

# Impact of climate change on the hydrogeology of two basins in northern France

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**Abstract** This study presents an analysis of climate-change impacts on the water resources of two basins located in northern France, by integrating four sources of uncertainty: climate modelling, hydrological modelling, downscaling methods, and emission scenarios. The analysis focused on the evolution of the water budget, the river discharges and piezometric heads. Seven hydrological models were used, from lumped rainfall-discharge to distributed hydrogeological models, and led to quite different estimates of the water-balance components. One of the hydrological models, CLSM, was found to be unable to simulate the increased water stress and was, thus, considered as an outlier even though it gave fair results for the present day compared to observations. Although there were large differences in the results between the models, there was a marked tendency towards a decrease of the water

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resource in the rivers and aquifers (on average in 2050 about  $-14\%$  and  $-2.5\text{ m}$ , respectively), associated with global warming and a reduction in annual precipitation (on average in 2050  $+2.1\text{ K}$  and  $-3\%$ , respectively). The uncertainty associated to climate models was shown to clearly dominate, while the three others were about the same order of magnitude and 3–4 times lower. In terms of impact, the results found in this work are rather different from those obtained in a previous study, even though two of the hydrological models and one of the climate models were used in both studies. This emphasizes the need for a survey of the climatic-change impact on the water resource.

## 1 Introduction

Global warming is unequivocal (IPCC 2007; Meehl et al. 2007), and is expected to lead to an increase in the use of water for cooling, energy production and irrigation, and to increased evapotranspiration (Döll 2002; Parry et al. 2007). This increased water use may be achieved by increased pumping from groundwater, rivers or dams, depending on the availability of the resource, which is also directly affected by climate change. In Europe, increased precipitation is likely to occur in winter in the northern areas, while southern Europe is expected to suffer a decrease in precipitation (Arnell et al. 2001; Christensen et al. 2007). Northern France is located on the border of these two zones and is therefore subject to considerable uncertainty, partly connected with the fact that the precipitation regime is linked to both the large-scale circulation and the regional pattern of soil moisture, with a signal that varies depending on the season (Vautard and Yiou 2009; Boé 2013). These variables have a large spread in the climate projections for Europe (Boé et al. 2009b), as confirmed by the analysis of the ENSEMBLE projections, which used several global and regional climate models over Europe and showed that the uncertainty was associated with both scales (Déqué et al. 2012).

Although it has a mid-latitude oceanic climate, northern France can suffer from water-resource issues, mainly because of the anthropogenic water demand. The high population density (above  $200\text{ inhabitants/km}^2$ ) particularly in the Paris area, together with intensive agriculture (for instance in the Beauce region) and a dense industrial fabric lead to high water demand for drinking, irrigation and cooling. Such pressures affect water resources in terms of quality (Meybeck et al. 1998; Verjus 2008), and in terms of quantity since excessively low groundwater levels have led to restrictions on use in some areas for several years. In such conditions, the evolution of the climate is causing concern about the availability of water resources, especially in the context of regional development, which is tending to increase the population density.

To gain better insight into the impact of climate change on the water resources of the Seine and Somme basins of northern France the REXHySS project included several sources of uncertainty: it used two emissions scenarios, seven climate models, three downscaling methods and seven hydrological models ranging from simple rainfall-discharge models to more complex hydrogeological models. Few previous studies have addressed the uncertainty connected with the combination of emissions scenarios, climate models, downscaling methods and hydrological modelling (Wilby and Harris 2006; Kay et al. 2009; Görgen et al. 2010; Chen et al. 2011, 2012); most studies have used either several downscaling methods but only a single hydrological model (Dibike and Coulibaly 2005; Khan et al. 2006; Prudhomme and Davies, 2009; Boé et al. 2009a; Quintana-Segui et al. 2010), or just one downscaling method with several hydrological models (Ducharne et al. 2007; Bae et al. 2011; Teng et al. 2012).

The first part of this article presents the observed climate data, and the hydrological models, downscaling methods and climate change projections used. Then, the projected climate change

in the two basins is presented, together with its impacts on hydrology in terms of water budget, river flows and aquifer levels. The uncertainties associated to the results are then discussed.

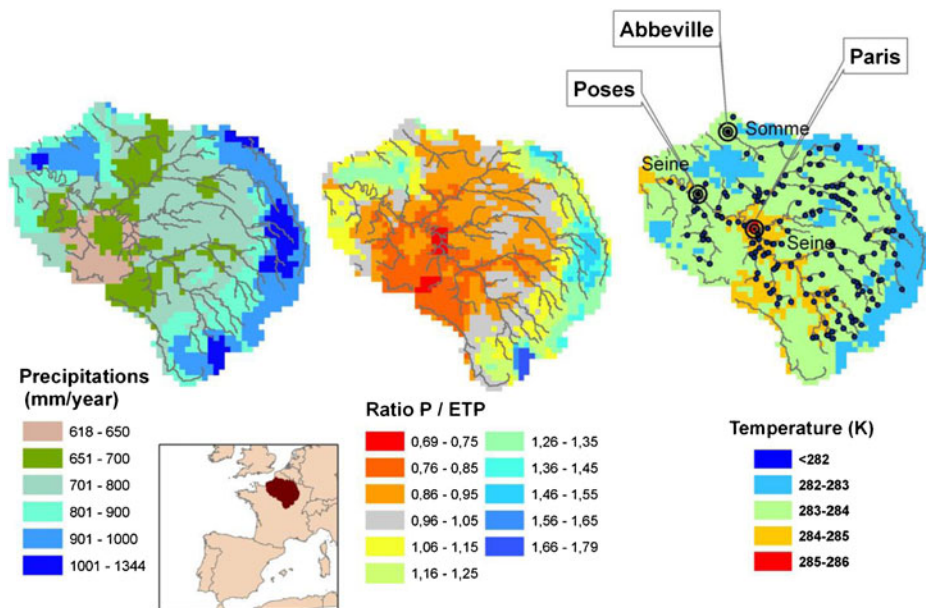
## 2 Materials and methods

### 2.1 Baseline climate data

The baseline climate data were taken from the SAFRAN analysis (Durand et al. 1993; Quintana-Segui et al. 2008) which provided the solid and liquid precipitation, downward solar and atmospheric radiation, 2-m air temperature and humidity and 10-m wind speed, all at an hourly time step on an 8-km grid. Daily potential evapotranspiration (PET) was then computed using the Penman Monteith formula (Monteith 1965). For the period 1971–2000, the mean annual precipitation is above 900 mm/year in the eastern part of the basin and can be lower than 650 mm/year in the western part (Fig. 1). Precipitation is lower than potential evapotranspiration in 55 % of the domain. Mean annual 2-m temperature varies by only 3 K throughout the domain, with warmer air in the urbanized areas and in the centre of the basin.

