



# Assessment of Climate Change Impacts on Water Resources in the Somme River Basin (France)

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## Abstract

Modelling the impacts of climate change on water resources in the Somme watershed in northern France is investigated with a multimodel ensemble to probe the sensitivity of hydrologic response to uncertainties in climate projections provided by general circulation models. At the Somme watershed scale, the average decrease in predicted recharge from seven climate models is  $-18.7\%$ . However, significant disparities appear between simulation results for different climate models. These variations are bounded between  $-30.4\%$  for the most pessimistic model and  $-5.6\%$  for the most optimistic model. Moreover, seasonal gaps are markedly important. For all climate models, the impacts on groundwater levels would be greater on plateaus than in humid valleys. The water level changes would be on the order of  $-10$  m on the plateaus for five climate models and between  $0.2$  m and  $0.5$  m in humid valleys. The impacts of two other climate models on water levels are rather low. In addition, the monthly average discharge of the Somme River and its tributaries is predicted to decrease by 2065. The seven-model average shows that the low outlet flow rate to the Somme basin would be reduced by  $23\%$  but with disparities between models. The decrease would be more severe in the Avre basin, with the minimal discharge reduced by  $32\%$ . This study is a first step towards addressing uncertainties in climate models such that an adaptive watershed management strategy could be devised for water resource managers.

**Keywords** Climate change · Water resources · Chalky aquifer · Somme River basin

## 1 Introduction

In the north of France and the Paris basin, the Upper Cretaceous chalk forms a major aquifer in the areas where it is not overlain by Tertiary deposits. Chalk groundwater plays a considerable role

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because its storage capacity ensures almost 90% of the river supplies (Crampon et al. 1993). This groundwater supports many wetlands, springs and streams. In the Somme River basin, the chalk aquifer represents the main water resource for water supply, industry and irrigation. Climate variability and change influence groundwater systems both directly through recharge and indirectly through changes in groundwater use (Taylor et al. 2013). Assessment of climate change impacts on water reserves is important for future land use planning and water resource management.

Numerical modelling is well established as the only possible resort to quantitatively assess of climate change impacts and thus to address sustainable long-term management of environmental and water resource problems. While the impacts of climate change on catchment hydrology and surface water at a watershed scale have been studied extensively in the referenced literature (de Wit et al. 2007; Middelkoop et al. 2001; Milly et al. 2005; Nohara et al. 2006; Li and Sankarasubramanian 2012; Skoulikaris and Ganoulis 2011; Wilby and Harris 2006; Wilby et al. 2006; Xu 1999), similar studies on the variability of groundwater recharge and aquifer reserves have been reported at a much lower rate (Allen et al. 2004; Brouyère et al. 2004; Gordeniaux et al. 2011; Loàciga 2003; Scibek and Allen 2006; Sulis et al. 2012). Few of these studies have reported the use of integrated physically based surface-subsurface models for impact assessments. This behaviour is due to the complexity of modelling climate change impacts on basin and regional scales. First, the state of the art attained in general circulation models (GCMs), which are the primary instruments for obtaining projections of future global climate change, demonstrates significant skill at the continental and hemispheric scales but shows that these models are inherently unable to represent local sub-grid-scale features and dynamics (Xu 1999; Hannah 2015). Outputs from GCMs are usually supplied by dynamical or statistical downscaling techniques to address this scale mismatch. However, numerous studies have acknowledged the disagreements between the various GCMs and between the different downscaling techniques targeting surface water resources studies (Wilby and Harris 2006; Wilby et al. 2006; Nohara et al. 2006). Other authors (Godrniaux et al. 2011; Sulis et al. 2012) reported similar conclusions for integrated surface and subsurface hydrologic responses driven by outputs from a multimodel climate ensemble. However, the importance of reported differences in groundwater recharge, river discharge and groundwater level fluctuations is not directly extrapolated to other case studies. This first issue is investigated in this work at the Somme River basin scale using a surface and subsurface physically based and distributed model driven by projections from seven members of a multimodel climate ensemble between 2046 and 2065.

This paper begins with a brief review of the basin's geology and hydrogeology. Next, the features and performance of the hydrodynamic model of the Somme basin are described. Then, climate data sets related to the retained seven climate models are analysed and compared. Finally, analyses of the simulations are presented in terms of the impact of climate change on the predicted recharge of the chalk aquifer, its piezometric level fluctuations and discharge to rivers with an overview of source uncertainties and prospect improvements.

## 2 Study Area: The Somme River Basin

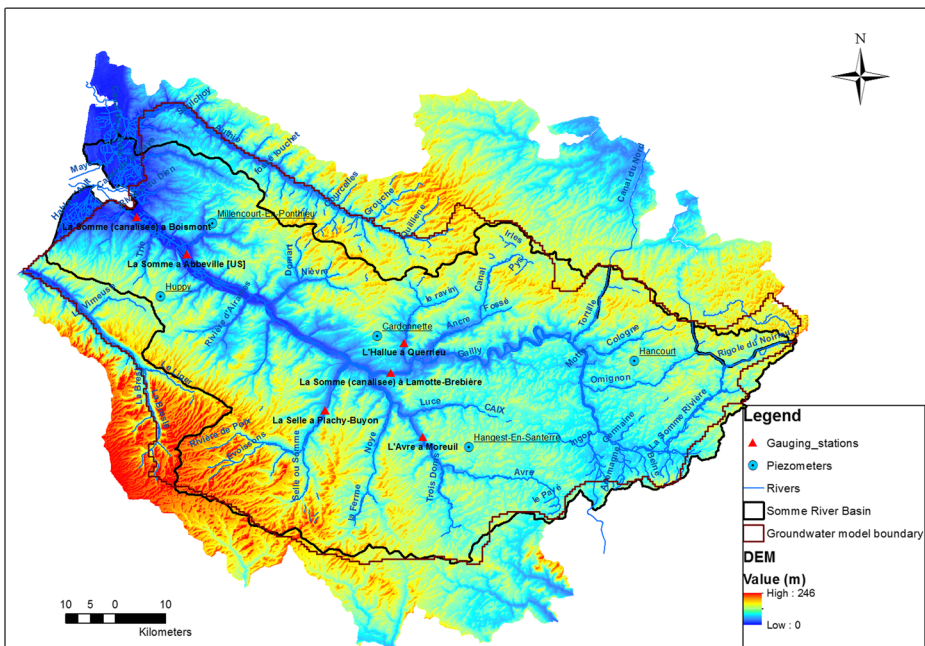
### 2.1 Site Description

The Somme River catchment extends over an area of 6433 km<sup>2</sup>. It is part of the northern aureole of the Upper Cretaceous of the Paris Basin. The Somme River flows 245 km upstream of the English Channel, and its major tributaries are Nièvre, Hallue and Ancre on the right bank and Avre and Selle on the left bank (Fig. 1). Its straightforward surface geology allows distinguishing lower and middle

Turonian marls, upper Turonian and Senonian chalks, sands, Tertiary clays, river alluvium, and silts of the Quaternary shelf. The hydrodynamic model of the Somme basin extends over an area of 7400 km<sup>2</sup> and covers the entire hydrologic catchment of the Somme basin, half of the south-western Authie basin in its north, and half of the north-western Bresle basin in its southwest (Fig. 1). The model is bordered by the Authie River and the Cambrésis heights on the north, Vermandois on the east, the Noyonnais hills on the southeast, the Bresle River on the southwest and the English Channel on the west (Amraoui et al. 2002).

## 2.2 Climatology and Hydrology

The meteorological data are available in daily time steps in both meteorological stations located in the Somme basin and on a regular grid of 8 km on each side given by the meteorological analysis system SAFRAN (Quintana-Seguí et al. 2008). The mean annual rainfall ranges between 850 in the northwest and less than 700 mm/year in the southeast of the basin. The mean annual potential evapotranspiration values are close to 800 mm/year. The daily discharge of the Somme River and its main tributaries is recorded at stream gauging stations (Banque hydro 2007). The mean monthly discharge of the Somme River at the Abbeville gauging station (which has a catchment area of 5560 km<sup>2</sup>) is close to the mean annual discharge, ranging between 26.80 m<sup>3</sup>/s in September and 42.40 m<sup>3</sup>/s in February, indicating the buffering effect of the groundwater system (Gascoïn et al. 2009). Groundwater flow supports the Somme River and its tributaries during lower water seasons and contributes approximately 80% of the Somme stream flows during higher water seasons (Amraoui et al. 2002; Pointet et al. 2003).



