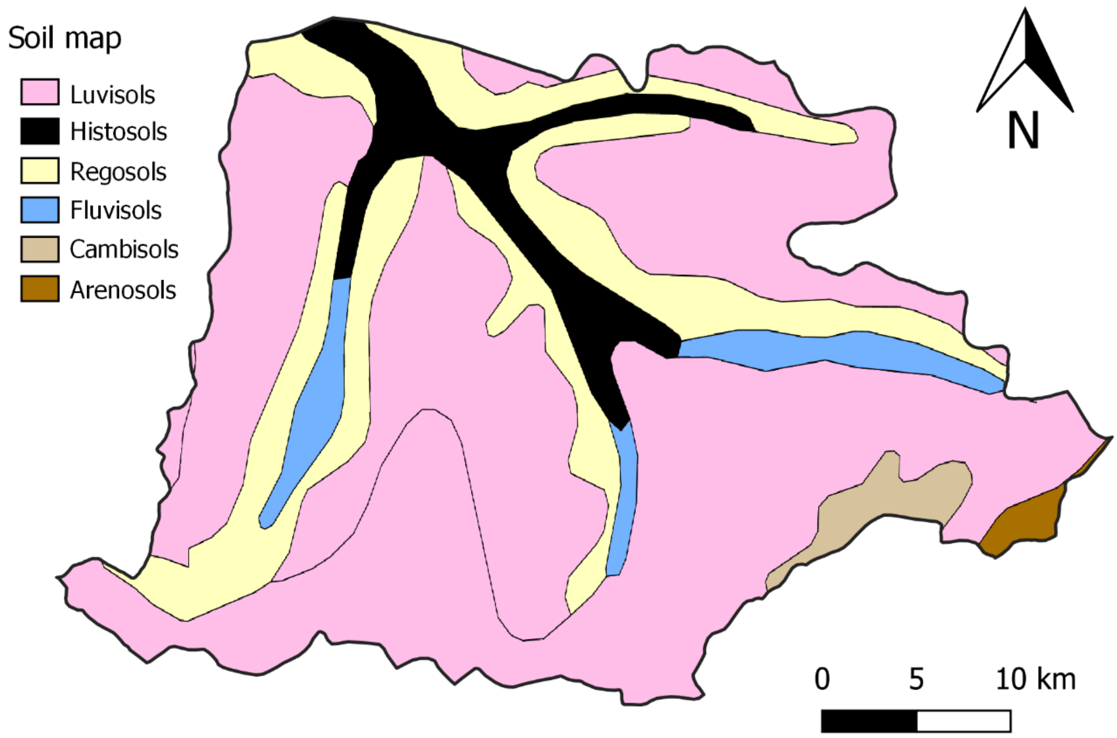


Figure 4: Soil map from BDGSF (Geographical Database of the French Soils)

3.1.4 Surface water bodies

The main affluents of the Avre River are, from upstream to downstream, the Trois-Doms River (18 km), the Noye River (26 km) and the Luce River (16 km). All these rivers drain the chalk aquifer during both dry and humid periods. Three gauging stations are available to monitor the river discharges of the Noye River and the Avre River. They are described in Table 1 and time series are shown in Figure 6.

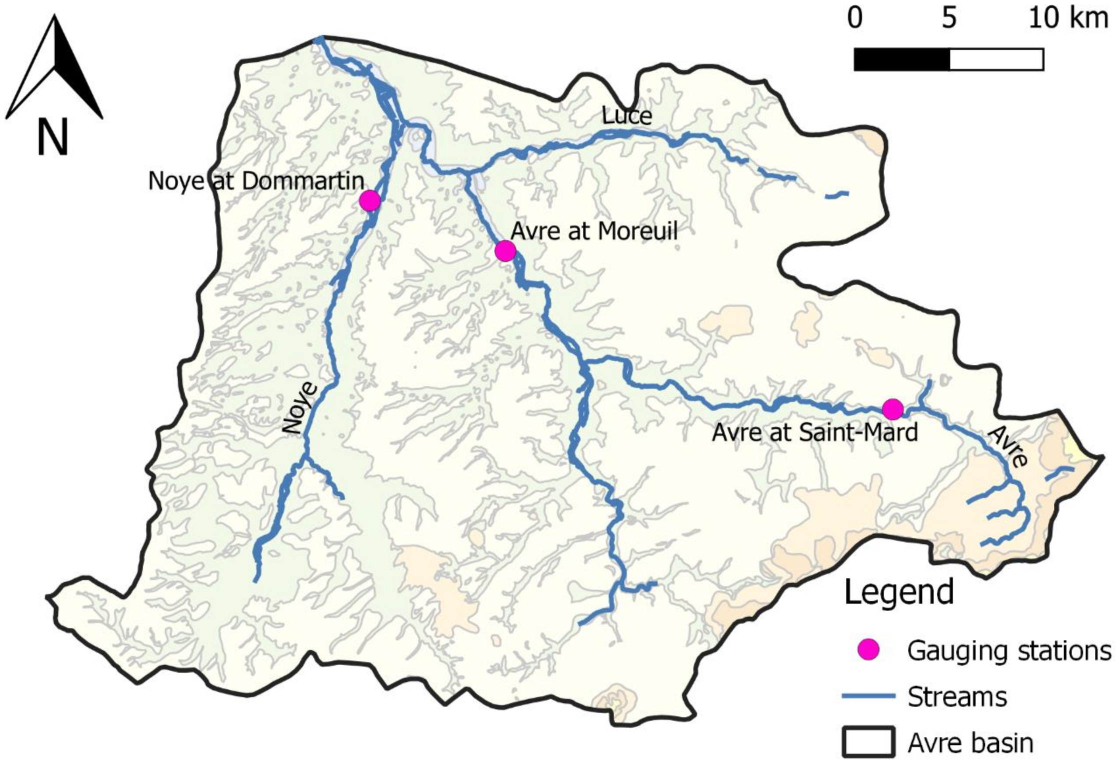


Figure 5: Main rivers and gauging stations of the Avre basin.

Table 1: Statistics of the flow gauges

Flow gauges	Average Q (m3/s)	Period	Surface (km^2)
E6406010	2.2	1968-2018	624
E6406035	0.3	2001-2018	113
E6407540	1.3	2010-2018	311

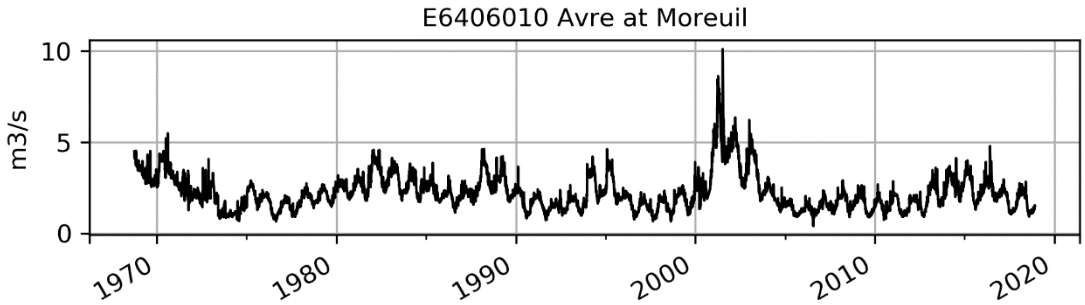


Figure 6: Time series of river discharges for the gauging station located at Moreuil.

3.1.5 Hydraulic head evolution

Figure 7 represents the spatial distribution of the hydraulic head observations and Figure 8 shows three examples of hydraulic head evolutions that are representative of the chalk aquifer behaviour. The hydraulic head evolution of the chalk aquifer is characterized by pluri-annual cycles superimposed with inter-annual cycles.