### 2.2 Hydrological models

To account for the uncertainty associated with the hydrological models, seven models already set up on the basins under study were used in the RExHySS project (Table 1). As the Seine and Somme basins are characterized by the presence of large aquifers that are estimated to account for 40 and 80 %, respectively, of the discharge at the outlets (Rousset et al. 2004; Négrel and Petelet-Giraud 2005), three of these models explicitly simulate multi-



**Fig. 1** Spatial distribution of the mean annual precipitation (*left*), ratio of the precipitation to potential evapotranspiration (*centre*) and 2-m temperature (*right*) on the domain, as provided by the SAFRAN analysis from 1971 to 2000

**Table 1** Main characteristics of the hydrological model and the statistical results obtained at the two main river gauges of the two basins: *SD* semi-distributed, *L* lumped, *D* distributed

		CLSM	EROS	GARDENIA	GR4	MARTHE	MODCOU	SIM
Spatial resolution		SD	SD	L	L	D	D	D
Water budget		Hourly	Daily	Daily	Daily	Daily	Daily	5 to 30 minutes
Energy budget		Yes	No	No	No	No	No	Yes
Aquifer transfer		1D	1D	1D	No	Pseudo-3D	Pseudo-3D	Pseudo-3D
Piezometric Head		No	Yes	Yes	No	Yes	Yes	Yes
References		<i>Ducharne et al., 2007, Gascoin et al., 2009</i>	<i>Thiéry 2004</i>	<i>Thiéry 2003</i>	<i>Perrin et al., 2003</i>	<i>Thiéry 1990, Habets et al., 2010</i>	<i>Ledoux et al., 2007, Korkmaz et al., 2009</i>	<i>Habets et al., 2008, Habets et al., 2010</i>
Somme Abbeville 5600 km <sup>2</sup>	Eff	0.67* (0.76)		0.85	0.67	(0.84)*	0.87	0.79
	Bias (%)	3.00*		-2.92	2.6	3.00*	-0.78	11.45
Seine Poses 65000 km <sup>2</sup>	Eff	0.87	0.86		0.81		0.625	0.79
	Bias (%)	-4.44	1.53		10.99		20.61	7.18

References written in italic provide details on the implementation of the model in the basin: Eff is the daily efficiency (Nash and Sutcliffe 1970) and bias  $((1.-Q_{sim}/Q_{obs})*100.)$ . The time period for the comparison with the observation in the Somme basin is from 25 dec 1985 to 27 Jul 2003 (6,400 days), the one in the Seine basin is from 1 Aug 1981 to 31 Jul 2001(6,938 days). A\* indicates that the period is from 1/8/1985 to 31/7/2003. The 7-day efficiency is given in parentheses. A grey box indicates that the hydrological model was not applied to the basin in question

layer aquifer transfer (MARTHE, MODCOU and SIM), three take aquifer storage into account with a 1D vertical approach (CLSM, EROS and GARDENIA), and one does not consider the aquifer explicitly (GR4). Two of the hydrological models are based on a soil-vegetation-atmosphere transfer scheme (CLSM and SIM), and thus compute the diurnal evolution of the water and energy budgets instead of using daily PET. Four of the models were applied to both basins, while two models were set up for the Somme basin only, and one for the Seine basin only.

As the hydrological models were already set up in the basins, their calibration period, calibration method and initial conditions differed, preventing the model performance from being attributed to the model structure or calibration practice. However, as the groundwater initial conditions may impact the simulations over several years, a common method was used for the three hydrogeological models: the initial piezometric heads were derived based on a steady simulation that used the mean annual recharge estimated from the first 10 years of the simulation. A brief analysis of the hydrological model results is presented in Table 1

for the main river gauges of the two basins shown in Fig. 1. According to the observed discharge availability, different periods were used for the two gauges. All models obtained reasonable results, with a daily efficiency (Nash and Sutcliffe 1970) above 0.67 and even above 0.8 in 68 % of the cases. However, the bias could be rather large, up to 22 % for MODCOU on the Seine basin. The electronic supplementary material (ESM1) gives additional insight into the monthly cycle. For the groundwater, an inter-comparison study had already been performed on the chalk aquifer of the Somme basin with MARTHE, MODCOU and SIM (Habets et al. 2010). On the 45 wells in common, MARTHE was shown to obtain best results, with a determination coefficient of 71 %, while MODCOU and SIM obtained 68 and 67 % respectively, the average biases being 0.88,  $-0.8$  and  $-0.19$  m.

### 2.3 Climate models and emission scenarios

Six time-slice climate projections made during CMIP3 and analysed in AR4 (Meehl et al. 2007) were used. These six projections are based on the A1B emissions scenario (IPCC 2000) and were selected on the basis of an analysis of their climate change impact projected over France and, more precisely, on the most marked change in terms of weather regime and precipitation. In addition to these six global climate models (GCMs), projections from the Arpege climate model (Gibelin and Déqué 2003) were used. This model was chosen because of its finer resolution over France (around 50 km) due to the use of a stretched grid. Two of the Arpege projections used different emissions scenarios (A1B and A2) and were only available for the end of the century, and the last one was available continuously from 1950 to 2100. Such continuous projection is important for hydrological impact studies because it can be used to infer a methodology to initialize the long-term response of the aquifer piezometric head for the time-slice projection.