**Fig. 1** Geographic map of the Somme River catchment. Piezometric, gauging and weather stations are shown

## 2.3 Hydrogeology

The chalky aquifer is the main water resource of the Somme Department. The volume of water extracted from the aquifer ranges between 100 million and 120 million cubic metres per year, with 51% used for drinking water supply (Amraoui et al. 2014). The main aquifer reservoir is composed of the permeable upper Turonian and Senonian chinks and, more locally, in the wet valley, of sands and old alluvial gravels. Similar to other basins in northern Europe, the chalk in this basin is a fractured rock with a fine-grained porous matrix (Price 1993; Brouyère et al. 2004; Goderniaux et al. 2011). The chalk matrix provides most of the porosity and storage capacity, and the fractures greatly enhance the permeability (Roux 1965; Crampon et al. 1993; Price 1993). The bedrock of the chalky aquifer consists of marl and marly/clayey chalk of the middle and lower Turonian “Dièves.” The effective bedrock, in fact, rarely meets with the roof of the middle Turonian marls but is rather defined by the depth where the cracks and bedding planes of the chalky rock become hydraulically closed, inducing significant decreases in its vertical and horizontal permeabilities. In practice, therefore, only fractured chalk material composes the aquifer. The compact chalk underlying the aquifer constitutes an aquitard. The chalk fracturing is low beneath the plateaus and becomes more developed in the wet and dry valleys, allowing higher transmissivities in these areas than under plateaus. Aquifer recharge is currently occurring between December and April. The chalky aquifer is hydraulically connected with shallow groundwater in the humid alluvium valley of the Somme, forming a single aquifer that is unconfined in 95% of the departmental territory. Groundwater levels are monitored in more than 54 piezometers. More details are reported by Roux (1978).

## 3 Hydrodynamic Model of the Somme Basin

The hydrodynamic model of the chalk aquifer of the Somme basin uses a finite difference groundwater modelling approach implemented in BRGM’s MARTHE code (Thiéry 2015b). The average thickness of the chalk aquifer is 51 m. The thickness varies from 25 m in the wet valley to 140 m on the higher ground.

The chalk aquifer is discretised with a single layer and a relatively coarse computational grid of 500 m × 500 m resolution except in the humid valley of the Somme, where the grid is locally refined to a 100 m spatial horizontal resolution to improve the accuracy of aquifer-river interactions (Amraoui et al. 2004). The transient groundwater model simulates fluctuations in groundwater level, river flow and spring discharge with a weekly time step. 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 (Thiéry 2015a). A digital terrain model is used to route runoff towards the river, and runoff can also infiltrate to form indirect recharge. The hydrogeological model of the Somme considers groundwater extractions used for agricultural, industrial and public water supply. The model was calibrated over the period between 1989 and 2006 based on a trial and error procedure. Six parameters were calibrated, including hydrological parameters (soil capacity, partition coefficient between surface runoff and infiltration, percolation delay), riverbed conductance, hydraulic conductivities and the storage coefficient of the chalk aquifer.

Observed time series of groundwater levels in 54 piezometers located in the Somme basin were used to evaluate simulated piezometric levels. The groundwater model adequately reproduces the observed groundwater response in most observation boreholes. To illustrate this feature, the root

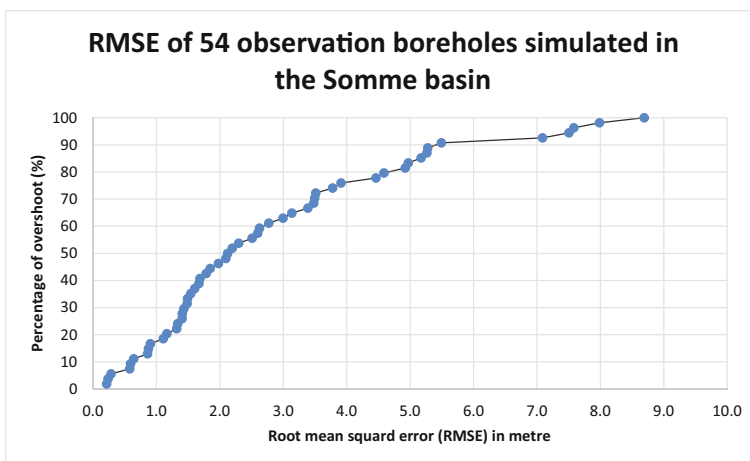
mean square error (RMSE) was calculated for each piezometer and plotted in Fig. 2. For more than 50% of the piezometers, RMSE values are lower than 2.1 m. For more than 80% of the piezometers, they are lower than 4.6 m. An example of observed and simulated groundwater levels upstream and downstream of the Somme basin is reported in Fig. 3.

In addition, in situ daily discharge measurements at five gauging stations located in the Somme River and its main tributary were used to evaluate simulated discharges. To illustrate this evaluation, a typical hydrograph of observed and simulated discharges in the Somme River at Abbeville station is plotted in Fig. 4. Globally, the observed discharge over the simulated period is well reproduced, and the Nash coefficient is 0.84. However, the model does not reproduce the rapid increase in the Somme discharge observed in January during the 2001 groundwater flood event; nevertheless, the flood peak observed in April is well simulated. This discrepancy can be explained by the simplified scheme used in the model (i.e., a simple percolation function) to represent the time delay of the flow in the unsaturated zone, which is not adequate for fractured unsaturated chalk behaviour under a heavy rainfall event (Thiéry et al. 2018).

#### 4 Climate Scenarios and Analysis of Input Climate Data

The climate projections of the seven GCMs forced by the median greenhouse gas emission scenario A1B from the 4th IPCC report (IPCC 2007) were provided by Météo France. These data were disaggregated using a statistical downscaling method (Boé et al. 2006) on a SAFRAN grid with 8 km resolution on each side (Vidal et al. 2010) covering the entire French territory. The GCMs are ARPEGE V3 (CNRM, Météo France); CGCM2.3.2, Meteorological Research Institute, Japan; CGCM3 (CCCMA Canada); ECHAM5, Max Planck Institute (Germany); GFDL-CM2.0 and GFDL-CM2.1, NOAA's Geophysical Fluid Dynamics Laboratory (USA); and GISS-MODEL-ER NASA's Goddard Institute for Space Studies (USA).

Disaggregated climate projections cover two time periods: the present time period referred to as the 'reference' period (1961–1990) and a future period (2046–2065). The use of two simulated periods is necessary to overcome the bias in the analysis of the impact of projections



**Fig. 2** Root mean square error values calculated from the observed and simulated time series for the 54 piezometers located in the Somme basin