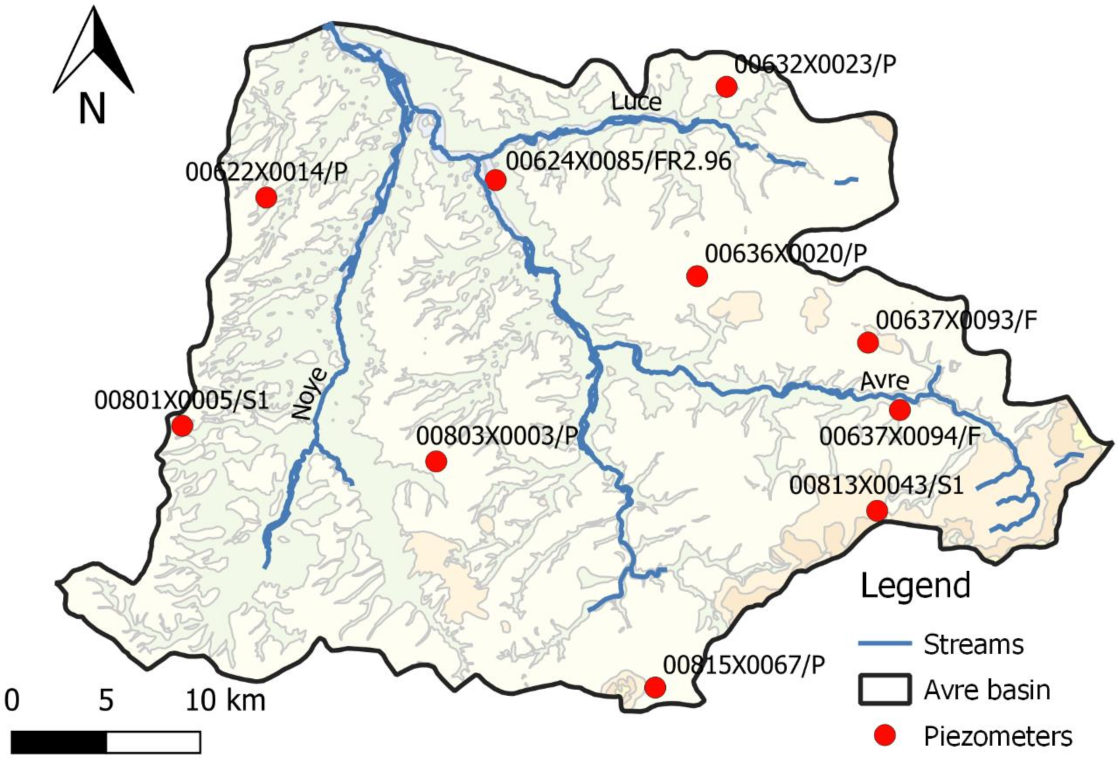


Figure 7: Spatial distribution of the available piezometers

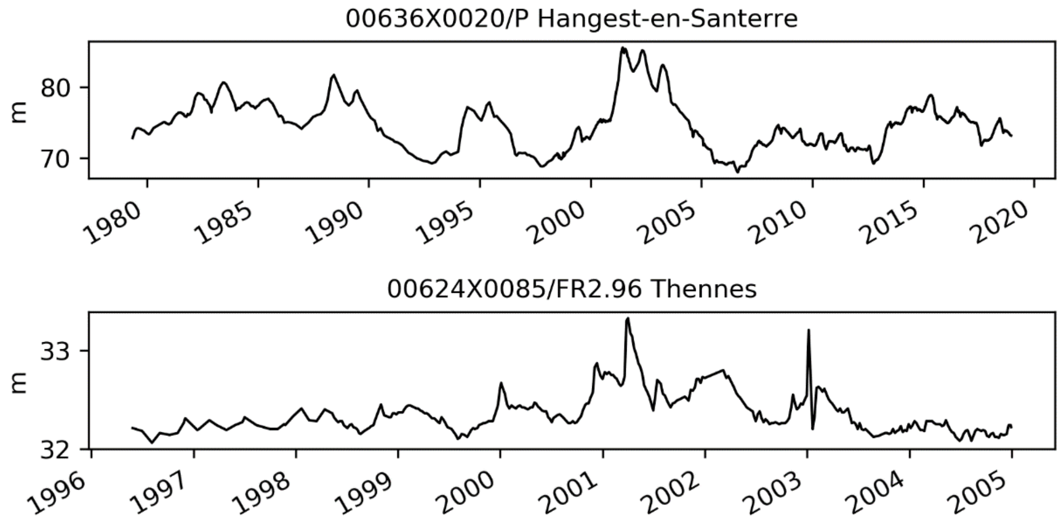


Figure 8: Time series of hydraulic head for two piezometers.

3.1.6 Climate

The climate condition of the Avre basin is semi-oceanic and temperate. Dominant winds come from the coast. According to the SAFRAN meteorological reanalyses (Vidal et al., 2010), the annual mean rainfall is equal to 700 mm/year in the 1958-2018 period. The mean annual temperature is 9°C, oscillating between a maximum daily mean temperature of 18.5 °C in July and a minimum of 1.3 °C in January. The mean potential evapotranspiration is 665 mm/year.

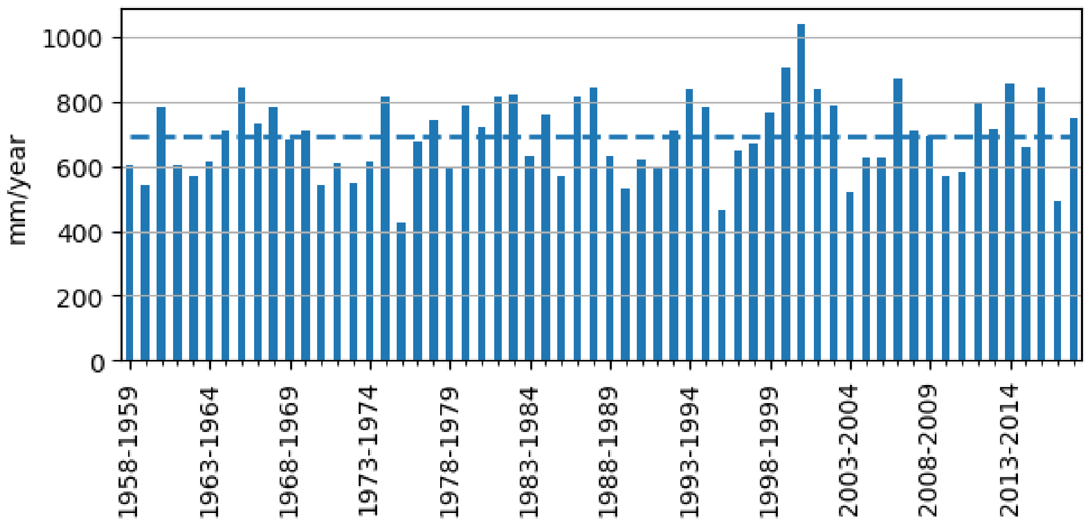


Figure 9: Time series of the precipitation (mm/year). The dashed line corresponds to the mean precipitation.

3.1.7 *Land use*

According to the Corine Land Cover database (cf. Figure 10), agriculture constitutes the major part of the land use of the Avre River basin. Forests are scattered and essentially constituted of oaks, hornbeam and lime trees. Swamps are also present in some locations.
The Avre basin is classified as a wetland of international importance according to the RAMSAR convention since the beginning of 2018.

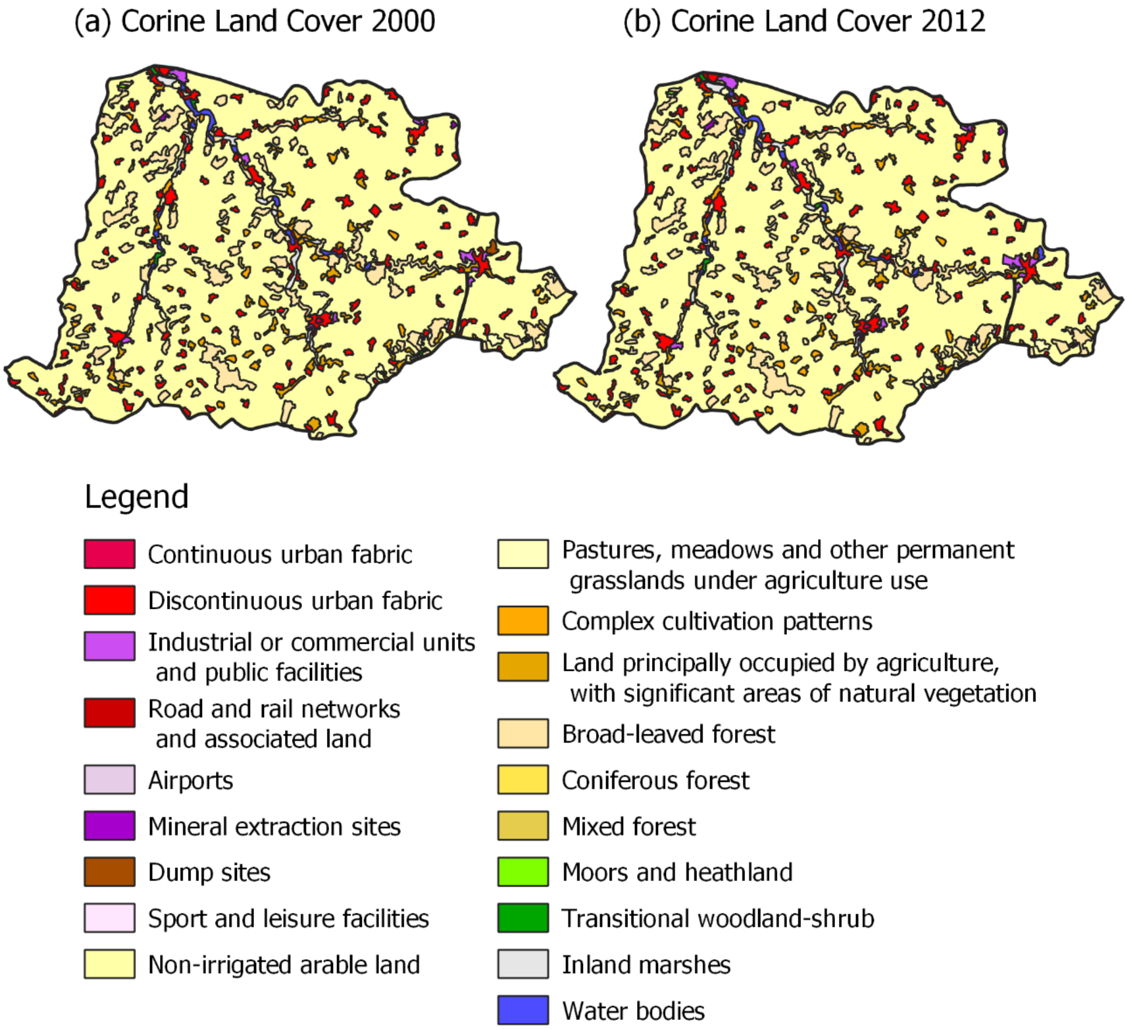


Figure 10: Land use maps from Corine (2000 and 2012)

3.1.8 *Abstraction/Irrigation*

The chalk aquifer is the only groundwater resource of the Avre basin. Three usages characterize this resource: drinking water with 39 wells located for most of them in the Noye and Trois-Doms river basins, agriculture (irrigation) in 83 well, and in a lesser extent industry with four wells. Agriculture and drinking water are the biggest water consumer. In 2003, 49% of the water use corresponds to agriculture and 43% corresponds to drinking water. During the period of irrigation, these percentages evolve to 73% and 24% respectively.

