The RheinBlick2050 and Imagine2030 projects: a perspective on the hydrological impacts of climate change in two river basins in Europe

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1 Introduction

The potential impacts of climate change on surface water have been an increasing concern among the community of hydrologists and water managers over the past two decades. As shown by the Intergovernmental Panel on Climate Change (IPCC 2007), the rise of global mean temperature observed in the past years will continue in the future and may result in strong regional modifications of temperature and precipitation characteristics. However the level of projected modifications seems to vary between regions and climate regimes. Therefore it can be expected that these climate changes will have various impacts on water bodies and on the water availability for ecosystems and human activities.

Many studies have been carried out over the last two decades to estimate the possible evolution of hydrological regimes in rivers that may be caused by the projected climate changes. This was done worldwide for many catchments, regions, countries or even at the continental scale (see e. g. ARNELL 1999; DANKERS & FEYEN 2008; FEYEN & DANKERS 2009 for a European perspective). The results of these various studies are often difficult to compare, as different hypotheses are made. However, it is quite interesting to compare them, especially in terms of methodology and uncertainty assessment.

Two recent research projects, RheinBlick2050 (GÖRGEN et al. 2010) and Imagine2030 (SAUQUET 2010), aimed at evaluating the impacts of climate change on surface water on two different basins: the Rhine (160,800 km² at Lobith gauging station) and the Garonne (32,350 km² at Lamagistère gauging station) river basins respectively. The two basins, though quite different in size, are characterised by mixed hydro-meteorological conditions (including mountainous conditions), a significant level of human influences (dams, abstractions) and high socio-economic stakes (water supply, hydroelectricity, waterways, agriculture, flood risk, etc.). The two basins were the subject of other climate change impact studies, indicating some significant changes on various aspects of the flow regime: see e. g. HURKMANS et al. (2010) or TE LINDE et al. (2010) in the case of the Rhine basin; CABALLERO et al. (2007) and TISSEUIL et al. (2010) in the case of the Garonne basin.

The RheinBlick2050 and Imagine2030 projects were carried out in a similar time frame by two different research groups. They adopted quite similar general approaches to quantify the possible impacts of climate change.

The objective of this article is to compare the main characteristics and outcomes of these projects. The aim is to underline what was common in these projects and what made them specific. This will also give an illustration on the levels of uncertainty that can be expected in different contexts.

The next sections present the objectives, motivations and general modelling approaches of the two projects. Then the basins studied and data sets used are shortly described. The methods and models applied are presented and the main results of each project are detailed. Finally, some concluding remarks are given on the main breakthroughs and difficulties found in these projects, before giving some prospects for future studies.

This paper is mainly based on the project final reports produced by GÖRGEN et al. (2010) for RheinBlick2050 (available at www.chr-khr.org/projects/rheinblick2050) and SAUQUET (2010) for Imagine2030 (available at imagine2030.lyon.cemagref.fr).

2 Objectives and motivations

The main characteristics of the two projects are listed in Table 1.

RheinBlick2050 is an initiative launched by the International Commission for the Hydrology of the Rhine Basin. It wished to involve the riverine countries of this transboundary basin to develop a common and consistent research framework across participating countries on the impacts of climate change on the basin. The main objective was to create state-of-the-art regional climate change projection ensembles and discharge projections (mean, high and low flows) for the near (2021 - 2050) and far (2071 - 2100) future, with a quantification of the associated uncertainties. The project established close linkages with the International Commission for the Protection of the Rhine that was interested in developing common climate change scenarios that might be used later in politically relevant climate adaptation strategies (with respect to many aspects such as navigation, flood protection, low flow alleviation, hydropower production, etc.).

Imagine2030 is a national French research project focusing on the Garonne River basin (south-western France). The focus was on characterising the risk of droughts and severe low flows on the basin in current conditions and in the future by the year 2030 (2015 - 2045 time slice). The possible future water shortages for two main water uses (irrigation and hydropower) were also investigated, considering business-as-usual water management rules. The basin authority (Adour-Garonne Water Agency), which is quite active in developing prospective studies on the basin, took part in the project and eased the links with the various water stakeholders.