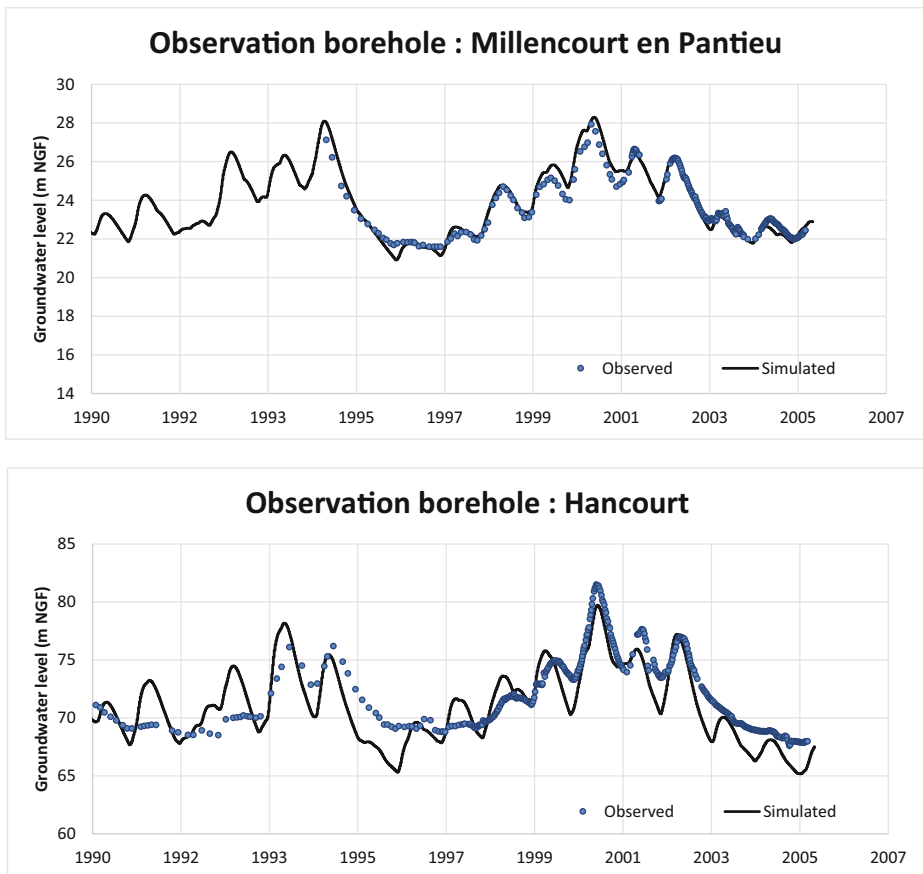


Fig. 3 Comparison between the observed and simulated groundwater levels at two observation boreholes

on water resources. This bias comes from possible differences between simulations of climate models and the real climate.

To assess the likely impacts of climate change on water resources for the Somme basin, spatially distributed data sets of daily rainfall and potential evapotranspiration (PET) from the

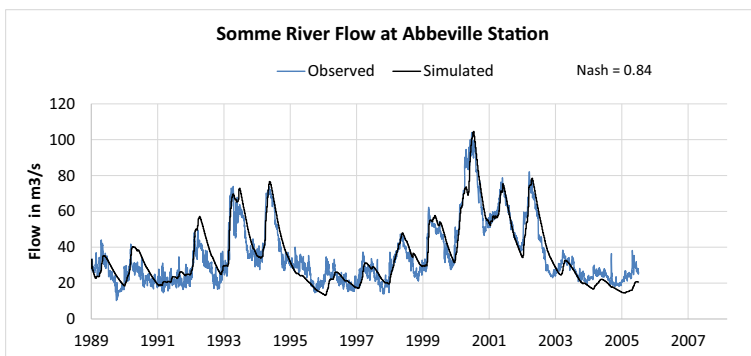


Fig. 4 Comparison between the observed and simulated discharge of the Somme River at the Abbeville gauging station

seven climate models were introduced into the Somme hydrodynamic model. Two periods were simulated for each of the seven climate models, the so-called reference period (1961–1990) and a second period known as the prospective period (2046–2065). The groundwater recharge, groundwater level and river flow evolution were simulated for these two periods. In the following, the groundwater extraction was assumed not to change between the reference period and the future period. For all prospective simulations, a starting period of six years was added to reduce the impact of the initial state of the piezometric levels in aquifers and streamflows on the simulation results. Obviously, the results of this starting period were excluded from subsequent analysis.

## 4.1 Methodology

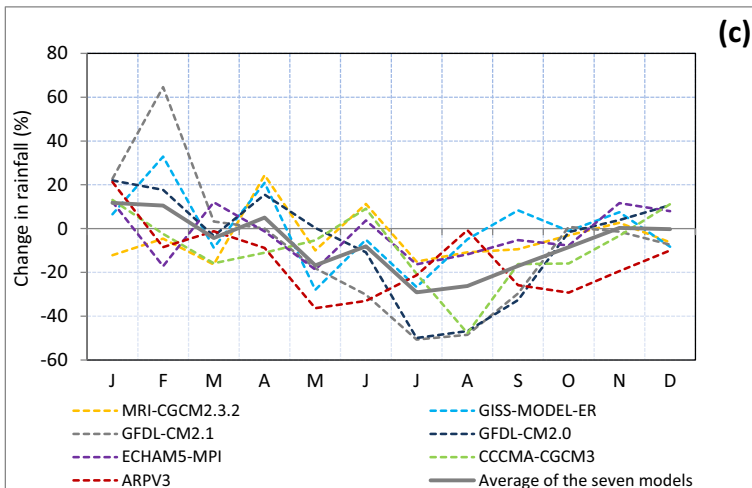
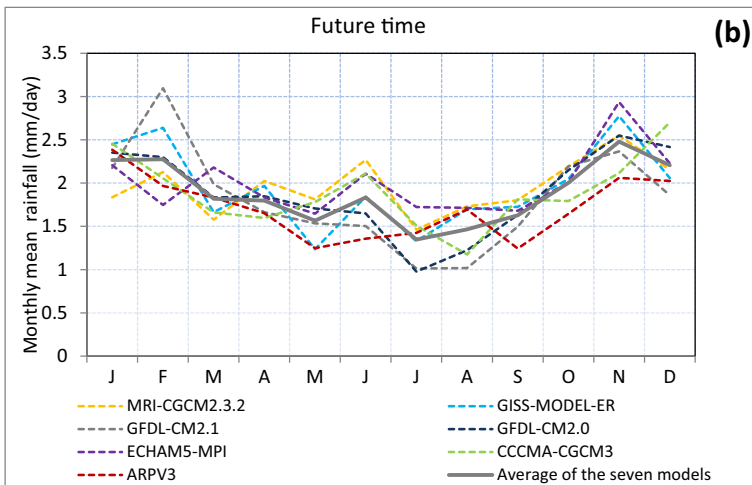
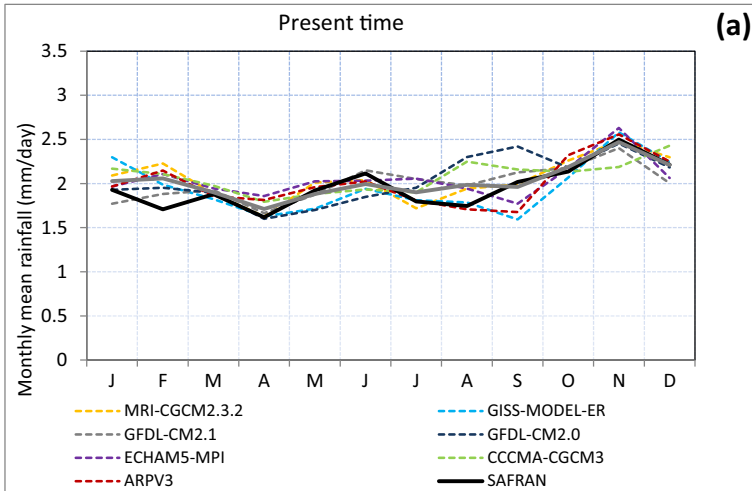
To determine the overall trend of rainfall and potential evapotranspiration given by each of the seven climate models by the 2065 time horizon at the Somme basin scale, inter-annual averages of their monthly values were calculated for the reference climate (1961–1990) and for the future climate (2046–2065). Moreover, monthly average values of the seven climate models were calculated for these two times periods. The inter-annual averages of observed monthly rainfall and PET (SAFRAN data) were also calculated for the reference period to ensure that climate simulation disaggregation compared favourably with observations.

## 4.2 Rainfall

The evolution of monthly mean precipitation for the present time period (1961–1990) and for the future time period (2046–2065) are shown in Fig. 5. In the reference period modelling compared to the observed rainfall in the Somme basin (SAFRAN), the ensemble average of climate models overestimated the average rainfall in January, February and August and slightly underestimated it in June. For the rest of the year, monthly average of the seven climate models superimposed quite well with the current state (i.e., SAFRAN) with a different behaviour depending on the particular climate model. By 2065, the seven climate models predicted a decrease in rainfall between May and October. The average decrease for all climate models during this period was  $-17.6\%$ , with greater reductions for the GFDL-CM2.1, ARPV3 and GFDL-CM2.0 models ( $-29.4\%$ ,  $-24.3\%$  and  $-23.5\%$ , respectively). The reductions in average rainfall were much lower for the MRI-CGCM232 and GISS models ( $-6\%$  and  $-9.5\%$ , respectively). On the other hand, for the months of January and February, the average rainfall for all climate models tended to higher precipitation (i.e.,  $11\%$ ). However, the differences in the magnitudes of change were very significant between climate models, and for a few cases, different prediction trends were concluded. Indeed, for January and February precipitation, the GFDL-CM2.1 model predicted an increase of  $43\%$ , while the MRI-CGCM232 model predicted a decrease of  $-8\%$ .