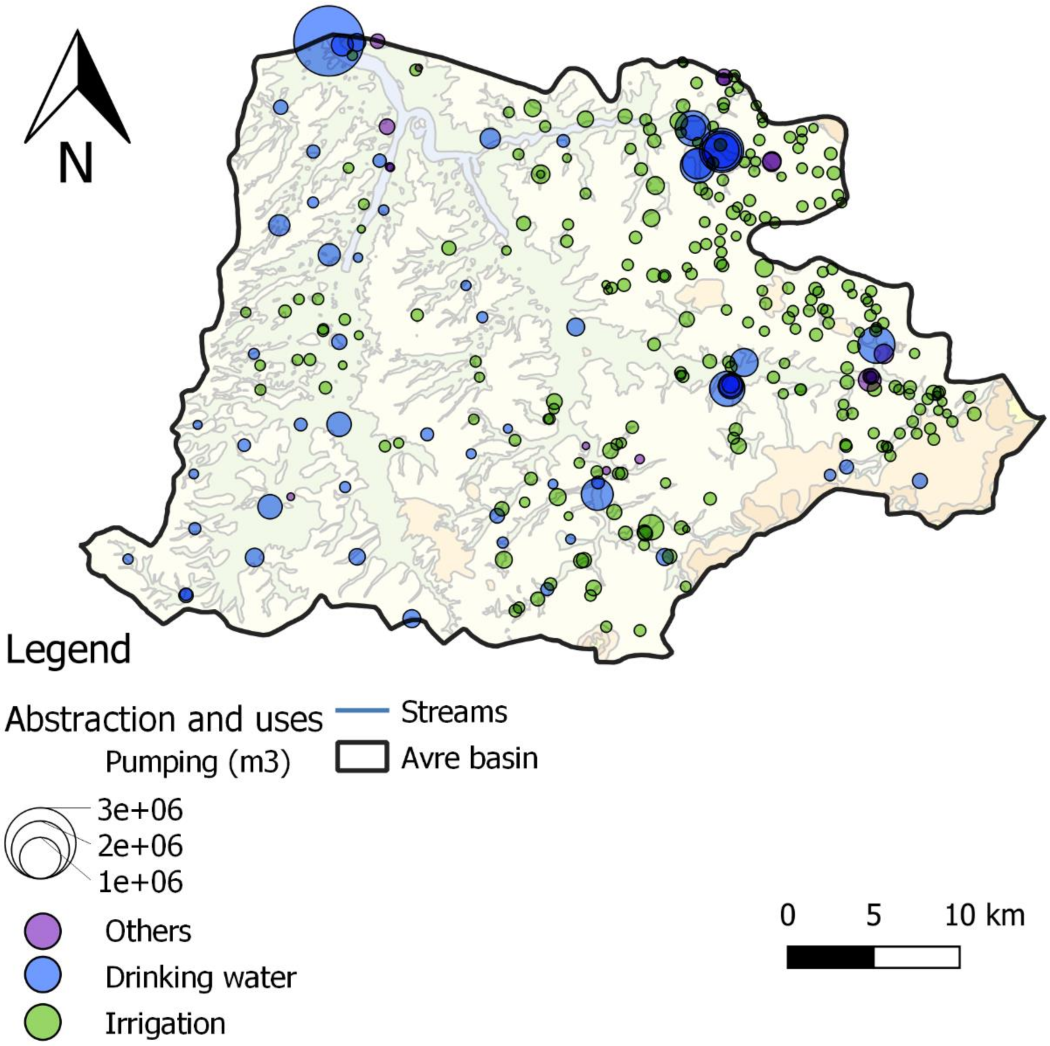


Figure 11: Spatial distribution of the pumpings classified by usages.

3.2 Climate change challenge

The Avre pilot site is located in the North-western Europe region where an increase of precipitation in winter is expected in accordance with the European Environment Agency (EEA) map (Figure 12).

At France scale, recent work based on CMIP5 (Coupled Model Intercomparison Project) models simulations using several climates models, emissions scenarios and different downscaling methods (Dayon 2015; Jouzel et al., 2014) shows an expected increase in precipitation in winter and decrease in summer. General increase in mean annual air temperature is expected that is more pronounced in summer. Results of national Climsec project indicate a continuous increase in soil dryness over the 21-century (Soubeyroux et al. 2011)

Previous study on the hydrological climate change impact in two basins located in the northern France show a marked tendency towards a decrease of the water resource in the rivers and aquifers (on average in 2050 about −14 % and −2.5 m, respectively) (Habets et al. 2013). Hydrological impact study in Somme river basin using projection from 7 GCM and median emission scenario A1B, shows a decrease in groundwater recharge (around -18.7% average of 7 climate models) and decline in river flow expected by 2065 (Amraoui et al 2019). However, two climate models show that high water level are possible confirming the likelihood groundwater flooding risk.

The main challenge in this area is to find adaptation measures to anticipate the future climate conditions in order to better manage available water resources regarding to demands under drought period. In addition, as groundwater Chalk permanently support Rivers and ponds in this area, it is important to ensure a good status in these ecosystems.
In the study area, the main expected issues due to climate change are related to the groundwater droughts.

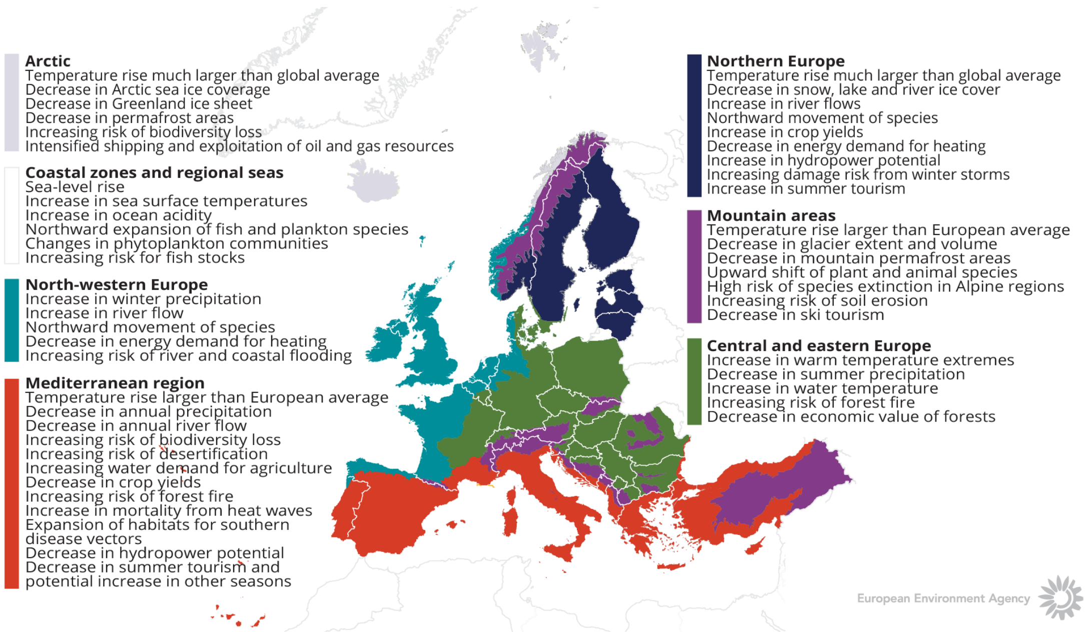


Figure 12 : Key observed and projected impacts from climate change for the main regions in Europe (European Environment Agency)

4 METHODOLOGY

The assessment of climate change effects on the groundwater resource in the Avre River basin uses the TACTIC standard climate change scenarios and the integrated hydrological model developed with the MARTHE computer code (see TACTIC toolbox reference). The ESTHER software allows to analysing droughts from output time series. Moreover, two adaptation scenarios were defined and their effects on both the groundwater levels and the river discharges were assessed by using the Somme hydrological model.