### 2.4 Downscaling methods

It is necessary to downscale climate projections to try to reduce their bias and to make them compatible with the finer spatial resolution of the hydrological models (Maraun et al. 2010). In REXHySS, three downscaling methods previously used over France were applied. Two of them, the conventional anomaly method (AN) and the quantile mapping (QM) are based on statistical comparison with local analysis, while the weather typing (WT) method is based on an analysis of large-scale circulation. They used the SAFRAN present-day climate data so that the downscaled climate projections reached 8-km spatial resolution. The AN considers that the mean local future climate is shifted but that there is no evolution of the frequency distribution of the variables, which means, for instance, that there is no modification of the precipitation spells (the number of wet days is the same in the future as at present). In our case, the anomalies were computed at the monthly time scale, following the method of Caballero et al. (2007), and considered as additive for the temperature and as multiplicative for the precipitation. The QM was more complex since not simply the mean of the variable but the whole probability density function was corrected, based on a seasonal approach. It was therefore usually applied on regional climate models (Déqué 2007). In order to be able to consider the relationship between the atmospheric variables, the QM was applied to a matrix containing the set of variables and not independently on each time vector variable. The WT (Boé et al. 2007 and 2009a) was based on the analysis of the large-scale processes to provide a relationship between the large and regional scales. It considered that similar large-scale patterns would lead to similar local-scale patterns. Thus, each day of a given season in the future was taken to have a proxy in the same season of the present-day analysis,

and this proxy was used to provide the spatial pattern and the diurnal cycle of the given day, with special treatment for the temperature, which was assumed to be significantly warmer in the future.

The three methods allow good consistency to be obtained in the parameter (e.g. a rainy day has humid 2-m air). Only the anomaly method conserves the average impact projected by the GCM. The averaged impact from the other two methods can differ from that of the GCM due to their more sophisticated bias correction, which can modify both the spatial pattern and the range of the impacts. Comparisons of these methods over France as a whole (Boé et al. 2009a) and on the Mediterranean part of France (Quintana-Segui et al. 2010 and 2011) have shown that, although the two most sophisticated methods, QM and WT, gave rather similar results compared to the simple AN one, they could lead to some important local differences on both average and extreme values (more precisely, mean summer temperature and driest summer precipitation).

WT was applied to all climate model runs, while QM and AN were applied only to the finer spatial resolution ARPEGE-V4 model runs. Thus, only the ARPEGE-V4 model runs with the A1B and A2 emissions scenarios were downscaled using the three methods (see Table 2). A detailed assessment of the downscaled climate projection for the present day is given in ESM1.

### 3 Results

#### 3.1 Projected climate change

Evolutions of the mean precipitation, PET and 2-m air temperature as provided by the 12 downscaled climate projections (DCPs hereafter) for the periods 2047–2067 (2050 hereafter) and 2082–2099 (2080 hereafter) as compared to the present day (1971–2000) on average over the domain are presented in Table 2. There is general agreement that the temperature will have increased by 1.7–2.7° in 2050, and 2.2–4.2° in 2080, and that the PET will have increased by 11–22 % by the 2050s and by 15–32 % by around 2080. There is less agreement on precipitation. On an annual basis, the evolution of precipitation varies by +0.4 to –14 % in 2050 and by +4 to –24 % in 2080, with only two of the 12 projections predicting an increase in precipitation. There is not much difference between downscaling methods on an annual basis but seasonal differences are more marked (see ESM2).

#### 3.2 Impact of climate change on the water budget

There were a total of 19 DCPs for the two periods and 11 hydrological modelling cases on the two basins, which makes a total of 209 possibilities. However, because of the simulation cost, not all the hydrological models used all the DCPs, and only 147 were effectively available (70 %). The impacts of climate change estimated by these 147 simulations on total runoff are presented in Fig. 2 and summarized in Table 3. The main result is a general agreement on a decrease of the total runoff for all the hydrological models and all the downscaled climate projections except the wettest ones (GM in 2080, and G1 in 2050). The average decrease is about 20 % in 2050 and about 30 % in 2080 (Fig. 2). However, there is a large spread, which is associated with both the DCPs and the hydrological models. The standard deviation connected with the various DCPs for a given hydrological model ranges from 2 to 19 %, and that connected with the various hydrological models for a given GCM ranges from 2 to 27 % (Table 3). Most of the discrepancies on the hydrological models are

**Table 2** Downscaled climate projection used and their impacts on the precipitation (*P*), potential evapotranspiration (*PET*) and 2-m temperature (*T*) averaged over the Seine and Somme basins for the 2050s and the 2080s as projected by the downscaled present-day GCM climate