## 4.3 Evapotranspiration

The evolution of monthly potential evapotranspiration (PET) for the present and future times and its change by 2065 (Fig. 6) show that all climate models predict a net increase in PET by 2065. The percentage of PET change is lower in winter and increases significantly in the summer and autumn, with different magnitudes according to the climate model. For the average of the seven climate models, the mean increase in PET is  $20\%$  in winter and  $33\%$





**Fig. 5** Distribution of monthly mean rainfall in the Somme catchment as projected by the seven climate models for (a) current time and (b) future time periods. (c) Percentage changes in rainfall projected by the seven climate models

in summer and autumn, except for the GFDL-CM2 climate model, which provides a significant PET increase in winter (51%), and the GISS climate model with a low PET increase in summer and autumn (17%).

## 5 Results and Discussions

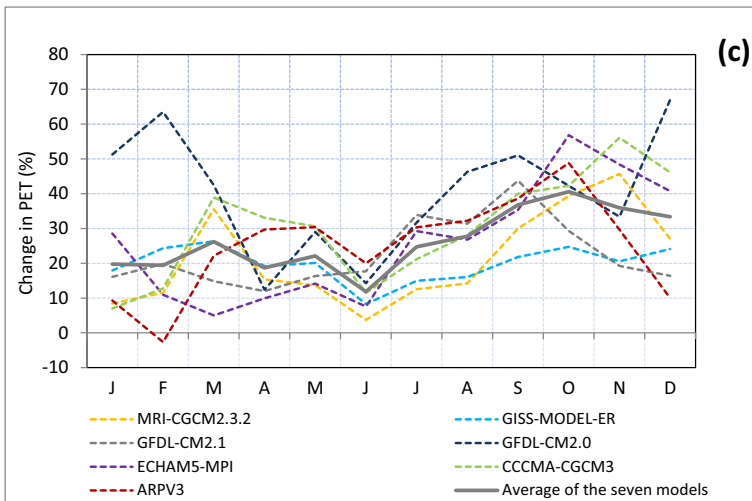
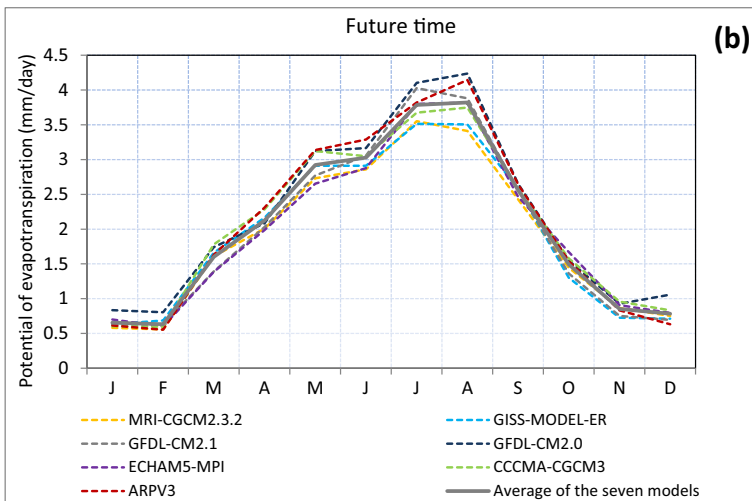
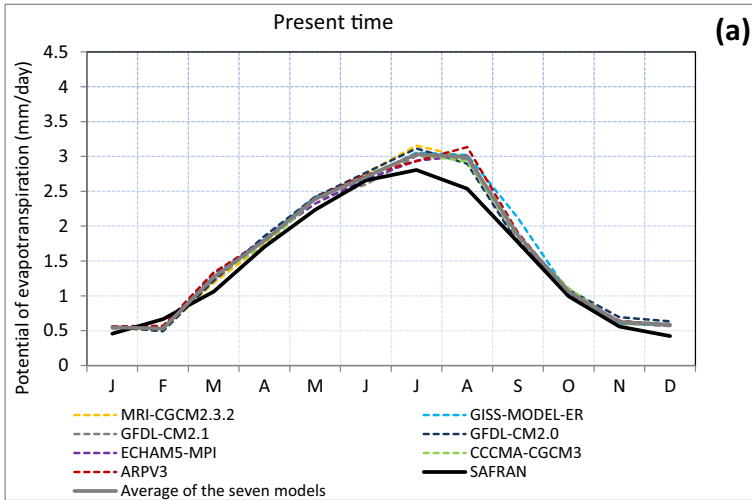
In this section, the effects of climate change on groundwater recharge, groundwater levels in the chalk aquifer and streamflow are assessed through the year 2065. The impact is quantified by comparing simulated results obtained with the data provided by each climate model for the future time period (2046–2065) to those simulated on the reference time period (1961–1991). Annual changes in groundwater recharge and minimal piezometric levels are presented; then, the local and seasonal responses of the system are analysed (piezometers and stream gauges).

### 5.1 Impact on Recharge to the Chalk Aquifer

For the seven climate models, mean annual recharge across the basin was calculated for the present and future times. Variations between these two recharge states lead to calculation of the percentage of change in this variable (Fig. 7). All climate models predict a recharge decrease by 2065 (Fig. 7); the average decline for the seven climate models is  $-18.7\%$ , with significant discrepancies between the models. Thus, the ARPV3 model is more pessimistic and provides an average decrease of  $-30.4\%$ , while the GFDL-CM2.1 and GISS models expect decreases of less than  $-10\%$  ( $-8\%$  and  $-5.6\%$ , respectively).

### 5.2 Piezometric Levels

To assess the impact of climate change on the minimal piezometric level in the chalk aquifer, difference maps between the computed mean piezometric surface level from the prospective simulations and that from reference simulations were created. Maps of change in calculated minimal piezometric levels (Fig. 8) show that, apart from climate models GFDL-CM2.1 and GISS, groundwater level changes in low-water periods are important on plateaus. These changes are in the range of  $-8$  to  $-10$  m depending on the climate model. However, changes are quite low in the wet valleys (between  $-0.2$  and  $-0.5$  m). For climate models, GFDL-CM2.1 and GISS, groundwater level changes are low (approximately  $-0.2$  m). On the other hand, changes are greater in the plateaus of sub-basins located on the left bank of the Somme and reach  $-1.5$  to  $-2$  m. However, a slight increase in the aquifer level (approximately between  $0.1$  and  $0.5$  m) occurs locally in the southern reliefs of the Somme basin. The mean monthly groundwater levels simulated for the reference climate and future climate at two observation boreholes are reported in Fig. 9. Compared to the present time and for all climate models studied, piezometers show lower monthly mean levels related to the decreases in recharge (Fig. 7). Models ARPV3, CCCMA-CGCM 3, MRI-CGCM2.3.2 and GFDL-CM2.0 are the most pessimistic, while models GFDL-CM2.1 and GISS are the most optimistic.