4.1 Climate data

In this study, only TACTIC standard climate change dataset are used to assess climate change impact on groundwater resources for the Avre 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 include 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 4.2. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	6.0	hadgem2-es
	"Wet"	4.5	ipsl-cm5a-lr
3-degree	"Dry"	6.0	hadgem2-es
	"Wet"	8.5	miroc-esm-chem

4.2 Hydrological modelling of climate change

The regional hydrological model of the chalk aquifer of the Somme Basin (Somme model) has been developed in its first version in 2002 (Amraoui et al., 2002) and completed, updated and recalibrated since then (Amraoui, 2004; Amraoui et al., 2014; Amraoui and Seguin, 2012; Arnaud, 2017). The Somme model uses the finite difference groundwater modelling approach implemented in the MARTHE computer code to compute the groundwater evolution of the chalk aquifer (Thiéry, 2020). MARTHE allows the simulation of flows in aquifer systems and river networks, including climatic and human influences. MARTHE implements the GARDENIA lumped parameter hydrological model to compute from surface water balance from climate data (i.e. rainfall and potential evapotranspiration (PET)), which includes surface runoff and groundwater recharge. More details on MARTHE functionalities are available in the Tactic Toolbox.

The assessment of climate change effects on the groundwater resource relies on:
1) The four selected TACTIC climate change scenarios representing an increase of global annual mean temperature by +1 and +3 degrees compared to reference period (1981-2010) under wet and dry conditions
2) The Somme model simulating groundwater conditions over the current period.

The application of delta change factors to the current local dataset of precipitation, PET and temperature generated the four TACTIC climate change scenarios. This method assumes no changes in the evolution of climatic variables for the current and the future climates.

The groundwater recharge, piezometric head and river discharge evolutions were simulated over the period 1958-2018 using the historical local climate data as well as the four climate projections generated from the delta change factors provided by TACTIC. In total, five simulations are available: four Tactic future simulations corresponding to the four Tactic standard future scenarios, and one historical simulation. Future climate simulations assume no changes in groundwater abstractions. Only the results of the 1981-2010 30-years periods are used to assess climate change impacts on groundwater and surface water resources.

4.2.1 Model description

The Somme model extends over an area of 7,400 km^2 and covers the entire hydrologic catchment of the Somme basin, half of the Southwestern Authie basin in its North, and half Northwestern of the Bresle basin in its Southwest (Amraoui et al., 2019). This model integrates the data described in paragraph 3.1. The borders of the Somme River basin includes the Authie River and the Cambrésis heights to the North, the Vermandois to the East, the Noyonnais hills to the Southeast, the Bresle River to the Southwest, and the English Channel to the West (Figure 13). Figure 14 shows the location of the Avre basin in the Somme model. The Somme model includes the full extent of the Avre basin.

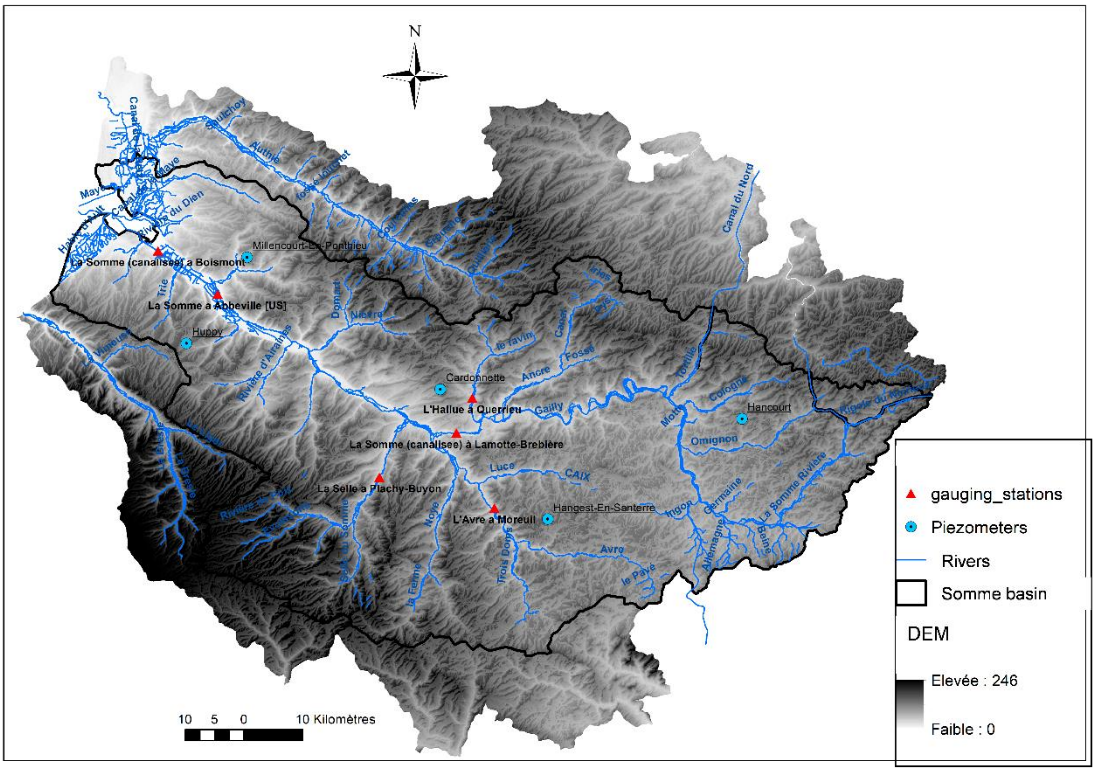


Figure 13 – Geographic map of the Somme River basin (Amraoui et al., 2019)

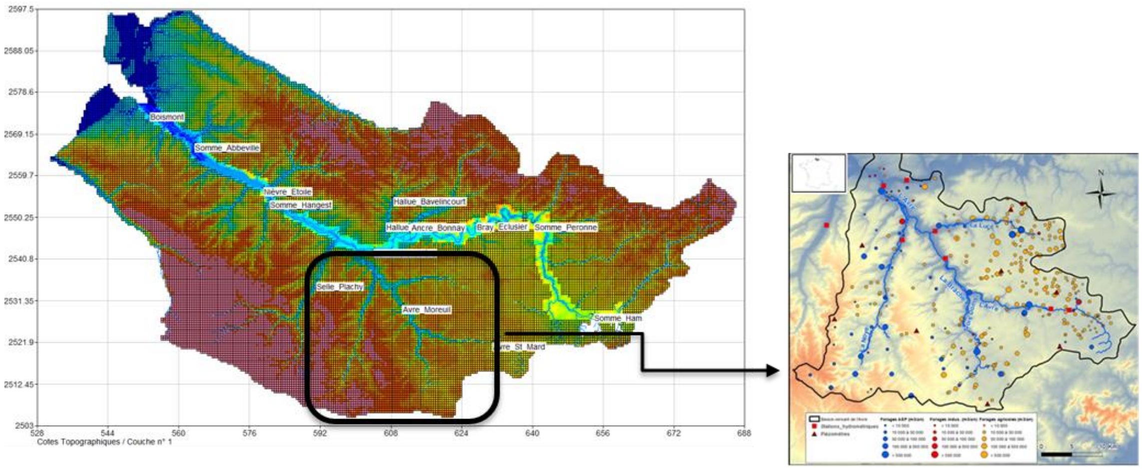


Figure 14 – Location of the Avre watershed in the Somme River basin – the black outline on the right figure represents the limits of the basin on a topographic map background

The chalky aquifer is discretized with a single layer and a computational grid of 500m x 500m resolution except in the humid valley of the Somme where the grid is locally refined down to 100m X 100m for an improved numerical discretization of the aquifer-river interactions close to the Somme river and its tributaries (Amraoui, 2004). In total, the model contains more than 66 000 computational cells. The model takes into account groundwater flow in the chalky layer, flow routing into the associated river system, and the interactions between these two sub-systems. Boundary conditions of the imposed potential type are applied to the west of the regional model and correspond to the see. Elsewhere, no flow limits are applied at the borders of the domain.

The Somme model takes into account all water withdrawals (agriculture, drinking water, industry). The model run in unsteady state conditions. It simulates the evolution of piezometric heads, stream river flows, and interactions between groundwater and surface water. The model runs with a daily time step when computing runoff and recharge and at a weekly time step when computing the groundwater flow in the aquifer system. The calibration period is 1989 - 2012 to include known observations.

The computation of the surface water balance uses spatial distributions of climate data including daily rainfall, PET, and soil parameters, using the lumped hydrological model GARDENIA. This model simulates the evolution of the piezometric heads and streamflows at each point of the river system. More details on this model are reported in Amraoui and Seguin (2012) and Arnaud (2017).

In this study, we used the 2017 version of the Somme model. In this version, the model was updated over the Avre basin with new refinement of the river grid to 100 m x 100 m, an actualisation of the withdrawal dataset over the 1989 – 2012 period, and an updated calibration of the hydrodynamic parameters (river-aquifer parameters and aquifer permeabilities).

In the frame of the TACTIC project, the model was updated over the period 1958-2018 with daily climatic data. Concerning water abstractions in aquifer and river, the acquisition of new datasets during the TACTIC project extends the withdrawal data from 1982 to 2018. Data on surface water withdrawals are available over the period 1992-2018 and over the period 1982-2018 for the groundwater withdrawals. These data, made available by the Artois Picardie Water Agency, were introduced into the Somme river model. Moreover, we assumed that the withdrawals prior to 1982 (from 1958 to 1981) are identical to those of 1982 for all types of uses (irrigation, drinking water supply, industry …). Indeed, analysis of groundwater withdrawals show that they do not vary significantly over the 1982-1992 period. The river water abstractions of the 1993 year were applied to the previous years (1958-1992).