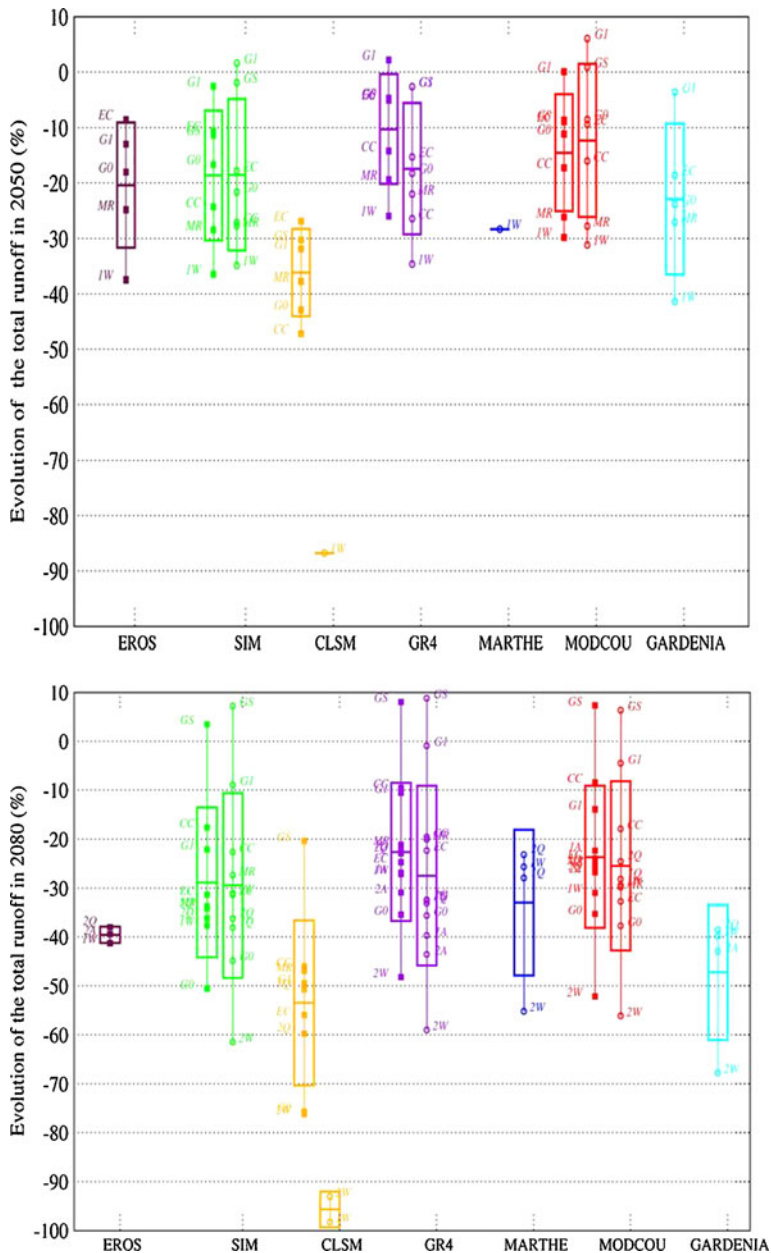
Acronym	GCM	emissions scenarios	downscaling method	2050			2080		
				P	PET	T	P	PET	T
2A	ARPEGE-V4	A2	AN				-15.3	29.9	4.2
2Q	ARPEGE-V4	A2	QM				-23.7	31.5	3.8
2W	ARPEGE-V4	A2	WT				-22.2	30.5	3.6
1A	ARPEGE-V4	A1B	AN				-11.8	22.6	3.3
1Q	ARPEGE-V4	A1B	QM				-18.0	25.3	2.9
1W	ARPEGE-V4-CONT	A1B	WT	-14.0	19.6	2.4	-15.9	25.9	3.1
G0	GFDL_CM2_0	A1B	WT	-4.3	21.9	2.7	-14.2	32.2	3.8
G1	GFDL_CM2_1	A1B	WT	-4.7	15.7	1.7	-9.5	26.2	3.0
EC	ECHAM5/MPI-OM	A1B	WT	0.4	13.1	2.2	-6.8	26.0	3.5
MR	MRI-CGCM2.3.2	A1B	WT	-4.5	11.3	1.9	-6.3	18.9	2.6
GM	GISS-MODEL-ER	A1B	WT	-0.8	11.8	1.7	3.8	15.8	2.2
CC	CCCMA_GCGM3_1	A1B	WT	-5.8	18.0	2.5	-3.2	23.9	3.2

A grey column means that the projection is not available for the period. The acronyms beginning with a number refer to the emissions scenarios (1 for A1B, 2 for A2), while the letter stands for the downscaling method. The other acronyms stand for projections using A1B emission scenario and WT

*AN* anomaly method, *QM* quantile mapping, *WT* weather typing

related to only one of them, CLSM. When CLSM is excluded, the standard deviation is lower than 9 % (Table 3). CLSM is the only hydrological model to project a median decrease of the total runoff larger than 30 % in 2050 and larger than 50 % in 2080. This is connected with an increase of the median actual evapotranspiration larger than 10 % in the two basins in the future. Indeed, the soil moisture in CLSM is sustained by an upward groundwater flux that almost doubles in the future compared to present days although the groundwater-level





**Fig. 2** Evolution of the runoff (%) for mid-century (*top*) and end-of-century (*bottom*), for each hydrological model (*x-axis*) for the Seine basin (*circles*) and the Somme basin (*squares*), for each downscaled climate projection. The acronyms of the DCPs are given and, for each model, the *boxes* indicate the average impact  $\pm$  the standard deviation

decreases. This, associated to some weaknesses on the management of the soil-water stress pointed out in an independent study, may lead to unrealistic results (see [ESM3](#) for a detailed analysis).



**Table 3** Anomaly on the total runoff in percent estimated for the two basins and the two periods in %

DCPs	Somme 2050		Seine 2050		Somme 2080		Seine 2080	
	All	All but 1	All	All but 1	All	All but 1	All	All but 1
2A					-44±1	Id	-32±6	Id
2Q					-31±7	Id	-37±14	-31±7
2W					-65±14	-60±5	-59±15	-50±3
1A					-40	Id	-25±4	Id
1Q					-32±5	Id	-33±13	-27±6
1W	-43±22	-34±5	-32±5	id	-43±27	-32±5	-34±6	-34±6
G0	-21±8	Id	-19±14	-13±6	-40±5	Id	-49±19	-40±9
G1	0±5	Id	-9±14	-3±7	-5±4	Id	-24±17	-16±6
EC	-15±5	Id	-12±9	-8±2	-29±6	Id	-34±15	-27±4
MR	-26±3	Id	-27±7	-24±4	-26±5	Id	-31±10	-27±7
GM	-1±2	Id	-14±11	-8±3	+4±8	Id	-1±13	-6±3
CC	-23±6	Id	-26±15	-18±5	-20±3	Id	-21±18	-12±5
Hydrological models	Somme 2050		Seine 2050		Somme 2080		Seine 2080	
CLSM	-87		-36±8		-96±4		-53±17	
EROS			-20±11				-39±2	
GARDENIA	-23±13				-48±14			
GR4	-19±12		-10±10		-28±18		-23±14	
MARTHE	-28				-33±15			
MODCOU	-12±14		-15±11		-27±15		-24±14	
SIM	-19±14		-19±11		-29±19		-29±15	