Therefore the two projects had a similar ambition to produce projections that could be useful for water managers and stakeholders for future decision making on these basins, with important stakes in both cases.

Table 1
Main characteristics of the RheinBlick2050 and Imagine2030 projects

	RheinBlick2050	**Imagine2030**
Period	2008 - 2010	2008 - 2009
Project type	International (Luxembourg, Germany, the Netherlands, France, Switzerland)	National (France)
Funding	International Commission for the Hydrology of the Rhine Basin and national institutions	Ministry for Ecology, Sustainable Development, Transport and Housing (France)
Institutions involved	CRP-GL, KNMI, Rijkswaterstaat, HLUG, BfG, Deltares, Cemagref, BAFU	Cemagref, EDF-LNHE, Adour-Garonne Water Agency
Co-ordination	Klaus Görgen (CRP-GL)	Eric Sauquet (Cemagref)
Focus	All parts of the hydrological regime	Low flows Impact of irrigation and hydropower

3 General modelling framework and uncertainty assessment

The general methodology adopted in the two projects is quite classical. It consists in chaining a number of modelling steps that mainly consist in (see e. g. BOÉ et al. 2009):

> considering greenhouse gas (GHG) emission scenarios
> simulating climate evolution for various variables at the global scale given the GHG scenario
> downscaling these simulations at the regional scale at a spatio-temporal resolution sufficient for hydrological modelling
> forcing hydrological models with downscaled climate inputs and simulating corresponding streamflow values

The possible changes in various flow variables can then be quantified between a reference period (current climate) and a future one, either in relative or in absolute terms.

Obviously, each modelling step will generate uncertainties due to the imperfection of models and the prospective nature of the work. This uncertainty will progressively increase when cascading the modelling steps, which will result in a potentially large overall uncertainty on flow outputs, that must be adequately quantified and accounted for (IPCC 2005). The relative roles of the different sources of uncertainties have been studied for example by WILBY (2005) and WILBY & HARRIS (2006), indicating that the climatic part of the chain may be the main source of uncertainty, but that hydrological uncertainties cannot be neglected either.

One way to account for these uncertainties is to consider a number of modelling options at each step of the modelling chains. The resulting uncertainty on flows can then be quantified as the bandwidths of all the simulations obtained.

The two projects adopted the same approach of using a number of climate projections and hydrological models, which produced uncertainty bands for all simulated variables. Specific attention was given to the way this uncertainty should be communicated and various graphical and numerical options were chosen (e. g. showing individual simulations or only ranges, giving the results in absolute or relative terms, etc.). Some illustrations are given in sections 6 and 7.

4 Basins and data

4.1 Basin characteristics and observed data

The Rhine and Garonne River basins are located in Central and Western Europe respectively. Their location is illustrated in Figure 1 and some of their characteristics are given in Table 2. Although quite different in size, the two basins have some interesting similarities. The upper parts of the basins are located in high mountains (the Alps for the Rhine and the Pyrenees for the Garonne) with some nival regime. These mountainous zones may be particularly sensitive to climate changes, although they are also those where the uncertainties on future conditions are among the largest (see e. g. ADAM et al. 2009; LOPEZ-MORENO et al. 2009). In the two catchments, some major tributaries are located in lowland zones with pluvial regime. It means that both basins have mixed regimes at their outlet. The upper parts are influenced by dams that have a major impact on observed flows. Some specific work on flow naturalisation was done in Imagine2030 to remove dam influence. In RheinBlick2050, it was chosen to use target stations situated downstream enough of the mountainous part to have only diffuse influence.

Data were available at a daily time step. The characterisation of the basins' hydrological behaviour in current conditions was done using climatic observed data sets that were at a resolution deemed sufficient to carry out the work (see Table 2). The two projects selected a number of target gauging stations spread over the basins (on the main stream or on tributaries, see Table 2) where the influence of climate changes was quantified.