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 the rivers flow rates measured at the gauging stations). The calibration of the Somme model was updated in 2017 over the Avre basin by Arnaud (2017). As part of the TACTIC project, and following the update of the Somme model with recent datasets, a recalibration was undertaken. The calibration was performed over the 1989-2017 period by trial and error approach and concerns only the Avre basin. This calibration concerns the permeability values of the chalk aquifer.

The model evaluation is focused on its capacity to mimic observed groundwater dynamics and river discharges measured at different observation points. The location of the piezometers and the gauging stations used in the evaluation of model calibration is shown in Figure 7 and in Figure 5.

Examples of comparison between the simulated and observed values of groundwater levels and river discharges are shown in Figure 15 and Figure 16. In addition, statistical criteria (Root Mean Square Error: RMSE, Mean Error: ME and the Nash criteria : NSE) were calculated on the basis of monthly values of the groundwater levels and river flow over the calibration period. Chalk groundwater dynamic is well reproduced by the model for the following piezometers: Guillaucourt (ME = -0.58; RMSE = 0.97m; NSE = 0.79); Hangest-en-Santerre (ME = 0.65; RMSE = 0.6.m; NSE = 0.8); Damery (ME = 0.62 and RMSE = 1.m; NSE = 0.84). The Avre River discharge at the Moreuil gauging station is well reproduced by the model with ME = 0.1, RMSE = 0.5 m^3/s and a NSE of 0.76 (NSE criterion is considered to be very good when it is greater than 0.7).

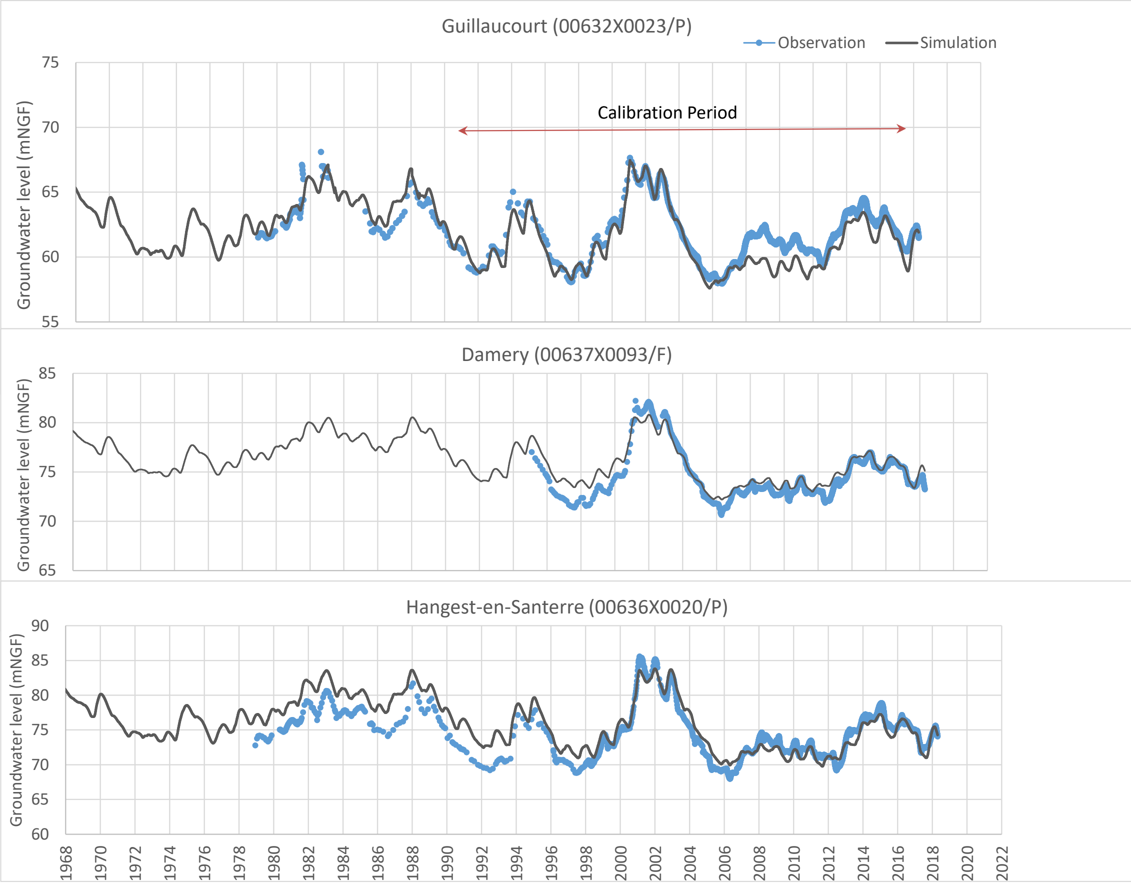


Figure 15 : Examples of observed and simulated groundwater levels in 3 piezometers located in Avre basin.

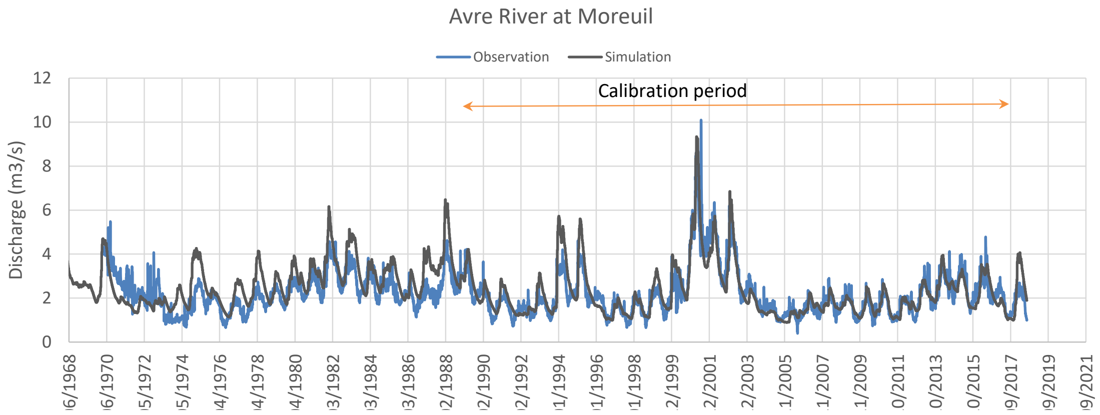


Figure 16 : Daily observed and simulated discharges in the Avre River at the Moreuil gauging station

4.3 Adaptation scenarios simulated with hydrological model

Adaptation measures to cope with the impact of climate change on water resources can relate to: 1) water demand, such as land use change, adaptation of irrigation techniques and economic instruments etc. 2) water offer, which mainly lean towards complementary resources such as active management, natural water retention measures, water transfer, etc. 3) Mixed (improving resilience) such as improving planning, control and allocation of resources, technological innovation etc.. Developing adaptation strategies at the territorial level is generally laborious since it involves climate, land use and socioeconomic scenarios. Two types of approaches exist: the top-down approach, which focuses on the analysis of physical vulnerability and the bottom-up approach, which attempts to assess the social vulnerability. The latter defines plausible scenarios and adaptation measures through participatory processes and workshops with the main actors. The top-down approach aims to identify the optimal measurement programs for the different climate scenarios.

The implementation of a participatory approach involving the main actors of the territory (elected officials, socio-economic actors, institutional users, etc.) and mobilizing foresight tools is laborious and cannot be carried out in this study given the project budget allocated to this task. It was difficult to interact with water stakeholders because of 2020 sanitary conditions (Covid19). Therefore, the method used is to rely on some of proposed actions, in the adaptation plan to climate change of the Artois Picardie basin (developed in 2016), to define two scenarios based on orientation actions already proposed in this plan in connection with water resources, drinking water supply and agriculture.

4.3.1 Adaptation scenarios used

Two adaptation scenarios were defined based on a reduction in water demand for drinking water supply and irrigation. The location of drinking water supply wells and agricultural boreholes is reported in figure 11.

The first scenario called SA1 : this scenario assumes a **20% reduction in withdrawals for drinking water supply** that would be expected through induced by the awareness of water savings among citizens, the improvement of water leaks in the water distribution network; rainwater recovery…

The second scenario called SA3: This scenario assumes a **30% reduction in irrigation withdrawals during irrigation period** who could be reached by the optimization of irrigation (practices & innovative devices for irrigation), by using less water-consuming crop; diversification of water resources (rainwater, treated wastewater, etc.).

The Somme hydrological model is used to simulate the groundwater level and river flow over the period 1981-2010 by considering a reduction of 20% of water drinking supply withdrawals distributed in the same way over the whole year and over all the pumping wells. In the same way, a simulation was carried out taking into account a 30% reduction in irrigation withdrawals during irrigation period (May to September), this reduction is applied to all agricultural boreholes. The results were compared to the reference simulation to assess the effects of withdrawals reductions on the groundwater level and the river flows (Avre River and its main tributaries).