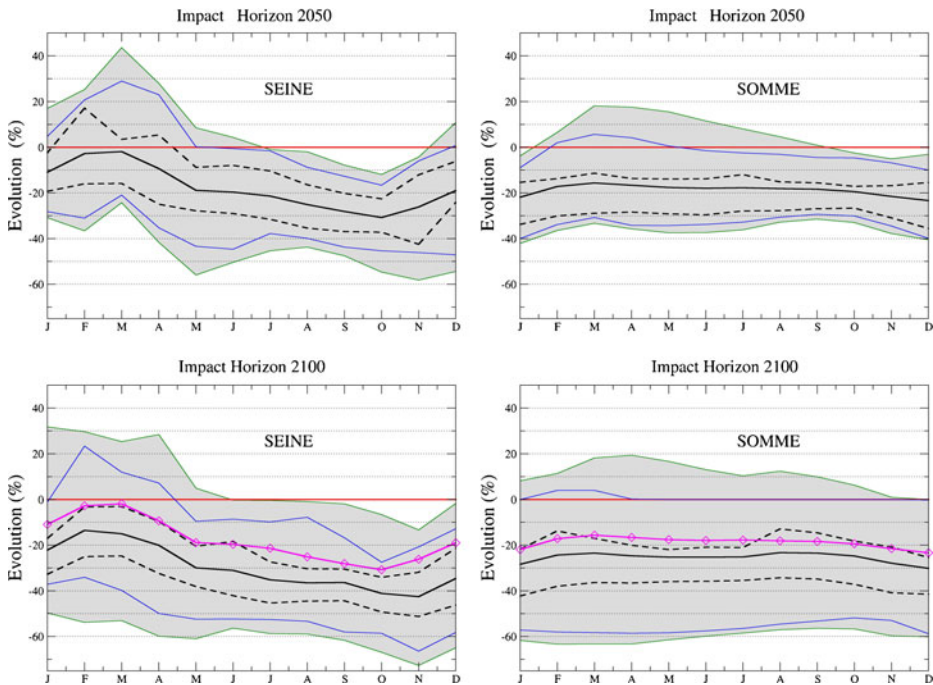
For each downscaled climate projection and hydrological model, the average anomaly  $\pm$  the standard deviation computed on the available simulations are given (but the average is not computed from the same number of members). For the *DCP*, the statistics obtained by all hydrological models except CLSM are also provided (*Id* means identical, no change)

When the average impact of climate change on total runoff without the CLSM model is analysed, it clearly appears that the range associated with DCP (about 0 to -30 % in 2050, and about +4 to -40 % for the DCPs using A1B emission in 2080) is larger than the range associated with hydrological modelling (-10 to -24 % in 2050, and about -23 to -48 % in 2080). The impact of the downscaling methods is also rather large, with an average impact on the Seine basin in 2080 varying from -32 to -50 % (Fig. 2 and Table 3).

### 3.3 Impact on river flows

Figure 3 presents the monthly anomalies of the Seine and Somme river flows in 2050 and 2080 compared to the present day climate. The sets of DCPs and hydrological models vary for each basin and each period as does the total number of simulations (see caption). The mean monthly anomalies in the Somme basin are around -20 % in 2050 and -30 % in 2080, while in the Seine basin, the decrease is larger in summer (-30 % in 2050, -40 % in 2080) than in winter (0 % in 2050 and -15 % in 2080).

In the Somme basin, about 10 % of the DCPs project almost no change on the annual cycle in both periods (slight increase in winter and slight decrease in summer), while in contrast, 10 % project a decrease of approximately 30 % in 2050 and above 50 % in 2080 throughout the year. The monthly variations are more pronounced in the Seine basin: more



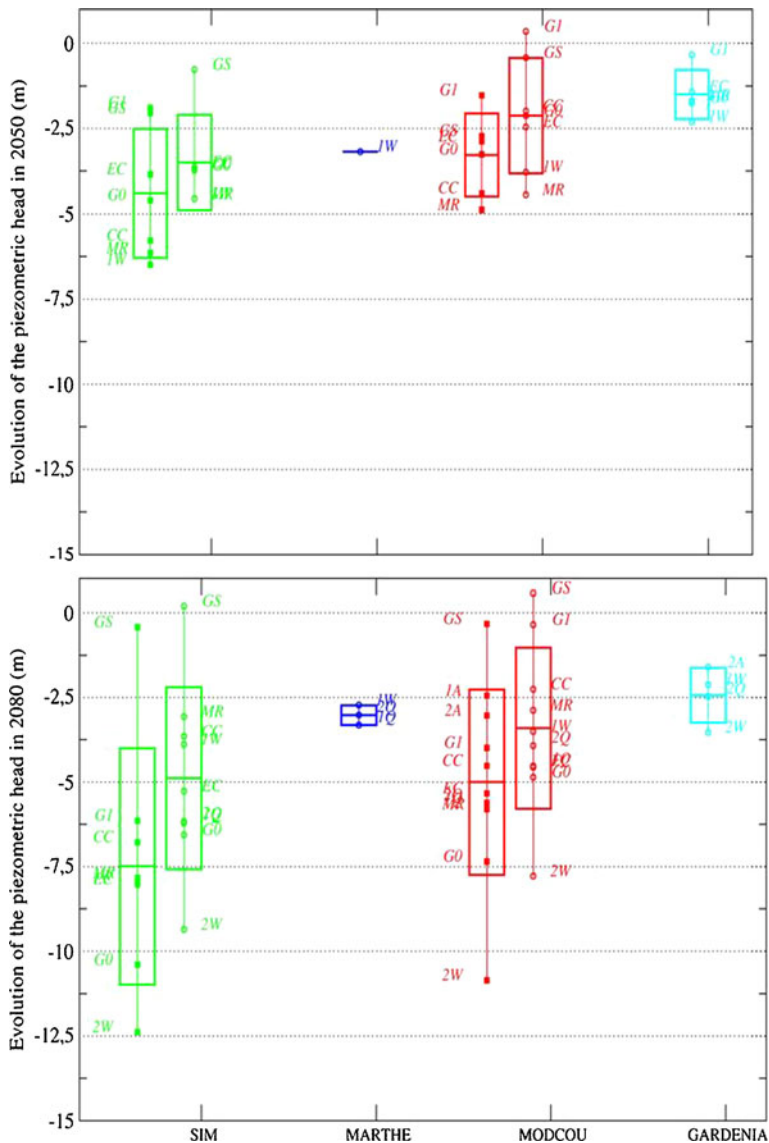
**Fig. 3** Monthly evolution of the Seine (*left*) and Somme (*right*) river flows for the mid-century (*top*) and end-of-century (*bottom*) relative to the simulated present day climate (1971–2000). The *envelope* represents the minimal and maximal values for each month, the continuous *blue thin lines* the 10 and 90 quantiles, the *dotted lines* the 25 and 75 quantiles, and the *black line* the average. The average in mid-century is plotted at the bottom with *pink diamonds*. The number of simulations varies on each plot: 36 and 37 for the Seine basin at mid-century and end-of-century, and 26 and 39 respectively for the Somme