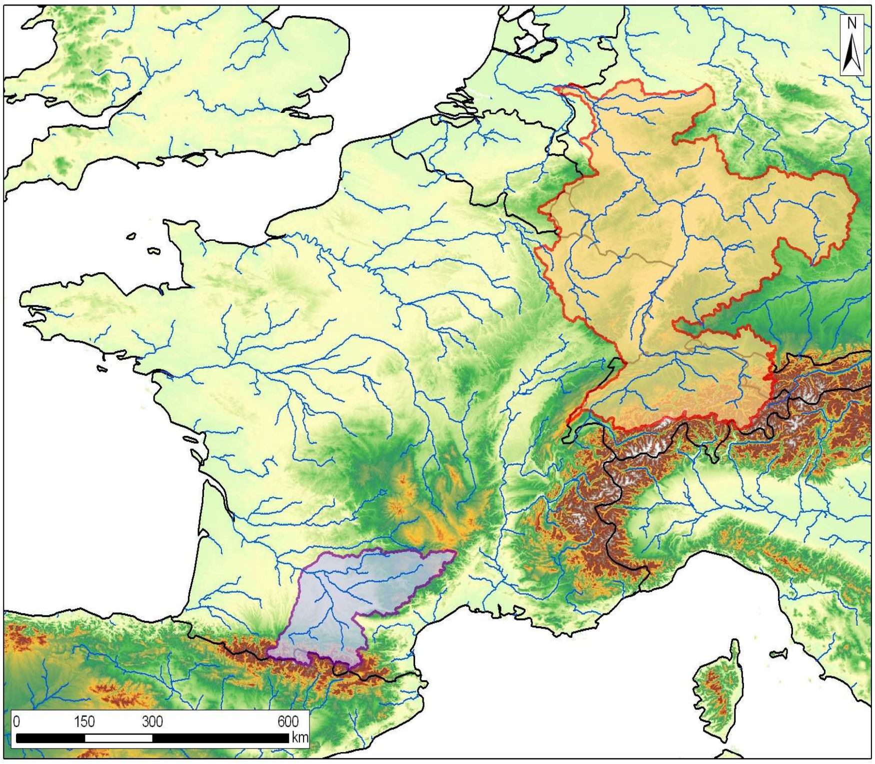


Figure 1: Location map of the Rhine basin at Lobith (in orange) and the Garonne basin at Lamagistère (in blue)

Table 2
Some characteristics of the Rhine and Garonne basins and data used

Basin (Project)	Rhine (RheinBlick2050)	Garonne (Imagine2030)
Downstream gauging station and area	Lobith (160,800 km²)	Lamagistère (32,350 km²)
Range in altitude	>3000 - 60 m a.s.l.	>3000 - 0 m a.s.l.
Mean annual flow	2,200 m^3/s (1901 - 2005)	400 m^3/s
Target gauging stations	8 stations : Rhine at Basel (35,897 km²) Rhine at Maxau (50,196 km²) Rhine at Worms (68,827 km²) Rhine at Kaub (103,488 km²) Rhine at Köln (144,232 km²) Rhine at Lobith (160,800 km²) Main at Raunheim (27,142 km²) Moselle at Trier (23,857 km²)	9 stations: Garonne at Valentine (2,230 km²) Salat at Roquefort (1,570 km²) Ariège at Foix (1,340 km²) Garonne at Portet (9,980 km²) Tarn at Millau (2,170 km²) Agout at Lavaur (2,300 km²) Tarn at Villemursur-Tarn (9,100 km²) Aveyron at Loubejac (5,170 km²) Garonne at Lamagistère (32,350 km²)
Flow data	Observed flows	Naturalised flows
Observed climatic data	CHR-OBS reference dataset of precip., temp. and sunshine duration/global radiation distributed on 134 subcatchments (KRAHE et al., unpublished)	8 x 8 km SAFRAN gridded inputs of precip., temp. and potential evapotranspiration (QUINTANA-SEGUI et al. 2008; VIDAL et al. 2010)
Reference period	1961 - 1990	1973 - 2003
Future time slices	2021 - 2050 (near future), 2071 - 2100 (far future)	2015 - 2045
GHG scenarios	A1B (primarily), A2, B1	A1B, A2
GCM	19 GCM considered, 5 GCM downscaled (ENSEMBLES project)	~ 15 GCM considered (IPCC AR4)
Downscaling and bias correction	Dynamical downscaling with RCMs + 4 bias corrections methods	Statistical spatial downscaling + Perturbation approach for temporal downscaling
Number of projections considered	+/- 20 (depending on testing conditions)	+/- 20 (depending on testing conditions)