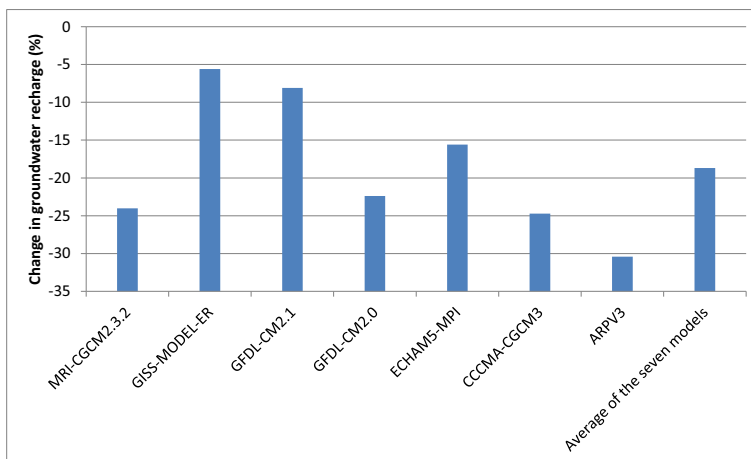


**Fig. 6** Distribution of monthly mean potential evapotranspiration in the Somme catchment as projected by the seven climate models for (a) current time and (b) future time periods. (c) Percentage changes in PET projected by the seven climate models

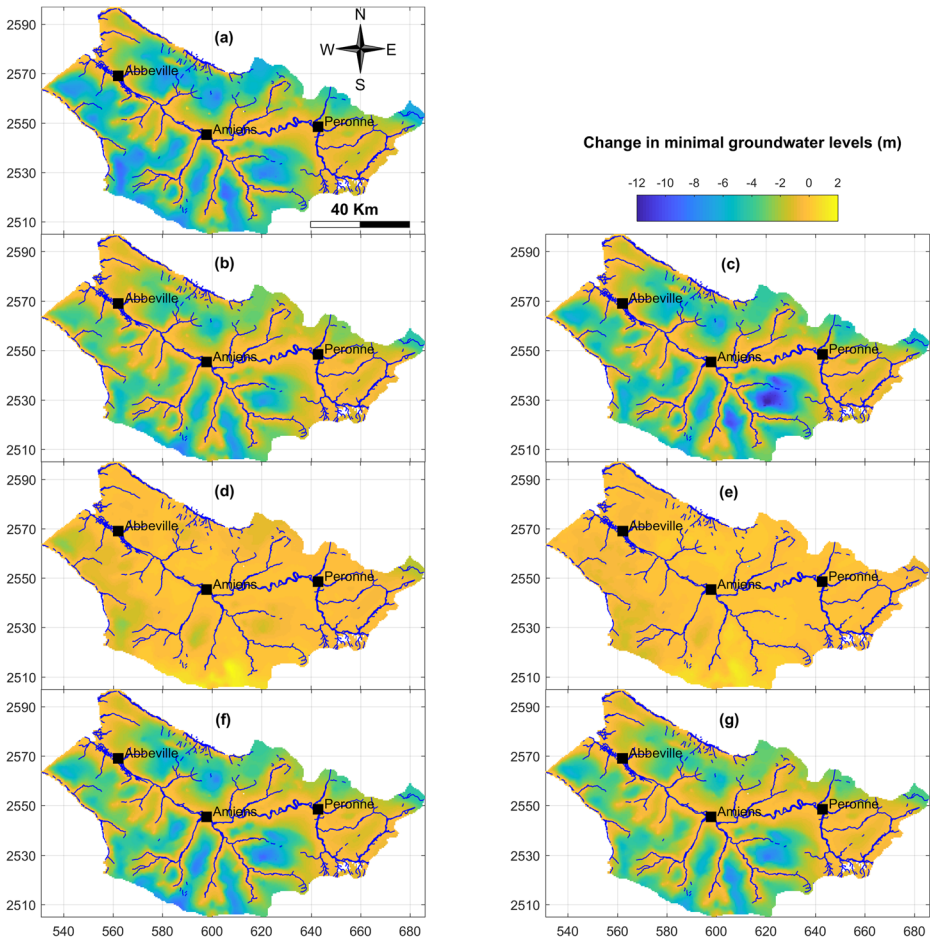
According to the simulation results for all climate models and comparison of reference climate and future climate, the piezometer located in Millencourt en Panthieu downstream along the Somme River shows a yearly groundwater level change of  $-1$  m by 2065 (average of the seven climate models), while the piezometer of Hangest en Santerre displays a mean change of  $-6.7$  m. The largest decline in the average groundwater level is observed in the Avre basin (Fig. 9b). Indeed, the change in mean monthly groundwater level in the Hangest en Santerre piezometer by climate models GFDL-CM2.0, CCMA-CGCM3, ARPV3 and ECHAM5-MPI are  $-10.7$  m,  $-8$  m,  $-7.6$  m, and  $-7.2$  m, respectively. Changes equal only  $-2.4$  m and  $-1.6$  m for the GFDL-CM2.1 and GISS climate models, respectively.

### 5.3 Streamflows

Similarly, the monthly mean streamflows of the Somme River and one of its main tributaries (i.e., Avre) calculated by the seven climate models are analysed for the present and future times (Fig. 10). The graph shows that all climate models predict declines in monthly mean streamflow of the Somme River by 2065 regardless of the season considered. The amplitude of decline depends on the climate model, and five climate models give a significant decrease in monthly mean streamflow. At the Abbeville gauging station near the outlet of the Somme basin, the mean monthly discharge during low water would be reduced by  $-23\%$  (average of seven climate models), with notable differences between the climate models (i.e.,  $-33.6\%$  and  $-8.3\%$  for ARPV3 and GISS climate models, respectively), as shown in Fig. 10b. A marked decrease is obtained for the Avre River with a streamflow reduced by  $-32\%$  on average, with extremes of  $-44\%$  and  $-8.7\%$  for the ARPV3 and GISS climate models, respectively (Fig. 10a).



**Fig. 7** Calculated percentages of change in mean annual recharge to the chalky aquifer for all climate models in the future relative to present time

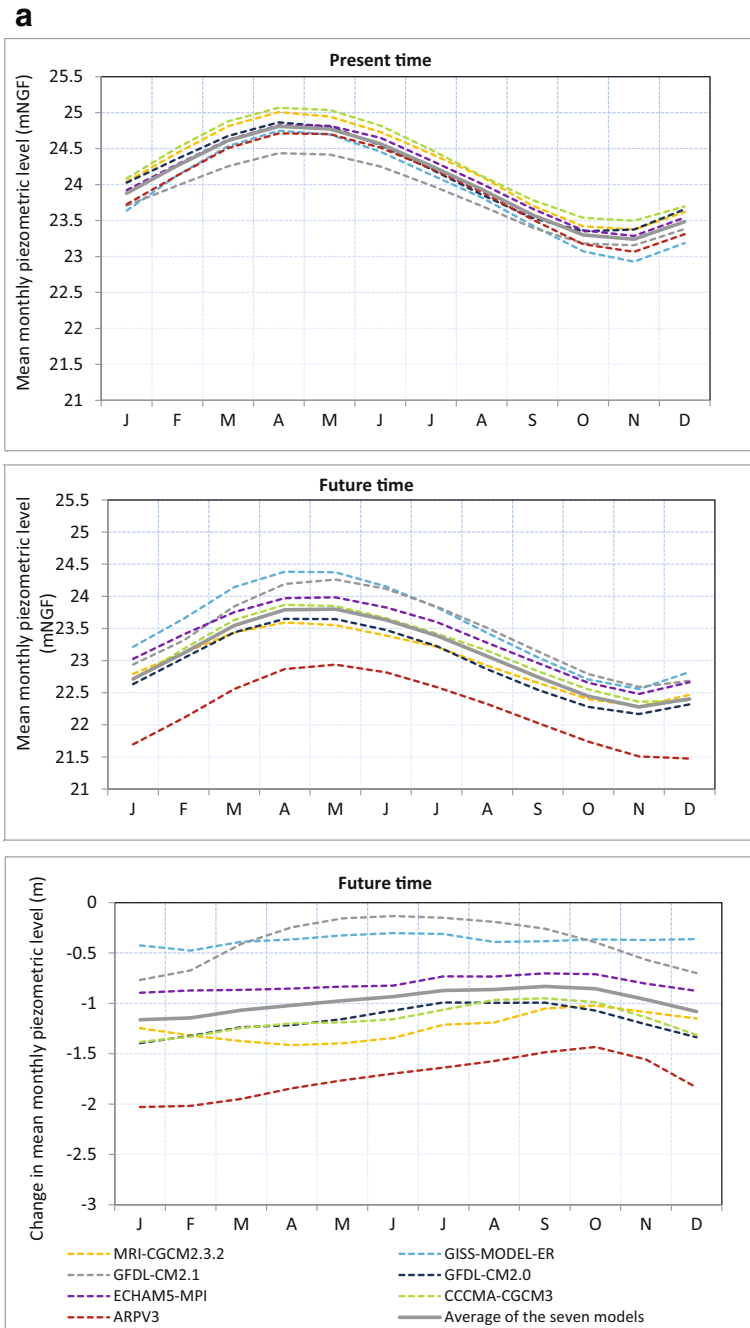


**Fig. 8** Predicted percentages of minimal groundwater levels change from 2046 to 2065 and 1961–1991 for all climate models

## 5.4 Discussion

Quantitative assessment of the impacts of climate change on surface and groundwater resources, including risks of flooding, remains a highly uncertain task. Uncertainties in projections of future changes are high, even if characterization of uncertainty has been improved recently (IPCC 2007; IPCC 2014). Primarily, projections of future precipitation are not adequately simulated in present climate models. For the winter period, in the Somme River catchment, different prediction trends are suggested. Consequently, quantitative projections of changes in river flow at the basin scale, relevant to water management, remain largely uncertain. These results agree with results from more recent studies (Milly et al. 2005; Nohara et al. 2006; Jackson et al. 2011).