than 25 and 10 % of the DCPs project an increase of the riverflow from February to April in 2050 and 2080 respectively, while 25 % of the simulations project a decrease of the summer discharge by about 30 and 40 % in 2050 and 2080 respectively. For the 2080s, 75 % of the simulations project a decrease of the discharge larger than the average decrease projected in the mid-century (Fig. 3).

### 3.4 Impact of climate change on piezometric heads

The piezometric heads in the Seine and Somme basins were simulated by two and four hydrological models respectively. The number of wells simulated varied: 143 wells located on the free part of the aquifer layers for SIM and MODCOU in the Seine basin, and, for the chalk aquifer of the Somme, 57 wells for GARDENIA and MARTHE, and 50 wells for MODCOU and SIM.

The average evolutions of the piezometric head projected by all available DCPs are a diminution of the piezometric by 2.45 and 3.72 m in the Somme basin in 2050 and 2080, respectively, and by 3.88 and 6.05 m in the Seine basin (Fig. 4, detailed results from the 1W continuous simulation are given in 4). The two most contrasted DCPs are 2W and GS for the two basins, which is consistent with the results obtained on the total runoff. On the Somme basin, for which four hydrological models were available, for a given DCP (2W), the largest uncertainty associated with the hydrological model represents 5 m, while, for a given hydrological model, the largest uncertainty reaches 8 m. When the results obtained with the same



**Fig. 4** Evolution of the piezometric head (m) on average for each of the simulated wells as projected by the hydrological models for each DCP for the Seine basin (*filled squares*) and the Somme basin (*circles*). The acronyms of the DCPs are given, and the *boxes* indicate the average impact  $\pm$  the standard deviation. The *upper panel* presents the results for the mid-century, and the *bottom one* the end-of-century

climate projection but with different downscaling methods are considered, the WT and QM methods reach a variation of 1, 3 and 5 m for MARTHE, SIM and MODCOU respectively, while the three downscaling methods lead to an uncertainty of 2 m for GARDENIA, which is the only model used for the three projections. GARDENIA presents the weakest evolution of the piezometric heads for a given DCP. This might be due to the fact that, in a lumped model, the piezometric heads are proportional to the level of a deep reservoir, and neither the evolution of

the piezometric head gradient nor the relationship with the river is explicitly considered. The evolution of the piezometric head is more pronounced on the Seine basin than on the Somme basin, which might be due to the selection of the piezometric wells, with more wells located close to the river in the Somme basin. The amplitude of the aquifer decrease is similar to that obtained by Goderniaux et al. (2011) in a Belgian basin, but larger than the amplitude obtained by Jackson et al. (2011) on a chalk aquifer in England. This could be explained by differences in the evolution of the precipitation.

#### 4 Discussion

A detailed analysis was made of the uncertainty with an appropriate statistical method to manage the heterogeneous set of available impact projections (see [ESM5](#)). Not surprisingly, the climate models appear to be the main sources of uncertainty, which is in agreement with the literature for about a decade (see, for instance, Arnell 1999; Bergstrom et al. 2001; Nijssen et al. 2001). The three other sources of uncertainty, i.e., the ones associated with downscaling methods, emissions scenarios and the hydrological models are about the same range of value and about three times lower than the one associated to the climate modelling, at least when one focuses on the annual discharge, and when only physically sound results were kept. Indeed, it was possible to reduce the uncertainty on the hydrological modelling by considering one model as an outlier for physical reasons, highlighting a good fit with a single observed variable (here, the riverflows) is not sufficient to enable a model to be considered as a suitable tool for a projection study. Other sources of uncertainty were, however, neglected in this study. For instance, some physical feedbacks as the impact of the CO<sub>2</sub> on plant transpiration or the modification of direct evaporation from groundwater are not explicitly taken into account by the models. Also, the land use was considered fixed, as was the anthropization of the water resources (no change in pumping pressure), although previous studies have shown their large impact on the water resource (Holman 2006; Candela et al. 2009). Furthermore, the uncertainty associated with the natural variability was not explicitly addressed, although it had a large impact on the discharge of French rivers over the last century, and is recognized as being important in the early decades of climate projections (Hawkins and Sutton 2009; Kay et al. 2009; Terray and Boé 2013). Although this uncertainty analysis is not complete, it nevertheless appears that none of the four sources of uncertainty taken into account can be neglected.