4.2 Climate projections and series resampling

To characterise the uncertainty in future climate conditions, the two projects adopted a similar approach by using an ensemble of projections. Some specific work was done to adapt the GCM outputs to the spatial and temporal scales necessary for the projects and to correct their bias. In RheinBlick2050, already existing RCM outputs, mainly produced by dynamical downscaling in the ENSEMBLES project (VAN DER LINDEN & MITCHELL 2009), were used as base data. In this project, the focus was on the reliability of dynamical downscaling approaches and the question of optimising bias correction. In Imagine2030 a statistical downscaling was applied to the GCM model results. The reliability of the simulations was evaluated in current conditions using a number of climatic indicators (e. g. mean precipitation or temperature). Although the regionalisation strategies were different in the two projects, they resulted in about 20 projections (control and projection timespans) that were eventually used to force the hydrological models.

Resampling techniques (based on nearest neighbour approaches, see LALL & SHARMA 1996; RAJAGOPALAN & LALL 1999; BEERSMA & BUISHAND 2003) were also applied in the two projects but with different objectives: in RheinBlick2050, they were used to generate long series for the evaluation of extreme flood events; in Imagine 2030, they were used to generate various scenarios for assessing the uncertainty in the temporal downscaling step.

5 Hydrological models

As there is a variety of existing hydrological models, a set of different modelling tools were used in each project to quantify the uncertainty related to the choice of the model structure. They correspond to various spatial discretisations (lumped, semi-distributed or distributed), conceptualisations and levels of complexity. All the selected models were already used for operational applications or climate impact studies.

RheinBlick2050 implemented the HBV134 semi-distributed model (EBERLE et al. 2005) that was extensively applied on the Rhine basin in the recent years. Some comparative references were provided by a set of seven simple lumped hydrological models. In the Imagine2030 project, two models were tested: the distributed CEQUEAU model (CHARBONNEAU et al. 1977) and the lumped GR4J model (PERRIN et al. 2003).

All models were used with a snow module to account for snow accumulation and melt on the upper parts of the basins. The models did not include specific modules to account for dams.

All models were evaluated on observed data to assess their reliability and ability to simulate the hydrological behaviour of the selected sub-basins. Some sensitivity analyses were performed, e. g. to the formulation of evapotranspiration.

A specific scheme was developed to evaluate the suitability of hydrological models to climate change impact studies. Indeed, in this context, models will be applied in future conditions that are much different from those for which they were initially calibrated. Given the underlying stationary hypothesis, models may lack robustness for applications in so different conditions. The testing scheme, based on the differential split sample test proposed by KLEMEŠ (1986), showed that blindly calibrating models under current conditions actually adds significant uncertainty to the modelling chain.

6 Main results on climatic evolutions

Projected evolutions of temperature and precipitation are illustrated in Figure 2.

On the Rhine basin, climate projections show a general increase in temperature. By 2021 - 2050, this increase ranges from 0.5 to 2.5°C in the winter season and from 0 to 2.0°C in the summer season. The change is projected to be more pronounced by the end of the century, ranging between 2.5 and 5.0°C all along the year.

In terms of precipitation, the signal is more uncertain. But the contrast between summer and winter changes is projected to increase in the far future: the winter precipitation is projected to increase (0 - 15 % by 2021 - 2050; up to 25 % by 2071 - 2100) while the summer precipitation is projected to decrease (no clear change by 2021 - 2050, 10 % to 30 % by 2071 - 2100).