Quantitative estimation of future climate change impacts on water resources and their management in the Somme River catchment should be improved. Improvements in understanding are related to the adequacy and availability of observation data, which depends on the development of enhanced monitoring technologies of the basin's meteorology, hydrology, and hydrogeology. The availability of adequate data is critical to understanding observed changes,



**Fig. 9** Predicted monthly mean groundwater level changes in piezometers (a) Millencourt en Panthieu and (b) Hangest en Santerre for future time

leading to improved and better calibrated models that can be used with more confidence for future climate projections. Recent work aiming to improve understanding the flow processes

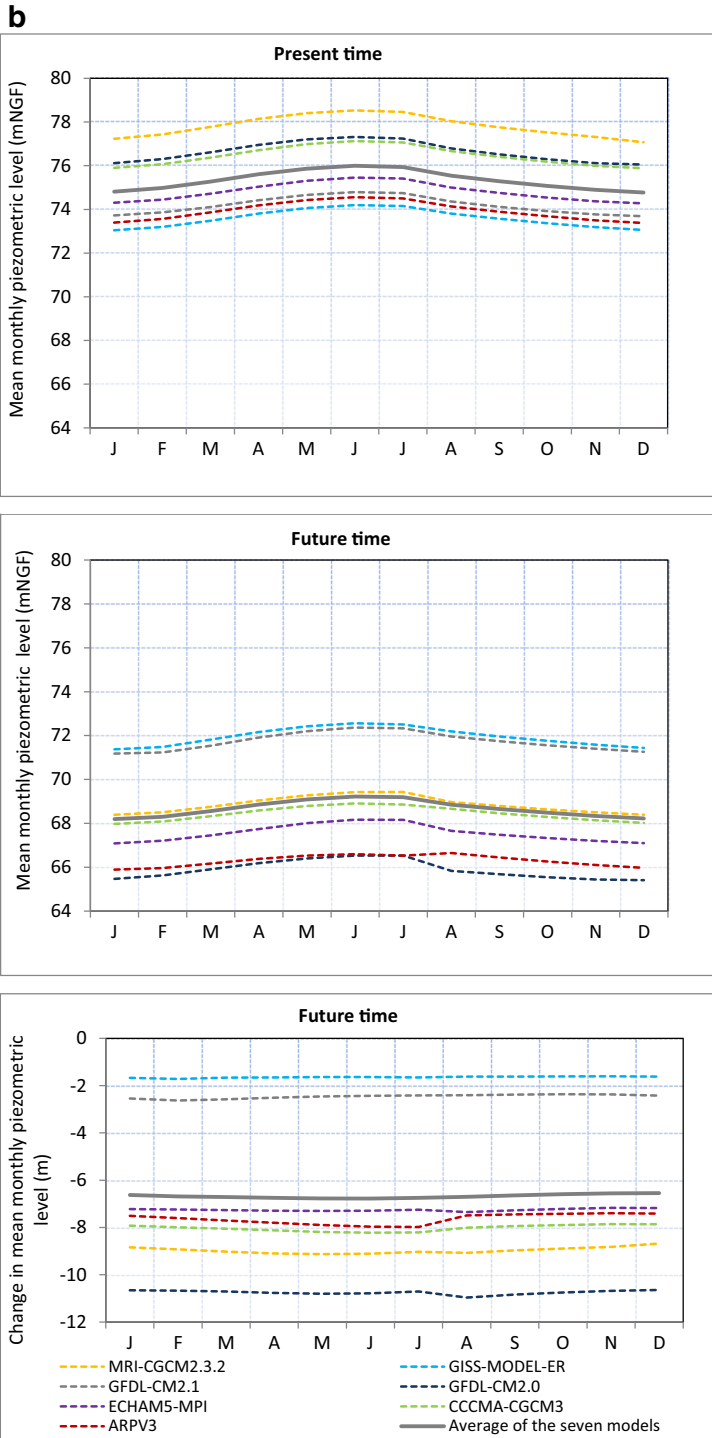
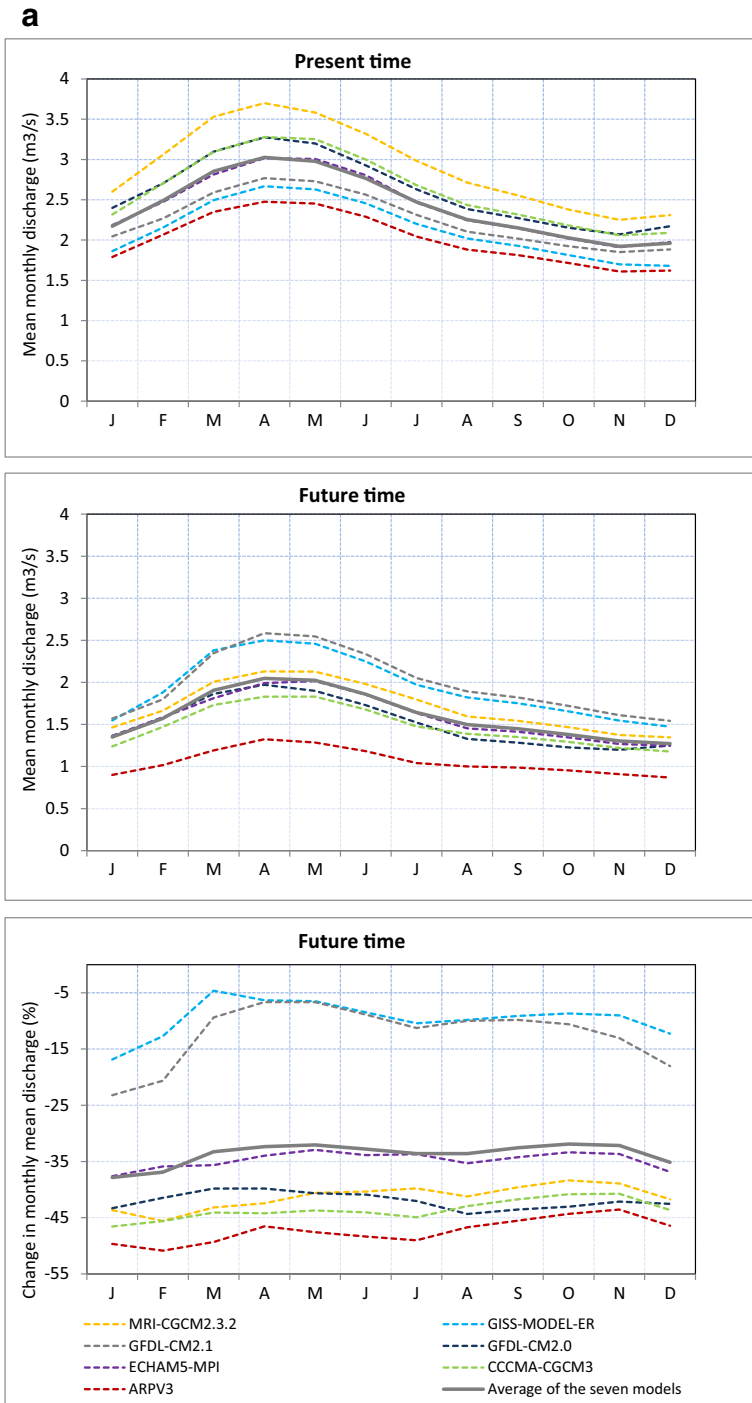


Fig. 9 continued.