The overall signal obtained in RexHySS is a clear decrease of the water resource of the Seine and Somme basins. This is consistent with the study by Boé et al. (2009a), which shares some hydrological projections with RexHySS, but rather different from the one by Ducharme et al. (2007), for which a larger increase of winter flow was compensating the decrease of summer flow to lead to a quite stable annual discharge. Such results were obtained by employing two of the hydrological models used in this study (CLSM and MODCOU) and a former climate projection with the A2 emission scenario. This is the first time that two fairly recent climate change impact studies on a French basin have provided such contrasted results. For instance, the results of Boé et al. (2009a) are quite consistent with those obtained in the Rhone and Garonne basins with earlier projections (Etchevers et al. 2002; Caballero et al. 2007). This is perhaps due to the fact that those two basins have a large snow component, for which global warming has quite a clear impact, whereas the Seine basin is hardly affected by snowfall and thus depends on the evolution of the rainfall, which is more uncertain. This reinforces the interest of knowing whether the use of CMIP5 climate projections would lead to similar results. CMIP5 GCMs also project a general tendency for an increase of winter precipitation and a decrease of summer precipitation in northern France (Terray and Boé 2013). A first comparison of regional climate

modelling performed in the framework of the CMIP5 Cordex experiment has shown a larger spread in winter precipitation. However, a full comparison is not yet possible because these projections have to be downscaled. Although the present article does not focus on the extremes, the hydrological extremes projected by REXHySS have been analysed in a companion paper (Ducharme et al. 2011), which reports that the risk of floods returning within 10-year and 100-year periods is quite stable.

## 5 Conclusion

This article has attempted to present a full analysis of the impact of climate change on the hydrological component of two basins located in northern France, by including the analysis of surface water and groundwater. A set of 147 hydrological projections based on seven hydrological models, seven climate models, three downscaling methods, and two emissions scenarios was analysed. There is a general agreement on a decrease of the river flow at the outlets of both basins by at least 14 % by the 2050s and at least 22 % by the 2080s. More than 90 % of the hydrological projections predict a decrease of the summer flow at the outlets of the Seine and Somme basins (although this is less true for the Somme in the 2080s), and a decline of the piezometric heads for at least 90 % of the wells.

However, the results present a large spread, with a magnitude of the signal on river flow and piezometric head of the same order of magnitude as the standard deviation. About 10 % of the hydrological projections estimated a chance of increased river flow in winter in the Seine and throughout the year in the Somme, while 10 % projected a decrease of more than 40 % of the river discharge at the outlets. The uncertainty on the evolution of the piezometric head seems even larger, since the range of variation can reach 8 m on average over the simulated piezometers.

The spread is mainly due to the uncertainty associated with the climate projections, especially because of two wetter downscaled climate projections that give an opposite signal on the evolution of the piezometric head and discharge. However, it has been shown that the other three sources of uncertainty taken into account in this study, i.e. the emission scenario, the downscaling method and the hydrological model, are also important, and that other sources of uncertainty as physical feedbacks and natural climate variability were not taken into account.

Therefore, there is a need to make a survey of the impact of climate change in such basins. A systematic approach will be helped by the availability of climate services, such as the DRIAS project over France (<http://www.drias-climat.fr>).

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## References

- Arnell N (1999) The effect of climate change on hydrological regimes in Europe: a continental perspective. *Glob Environ Chang* 9:5–23
- Arnell NW et al (2001) Hydrology and water resources. In: McCarthy JJ, Canziani O, Leary NA, Dokken DJ, White KS (eds) *Climate change impacts, adaptation, and vulnerability. Contribution of Working Group II to the TAR of the IPCC*. Cambridge University Press, Cambridge, pp 191–233
- Bae D-H, Jung I-W, Lettenmaier D (2011) Hydrologic uncertainties in climate change from IPCC AR4 GCM simulations of the Chungju Basin, Korea. *J Hydrol* 401:90–105

- Bergstrom S, Carlsson B, Gardelin M, Lindstro G, Pettersson A, Rummukainen M (2001) Climate change impacts on runoff in Sweden: assessments by global climate models, dynamical downscaling and hydrological modelling. *Clim Res* 16:101–112
- Boé J (2013) Modulation of soil moisture-precipitation interactions over France by large-scale circulation. *Clim Dyn* 40(3–4):875–892
- Boé J, Terray L, Habets F, Martin E (2007) Statistical and dynamical downscaling of the Seine basin climate for hydro-meteorological studies. *Int J Climatol* 7(12):1643–1655
- Boé J, Terray L, Habets F, Martin E (2009a) Projected changes in components of the hydrological cycle in French river basins during the 21st century. *Water Resour Res* 45, W08426
- Boé J, Terray L, Cassou C, Najjac J (2009b) Uncertainties in European summer precipitation changes: role of large scale circulation. *Clim Dyn* 33:265–276
- Caballero Y et al (2007) Hydrological sensitivity of the Adour-Garonne river basin to climate change. *Water Resour Res* 43(7). doi:[10.1029/2005WR004192](https://doi.org/10.1029/2005WR004192)
- Candela L, von Igel W, Javier Elorza F, Aronica G (2009) Impact assessment of combined climate and management scenarios on groundwater resources and associated wetland (Majorca, Spain). *J Hydrol* 376:510–527
- Chen J, Brissette FP, Poulin A, Leconte R (2011) Overall uncertainty study of the hydrological impacts of climate change for a Canadian watershed. *Water Resour Res* 47, W12509
- Chen H, Xu C-Y, Guo S (2012) Comparison and evaluation of multiple GCMs, statistical downscaling and hydrological models in the study of climate change impacts on runoff. *J Hydrol* 434–435:36–45
- Christensen JH et al (2007) Regional climate projections. *Climate change 2007: the physical science basis. Contribution of Working Group I to the AR4 of the IPCC*. Cambridge University Press, Cambridge
- Déqué M (2007) Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. *Glob Planet Chang* 57:16–26
- Déqué M, Somot S, Sanchez-Gomez E, Goodess CM, Jacob D, Lenderink G (2012) The spread amongst ENSEMBLES regional scenarios: regional climate models, driving general circulation models and interannual variability. *Clim Dyn* 38:951–964
- Dibike YB, Coulibaly P (2005) Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. *J Hydrol* 307(1–4):145–163
- Döll P (2002) Impact of climate change and variability on irrigation requirements: a global perspective. *Clim Chang* 54:269–293
- Ducharne A et al (2007) Long term prospective of the Seine river system: confronting climatic and direct anthropogenic changes. *Sci Total Environ* 375:292–311
- Ducharne A et al (2011) Evolution potentielle du régime des crues de la Seine sous changement climatique. *Houille Blanche* 1(51–57):37
- Durand Y, Brun E, Mérindol L, Guyomarc'h G, Lesaffre B, Martin E (1993) A meteorological estimation of relevant parameters for snow models. *Ann Glaciol* 18:65–71
- Etchevers P, Golaz C, Habets F, Noilhan J (2002) Impact of a climate change on the Rhone River catchment hydrology. *J Geophys Res A* 107(D16):4293
- Gascoin S, Ducharne A, Carli M, Ribstein P, Habets F (2009) Adaptation of catchment-based land surface model to the hydrogeological setting of the Somme River basin (France). *J Hydrol* 368(1–4):105–116
- Gibelin A-L, Déqué M (2003) Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. *Clim Dyn* 20(4):327–339. doi:[10.1007/s00382-002-0277-1](https://doi.org/10.1007/s00382-002-0277-1)
- 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
- Görgen K et al (2010) Assessment of climate change impacts on discharge in the Rhine River Basin: results of the RheinBlick2050 Project. CHR report, I-23, CHR, Lelystad, The Netherlands, 229 pp
- Habets F et al (2008) The SAFRAN-ISBA-MODCOU hydrometeorological model applied over France. *J Geophys Res* 113, D06113
- Habets F et al (2010) Multi-model comparison of a major flood in the groundwater-fed basin of the Somme River (France). *Hydrol Earth Syst Sci* 14(1):99–117
- Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. *BAMS* 90(8):1095–1107
- Holman IP (2006) Climate change impacts on groundwater recharge: uncertainty, shortcomings, and the way forward? *Hydrogeol J* 14(5):637–647
- IPCC (2000) A special report of Working Group III of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Cambridge Press, Cambridge, 27 pp
- IPCC (2007) Core writing team. In: Pachauri RK, Reisinger A (eds) *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Cambridge Press, Cambridge, 104 pp