In addition, a third simulation was achieved without any abstraction in groundwater and rivers in order to evaluate the effect of abstractions on the river flows. Impact of tested adaptation scenarios on the groundwater level and river flow was assessed

4.4 Uncertainty

The most important sources of uncertainty concern the data on groundwater and river water withdrawals, which were not known before 1982 and 1993 respectively. Therefore, the assumption made on withdrawals before 1982 for groundwater uses and 1993 for rivers constitutes an important source of uncertainties. In addition, the withdrawal variation over time is not known, only annual volumes are known.

5 RESULTS AND CONCLUSIONS

This section assesses the impact of climate change on the evolution of groundwater recharge, groundwater levels, and river stream flows. Results show comparisons between each future periods of the four Tactic scenarios and the reference period (1981–2010) in terms of annual changes of groundwater recharge and mean, low and high groundwater level. Analyses carried out for the Tilloloy piezometer (corresponding to the 00813X0043/S1 piezometer in Figure 7) and river stream gauges propose local and seasonal responses of the system to the future climate change.

5.1 Effects of climate changes on precipitation, evaporation, and groundwater recharge

Figure 17 compares the monthly mean seasonal cycle of precipitation and PET computed for the four future Tactic simulations in relative changes with respect to the reference historical simulation. Dry scenarios correspond to the simulations labelled with minimum changes and wet scenarios to the simulations labelled with maximum changes. Three scenarios (+1°C dry, +3°C dry and +3°C wet) present increases of precipitation during winter. Precipitation rises also occur in summer for 1°C and 3°C wet scenarios. Conversely, precipitation decreases occur in summer for both the 1°C and 3°C dry scenarios. Monthly changes in PET shows an increase for all scenarios, and it is more important in summer under +3°C global warming

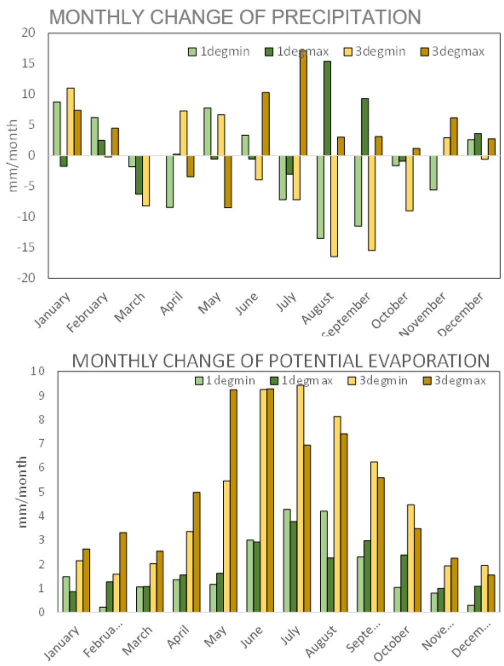


Figure 17: Monthly changes of precipitation and PET under +1° C and +3°C for the 4 Tactic standard scenarios. In the legend, the “min” suffix means dry and “max” means wet.

Regarding groundwater recharge, results shows that the 1°C and 3°C dry scenarios generate a decrease of -5.5% and -13% respectively with respect to the reference period in terms of mean annual changes in average over the Avre basin. The 1°C and 3°C wet scenarios generate an increase of +0.7 % and +3.79% respectively.

5.2 Effects on piezometric heads and river flows

5.2.1 Change in groundwater resources

Applying the Somme model with MARTHE enables simulated outputs in the format of grid/raster for pre-defined time-intervals. These gridded outputs were printed with a 30 days interval. Therefore, it was possible to analyse, not only the mean changes (the difference between the simulated future periods and the simulated reference period), but also to analyse the changes for relatively dry and wet periods throughout the years, respectively. Figure 18 shows the relative changes of simulated piezometric heads between the four future Tactic simulations and the reference period (1981-2010) computed for each grid cell of the Somme model focused on the Avre basin. Representing the time of the year with lowest groundwater levels, a change of the 5 % quantile of the simulated 30 periods is shown (Future Q5 – Past Q5). This typically occurs during the summer and fall period. In the same way, the 95 % quantile is used to illustrate the changes of the period with highest groundwater levels, typically during the winter or early spring.

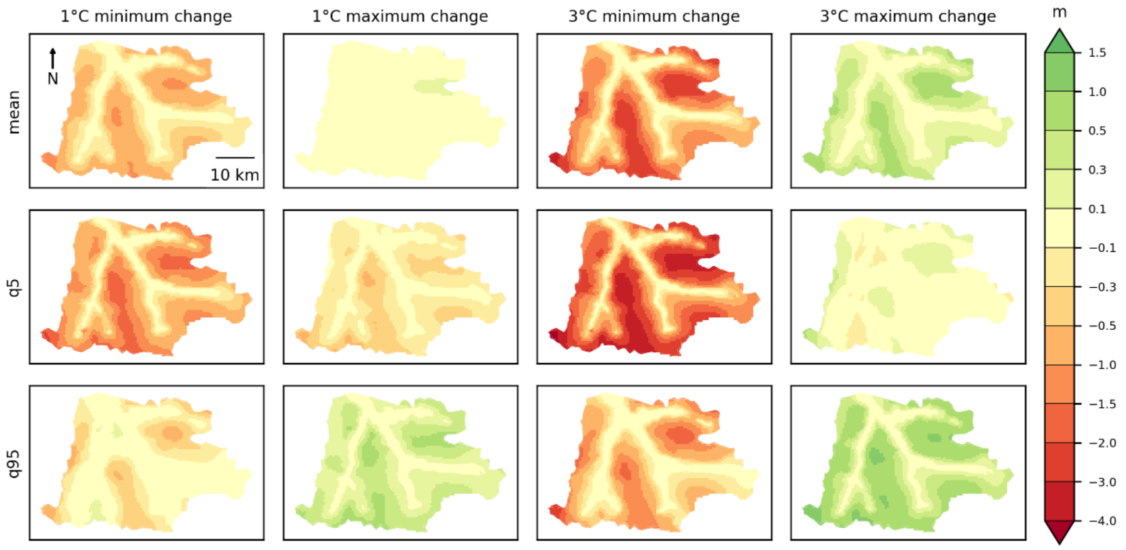


Figure 18 : Changes in mean, high and low shallow groundwater levels simulated with the four TACTIC standard scenarios

Results show an increase of mean groundwater levels for the 3°C wet scenario (maximum change scenario), while no significant changes appear for the 1°C wet scenario. The change of groundwater levels for Q95 shows increases for the two scenarios. The change for Q5 shows decreases for the 1°C wet scenario while no significant pattern appear for the 3°C wet scenario.

Both 1°C and 3°C dry scenarios show decreases of mean groundwater levels. This decrease becomes accentuated for the 3°C dry scenario and can reach locally -3 m. The changes for Q5

and Q95 are in accordance for decreases in the future, which can reach locally about -6 m locally for the 3°C dry scenario for Q5.
Changes occur mainly on plateaus than on wet valleys. Those results concord with the relative changes computed for the groundwater recharge over the Avre domain described previously.

5.2.2 Climate change impact on drought evolutions

One way to evaluate the ability of the simulation to capture extreme events is to use the Standardized Piezometric Level Index (SPLI). The SPLI is an indicator used to compare groundwater level time series and to characterize the severity of extreme events such as long dry period or groundwater overflows (Seguin, 2015). The SPLI indicator is based on the same principles as the Standardised Precipitation Index (SPI) defined by McKee et al. (1993) to characterize meteorological drought at several time scales. First, monthly mean time series are computed from time series of piezometric heads. Then, twelve monthly time series (January to December) are constituted over the N years of the time series period. For each time series of N monthly values, a non-parametric kernel density estimator allows estimating the best probability density function fitting the histogram of monthly values. At last, for each month from January to December, a projection over the standardised normal distribution using a quantile-quantile projection allows deducing the SPLI for each value of the monthly mean time series of piezometric heads. The SPLI values most often range from -3 (extremely low groundwater levels corresponding to a return period of 740 years) to +3 (extremely high groundwater levels). The SPLI allows representing wetter and drier periods in a similar way all over the simulated domain.

Figure 19 shows the SPLI evolution for the Tilloloy piezometer located over the Avre basin (corresponding to the 00813X0043/S1 piezometer in Figure 7), which presents results representative of the behavior of the other piezometers located over the Avre basin. The SPLI was computed from the 1981-2010 reference period for the four future simulation using the Tactic climate changes projections and for the historical simulation. The SPLI indicator computed for the historical simulation shows a 21-months length drought in 2005 (evolution not shown here). The SPLI evolutions of Figure 19 shows the most important increase of the severity and length of droughts for the 3°C dry scenario, especially in 1992, 1997 and 2005. In 2005, the projected length of the 3°C dry simulation drought is 41 months, i.e. twice the length of the historical drought.

The 1°C dry scenario also shows an important increase of the severity of droughts in 1997 and 2005. For this scenario, the 2005 drought lasts 26 months. At last, the 1°C and 3°C wet scenarios show an increase of the severity of droughts in 2005 less significant, with similar durations compared to the 2005 historical drought.