**Fig. 10** Predicted monthly mean discharges in (a) the Avre River at Moreuil and (b) the Somme River at Abbeville gauging stations for present and future times

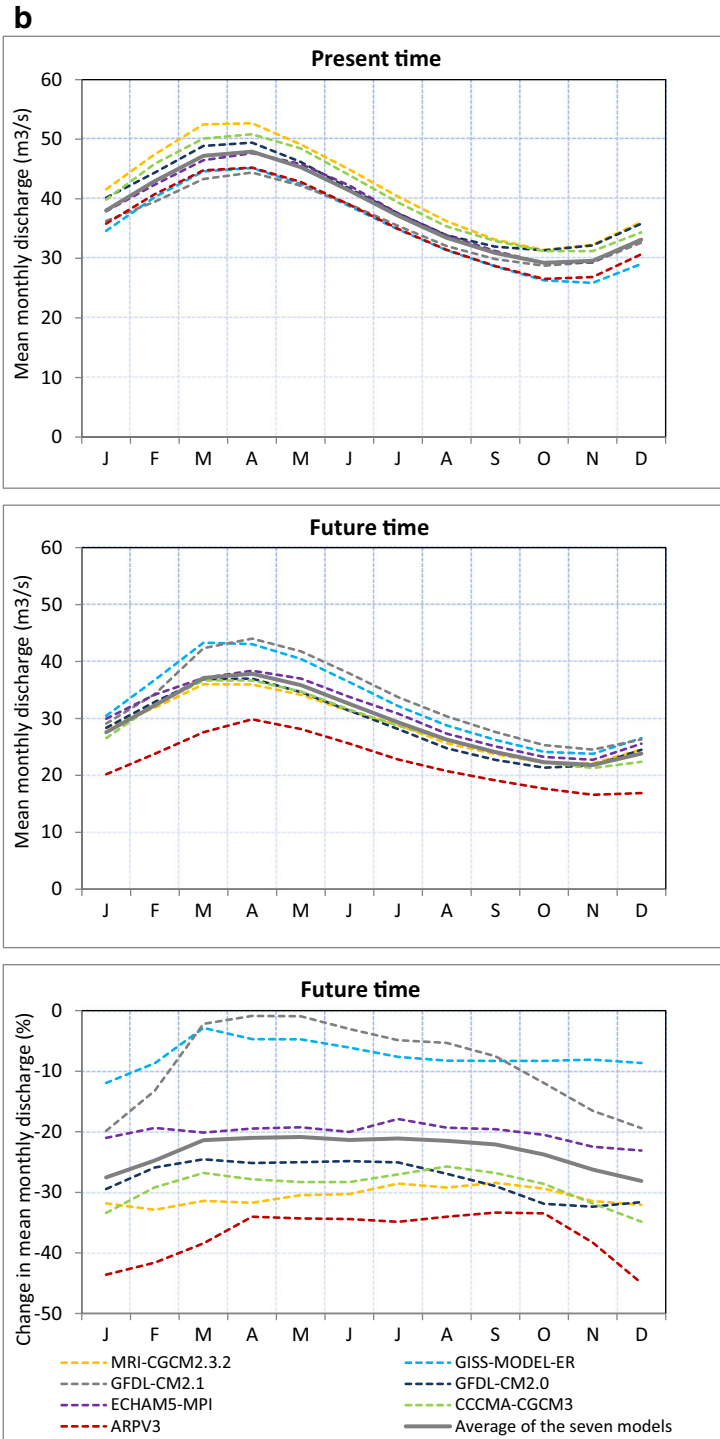


Fig. 10 continued.



that occur in the unsaturated fractured chalk by setting up an experimental monitoring site (Thiéry et al. 2018) has shown that the use of composite constitutive functions (hydraulic conductivity-saturation and pressure-saturation) that integrate the increase in hydraulic conductivity near saturation allows improved recharge estimation. This recharge matches the groundwater response to long and heavy rainfall events.

As demonstrated in this study, the impact assessment of climate change based on only one or few modelling scenarios may lead to contrasting projections of river streamflows and recharge to the chalky aquifer and consequently, of changing groundwater levels. Therefore, a new framework for handling uncertainty is needed to support decision makers and operational water managers. Wilby and Harris (2006) showed how components of uncertainty affecting projections for the Thames River can be weighted to obtain conditional probabilities for future impact assessments by the 2080s. These authors combined sources of uncertainty from four GCMs, two greenhouse gas emission scenarios, two statistical downscaling methods, two approaches for hydrological modelling and two sets of hydrological model parameters. They concluded that low flows in the Thames are more influenced by uncertainties in climate change scenarios and downscaling of different GCMs than by uncertainties in hydrological modelling, which were found to be comparatively minor. Although these results cannot be directly transposed to other river basins, considering different sources of uncertainty in a probabilistic framework is recommended to determine key factors leading to uncertain climate change. The study presented in this paper is a first step towards this research endeavour.

Uncertainty related to hydrological parameters and to the choice of calibration variables (Finger et al. 2015; Goderniaux et al. 2015) can contribute significantly to overall uncertainty. The remaining uncertainties in the model are related to poorly known input data, such as the time-dependent volumes of withdrawn or injected waters and measured data used for calibration. Other sources of uncertainty concern the future evolution of landscapes, such as land uses, which could have significant impacts on the proportions of infiltration and surface runoff during periods of heavy rainfall. In addition, the fact that the models do not consider the future evolution of vegetation cover and its impact on evapotranspiration increases the uncertainty in the evolution of groundwater recharge.

The wide variety of groundwater modelling concepts may introduce other sources of uncertainty into modelling climate change impacts on water resources in the Somme basin. For instance, all presented calculations are based on the Dupuit assumption, neglecting the vertical flow components. While the integrated hydraulic approach for modelling groundwater flow significantly speeds up the computational process, the introduction of this assumption might introduce errors for predicting recharge delay in thick unsaturated zones of the chalky aquifer. Another model limitation that introduces other uncertainties for modelling climate change is the complexity of unsaturated flow mechanisms in fractured chalk (Mathias et al. 2005), which are important for simulating flood events driven by fast-rising water levels in aquifers. Introducing these physics and structure into ensemble multi-modelling scenarios for modelling climate change impacts at the scale of the Somme basin is a challenging task. In practice, when only the impact on groundwater recharge is the main interest, simplistic approaches could be enhanced for regional-scale models to improve the unsaturated zone time transfer as a function of the accumulating precipitation. Goderniaux et al. (2015) used an approach to account for the processes in the unsaturated chalk from knowledge of measurements providing local van Genuchten parameters. They concluded that the use of a simpler and less time-consuming approach would be preferred. Similar studies conducted in the UK (Jackson et al. 2011) have used a simple recharge assessment approach in chalky basins to assess the impact of climate change on aquifer recharge.

## 6 Conclusions

Groundwater is the main available water resource for water supply in the French Somme Department. Therefore, assessing the potential effects of climate change on this resource is necessary, which leads to the development of an adaptive management plan for water resources at the basin scale. An existing calibrated hydrodynamic model of the Somme basin is used to study the impacts of climate change on groundwater recharge to the chalky aquifer, piezometric level fluctuations and streamflows to the draining river network. The simulations are based on the upstream prediction of climate data sets stemming from the results of seven climate models derived from the IPCC's A1B scenario. A good agreement is achieved among the seven scenarios when analysing the decrease in the mean annual recharge and discharge to streamflows by 2065. The Somme basin-wide average decrease in calculated recharge from the results of the seven climate models is  $-18.7\%$ . However, significant discrepancies still appear between the model results because the variations are bounded between  $-30.4\%$  and  $-5.6\%$  for the ARPV3 and GISS climate models, respectively. Moreover, seasonal gaps are markedly important because the conjunction of rainfall decrease and evapotranspiration increase between May and October reduces net recharge over this period. For all climate models, the impact on the groundwater levels is greater on plateaus than in humid valleys. The groundwater level change is  $-10$  m on plateaus (for five climate models) and between  $-0.2$  m and  $-0.5$  m in humid valleys. The impacts of climate models GFDL-CM2.1 and GISS-MODEL-ER on groundwater level change are rather low. In addition, the monthly average streamflow of the Somme catchment and its tributaries is predicted to decrease by 2065. The seven-model average shows that the low discharge to the Somme River would be reduced by  $-23\%$  but with disparities between models ( $-33.69\%$  and  $-8.5\%$  for the ARPV3 and GISS climate models, respectively). The decrease would be more severe in the Avre basin, with a net discharge reduction of  $-32\%$ .