On the Garonne basin, the temperature rise by 2015 - 2045 may be between 1 and 2°C, but could be more pronounced in the summer season. The change on precipitations is largely uncertain, but there may be some decrease in summer precipitation up to 10 % by 2015 - 2045.

In the two basins, the changes in climate conditions should go towards more contrasted seasons. The projected changes in temperature seem more certain than on precipitation, which is in agreement with the fact that climate models model temperature better than precipitation. The rise in temperature will have some consequences on snowfall in the mountainous areas, which will most likely be partly replaced by rainfall.

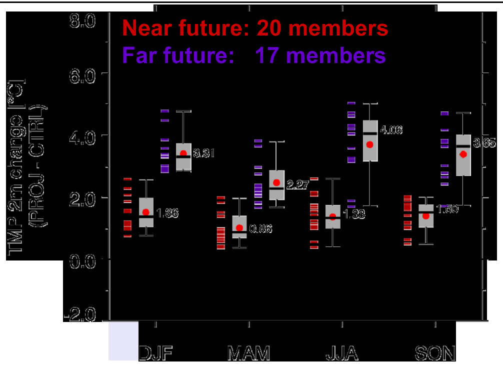
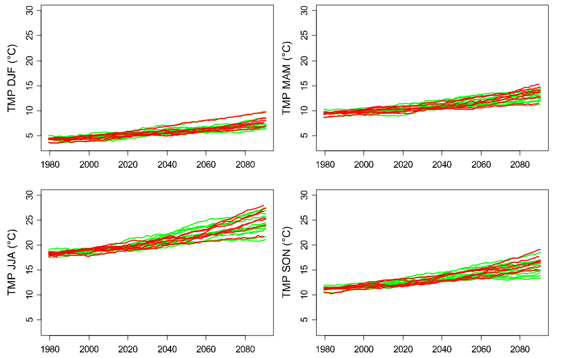
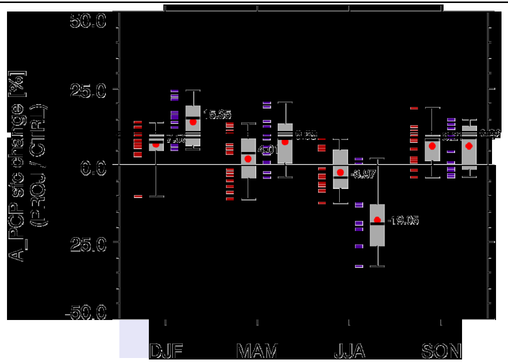
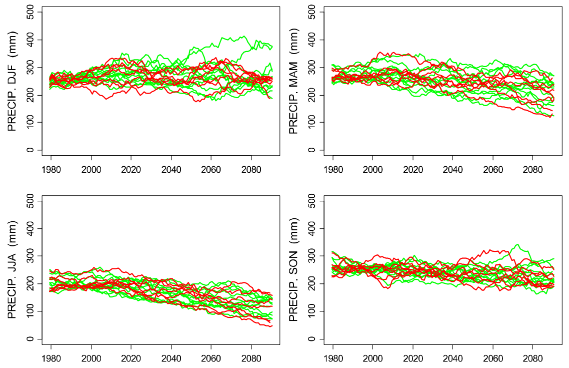
	Rhine basin	Garonne basin
Temperature		
Precipitation		

Figure 2: Seasonal evolutions of temperature and precipitation for the Rhine basin at Lobith and the Garonne basin at Lamagistère. Left: Ranges of relative changes for near (2021 - 2050) and far (2071 - 2100) futures compared to 1961 - 1990 (Source: GÖRGEN et al. 2010); Right: Evolution of the ranges of actual values over the 1980 - 2100 period (Source: SAUQUET 2010) (GHG scenarios: A2 (red) and A1B (green))

7 Main results on hydrological variables

RheinBlick2050 investigated a number of hydrological variables, characterising mean flow, flow regime, low and high flows. The Imagine2030 project investigated the same aspects except high flows, as the project focussed on water resources.