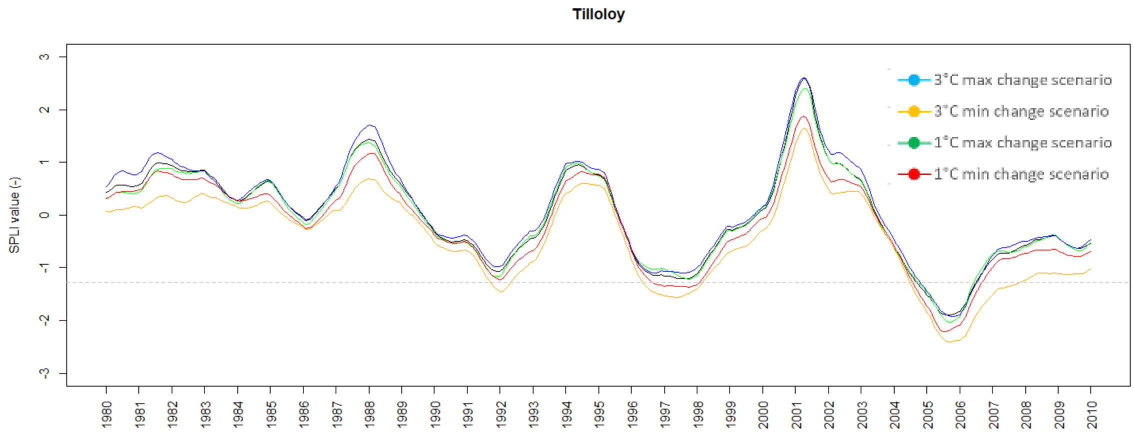


Figure 19: SPLI evolution for the reference period and the four Tactic standard scenarios for the Tilloloy piezometer.

5.2.3 Change in river flow

Figure 20 represent the monthly mean river flows of Avre river at Moreuil gauging station calculated over 30-years for the historical period and under the four Tactic climate change standard scenarios.

Figure 21 shows the monthly mean seasonal cycle of the relative changes of simulated river stream flows for the Avre River at the Moreuil gauging station between the four Tactic future simulations and the historical simulation. The 1°C and 3°C dry scenarios show a decrease of the river discharges for all months. The high flow period from November to March present marked decreases with about -15% and -25% of changes in winter for the 1°C and the 3°C dry scenarios respectively. Changes for the 3°C dry scenario are more severe than for the 1°C dry scenario in all seasons.

Conversely, the 1°C and 3°C wet scenarios depict an increase of the simulated stream river flows for the high flow period, with a bigger impact of the 3°C wet scenario.

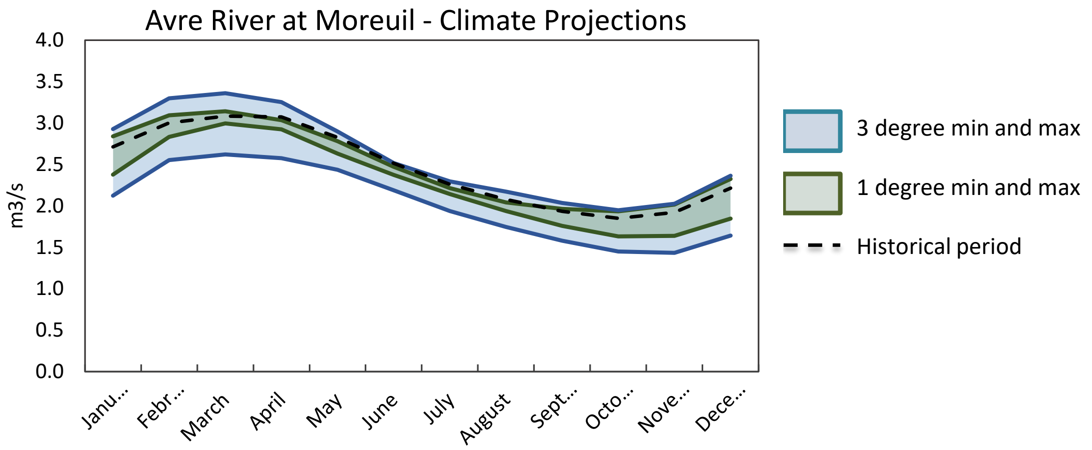


Figure 20 : Monthly mean Avre river discharge at Moreuil station calculated over 30 years for the reference period and for the Tactic standard scenarios

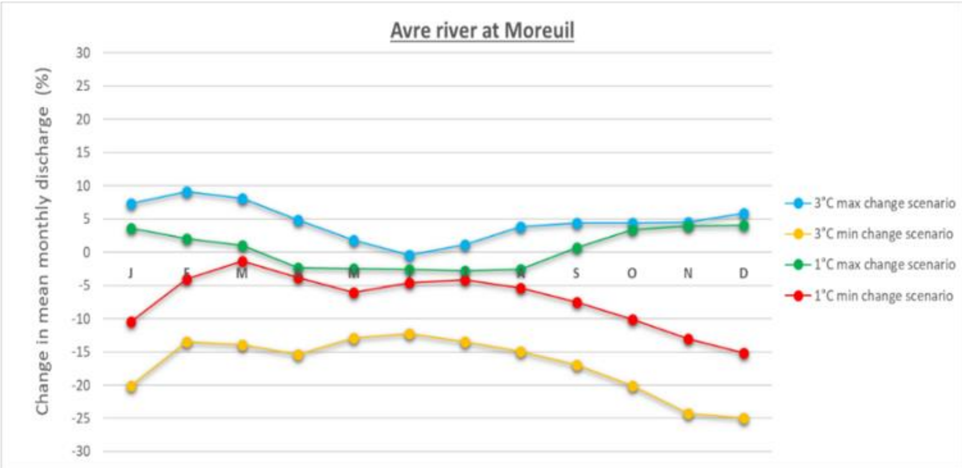


Figure 21 : Monthly mean seasonal cycles of the river discharges for the Avre River at the gauging station located at Moreuil. Results for the four Tactic future simulations are shown relative to the historical simulation.

5.3 Effects of adaptation scenarios on water resources

5.3.1 Effects on groundwater level

Figure 22 shows the change in average groundwater level over the 30-years period (1981-2010) induced by the SA1 adaptation scenario compared to the mean reference groundwater level simulated over the same period with current withdrawals. Reduction in drinking water withdrawals has a local impact at and around wellfield, in particular those located at the upstream of the Luce basin for which the rise in the water table appears significant with a maximum local groundwater level rise of +1.4 metres.

Figure 23 shows the change in mean groundwater level and average groundwater level of July, over 30 years, induced by the SA3 adaptation scenario compared to the mean reference groundwater level. Concerning the impact of SA3 scenario on the mean groundwater level, there is an increase in water table over a large area over the north of the basin. This is due to an important use of the irrigation on this part of the basin.

The impact of the SA3 adaptation scenario is much greater in July and August as shown on the right map in Figure 23. Indeed, as more than half of the annual volume used for irrigation is withdrawn between July and August, the impact on the water level is more important for these two months. The increase in the water table is greater on the plateaus (in particular the Santerre plateau) and at the head of watersheds than in the wet valley. The increase in the water table in July can reach 2.43 m locally for the AS3 scenario.

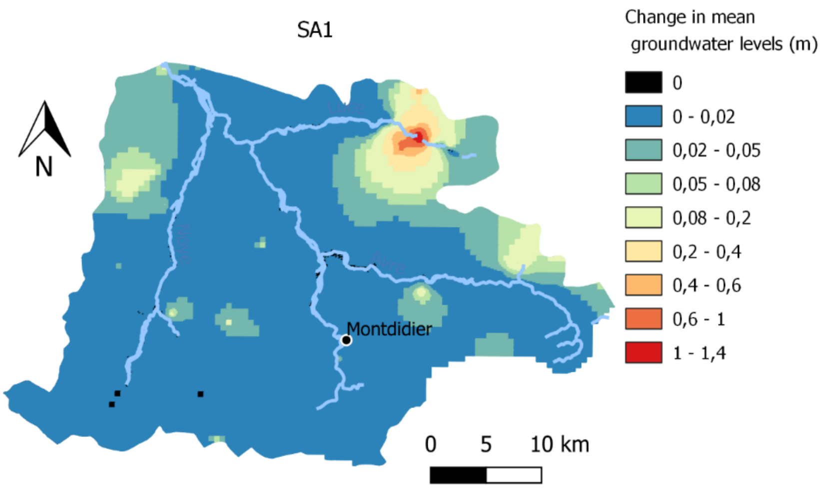


Figure 22 – Change in mean groundwater level for the SA1 adaptation scenario in relative to current situation.