- 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
- Kay AL, Davies HN, Bell VA, Jones RG (2009) Comparison of uncertainty sources for climate change impacts: flood frequency in England. *Clim Chang* 92:41–63
- Khan MS, Coulibaly P, Dibike Y (2006) Uncertainty analysis of statistical downscaling methods. *J Hydrol* 319(1–4):357–382
- Korkmaz S, Ledoux E, Önder H (2009) Application of the coupled model to the Somme River basin. *J Hydrol* 366:21–34
- Ledoux E et al (2007) Agriculture and groundwater nitrate contamination in the Seine Basin: the STICS-MODCOU modelling chain. *Sci Total Environ* 375:33–47
- Maraun D et al (2010) Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. *Rev Geophys* 48, RG3003
- Meehl GA et al (2007) Global climate projections. In: Solomon S et al (eds) *Climate change 2007: the physical science basis. Contribution of Working Group I to the AR4 of the IPCC*. Cambridge Univ. Press, Cambridge
- Meybeck M, de Marsily G, Fustec E (1998) *La Seine en son bassin: fonctionnement écologique d'un système fluvial anthropisé*. Elsevier, Paris
- Monteith JL (1965) *Evaporation and environment*. 19th Symposia of the Society for Experimental Biology, University Press, Cambridge, pp 205–234
- Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models. *J Hydrol* 10(3):282–290
- Négrel P, Petelet-Giraud E (2005) Strontium isotopes as tracers of groundwater-induced floods: the Somme case study (France). *J Hydrol* 305:99–119
- Nijssen B, O'donnell GM, Hamlet AF, Lettenmaier DP (2001) Hydrologic sensitivity of global rivers to climate change. *Clim Chang* 50:143–175
- Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) (2007) *Contribution of Working Group II to the AR4 of the IPCC Change*. Cambridge University Press, Cambridge, 976 pp
- Perrin C, Michel C, Andréassian V (2003) Improvement of a parsimonious model for streamflow simulation. *J Hydrol* 279(1–4):275–289
- Prudhomme C, Davies H (2009) Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK, part 2: future climate. *Clim Chang* 93:197–222
- Quintana-Segui P et al (2008) The SAFRAN atmospheric analysis: description and validation. *J Appl Meteorol Climatol*. doi:10.1175/2007JAMC1636.1
- Quintana-Segui P, Ribes A, Martin E, Habets F, Boé J (2010) Comparison of three downscaling methods in simulating the impact of climate change on the hydrology of Mediterranean basins. *J Hydrol* 383(1–2):111–124
- Quintana-Segui P, Habets F, Martin E (2011) Comparison of past and future Mediterranean high and low extremes of precipitation and river flow projected using different statistical downscaling methods. *Nat Hazards Earth Syst Sci* 11(5):1411–1432
- Rousset F et al (2004) Hydrometeorological modeling of the Seine basin using the SAFRAN-ISBA-MODCOU system. *J Geophys Res A* 109(D14)
- Teng J, Vaze J, Chiew FHS, Wang B, Perraud JM (2012) Estimating the relative uncertainties sourced from GCMs and hydrological models in modeling climate change impact on runoff. *J Hydrometeorol* 13:122–139
- Terray L, Boé J (2013) Quantifying 21st-century France climate change and related uncertainties. *C R Geosci* 345:136–149
- Thiéry D (1990) Logiciel MARTHE. Modélisation d'Aquifère par un maillage Rectangulaire en régime Transitoire pour le calcul hydrodynamique des écoulements, version 4.3. BRGM report, 4S/EAU R32210, BRGM, Orleans, France
- Thiéry D (2003) Logiciel GARDENIA version 6.0—Guide d'utilisation. BRGM report, RP-52832-FR, 102, BRGM, Orleans, France, 42 pp
- Thiéry D, Moutzopoulos C (1995) Un modèle hydrologique spatialisé pour la simulation de très grands bassins: le modèle EROS formé de grappes de modèles globaux élémentaires. ORSTOM editions, ORSTOM, Marseille, France, pp 285–295
- Vautard R, Yiou P (2009) Control of recent European surface climate change by atmospheric flow. *Geophys Res Lett* 36, L22702
- Verjus P (2008) *Elaboration du SDAGE du bassin Seine Normandie relatif à la gestion de la rareté de la ressource en eau*. Houille Blanche. doi:10.1051/lhb:2008026
- 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