7.1 Mean flow and flow regime

The evolutions of mean annual flows are illustrated in Figure 3. On the Rhine basin, a change towards increasing mean flows can be observed on the downstream stations for the near future, but no change is simulated for the far future. On the upper stations, no significant change is observed. On the Garonne basin, there is a significant change towards decreasing mean flows on all stations (about 10 % on average).

In terms of regime, there should be a progressive shift of flow regime on the upper Rhine basin. This is mainly due to the decrease of snow cover and an earlier snowmelt. In the tributaries of the middle Rhine (e. g. Moselle), the likely increase of winter precipitation and decrease of summer precipitation will result in a more contrasted annual cycle of flows, increasing in winter and decreasing in summer. Therefore the combination of the two changes will yield a clear change on the lower Rhine (Lobith) with shifted and more contrasted flows.

On the Garonne basin, the Pyrenees part of the basin will be, like the upper Rhine, much affected by the change in snow dynamics. The reduced snow cover due to increased temperature will result in a significant decrease of spring flows. More generally, all monthly flows will be affected and will decrease, with changes between 10 to 25 %.

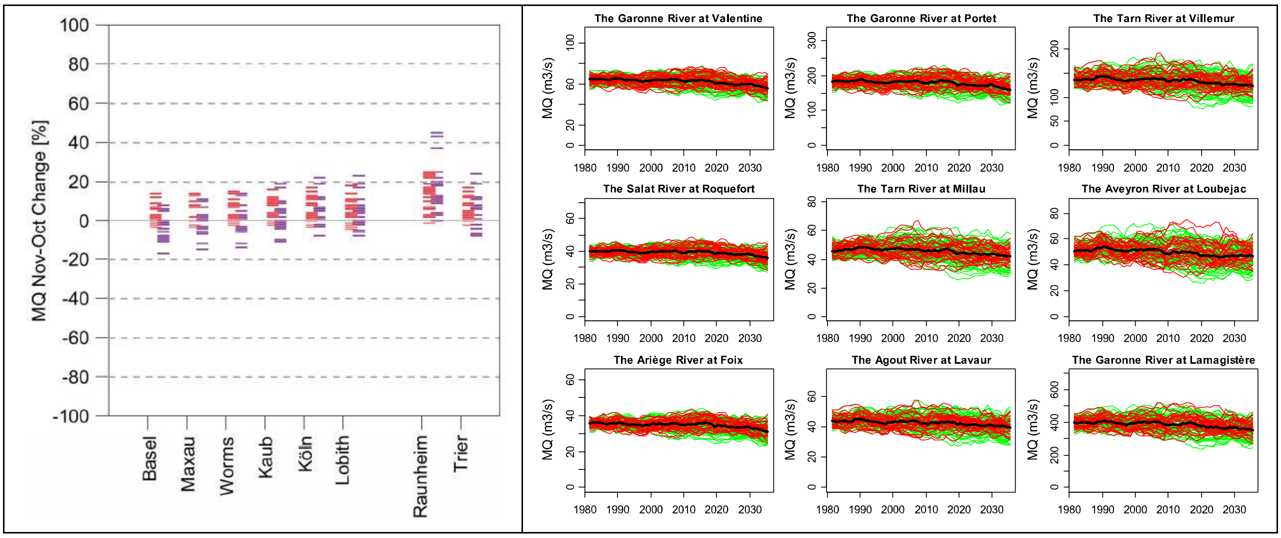


Figure 3: Left: Ranges of relative changes of mean flows (%) over the 8 stations of the Rhine basin for the near (red) and far (purple) futures obtained with the HBV134 model (Source: GÖRGEN et al. 2010); Right: Evolution of the ranges of mean flows (m^3/s) over the 9 stations of the Garonne basin over the 1980 - 2040 obtained with the CEQUEAU model (Source: SAUQUET 2010) (GHG scenarios: A2 (red) and A1B (green); median in black)

7.2 Low flows

On the Rhine basin, the projected winter low flow discharges tend to increase for the near and far futures (0 % to 15 %). Conversely, a decrease of summer low flows is discernible in projections of the far future (-30 % to -10 %).