This work has highlighted the inherent uncertainty related to climate models on projected groundwater resources change at the Somme basin scale. Including other sources of uncertainty (multi-scenario RCP, future evolution of land-use and vegetation cover) in climate change impacts will improve our ability to develop best adaptation measures for sustainable water resources management.

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## Compliance with Ethical Standards

**Conflict of Interest** The authors do not have any conflict of interest to report.

## References

- Allen DM, Mackie DC, Wei M (2004) Groundwater and climate change: a sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada. *Hydrogeol J* 12:270–290
- Amraoui N, Golaz C, Mardel V, Negrel PH, Petit V, Pinault J-L, Pointet TH (2002) Simulation par modèle des hautes eaux de la Somme. Report BRGM/RP-51827-FR
- Amraoui N, Wuilleumier A, Thiery D, Caous JY, Noyer M-L, Gaudfeyroy MJ (2004) Mise à jour du modèle des hautes eaux de la Somme. Report BRGM/RP-53211-FR

- Amraoui N., Castillo C, Et Seguin J-J (2014) Evaluation de l'exploitabilité de ressource en eau souterraine de la nappe de la craie du bassin de la Somme. Report BRGM/RP-63408-FR
- Banque hydro (2007) Banque nationale de données pour l'hydrométrie et l'hydrologie. Ministry of Ecological and solidarity Transition, France. <http://hydro.eaufrance.fr>
- Boé J, Terray L, Habets F, Martin E (2006) A simple statistical-dynamical downscaling scheme based on weather types and conditional resampling. *J Geophys Res* 111:D23106. <https://doi.org/10.1029/2005JD006889>
- Brouyère S, Carabin G, Dassargues A (2004) Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer basin, Belgium. *Hydrogeol J* 12:123–134
- Crampon NJ, Roux J-C, Bracq P (1993) Hydrogéologie de la craie en France. *Hydrogéologie* 2:81–123
- de Wit MJM, Hurk B, Warmerdam PMM, Torfs PJJF, Roulin E, Deursen WPA (2007) Impact of climate change on low-flows in the river Meuse. *Clim Chang* 82(3–4):351–372
- Finger D, Vis M, Huss M, Seibert J (2015) The value of multiple data set calibration versus model complexity for improving the performance of hydrological models in mountain catchments. *Water Resour Res* 51:1939–1958. <https://doi.org/10.1002/2014WR015712>
- Gascoin S, Duchame A, Ribstein P, Carli M, Habets F (2009) Adaptation of a catchment-based land surface model to the hydrogeological setting of the Somme River basin (France). *J Hydrol* 368(1–4):105–116
- Goderniaux P, Brouyère S, Blenkinsop S, Burton A, Fowler HJ, Orban P, Dassargues A (2011) Modeling climate change impacts on groundwater resources using transient stochastic climatic scenarios. *Water Resour Res* 47:W12516. <https://doi.org/10.1029/2010WR010082>
- Goderniaux P, Brouyère S, Wildemeersch S, Therrien R, Dassargues A (2015) Uncertainty of climate change impact on groundwater reserves: application to a chalk aquifer. *J Hydrol* 528:108–121. <https://doi.org/10.1016/j.jhydrol.2015.06.018>
- Hannah L (2015) Climate change biology. 2nd Edition, Elsevier. doi:<https://doi.org/10.1016/C2013-0-12835-8>
- IPCC (2007) Climate change 2007: synthesis report. Contributions of working groups I, II, and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland
- IPCC (2014) Climate change 2014: synthesis report. Contributions of working groups I, II, and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland
- Jackson CR, Meister R, Prudhomme C (2011) Modelling the effects of climate change and its uncertainty on UK chalk groundwater resources from an ensemble of global climate model projections. *J Hydrol* 399:12–28
- Li W, Sankarasubramanian A (2012) Reducing hydrologic model uncertainty in monthly streamflow predictions using multimodel combinations. *Water Resour Res* 48:W12516. <https://doi.org/10.1029/2011WR011380>
- Loàciga HA (2003) Climate change and ground water. *Annal Assoc Am Geogr* 2(1):30–41
- Mathias SA, Butler A, McIntyre N, Wheeler HS (2005) The significance of flow in the matrix of the chalk unsaturated zone. *J Hydrol* 310(1–4):62–77
- Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438:347–350
- Nohara D, Kitoh A, Hosaka M, Oki T (2006) Impact of climate change on river discharge projected by multimodel ensemble. *J Hydrometeorol* 7:1076–1089
- Pointet T, Amraoui N, Golaz C, Mardhel V, Ph N, Pennequin D, Pinault J-L (2003) Contribution of groundwaters to the exceptional flood of the Somme river in 2001, observation, assumptions, modeling. *La Houille Blanche* 6:112–122
- Price M (1993) Groundwater movement in the chalk aquifer in England. *Hydrogéologie* 2:147–150
- Quintana-Segui P, Le Moigne P et al (2008) Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over France. *J App Meteorol Clim* 47:92–107
- Roux J-C (1965) Hydrogéologie du bassin de la Somme. *Bulletin BRGM* 3:1–44
- Roux J-C (1978) Les écoulements de type karstique dans la craie de Normandie. *Mémoires BRGM* 1:531–553
- Scibek J, Allen DM (2006) Modeled impacts of predicted climate change on recharge and groundwater levels. *Water Resour Res* 42:W11405. <https://doi.org/10.1029/2005WR004742>
- Skoulikaris C, Ganoulis J (2011) Assessing climate change impacts at river basin scale by integrating global circulation models with regional hydrological simulations. *Eur Water* 34:55–62
- Sulis M, Paniconi C, Marrocu M, Huard D, Chaumont D (2012) Hydrologic response to multimodel climate output using a physically based model of groundwater/surface water interactions. *Water Resour Res* 48:W12510. <https://doi.org/10.1029/2012WR012304>
- Taylor RG, Scanlon B et al (2013) Ground water and climate change. *Nat Clim Change* 3:322–329
- Thiéry D. (2015a) Validation du code de calcul GARDÉNIA par modélisations physiques comparatives. Report BRGM/RP-64500-FR
- Thiéry D (2015b) Code de calcul MARTHE – Modélisation 3D des écoulements dans les hydrosystèmes - Notice d'utilisation de la version 7.5. Rapport BRGM/RP-64554-FR
- Thiéry D, Amraoui N, Noyer ML (2018) Modelling flow and heat transfer through unsaturated chalk – validation with experimental data from the ground surface to the aquifer. *J Hydrol* 556C:660–673

- Vidal JP, Martin E, Franchistéguy L, Baillon M, Soubeyrou JM (2010) A 50-year high-resolution atmospheric reanalysis over France with the SAFRAN system. *J Climatol* 30:1627–1644
- Wilby RL, Harris I (2006) A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the river Thames, UK. *Water Resour Res* 42:W02419. <https://doi.org/10.1029/2005WR004065>
- Wilby RL, Whitehead PG, Wade AJ, Butterfield D, Davies RJ, Watts G (2006) Integrated modeling of climate change impacts on water resources and quality in a lowland catchment: river Kennet, UK. *J Hydrol* 330: 204–220
- Xu C (1999) Climate change and hydrologic models: a review of existing gaps and recent research developments. *Water Resour Manag* 13(5):369–382

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