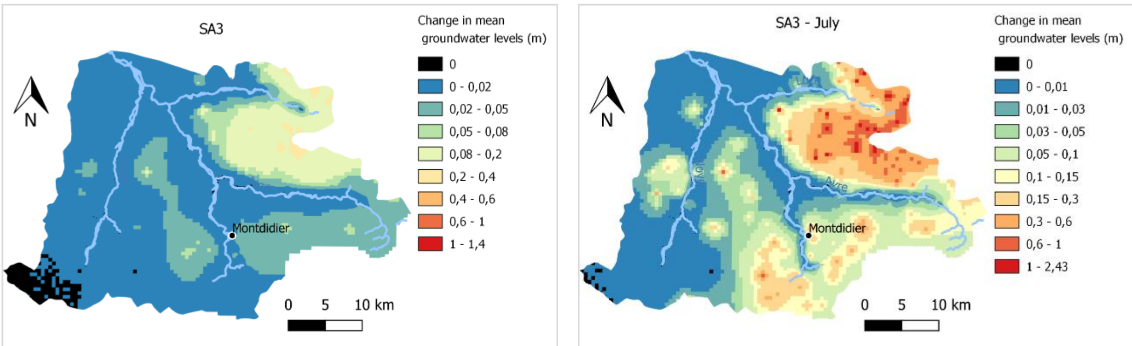


Figure 23 : Change in mean groundwater level over 30 years (map on the left) and in July mean groundwater level (map on the right) for the SA3 adaptation scenario in relative to current situation.

5.3.2 Effects on River flow

The impact of the tested adaptation scenarios on the river flow is quantified by comparing simulation results obtained for each adaptation scenarios to those obtained for the reference period (1981-2010) using current abstraction conditions. Figure 24 shows that the impact of the SA1 adaptation scenario on the mean monthly discharge of the Avre River at Moreuil is very low (less than 1%) and remains stable over the years. The impact of the SA3 adaptation scenario is significant during the irrigation period and reached 3.7% in July. The figure shows also that the impact of the current water abstraction (red curve) ranges between 4% and 10% depending on the considered month.

The impact on the Avre river flow is more visible at the upstream of the basin (i.e. the Saint-Mard gauging station in Figure 25 reaching 8.5% for the SA1 scenario and 7.5% for SA3 scenario.

Effects of current pumping(red curve) at the upstream of the Avre River and the Luce River is important, 10% to 30% and 18% à 40% respectively, as shown in Figure 25.

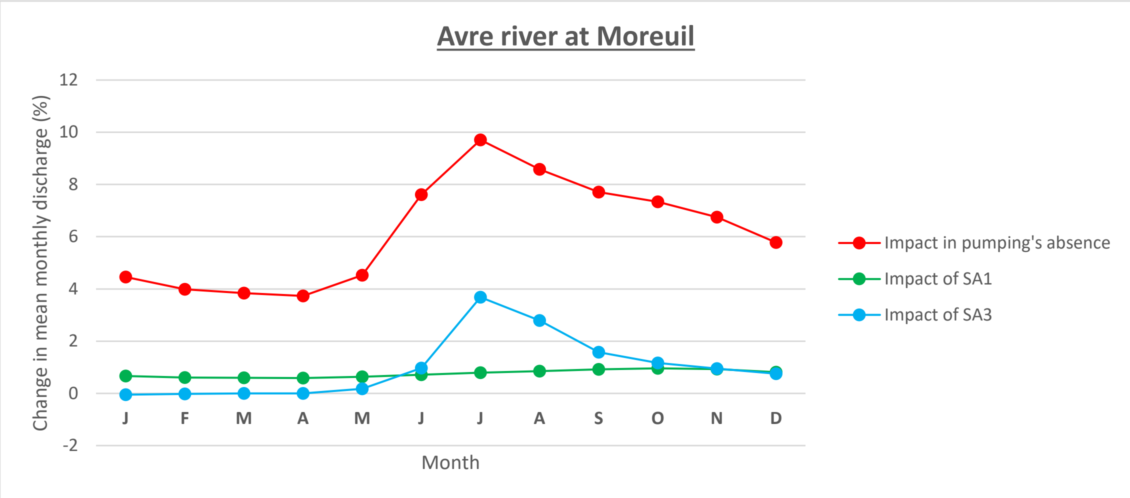


Figure 24 : Change (in %) of monthly mean discharge in Avre River at Moreuil for SA1 and SA3 adaptation scenarios compared to the reference period.

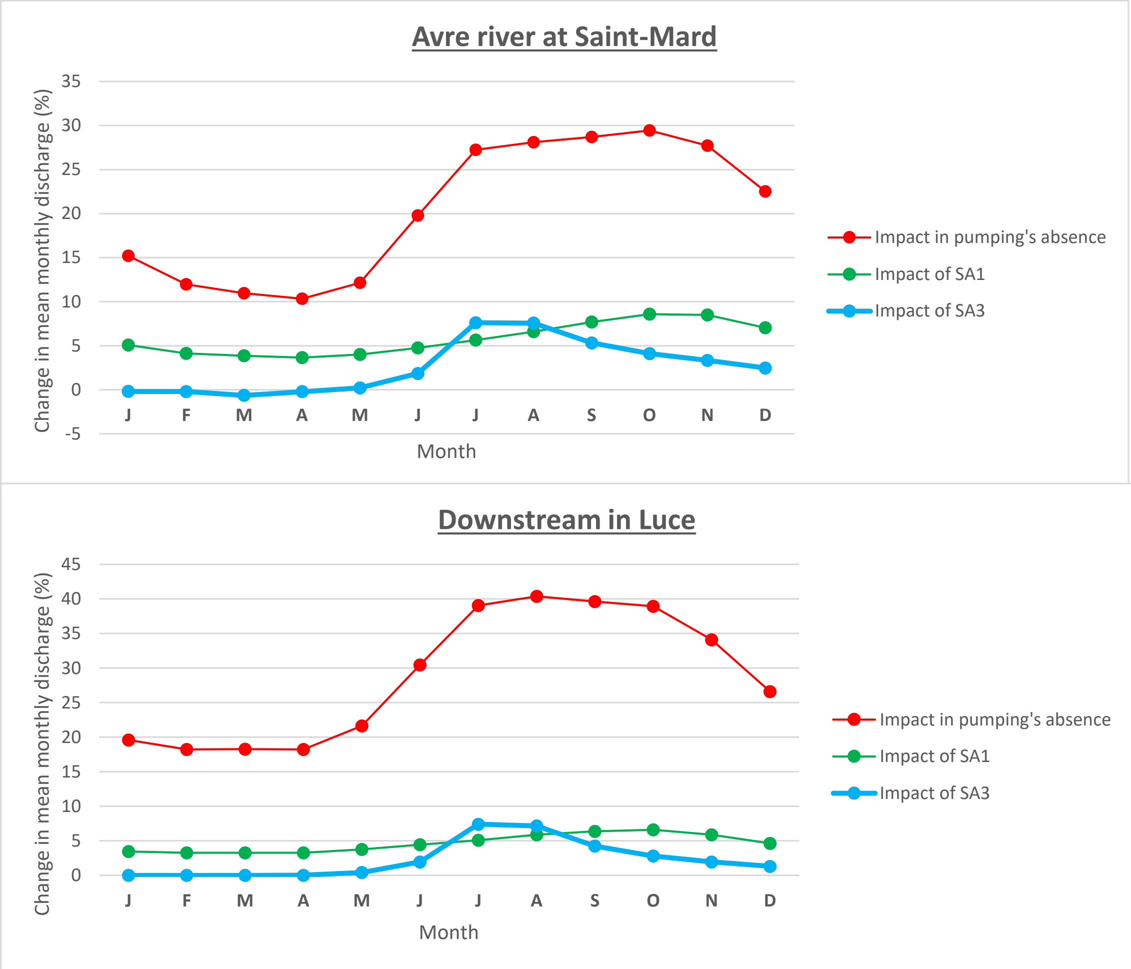


Figure 25 : Change (in %) in monthly mean discharge in Avre River at Saint-Mard and at the outlet of the Luce River for SA1 and SA3 adaptation scenarios compared to the reference period

5.4 Conclusion

For the Avre basin, dry scenarios with lower precipitations show higher impacts on the groundwater conditions than wet scenarios with higher precipitations. Such a result is due to a global increase of PET whatever the considered scenarios, meaning much less effective rainfall available for groundwater recharge for dry scenarios. Dry scenarios shows longer drought periods with decreases of groundwater levels during all the years that can reach about -6 m (on the plateaus) in periods of lower water table (e.g. in summer) in the worst scenario (i.e. the 3°C dry scenario). River discharges diminishes throughout all the year with -20 % of the river base flow expected for the 3°C dry scenario with respect to the 1981-2010 period. The wet scenarios shows increases of groundwater levels (reaching +1.5 m locally) and river discharges (+ 9% maximum) during winter. Absolute changes are nevertheless lower for the wet scenarios than for the dry scenarios.

Concerning the tested adaptation scenarios, the scenario assuming a drinking water withdrawals reduction has a local impact on groundwater level, at and around wellfield. On the other side, the scenario assuming an agricultural abstractions reduction has an impact on groundwater over a large area in Santerre plateau and Avre basin upstream where agricultural boreholes density is greater.

At the territorial level, the development of adaptation scenarios to mitigate climate change need to be done with territory actors. A participative approach involving the main actors of the territory (socio-economic actors, institutional users, etc.) and mobilizing foresight instruments should be privileged.

Finally, raising public awareness of the climate change effects on water resources and the implementation of several actions and adaptation measures will reduce the climate change effects on groundwater resources.

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