On the Garonne basin, there is a general decrease of low flows on all sub-basins. This drop in water availability may reach 50 % on some parts of the basin by 2015 - 2045.

This lower availability of water during the dry season may cause important problems in terms of water allocation between the different users.

7.3 High flows

A specific approach was implemented in the RheinBlick2050 project to evaluate the changes in flood quantiles from the mean maximum annual flood up to the 1250-year return period flood. To estimate floods for the largest return periods, the 30-year long time slices of projected flows are not sufficient. Therefore a stochastic resampling technique (based on nearest-neighbour approach, see BEERSMA & BUISHAND 2003) was used to generate 3000-year long series of climate inputs showing similar statistical characteristics. Then these series were fed to the HBV134 hydrological model to produce long discharge time series that could then be statistically analysed. Results indicate that high flows are projected to increase in the tributary rivers and in the lower part of the Rhine river (Cologne and Lobith). For the upstream part of the Rhine River (Basle, Maxau, Worms), no clear conclusions could be drawn. It can be noticed that scenario bandwidths were larger for the far future and for the less probable events.

8 The issue of human activities

The Imagine2030 project investigated the issue of water availability for two demanding activities on the catchment, namely hydropower and irrigation. Models based on temperature were developed to estimate the evolution of electricity demand (hydropower for heating) and water demand for plants (irrigation). Water management rules were considered as unchanged in the future.

In the case of hydropower, the application was made on the Ariège basin (Pyrenees part of the basin). Results show that there should be a general decrease of hydropower production, with more frequent constraints to sustain river discharges in summer. In the reservoirs, the storages should be less variable due to lower water inputs in the spring season. This should incite water managers to adapt management rules in the future.

In the case of irrigation, an application was made on the Aveyron basin in the eastern part of the basin. Results suggest that there should be a significant increase in water demand due to increasing temperatures (between 10 to 20 % depending on the scenarios). This will increase the pressure on water resources, especially during the summer season. Note that these estimates do not account for possible changes in crops or irrigation practices.

9 Conclusions and perspectives

The RheinBlick2050 and Imagine2030 projects similarly investigated the potential impacts of climate changes on the hydrological regimes of the Rhine and Garonne respectively. These two basins show very important stakes in terms of water use. Although they were run independently, the two projects adopted similar approaches. One of these similar characteristics is that, in the perspective of quantifying uncertainties, they chose various modelling options (so-called multi-model approaches) at each step of the modelling chain leading from GHG emission scenarios to hydrological projections.

Interestingly, a few similarities can be observed in the evolution of some hydrological variables on the two basins, among which is the decrease of summer flows that may create larger constraints on water resources. Obviously, there are also some differences. Whereas lower summer flows may be balanced by higher winter flows in parts of the Rhine basin, the Garonne basin will likely experience a general decrease of flows in all seasons. This may make the Garonne basin a 'hot spot' for water management in the future years as the water demand may increase in parallel if nothing is changed in terms of water use.

Apart from the main projected changes, the two projects investigated methodological issues that are important to consider in such prospective studies. The issue of uncertainty quantification appeared crucial in the two projects. This involved an assessment of the reliability of each step of the modelling chain (climate modelling and downscaling, hydrological modelling). For example, in the RheinBlick2050 project, the reliability of dynamical downscaling approaches and bias corrections was evaluated, while Imagine2030 more focused on the whole range of GCMs. Appropriate numerical criteria and graphical representations were also proposed to communicate uncertainty. Bandwidths associated with projections are crucial for managers to fully interpret the significance and likelihood of predicted changes. Both projects were closely conducted with feedbacks from water managers, which should facilitate the use of project results for decision-making.

There are obviously still some limitations and unknowns in the results produced by the two projects, which would require further work. Among them are the needs for improved models at each step of the modelling process. Accounting for the human influences and socio-economic aspects should also be improved, along with the definition of adaptation measures. No doubt that the potential difficulties that could be induced by climate change in terms of risks and water resources management will encourage further investigations on these two basins.

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Projects:

- Development of hydrological models
- Flood forecasting
- Impacts of climate change on surface water

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